NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 185

GRADE EFFECTS ON TRAFFIC FLOW STABILITY AND CAPACITY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- HIGHWAY DESIGN
- ROAD USER CHARACTERISTICS
- TRAFFIC CONTROL AND OPERATION

TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D.C. 1978

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.

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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.

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FOREWORD

By Staff
Transportation
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This report will be of primary interest to highway designers concerned with the effect of grades on traffic performance and consequently on highway capacity, and to highway researchers interested in vehicle capabilities or the use of traffic flow simulation models. Traffic engineers and others concerned with the quality of traffic operations also will find the contents useful. Three major subject areas are treated: (a) study of vehicle performance with respect to acceleration and speed maintenance capabilities; (b) the development, description, and application of a simulation model for rural two-lane, two-way traffic simulations; and (c) evaluation of traffic behavior related to over-width vehicle movements. As well as presenting findings based on investigations made during the course of this project, the report has further value because it has assembled in one document information from a number of other studies.

Variability in vehicle performance capabilities can be a major factor affecting the quality of traffic flow. The performance differences are especially significant on grades, where they increase the likelihood of traffic instabilities, accidents, and reduction of highway capacity. The associated problems may have been aggravated in recent years as the vehicle population has become more diversified. The numbers of both low-performance cars and high-performance sports cars have increased, as has the number of campers and house trailers. At the same time, truck performance capabilities have markedly increased, so that the equivalency factors used in the *Highway Capacity Manual, 1965* have now become outdated.

Awareness of these changes led to initiation of a research project within NCHRP to determine modern vehicle performance characteristics and evaluate their impact on traffic flow. Performance was to be measured by field testing. The evaluation aspect was to be accomplished primarily through the use of simulation models. Additionally, because of their possibly similar impacts on traffic flow characteristics, a field study of the operational effects of wide-load movements was incorporated in the project scope.

The findings that evolved are somewhat different in nature from those anticipated at the beginning of the project. This occurred because of changes in the research plan during the course of the work, made in response to interim findings and in recognition of similar research being conducted by others.

For example, the wide-load studies planned for this project were reduced in scope because a significantly larger FHWA project with an abbreviated timetable was simultaneously carried out by Midwest Research Institute. Appendix J of this report presents some principal findings from that investigation. As another example, the objective of calculating vehicle equivalencies for individual vehicle types was influenced by research findings. The contribution of a vehicle type to the truck factor was found to be a nonlinear function of the vehicle's speed, which is in general agreement with current practice. However, it was found that the truck factor itself should be a nonlinear combination of the contributions from individual vehicles. (The linear form for the truck factor that is in current use does not correctly predict the effects of mixed impeding vehicle types or the effects of a single impeding vehicle type over a reasonable range of percentages.) Results from the simulation were then used to establish equivalency information for a wide variety of vehicles on highways with a 65-mph design speed and speed limit, and 46 percent to 80 percent no-passing zones.

The simulation model can be applied to specific geometries and flows of interest or to extend the equivalency information to additional design speeds, speed limits, and no-passing percentages. To expedite additional application, several appendices of the report detail the development of the model and describe the computer program and its operation. The program, which contains approximately 4,000 statements, is not listed in the report; copies may be obtained at nominal cost upon request to the Program Director, National Cooperative Highway Research Program, 2101 Constitution Avenue, N.W., Washington, DC 20418.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 3-19 by the Highway and Traffic Systems Section, Engineering Sciences Division, Midwest Research Institute, under the direction of Dr. Michael C. Noland, Division Director, and Dr. William Glauz, Section Manager. The principal investigator at MRI, A. D. St. John, Senior Advisor, Transportation Systems, was assisted by Donald R. Kobett, Senior Engineer, Transportation Systems (now Computer Application Engineer, Black and Veatch Engineers, Kansas City, Mo.). Rosemary Moran, Mike Sharp, and Duncan Sommerville also assisted Mr. St. John.

The System Development Corporation collected, reduced, and sorted data on passing behavior. The principal investigators at SDC were: Browne C. Goodwin, John Nemeczky, and Dr. Prem K. Munjal.

Vehicle performance tests were conducted and reported by the Digitek Corporation.

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GRADE EFFECTS ON TRAFFIC FLOW STABILITY AND CAPACITY

SUMMARY

The principal objective of this project was to model, simulate, and interpret flows on two-lane highways in which vehicle types of a wide variety were properly represented. The approach taken to attain this objective included, among other factors, an accurate representation of vehicle acceleration capabilities, driver use of vehicle capabilities, driver behavior in passing opportunities, and estimates of the frequencies with which each vehicle type appears. Information was also sought concerning the effect oversize vehicles have on the service and safety provided to other highway users. Special attention was devoted to the safety measures employed in the movement of oversize loads.

The research activities and major findings for each of the areas of investigation are summarized as follows:

- *Research Activity*—The acceleration performances of passenger cars, pickups, and recreational vehicles were investigated in a field test and supplemented by other data in the technical and popular literature. An engineering analysis was used to codify the results and relationships.
- *Findings*—

1. The acceleration performances of passenger cars, pickups, and recreational vehicles can be represented as a linear function of speed.
2. The numerical values for the acceleration performance capability of passenger and recreational vehicles can be estimated by using their brake horsepower, weight, gear ratios, projected frontal areas, and general geometric configurations.
3. The characteristics required to make the foregoing estimates are not available in convenient form for either registered vehicles or vehicles sold.
4. For most passenger cars and recreational vehicles, the effect of grade on acceleration capability can be estimated by the simple algebraic addition of the gravity component.
5. By using performance equations, estimates of the vehicle population, and speed measured on a 9-percent grade by another investigator, it was determined that on long, upgrade pulls, the drivers of passenger and recreational vehicles restrict the long period demands for performance to about seven-tenths of the maximum available horsepower.

- *Research Activity*—The representation of truck acceleration performances was based on a detailed energy model, the evaluation of separate losses as reported in the literature, analytical tests against field measurements reported in the literature, and finally the selection of a simple but adequate performance equation.
- *Findings*—

1. The acceleration and speed maintenance capabilities of trucks can be estimated by using a modification of the SAE performance prediction equation coupled with a correction for gear shift delays.
2. The SAE coefficients for chassis and aerodynamic losses were reduced in accord with data reported in the literature and for best correspondence with field measurements.
3. For trucks, the effect of grade on acceleration capability is not accurately represented by the algebraic addition of the gravity component. A satisfactory estimate is provided by the approximation including the effects of gear shift delays.

• *Research Activity*—Data were collected on the physical characteristics of a sample of mobile-home and modular-house combinations observed in transit. These data were used in conjunction with the truck performance equation to compare the mobile-home and modular-house combinations with the conventional truck population.

• *Findings*—

1. Practically all mobile-home and modular-house combinations have weight-to-net-horsepower (W/NHP) ratios in the range 100 to 200 lb/NHP. A very few modular-house combinations have ratios up to 330 lb/NHP.

2. The mobile-home and modular-house combinations have large frontal areas (small weight/area ratios). Their maximum speeds on moderate grades, ±2 percent, are 5 to 10 mph lower than the speeds of trucks with equal W/NHP ratios. Their maximum speeds on steep grades are nearly equal to the speeds of trucks with equal W/NHP ratios.

• *Research Activity*—The literature contains extensive data on passing behavior. In this project, these data were supplemented by data collected at three passing zones, only one of which had a steep grade within the zone; the other two sites were in rolling terrain on a heavily traveled highway, so that extensive platooning occurred. The collected data therefore extended the available information to lower leader speeds and to passes made in and from platoons.

• *Findings*—

1. Impeded vehicles not immediately behind the leader of a platoon accept passing opportunities less frequently (52 percent) than the vehicle immediately behind the platoon leader.

2. When no oncoming vehicle is in sight, passing opportunities are accepted immediately after entering the passing zone with higher frequencies than would be expected from the leader speed and sight distance.

3. On the basis of small samples, passing opportunities are accepted with similar frequencies when the vehicles involved (passer or impeder) are passenger vehicles, vans, recreational vehicles, or trucks. Recreational vehicles and trucks are seldom potential passers in upgrade flow; therefore, the data are insufficient to apply the findings to this case.

4. Passing opportunities are accepted with essentially equal frequencies in upgrade and downgrade flows when the effects of leader speed and sight distance are accounted for.

• *Research Activity*—After the computer simulation was tested and adjusted it was applied to different alignments and vehicle populations. However, the greatest number of runs were made with a 65-mph average highway speed, nearly balanced flows, and a percent no-passing that varied from 46 to 80 percent. It is only for this range of variables that results were generated in sufficient quantity to permit generalization.

• *Findings*—

1. The difference in capacity between two unidirectional lanes (4,000 pcph) and two opposing direction lanes (2,000 pcph) is most likely due to driver workloads associated with monitoring oncoming vehicles in the opposing direction flow.

2. The combination of vehicle-performance limits and driver restraint in the use of performance causes significant speed reductions on long grades of 4 percent or greater in flows that are 100-percent passenger vehicles.

3. The current form of the truck factor neglects nonlinear effects and introduces errors in estimates for the effects of varying truck percentages and the effects of heterogeneous truck populations.

4. A nonlinear form derived for the truck factors provides usable estimates of passenger-car speeds in balanced flow traffic with varying percentages of trucks and in balanced flow traffic with different, heterogeneous populations of impeding vehicles.

5. The nonlinear truck factor depends on the percent of each impeding type and on the over-all speeds of each impeding vehicle type traveling alone on the geometrics of interest.

6. The nonlinear truck factor can be used to estimate the effects of the crawl speeds used downgrade by trucks on the passenger-car speeds.

• *Research Activity*—The computer simulation was also used to test the effects of vehicle dimensions and the effects of changes in percent no-passing.

• *Findings*—

1. Differences in length between normal vehicles, such as the 19-ft camper vs. the 36-ft-travel-trailer combination, do not have a significant effect on flows in which the over-all average speed of the passenger cars is greater than 30 mph.

2. In a 600-vph total flow through rolling terrain on a two-lane highway, the 300-lb/NHP trucks replaced by 300-lb/NHP modular-house combinations produced a small decrease (0.5 to 3.0 ft/sec) in passenger-vehicle speeds. (There was no allowance for stops or speed reductions at bridges or other narrow features.)

3. The advantages of a 59-percent no-passing facility over an 80-percent no-passing facility are reflected by increased speeds at total flows under 600 vph. On a 59-percent no-passing facility, passing is prohibited on 59 percent of the total lane length.

• *Research Activity*—Accident involvement rates were predicted by using simulation results in conjunction with Solomon's report (*57*), where involvement rates are presented as a function of deviation from the mean speed. Estimates were based primarily on nearly balanced flows on a 65-mph highway in a variety of terrains.

• *Findings*—

1. For flows of passenger cars, only the rate (vehicle involvements per vehicle mile) is nearly constant over the range from light flows to flows approaching capacity.

2. In flows up sustained grades of 4 to 8 percent, vehicle populations with many recreational vehicles and a few trucks have involvement rates that are about 133 percent of the rates of flows with all passenger vehicles.

3. In flows up sustained grades of 4 to 8 percent, with sizable fractions of low-performance trucks and truck populations, the involvement rates can increase to 175 to 250 percent of the rates for flows with all passenger cars.

4. In flows on severe rolling terrain, the accident involvement rate is slightly increased by the presence of recreational vehicles and trucks.

5. The accident rates are increased in flows down sustained grades of magnitude greater than 4 percent by trucks using crawl speeds to maintain control.

• *Research Activity*—The potentials for instabilities in traffic flows were evaluated from simulation results quantified on a per vehicle mile basis, using the simulation results on the platoons of vehicles that overtake the impeders and on the perturbations, within the platoons, that are caused by passing maneuvers and aborted passes.

• *Findings*—

1. In flows of passenger cars only, the potential for instabilities in flows approaching capacity increases to four times the value for light flows.

2. In mixed flows up sustained grades, significant numbers of low-performance trucks can increase instability potential severalfold over values for passenger cars only.

3. In mixed flows up sustained grades, with many recreational vehicles and few trucks, the instability potential is intermediate between the values for passenger cars only and for flows dominated by low-performance trucks.

4. In rolling terrain, the presence of trucks and recreational vehicles causes a moderate increase in the potential for instability.

5. In flows where instability potentials and accident involvement rates are highly elevated because of steep sustained grades and low-performance vehicles, a lower speed limit ameliorates the situation.

• *Research Activity*—Data were obtained in this project and in a related FHWA-HUD project on the movement of mobile-home and modular-house loads with widths of 12 and 14 ft. The data were collected by direct observations and by time-lapse photography. The photographing was conducted from the cab of the towing tractor, inside the load, and from the escort vehicles.

• *Findings*—

1. Wide loads cause the least disturbance to other traffic on Interstate and other high-design type, multilane facilities, especially when the wide load is permitted and capable of maintaining a speed of 50 mph or more.

2. Overtakers on divided highways reacted in a less hazardous fashion (see Chapter Two for measure of hazard), if the wide load was traveling near their speed. They reacted most cautiously, not to the wide load, but to a rear escort with high-intensity flashers (the low-intensity flashers on the wide load were generally ineffective); similar approaches were made to 12- and 14-ft-wide loads.

3. Wide-load combinations did not experience noticeable difficulty negotiating ramps or merging into traffic.

4. Overtakers approached the wide loads more cautiously on two-lane highways than on multilane facilities. They made less hazardous approaches to wide loads traveling at high speeds, and they approached rear escorts with high-intensity flashers very cautiously.

5. In the opposing traffic on two-lane highways, vehicles moved laterally away from the front escort and from the wide load with a total movement dependent on available lane width; autos moved further from their normal position and decelerated more than trucks did. Some of the autos used part of the shoulder on 10-ft lanes approaching a 14-ft-wide load. Because of their own greater width, all of the trucks used part of the shoulder in the same situation.

7. Queuing behind wide loads is common on two-lane highways. The presence of a rear escort appears to enhance queuing.

8. Rear escorts appear to be unnecessary on divided highways and on some high-design type, two-lane highways. The functions of the rear escort in these situations would be served by high-intensity flashers on the rear of the wide load.

9. Lead escorts on two-lane highways can provide valuable assistance in the orderly movement of the wide load and other traffic. The full value of the lead escort requires two-way radio communication between the drivers.

10. The inappropriate responses of some escort drivers indicate that improved safety and service might be obtained by mandatory training and licensing.

11. Tire problems occur frequently enough on the mobile and modular house loads to warrant a special study.

12. Wide-load routing should give preference to Interstate and multiple-lane facilities and lower priority to high-grade two-lane facilities. Low-standard two-lane highways with narrow lanes and short sight distances should be avoided unless absolutely necessary.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The nonuniform performance capabilities of vehicles comprise a major detrimental factor in the flow of traffic on two-lane roads and on multilane highways. The performance differences, which are more pronounced on grades, increase the likelihood of traffic instabilities, accidents, and loss of highway capacity. This problem is further influenced by a diversification of the vehicle population in the United States as regards both performance capability and size. There is an increase in the proportion of cars of very low performance, cars of very high performance, and campers and travel trailers. Concurrently, truck performance capability has increased markedly. The range of load widths has been influenced by the increased road transport of mobile homes and modular houses. Load widths of 10 to 14 ft equal or exceed those of the lane on some highways.

Major objectives of this research were to provide and apply a methodology to determine the performance capabilities of vehicles on public highways, to determine equivalency factors for low-performance vehicles, and to determine the role that performance and size play in traffic instabilities, accidents, and loss of capacity.

In attaining these objectives, the acceleration and speed-maintenance capabilities of a wide range of vehicles were determined with performance tests and analyses of data in the literature. The vehicles included trucks and combinations, buses, campers, travel trailers, passenger cars of low performance, and other atypical vehicles found on Interstate and primary highway systems.

A computer simulation was developed based on field measurements and data published in the literature. The simulation was applied to determine equivalencies and to explore the accident implications of the two-lane, two-way traffic situations.

A major goal of this project was to provide guidance for the establishment of regulations covering the road transport of wider than normal loads. This was to be accomplished by determining, through direct observations, the effects on safety and traffic flow of 12- and 14-ft-wide loads on highways in varying terrain. The work on this phase was curtailed in light of data from a more extensive FHWA project in the subject area. A summary of the FHWA project results, however, is included in this report.

CHAPTER TWO

FINDINGS

This chapter is divided into three sections. The first deals with the acceleration and speed-maintenance capabilities of a wide range of vehicle types found on public highways. The second section describes the essential features of a computer simulation for two-lane, two-way traffic and includes the results from the simulation. The third section describes the behavior observed in traffic flow near over-regulation-width loads.

ACCELERATION AND SPEED-MAINTENANCE CAPABILITY

Passenger, Recreational, and Utility Vehicles

Test results reported in the literature and those obtained in this project indicate that the acceleration capability of passenger cars, pickups, and recreational vehicels is a linear function of speed:

$$a = a_0 [1 - (V/\bar{V}_m)] \quad (1)$$

where:

a = acceleration capability at speed V on a zero grade;
a_0 = maximum acceleration at a speed near zero; and
$\bar{V}_m$ = a pseudo-maximum speed. This is the maximum speed indicated by the linear relation between acceleration and speed when data are fitted in the normal operating range. This maximum occurs at $a = 0$.

Engineering analyses and correlation tests indicate that a_0 and $\bar{V}_m$ can be predicted from measurable characteristics of the vehicles. A single expression predicts the maximum acceleration, a_0, for passenger cars, for pickup trucks, for light trucks up to 2-ton rating, and for these vehicles pulling trailers. The equation is:

$$a_0 = 0.86 + 31.38 \left(\frac{r_1 r_2}{W/\text{bhp}}\right) \quad (2)$$

where:

a_0 = maximum acceleration, ft/sec²;
r_1 = transmission first gear ratio;
r_2 = rear axle ratio;
W = vehicle or combination gross weight, lb; and
bhp = manufacturer's maximum rated brake horsepower.

Analysis of performance data in Ref. (*35*) indicates that for motor homes and large sport vans a more accurate expression is:

$$a_0 = -0.6744 + 29.77 \left(\frac{r_1 r_2}{W/\text{bhp}}\right) \quad (3)$$

For all of the foregoing vehicles, the pseudo-maximum speed is estimated by the expression

$$\bar{V}_m = 10.28 + 0.60\sqrt[3]{1/[\alpha(W/\text{bhp})]} \quad (4)$$

where:

$\bar{V}_m$ = pseudo-maximum speed of Eq. 1, ft/sec;
W = gross weight, lb;
bhp = manufacturer's maximum rated brake horsepower;
$\alpha = \left(\frac{\rho C_D A}{2W}\right) + C_{RV}$, sec²/ft²;
ρ = atmospheric mass density, (lb sec²)/ft⁴;
C_D = aerodynamic drag coefficient;
A = projected frontal area of vehicle or assembled combination, ft²; and
C_{RV} = coefficient of V^2 in equation for rolling resistance in Appendix A (0.65×10^{-6} for speed in units of ft/sec).

Altitude effects appear in the expressions for both a_0 and $\bar{V}_m$. Brake horsepower is corrected for elevation, E(ft), by the factor $(1 - 0.0004\,E)$. The aerodynamic drag is reduced at higher elevations because of reduced atmospheric density. The correction factor for atmospheric density is $(1 - 0.000006887\,E)^{4.255}$.

Commercial-Vehicle Acceleration and Speed-Maintenance Capability

Several techniques and associated results are currently in use to predict the performance of commercial vehicles. In Huff and Scrivner (*3*), a simple analytical formulation is used in conjunction with vehicle tests to describe the acceleration and deceleration of a heavy truck (392 lb/NHP) on grades. In Firey and Peterson (*4*), coasting test results are used in an analytical model to produce performance curves for a variety of weight/power ratios, vertical curves, and grades. Their work takes explicit account of gear shift delays, but does not identify separate power losses. The SAE-recommended practice (*5*), on the other hand, treats steady-speed power losses in detail, but it is not intended to apply to dynamic situations in which gear shifts are important. Smith (*6*) describes a comprehensive investigation and proprietary computer program that calculates performance with a detailed account of vehicle characteristics and driver decisions.

In this project, computational techniques and results were sought that would account for important vehicle characteristics and for shift delays. The specific account of individual vehicle characteristics is required for application to the wide and changing variety of vehicles on the road. The importance of treating shift delays explicitly, if possible, is shown by even the simplest calculations of dynamic situations.

In the research program, a highly detailed analytical model was developed and computerized based on the SAE-recommended practice (*5*). A simplified model was also developed; however, in comparing its results with results from the detailed model, the latter model was shown to be more convenient for computations. The computer program of the more detailed model uses assignable engine characteristics of net horsepower versus rpm and then designs a transmission according to standard practice. The program calculates vehicle performance on grades with an explicit account of the engine characteristics and decelerations during gear shifts. Gear ratios may be skipped where it would be beneficial.

After testing the model and comparing the computer-generated acceleration-speed histories with data published by the Western Highway Institute (*8*) and the Road Research Laboratory (*9*), it was found that (1) engine inertia could be important in the low-speed gear ratios; (2) the accelerations of very heavy, low-performance trucks were underestimated; and (3) the performance of lightly loaded trucks was slightly overestimated.

Four areas of possible adjustments were noted: (1) the time required to shift gears, (2) the rolling losses, (3) the chassis losses, and (4) the aerodynamic losses. Data from Refs. (*6*), (*8*), (*10*), and (*11*) were used to evaluate the need for adjustment in the individual areas. As a result, two changes were made to the original SAE coefficients.

The rolling force, which is linearly dependent on speed, was reduced to 22 percent of its original value. The aerodynamic drag term was reduced to 72 percent of its original value.

The adjustments improved the agreement between the calculated and published performance values. The calculated values for lightly loaded trucks (100 or 200 lb/NHP) remain slightly high. It is possible that driver motivation is not as great in a truck with fairly high performance. In these trucks, the number of gear ratios skipped may also be somewhat greater than is consistent with highest performance.

The detailed computer program simulated trucks starting and accelerating on both positive and negative grades. Runs were also made in which trucks entered positive grades at high speed, made successive down shifts, and arrived at steady crawl conditions. It was found that the effects of grades are not accurately represented by the simple addition of a gravity component to the zero-grade performance. This simple adjustment overestimates the effects of grades. The reason is associated with the gear shifts.

When a gear shift is made on an upgrade, the grade effect causes additional deceleration during the coast. On the basis of this effect alone, one might erroneously conclude that the simple addition of a gravity component would underestimate the over-all grade effect. This conclusion ignores the importance of the fraction of time the engine is usefully employed.

When a heavy truck starts and accelerates on zero grade, a short time is spent in each low-speed gear ratio after the first. However, the time to shift gears is about 1.5 sec. Thus, a large fraction of the time is spent coasting without power applied. If the same truck starts on a positive grade, the acceleration in each gear ratio is lower and the time in each ratio is longer. Therefore, the engine is usefully employed a larger fraction of the time.

On a downgrade, the penalty for shift delays may become extreme. It may be advantageous to skip a gear ratio and initially operate the engine after the shift at a relatively low speed and power, but thereby increase the fraction of time the engine is employed.

A simple and useful performance equation was derived by employing the concept that the engine is employed a varying fraction of the total time. The simple performance equation is

$$A_e = \left[\frac{\eta V}{\eta V + S_p t_s (\bar{A}_p - \bar{A}_c)} \right] \bar{A}_p, \; V > V_1 \qquad (5)$$

where:

A_e = the effective acceleration, ft/sec^2;
η = a parameter dependent on the range of engine speeds normally employed; typical values range from 0.33 to 0.43 (0.4 is recommended);
V = vehicle speed, ft/sec;
$\bar{A}_p$ = power-limited acceleration (i.e., with engine employed and vehicle at speed V); the bar indicates the use of average available net horsepower, ft/sec^2;
S_p = one times the sign of $\bar{A}_p$ (which can be either + or −);
t_s = actual time required to shift gears, sec;
$\bar{A}_c$ = acceleration in coasting at vehicle speed V, ft/sec^2; the bar indicates the use of an average gear ratio for the coasting chassis losses; and
V_1 = maximum speed in lowest speed gear ratio, ft/sec.

Both $\bar{A}_p$ and $\bar{A}_c$ include the direct added effect of the gravity components associated with grades. Also, $\bar{A}_c$ will normally be negative except on downgrades.

When vehicle speed is less than V_1, the transmission will be in the first ratio and the normal shift delay compensation is not applicable. For this situation, the product ηV in both the numerator and denominator is replaced by V_1. Estimates for V_1 are given in Appendix C. However, a usable average value is 10 ft/sec.

The equations for $\bar{A}_p$ and $\bar{A}_c$ are the forms modified from the SAE-recommended practice. Very simple forms with satisfactory accuracy are obtained by using (1) average available net horsepower is 0.94 of rated maximum, and (2) engine inertia and the chassis losses are based on an engine with 200 NHP. Thus:

$$\bar{A}_p = \left\{ \frac{15145\, C_{pe}}{(W/\text{NHP})\, V} - 0.2445 - 0.00044\, V - \frac{0.0228}{(W/A)} V^2 C_{de} - g \sin \alpha \right\} \Big/ \left[1 + \frac{14080}{(W/\text{NHP})\, V^2} \right] \qquad (6)$$

$$\bar{A}_c = \frac{-222.9}{(W/\text{NHP})\, V} - 0.2445 - 0.00044\, V - \frac{0.228}{(W/A)} V^2 C_{de} - g \sin \alpha \qquad (7)$$

where:

C_{pe} = altitude correction factor converting sea level net horsepower to local elevation = $(1 - 0.00004\, E)$ for gasoline engines;
C_{de} = altitude correction factor converting sea level aerodynamic drag to the local elevation of E(ft) = $(1 - 0.000006887\, E)^{4.255}$;
V = vehicle speed, ft/sec; use $V = V_1$ if $V < V_1$;
W = gross weight, lb;
NHP = rated net horsepower at sea level conditions;
A = projected frontal area, ft^2;
g = acceleration due to gravity = 32.17 ft/sec^2;
α = grade angle, radians; and
$\sin \alpha \approx$ percent grade/100.

Eqs. 5, 6, and 7 have been employed in the simulation to calculate the performance curves shown in Figures 1 and 2. A complete set of performance curves is presented in Appendix E. The curves may be used to estimate the speeds of trucks on grades or in rolling terrain. As shown later, these speeds are needed to calculate a truck factor. The equations and performance curves are also used to compare the acceleration and speed performances of trucks and of combinations with a mobile home or modular house load.

The truck performance equations include a specific allowance for delay in gear shifts, with 1.5 sec used in the numerical calculations. However, it is recognized that driver skill and motivation enters in the selection of shift points and ratios. There are other factors that may cause variations in truck performance. The transmission is as-

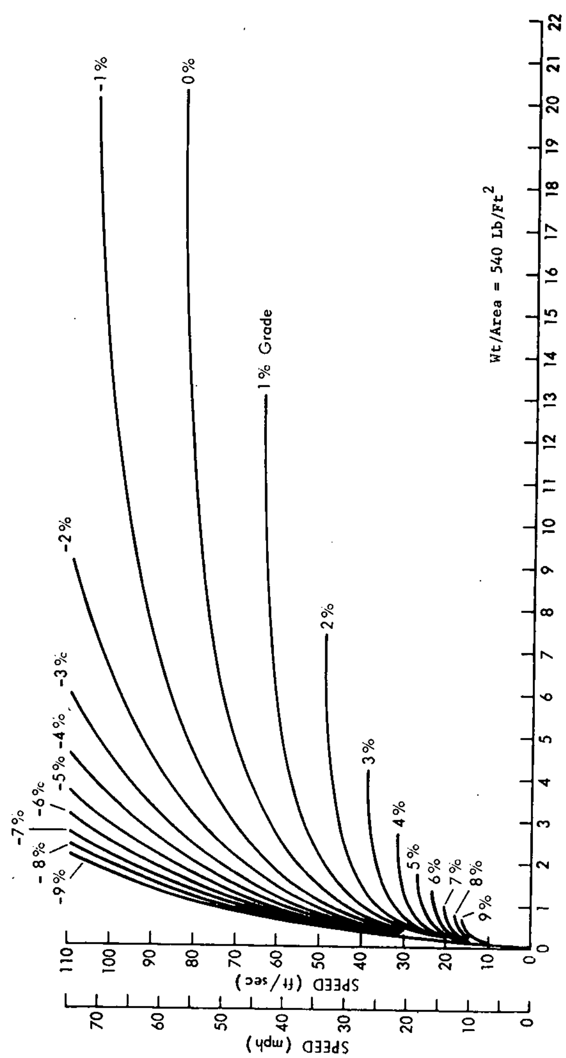

Figure 1. Speed-distance relation for a 300-lb/NHP truck accelerating from rest.

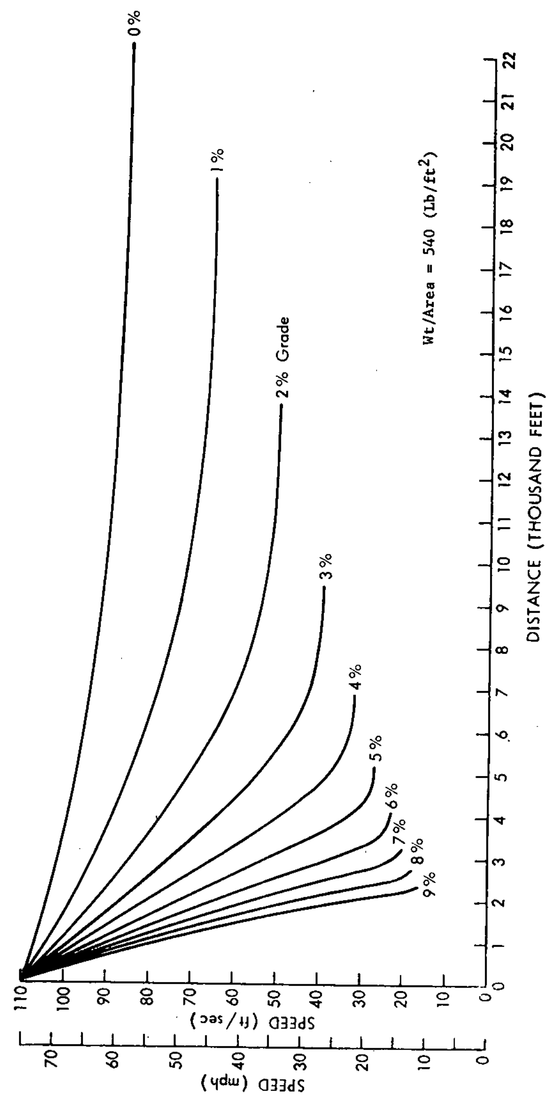

Figure 2. Speed-distance relation for a 300-lb/NHP truck decelerating from 110 ft/sec.

sumed to have typical ratio steps and a sufficient number of ratios to cover the speed range over which the vehicle is capable of operating. These assumptions should hold true for equipment used in long haul operations. Economic factors should preclude the use of mismatched transmissions or axle ratios. However, in short-haul equipment found near urban areas and in construction work, economic factors may favor transmissions with wide steps or over-all ratios insufficient to reach the high speeds the unit would otherwise attain on the basis of gross weight and net horsepower.

Vehicle Populations

For the purposes of this project a vehicle population is defined by three kinds of data:

1. The types and lengths of vehicles.
2. The frequencies at which the vehicle types appear in the traffic stream.
3. The acceleration and speed capabilities of the individual vehicle types.

The equations that can be used to estimate performance capabilities from data on the power, weight, and size of the vehicles were described in the previous section. However, there is currently no convenient way to obtain all the information needed to define vehicle populations. The sources of data are technical publications, popular literature, registration files, results from surveys and questionnaires, field observations and measurements, and performance data compiled by the National Highway Safety Bureau.

In particular, the statistical issue of *Automotive Industries* is a most useful technical publication from which estimates of the passenger-vehicle population can be obtained. The estimate requires a large amount of compilation labor, application of the equations for performance estimates, and application of engineering judgment. Estimated performance characteristics based on this process for domestic and imported passenger vehicles for the 1971 Model year are given in Table 1.

On the basis of this analysis, three passenger vehicle types were selected, as described in Table 2, to represent the population. It is recognized that this selection is based on vehicles sold in a Model year rather than on the population

TABLE 1

SUMMARY OF 1971 MODEL YEAR ESTIMATED PERFORMANCE CHARACTERISTICS—DOMESTIC AND IMPORTED PASSENGER VEHICLES

W/Bhp Range	Bhp	Vehicle[a/] Types	Wt/Bhp (average)	Wt (lb) (average)	$r_1 \cdot r_2$ (average)	$\bar{V}$max (ft/sec)	a_o (ft/sec^2)	Percent
8-10	405	I	9.09	3,681	6.38	151.3	22.95	5.9790
	392	C	9.04	3,540	7.28	154.3	26.13	1.0935
10-12	369	F	11.53	4,250	6.81	141.8	19.41	5.5960
	356	I	10.59	3,767	6.74	145.1	20.87	0.5370
	317	C	11.13	3,528	7.18	144.5	21.12	1.1685
12-14	337	F	12.97	4,374	6.73	137.8	17.17	11.0445
	286	I	13.97	3,991	6.78	135.3	16.09	1.9800
	273	C	13.15	3,585	7.58	137.8	19.01	0.7645
14-16	335	F	14.64	4,898	7.22	136.7	16.34	4.9505
	266	I	15.12	4,026	6.40	132.3	14.14	7.5290
	231	C	14.72	3,402	7.49	135.4	16.47	1.6585
16-20	254	F	18.05	4,580	6.94	126.0	12.98	12.5930
	223	I	17.55	3,912	6.25	125.5	12.17	5.4950
	203	C	17.56	3,559	6.39	125.9	12.32	2.5665
	117	SC	18.3	2,150		111.4	12.30	1.2050
20-24	234	F	20.85	4,884	7.00	122.6	11.39	4.8320
	143	C	23.20	3,312	5.87	113.5	9.12	1.8740
	112	SC	22.82	2,563	5.66	109.3	9.76	1.1715
24-28	144	I	25.98	3,739	6.85	110.0	9.14	0.9850
	124	C	26.67	3,317	7.37	108.8	9.59	5.3850
	94	SC	25.16	2,360		103.8	9.51	5.4035
28-32	145	F	28.90	4,200	5.61	106.8	6.95	0.1250
	140	I	28.76	4,033	7.44	108.8	8.96	0.1870
	100	C	30.32	3,045	9.46	102.4	10.66	1.1440
	93	SC	30.49	2,836		102.8	8.44	4.9450
32-36	75	C	33.30	2,500		94.6	9.0	0.7080
	75	SC	32.70	2,450		96.9	9.1	1.4205
36-40	63	SC	37.58	2,385		92.3	8.55	2.2065
> 40	63	SC	52.0	3,300		91.2	7.60	4.9500
	81	C	56.1	4,570		94.4	7.40	0.2245
	42	SC	60.7	2,530		81.4	7.30	0.2780

a/ F = full sized, I = intermediate, C = compact, SC = subcompact.

in service or observed on a highway. However, the selection appears consistent with performances observed on steep grades (*44*).

A similar type of estimate could be obtained from registration data if both weight and horsepower (or taxable horsepower) were included. At the time of this investigation, however, no state recorded both the weight and a measure of horsepower.

The popular literature was used to establish the correlation between weight and length for travel and camper trailers, as shown in Figure 3. The weights include an allowance for water and gear equal to: 750 lb for 2,000-lb trailers; 1,000 lb for 3,000-lb trailers; and 1,250 lb for trailers over 4,000 lb. However, an addition of 12-percent weight was necessary to construct a population of combinations with the weight, horsepower, and weight/horsepower ratios given by Wojcik and Mellinger (*43*). The combinations employ four classes of trailers with the characteristics given in Table 3. The representative combinations appear in Table 4. The aerodynamic drag coefficient $C_D = 0.59$ was used to calculate pseudo-maximum speeds in Table 4.

Three combination types were selected on the basis of Table 4 values and revised slightly to reflect data collected by Werner (*44*). The final characteristics are given in Table 5.

TABLE 2

PASSENGER-VEHICLE TYPES (STANDARD SEA LEVEL CONDITIONS)

Description	Maximum Acceleration (ft/sec^2)	Pseudo Maximum Speed (ft/sec)	Length (ft)	Percent	Range Represented (lb/BHP)
High performance	14.0	135	18	63	8-20
Medium performance	9.5	110	18	27	20-32
Low performance	8.0	100	18	10	> 32

Data from the technical publications and the popular literature were used to establish the range of performances for campers. There was essentially no way to estimate the distribution of performance characteristics, especially since the vehicles can be lightly or heavily loaded. From Ref. (*43*) it appeared that sizable fractions have covers or light, small shells, and should perform like passenger cars. A tentative selection of performance characteristics therefore was made, and, subsequently, data from Werner (*44*) were used to adjust the values to those given in Table 6. The results indicate that the high-performance campers (34 percent of campers) are best represented as a combination of medium- and high-performance passenger cars.

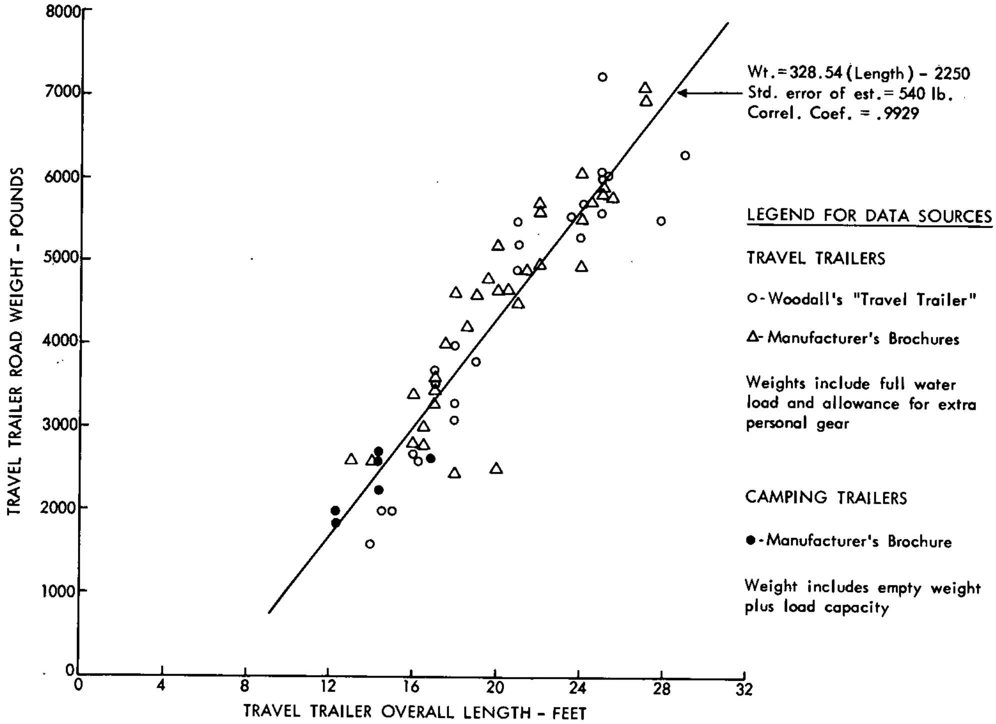

Figure 3. Travel trailer weight and length relationship.

TABLE 3

TRAVEL TRAILER CHARACTERISTICS

Class	Length (ft)	Road Weight (lb)	Projected Front Area (ft^2)	Percent Represented
1	10	1,000	46	10
2	14	2,400	55	40
3	18	3,700	64	40
4	27	6,600	64	10

The range of motor home performance can be estimated from data and tests in the literature. The initial estimates were revised to conform to the speed-on-grade data collected by Werner (*44*). The characteristics are given in Table 7.

The distributions of vehicle types in traffic flows were based on field observations and the following data sources and environments:

Siria (*45*)—U.S. and Interstate rural highways.
Werner (*44*)—Primary rural highways near Canadian national parks.
Munjal (*42*)—Essential primary state route; long-distance traffic (Pacheco).
Munjal (*42*)—Secondary state route near urban area (Topango Canyon).
Wright and Tignor (*46*)—U.S. rural highways; truck population in 1965.

Three truck types were chosen (see Table 8) based on the Wright and Tignor data. The truck population measured by Wright and Tignor appears to correspond to that observed recently by Werner in a National Park Area. The populations measured by Munjal in 1973 on the primary and secondary rural routes require different distributions. The distributions in Table 9 were constructed on the basis of truck configurations and the speeds on a 5-percent grade. Intercity bus performance lies between the high performance and typical truck types and should be represented by a mixture of these types.

The distributions of recreational vehicle types from Refs. (*42*) and (*44*) were used to complete Table 10. In non-recreational areas, T may range up to 25 percent and R appears to range between 4 and 7 percent. In recreational areas, T may be as low as 2 percent; R ranges up to 36 percent. The representations of vehicle populations are given in the last two columns of Table 10. The populations implicitly account for unusual and utility vehicle types that are not explicitly identified. The assignments, given in Table 11, have been made on the basis of speeds observed on a 9-percent grade (*44*) and the performance tests conducted for this project.

SIMULATION FOR TWO-LANE, TWO-WAY TRAFFIC

Requirements for Project Purposes

The simulation developed in this project was required to have the capability to determine the effects of vehicle types and highway geometries on capacity, service, and safety. To meet these requirements, the simulation needed to include an account of vehicle-performance characteristics, driver use of performance characteristics, overtaking and following, and driver decisions in passing maneuvers.

The simulation developed by Franklin Institute Research Laboratories (*31*) and improved by North Carolina State University (*39*) contained some, but not all, of the re-

TABLE 4

REPRESENTATIVE TOW VEHICLES AND TRAVEL TRAILER COMBINATIONS

Tow Type	BHP	$r_1 r_2$	Trailer Class	Projected Area (ft^2)	GCW (lb) & (total length)	W/BHP	W/A (lb/ft^2)	Maximum Acceleration a_o (ft/sec^2)	Pseudo-Maximum Speed $\bar{V}_{max}$ (ft/sec)	Comments	
Car	375	7.0	2	55	7,500	20.00	136	11.83	113.02	With standard gear ratio	Representative of highest performance 10%
Car	↓	8.2			(32)			13.73		With towing gear ratio	
Pickup	↓	10.0						16.55			
Car	325	7.0	1	46	5,940	18.28	129	12.02	114.11		
Car	↓	8.2			(28)			14.94			
Pickup	↓	10.0						18.03			
Car	375	7.0	4	64	12,200	32.53	191	7.61	108.08		Representative of performance of median combinations
Car	↓	8.2			(45)			8.77			
Pickup	↓	10.0						10.51			
Car	275	7.0	3	64	8,960	32.58	140	7.60	101.76		
Car	↓	8.2			(36)			8.76			
Pickup	↓	10.0						10.49			
Car	225	7.0	2	55	7,500	33.33	136	7.45	100.74		
Car	↓	8.2			(32)			8.58			
Pickup	↓	10.0						10.27			
Car	125	7.5	2	55	7,170	57.36	130	4.96	89.04	In lowest performance 5%	Representative of lowest performance combinations
Pickup	↓	10.0			(32)			6.33			
Car	175	7.0	4	64	12,200	69.71	191	4.01	91.58		
Car	↓	8.2			(45)			4.55			
Pickup	↓	10.0						5.36		In lowest performance 1%	
Car	125	7.5	3	64	8,625	69.00	135	4.27	86.30		
Pickup	↓	10.0			(36)			5.41			
Car	90	9.5	2	55	6,385	70.94	116	5.06	83.59		
					(28)						

C_D = 0.59 for all cases.

TABLE 5

CHARACTERISTICS OF SELECTED TRAVEL TRAILER COMBINATIONS (STANDARD SEA LEVEL CONDITIONS)

Description	Maximum Acceleration (ft/sec^2)	Pseudo Maximum Speed (ft/sec)	Length (ft)	Percent
High performance	12.0	110	32	10
Medium performance	9.2	104	36	80
Low performance	6.2	104	36	10

TABLE 6

CAMPER CHARACTERISTICS (STANDARD SEA LEVEL CONDITIONS)

Description	Maximum Acceleration (ft/sec^2)	Pseudo Maximum Speed (ft/sec)	Length (ft)	Percent
Medium performance	10.0	100	19	56
Low performance	7.6	91	19	10

TABLE 7

MOTOR HOME CHARACTERISTICS (STANDARD SEA LEVEL CONDITIONS)

Description	Maximum Acceleration (ft/sec^2)	Pseudo Maximum Speed (ft/sec)	Length (ft)	Percent
Nominal performance	10.4	100	22	85
Low performance	7.0	100	26	15

TABLE 8

CHARACTERISTICS OF SELECTED TRUCK TYPES

Description	W/NHP	W/A	Length	Percent	Fraction Single Units
High Performance	125	300	40	66	0.563
Typical	300	580	65	23	0.077
Low Performance	400	895	65	11	0.0

TABLE 9

TRUCK POPULATIONS

Type	W/NHP	Percent in Flows: Primary Route	Recreation Area	Secondary Route
High performance	125	41	66	75
Typical	300	48	23	20
Low performance	400	11	11	5

TABLE 10

PERCENTS OF INDIVIDUAL VEHICLE TYPES IN POPULATIONS

Type No.	Description	Primary Highway Nonrecreational Area	Primary Highway Recreational Area
1	Low Performance Truck	0.11 T[a]	0.11 T[a]
2	Typical Truck	0.48 T	0.23 T
3	High Performance Truck	0.41 T	0.66 T
4	Low Performance Camper	0.0494 R[b]	0.0345 R[b]
5	Low Performance Travel Trailer	0.0248 R	0.0382 R
6	Low Performance Motor Home	0.0060 R	0.0083 R
7	Medium Performance Camper	0.2768 R	0.1934 R
8	Nominal Performance Motor Home	0.0340 R	0.0468 R
9	Medium Performance Travel Trailer	0.2808 R	0.3773 R
10	High Performance Travel Trailer	0.1713 R	0.1842 R
11	Low Performance Car	0.100 P[c]	0.1 P[c]
12	Medium Performance Car	0.27 P + 0.112 R	0.27 P + 0.0782 R
13	High Performance Car	0.63 P + 0.0561 R	0.63 P + 0.0391 R

(a) T = Percent of trucks in the population.
(b) R = Percent of recreational vehicles plus utility trailer vehicles in the population.
(c) P = Percent of passenger vehicles and 1/2 ton pickup trucks in the population.

TABLE 11

ASSIGNMENT OF VEHICLE TYPES OTHERWISE UNIDENTIFIED

Type	Assignment to Explicit Types
1/2 ton pickup	passenger vehicles
Passenger vehicle or pickup with utility trailer or with vehicle trailer	treat as travel trailer combinations with distribution-- 3% lowest performance 47% medium performance 50% high performance
converted school bus	treat as travel trailer combinations with above distribution
recreational van	(same as above)
high performance camper	66% medium performance passenger vehicle 34% high performance passenger vehicle

quired capabilities. In particular, only truck performance was included in the improved version; driver use of performance capabilities was neglected, and the overtaking and following logic was oversimplified for the present purposes.

A description of the simulation developed in this project is presented in Appendix G. Equations and numerics employed are included in Appendix H. The following section provides a brief description of the important elements in the simulation and the data employed.

Speeds

Speeds play important roles in the simulation. They are required in the input and are used internally; the speeds achieved in the simulation also form part of the output.

Input to the simulation contains a mean speed and standard deviation. These values define for the simulation the distribution of the speeds that the individual drivers would prefer to use on the tangent and gently curving sections of the simulated highway. These speeds correspond closely to the distributions of spot speeds measured in the real world in very light traffic in sections that do not contain restrictive geometrics. Additional input to the simulation can specify speeds that individual categories of vehicles (trucks, recreational vehicles, or passenger cars and pickups) would prefer that are biased up or down. The input values are used in a stochastic process to assign each simulation vehicle a "desired speed." This is the normal "desired" speed for the vehicle—in other words, the vehicle's preferred speed of travel in the absence of unusual local geometrics or impeding vehicles, provided it has the performance required. Within the simulation, the desired speed can be reduced in a horizontal curve, on the approach to the curve, or—for a truck—on a long, steep downgrade. A vehicle's desired speed is increased during a passing maneuver. The input distribution of desired speeds is associated with the highway design speed and/or speed limit.

Over-all travel speeds are obtained in the simulation in the section of highway designated for data collection. The mean and standard deviation of over-all travel speeds is obtained in each direction of travel for each vehicle category (passenger cars and pickups, recreational vehicles, and trucks).

The operating speeds measured in the simulation are obtained in near-accordance with the definition in the "Highway Capacity Manual" (*53*). The operating speed is estimated as the mean over-all travel speed of a sample of passenger cars, the sample being restricted to the medium- and high-performance passenger cars whose desired speeds fall within a designed range, so that the mean "desired" speed of the sample is the design speed. Exact accordance with the Manual requires a sample restricted to passenger cars with desired speeds exactly equal to the design speed. Thus, the sample size would be unpredictable but assuredly very small.

In all simulation runs reported, the sample was designated so that the design speed corresponded to the 85th percentile of the desired speeds. No attempt was made to use calculated operating speeds as the basis for service levels. All evaluations directed to equivalency employed the mean over-all speed of passenger cars, which is established by a larger sample size and is not restricted to the definition of operating speeds.

Passing Behavior

The literature contains extensive data on passing behavior. Especially valuable were data on the frequencies with which drivers accept passing opportunities and the margins of safety associated with the completion of the maneuvers (*30* through *34*).

The data collected for this project, which were used to supplement and extend the data in the literature, apply only to situations in which there is no oncoming vehicle in sight when the passing opportunity begins. Data were obtained at passing zones that had some, but not all, of the characteristics sought. Only one of three passing zones was on a steep-sustained grade. That zone was on a 5-percent grade, was about 1,100 ft long, and was the only passing zone for more than a mile on a secondary highway with low design speed. The other two passing zones had saddle shaped vertical alignments and were 1,200 and 2,300 ft long, respectively. However, the latter two zones were on a heavily traveled primary highway in rolling terrain with a slight over-all grade, so that numerous platoons formed.

The data provided two important extensions of the knowledge on acceptance of passing opportunities. The data from the secondary highway extended to lower leader speeds than previously available. The data from the primary highway sites provided information on passing within and from platoons of three or more vehicles. This information is very important to project goals and was previously unavailable.

The collected data on passing acceptances were analyzed and the following conclusions were drawn:

1. In agreement with the data in the literature, when there is no oncoming vehicle in sight, the probability that a passing opportunity will be accepted depends most strongly on the speed of the impeding leader and the passing sight distance.
2. With the effects of leader speed and sight distance accounted for, the differences between upgrade and downgrade acceptances are small or insignificant.
3. Impeded vehicles having one or more other platooned vehicles between them and the platoon leader accept passing opportunities less frequently (52 percent) than the impeded vehicle directly behind the platoon leader.
4. On the basis of small samples, there is no statistically significant effect on acceptance frequencies associated with the following conditions:

Impeding leader = vans and campers
= bus, truck, or trailer combinations; and
Passing vehicle = vans and campers on downgrades (these vehicles are seldom impeded on upgrade)
= trucks and trailer combinations on downgrades (these vehicles are seldom impeded on upgrade).

5. In addition to the effects of leader speed and passing sight distance, the probability of accepting a passing opportunity is enhanced if the opportunity begins at the entrance to the passing zone or shortly after. This influence appears only for leader speeds greater than 30 mph.

The last finding, enhancement of acceptances, is based on data collected simultaneously at two passing zones within about 1½ mi of each other on the same highway. Additionally, the passing zones had similar vertical and horizontal alignments. The vertical alignments were saddle shaped, and both zones had horizontal curves at each end. Figure 4, which contains data from both directions of travel, shows a comparison of the acceptance frequencies. Note that site 3 was a 1,200-ft passing zone; and site 2, a 2,300-ft passing zone. The longer passing zone contained a service station that was out of business and set well back from the road. The service station, the major observed difference in the zones, was not considered a sufficient explanation for the different passing behavior in the two zones. It is emphasized that many refused passing opportunities occurred within the longer zone where the remaining sight distance was greater than that accepted for the shorter zone. That is, the vanishing (zero) acceptance rate for sight distances of 600 to 1,800 ft in the longer zone is well established.

It was difficult to combine the data from the current project with the extensive data reported by Franklin Institute Research Laboratories (FIRL). The FIRL data were collected primarily in long passing zones with long sight distances. Under those conditions, an entrance enhancement effect would be difficult to detect, since acceptances near the beginning of the zone are high because of the long sight distance. On the other hand, the data collected in this project are dominated by the entrance enhancement for leader speeds greater than 30 mph.

The simulation contains the effect of enhancement of passing acceptance for opportunities occurring within the first 400 ft of the passing zone. This effect can be important in terrains where passing zone lengths are short or moderate.

In assembling the results from the two sources, a compromise was made. In effect, the compromise provides small but nonzero acceptance probabilities past the entrance enhancement distance where zero acceptances were actually observed in this project for sizable remaining sight distances. However, the entrance enhancement influence is more moderate than would be indicated by the data from the project alone.

Figures 5 and 6 show the basic probabilities for pass acceptance used in the simulation. Figure 5 is for the situations where no oncoming vehicle is in sight. The values shown are the result of combining data from the literature with data collected in this project. The curve for the 40-ft/sec leader speed is in exact agreement with the FIRL results. The data from the current project supported this curve exactly, with a total of 223 opportunities measured at two of the field sites. The curves for 30-ft/sec and

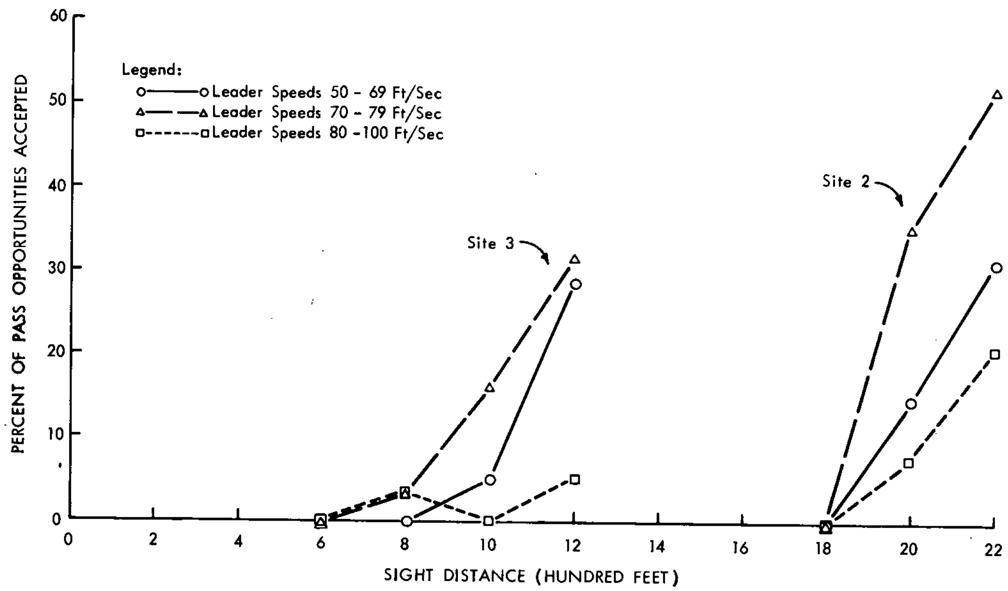

Figure 4. Percent of passing opportunities accepted at two sites on California Route 152.

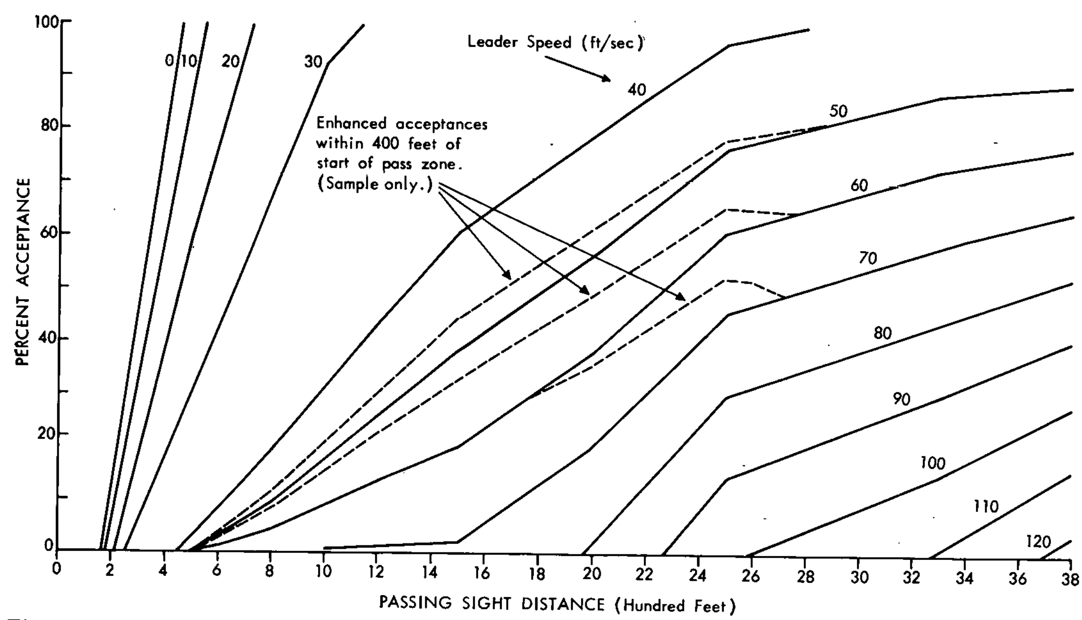

Figure 5. Percent of passing opportunities accepted with sight distance constraint.

slower leader speeds are based exclusively on data from the current project. The data comprised 24 opportunities measured at one of the field sites. The zero leader speed is the result of extrapolation, which was done to provide a test of reason. For speeds greater than 40 ft/sec, 1,205 opportunities from three sites were recorded and analyzed. The dashed curves in Figure 5 illustrate the enhancement of acceptance probability within the first 400 ft of the passing zone. The enhancement diminishes to zero for very high leader speeds (not illustrated).

Figure 6 applies to the situation in which an oncoming vehicle is in sight when the passing opportunity occurs. The curves in Figure 6 are based on data in the literature (*30* through *33*).

There are sizable differences between the acceptance rates in Figures 5 and 6. With no oncoming vehicle in sight (Fig. 5) the rates at short distances are much higher than those in Figure 6. This is consistent with the idea that an implicit hazard (short sight distance) is less of a deterrent to passing than an explicit hazard (oncoming vehicle in view). With 70- to 80-ft/sec leader speeds the acceptance rates are similar. The values for higher leader speeds are extrapolations, and they imply that opportunities at large distances will be accepted more frequently with the oncoming vehicle in sight. This is not inconsistent with human factor considerations. A distant vehicle confirms the visibility, and the absence of a readily perceptible closure speed enforces the idea of large distance. How-

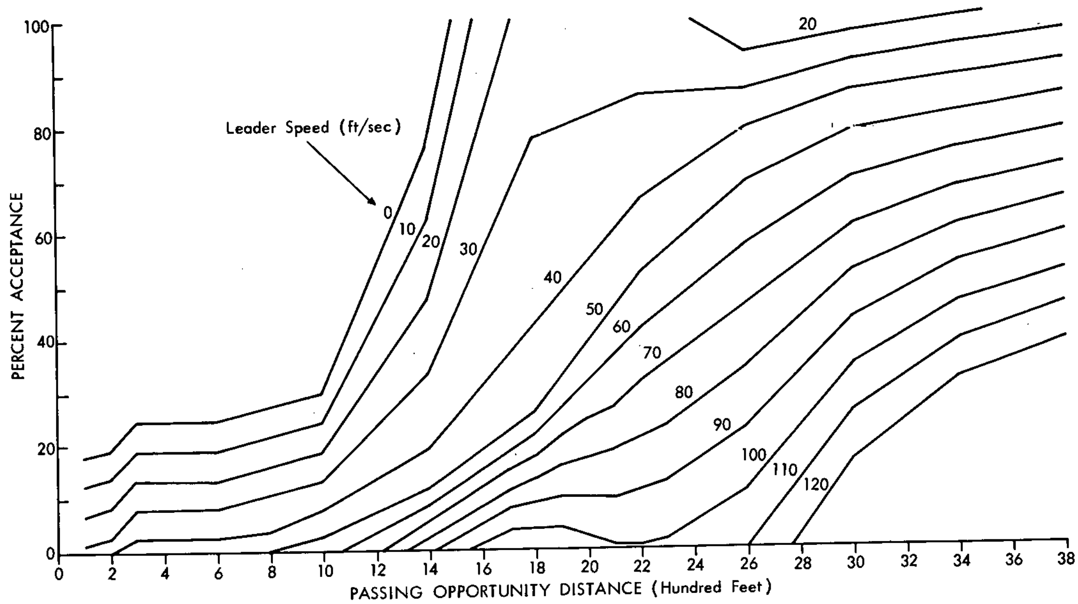

Figure 6. Percent of passing opportunities accepted with oncomer's vehicle in sight.

ever, the values for very high leader speeds play a very small role in the simulations that have been performed and interpreted.

Figures 5 and 6 both apply to the decisions made by the impeded vehicle immediately behind the platoon leader. If the impeded vehicle is further back in the platoon, the factor 0.52 is applied to the probability. Two additional factors are applied, based on observations by Crawford (*34*). Another multiplicative factor, 0.5, is inserted if the impeded vehicle is in or approaching a curve to the right with no oncoming vehicle in sight. If an oncoming vehicle is in sight in that alignment, the factor zero is used.

Vehicle Performance Characteristics

The performance capabilities of the vehicle types described earlier and detailed in Appendixes A and C were employed in the simulation where the influence of local grade was included.

By using data supplied by Werner (*44*) and Williston (*36*), it was determined that drivers of passenger and recreational vehicles limit their long-period performance demands to about seven-tenths of the maximum available horsepower. This constraint is employed in the simulation. Note, however, that performance capability is only one of several factors limiting actual accelerations and speeds.

Following and Overtaking

The equation used for interaction between leader and follower was based on simulation models developed previously. The equation provided realistic overtaking and following for free-flowing and congested conditions. Impeded vehicles having the desire and performance capability to pass go into a close-following state. Tables 12 and 13 display a set of conditions defined by the equation. When gaps between vehicles become less than desired because of platoon dynamics or passing maneuvers, the situation is rectified with decelerations that are moderate, if possible.

Vehicle Performance in Accelerating and Passing

Data in Ref. (*47*) were used to analyze the accelerations used by drivers. One acceleration sequence in the data appeared to be constrained by vehicle-performance limits. The remaining sequences indicated that drivers chose accelerations that could be approximated by a simple equation

$$\text{Preferred Acceleration} = 1.2 + 1.04\,(\text{desired speed} - \text{current speed}) \qquad (8)$$

where acceleration is in units of ft/sec^2 and speeds are ft/sec. Drivers would, of course, cease to accelerate when and if their desired speeds were reached. This equation was incorporated in the simulation as a constraint on accelerations any time a vehicle was below its desired speed.

Eq. 8 was also used to constrain accelerations planned and employed for passes. (Vehicle performance capability may be a more restrictive constraint.) However, the desired speed for the pass maneuver was elevated above the normal desired speed. This feature was consistent with the observations of all investigators—namely, that passers seldom used maximum or large accelerations in passes unless the margin for safety decreased during the maneuver. In the simulation, vehicles employ their maximum accelerations if they are committed to complete the pass and are also faced with a critical or negative safety margin. If uncommitted to pass, the vehicles abort passes in which the safety margins become critical or negative.

The critical safety margin is set at 2 sec for a pass with an oncoming vehicle in sight, and is 0 sec for a pass limited by sight distance or the end of the passing zone. These values were selected from the character of critical safety margin distributions reported by investigators.

Vehicles in the simulation are not allowed to embark on absurd or hopeless passing maneuvers. (Data appear to be anomalous in this subject area. Controlled and uncontrolled tests indicate that drivers are not capable of making good judgments. However, only a small fraction of passes

TABLE 12

SPEED OF FOLLOWER (FT/SEC) WITH DEPENDENCE ON LEADER SPEED AND GAP BETWEEN VEHICLES

GAP (ft)	LEADER SPEED (FT/SEC) 0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0
5	.2	7.9	15.5										
10	1.7	9.3	16.8										
20	4.7	12.0	19.3	26.5									
30	7.6	14.7	21.7	28.8	35.8								
40	10.5	17.3	24.1	31.0	37.8	44.7							
50	13.2	19.9	26.5	33.1	39.8	46.4							
60	15.9	22.4	28.8	35.2	41.7	48.1	54.6						
80	21.1	27.2	33.3	39.3	45.4	51.5	57.6	63.7					
100	26.1	31.8	37.5	43.3	49.0	54.8	60.5	66.2					
150	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5			
200	47.8	52.2	56.5	60.9	65.3	69.7	74.0	78.4	82.8	87.2	91.5		
250	57.1	60.9	64.8	68.6	72.4	76.3	80.1	84.0	87.8	91.7	95.5		
300	65.5	68.9	72.2	75.6	79.0	82.4	85.8	89.2	92.5	95.9	99.3	102.7	
400	80.1	82.7	85.4	88.0	90.7	93.3	95.9	98.6	101.2	103.8	106.5	109.1	111.8
500	92.4	94.5	96.5	98.6	100.7	102.7	104.8	106.8	108.9	110.9	113.0	115.0	117.1
600	103.0	104.6	106.1	107.7	109.3	110.9	112.5	114.0	115.6	117.2	118.8	120.3	121.9
700	112.1	113.3	114.5	115.7	116.8	118.0	119.2	120.4	121.6	122.8	124.0	125.2	126.4
800	120.0	120.9	121.8	122.6	123.5	124.4	125.2	126.1	127.0	127.8	128.7	129.6	130.4
900	127.0	127.6	128.2	128.8	129.4	130.0	130.6	131.2	131.7	132.3	132.9	133.5	134.1

TABLE 13

SPEED OF FOLLOWER (FT/SEC) IN CLOSE FOLLOWING STATE, DEPENDENCE ON LEADER SPEED AND GAP BETWEEN VEHICLES

GAP (ft)	LEADER SPEED (FT/SEC) 0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0
5	.2	7.9	15.6										
10	1.7	9.4	17.0	24.7									
20	4.7	12.2	19.8	27.3	34.8								
30	7.6	15.0	22.5	29.9	37.3	44.7							
40	10.5	17.8	25.1	32.4	39.7	47.1	54.4						
50	13.2	20.4	27.7	34.9	42.1	49.3	56.6						
60	15.9	23.0	30.2	37.3	44.4	51.6	58.7	65.8					
80	21.1	28.1	35.0	42.0	49.0	55.9	62.9	69.8	76.8				
100	26.1	32.9	39.7	46.5	53.3	60.1	66.9	73.7	80.5	87.3	94.1		
150	37.5	44.0	50.4	56.9	63.3	69.8	76.2	82.7	89.1	95.6	102.0	108.5	114.9
200	47.8	54.0	60.1	66.3	72.4	78.6	84.7	90.9	97.1	103.2	109.4	115.5	121.7
250	57.1	63.0	68.9	74.8	80.7	86.6	92.5	98.4	104.3	110.2	116.1	122.0	127.9
300	65.5	71.2	76.8	82.5	88.2	93.9	99.6	105.3	111.0	116.7	122.4	128.1	133.7
400	80.1	85.4	90.8	96.1	101.5	106.8	112.1	117.5	122.8	128.1	133.5	138.8	144.1
500	92.4	97.5	102.6	107.6	112.7	117.7	122.8	127.9	132.9	138.0	143.0	148.1	153.2
600	103.0	107.8	112.7	117.5	122.3	127.2	132.0	136.8	141.7	146.5	151.4	156.2	161.0
700	112.1	116.7	121.4	126.0	130.7	135.4	140.0	144.7	149.3	154.0	158.6	163.3	167.9
800	120.0	124.5	129.0	133.5	138.0	142.5	147.0	151.5	156.0	160.5	165.0	169.5	174.0
900	127.0	131.4	135.8	140.1	144.5	148.9	153.2	157.6	162.0	166.3	170.7	175.1	179.5

are aborted or are concluded under conditions requiring significant yielding by the oncoming vehicle or the vehicle being passed.) The evaluation depends on estimates of the time available to pass and the time required to pass. The time available to pass is estimated from the information available to the passer within the local passing sight distance. The time required to pass is based on the passing vehicle type, performance ability on the local grade, driver preference on maximum speed in the pass, the speeds of both vehicles, the probable accelerations to be used by the impeder, and the gain required for the passer to clear the impeder. Details of the equations used are given in Appendix H.

Vehicle Speeds in Horizontal Curves

Vehicles in the simulation may reduce their speeds in horizontal curves and in the approaches to horizontal curves if the curve geometrics warrant. The speeds used in the simulation are based on analyses of data in Refs. (*40*) and (*41*).

The data in Ref. (*40*) were collected, at five curves with curvatures from 2.0 to 7.0 deg/100 ft, to study the speeds used and the paths followed by vehicles in horizontal curves. Our analysis of the data showed that on each horizontal curve the speed distribution was essentially normal between the 1 and 99th cumulative percentiles. Further, the 1-percentile (very slow) drivers accepted lateral accelerations of about 0.025 g in the curves where their speeds were 33 to 49 mph; the 99th-percentile (very fast) drivers accepted lateral accelerations that increased from 0.21 g to 0.43 g as their speeds ranged from 84 down to 72 mph. (The lower speeds and the high lateral accelerations were associated with sharper curves.)

Some of the data in Ref. (*41*) were collected on curves with small radii. These data indicated that for very sharp curves the slowest drivers (now at very low speeds) would accept lateral accelerations of 0.29 g and that on the same curves the fastest drivers would accept about 0.50-g lateral acceleration.

By combining the analyses of data from Refs. (*40*) and (*41*), a relation between speed and acceptable lateral acceleration was established both for the 1-percentile (slowest) drivers and for the 99th-percentile (fastest) drivers. These two relationships, together with the truncated normal distribution, provide an estimate of the curve-limited speeds in a horizontal curve as a function of its radius and superelevation. These estimates were made and employed within the simulation model. Additional details are given in Appendix H. It is worth noting also that the relationship for the 99th-percentile drivers was revised based on Ref. (*59*) and experience with the simulation model. The revision, which has not been tested, is included in Appendix H.

Truck Crawl Speeds on Long, Steep Downgrades

In the development of another computer simulation (*58*), the data in Ref. (*48*) were analyzed to obtain estimates of the crawl speeds used by trucks on long, steep downgrades. The analysis was based on a simple model, which postulates that truck brake capability (engine plus wheel) should be proportional to vehicle gross weight, brake capability being defined as the maximum allowable rate that energy can be dissipated (Btu/sec) for an extended time at constant speed. Thus, for a truck descending a grade at constant speed, the dissipation rate is proportional to the product of speed and grade angle. Consequently, the crawl speeds should be inversely proportional to the grade. For this project, the data in Ref. (*48*) were analyzed according to the foregoing model to provide an estimate for downgrade, mean crawl speeds, as follows:

$$V_{crawl} = 293/(-\alpha) \qquad \text{(ft/sec)} \qquad (9)$$

in which α equals magnitude of grade in percent. Standard deviations of crawl speeds varied; however, 10 ft/sec was an average of the observed values. The published mean crawl speeds varied by ±27 percent from the value defined by Eq. 9. Speeds usually were not influenced unless the grade was at least 1 mi long and had a severity of 4 percent or more. Crawl speeds began to rise when trucks got to within 2,000 or 3,000 ft from the grade foot. The capability to duplicate this behavior was incorporated in the simulation.

Simulation Adjustment and Validation

Very little remained to be adjusted after the simulation was assembled. The major elements had been set to correspond with real world data. The preset elements included:

- Performance capabilities of vehicle types.
- Driver restraint in employment of performance capability over long time periods in passenger vehicles and recreational vehicles.
- Driver preferences on acceleration use.
- Realistic leader-follower interactions.
- Probabilities that passing opportunities would be accepted.
- Upper bounds on speeds used in passes.
- Bounds normally employed in acceleration for passing maneuvers.
- Vehicle performance constraints in passing maneuvers.

The features considered for adjustment were as follows:

- The thresholds for aborting passes and for pressing committed maneuvers to completion.
- The criteria for extending passing maneuvers to include an additional impeding vehicle.
- The probability that an impeded vehicle will reconsider an oncoming passing opportunity during the time of one review period in the simulation. (The impeded vehicle is always motivated to consider a passing opportunity while overtaking the impeder and whenever a new passing opportunity begins.)
- The distribution of time headways for vehicles entering the simulation.

The first two items had been assigned values based on time headway safety margins published by other investigators. The third item, known to be greater than zero and probably less than one, was assigned the value 0.2. The entering headways (fourth item) used the parameters from Ref. (*38*) in Schuhl's distribution.

Prior to making long simulation runs, the simulation was tested for its accuracy in representing the intended numerous details in passing maneuvers, multiple passing maneuvers, passing aborts, response to situations blocking passing possibilities, following and overtaking, responses to road alignment features, observance of passing-zone boundaries, and restriction of responses by vehicles to information within their local sight distances. These tests were made with numerous posed situations and with program output on the behavior of the vehicles in subsequent 1-sec time periods.

The computer model was tested by comparing simulation results with the data reported by Normann (*50, 51*) and Prisk (*52*), and the data summarized in the "Highway Capacity Manual" (*53*). The need for adjustment was evaluated by examining numerous calculated quantities, many of which were not part of the standard simulation program output. These quantities included the number of vehicles passed, the number of pass extensions (to pass an additional impeder), the distributions of speeds, the times required to pass, the distribution of time safety margins, the frequency of passing aborts, and the frequency with which the ends of passing zones were violated.

The simulation runs for comparison with Normann's data used passenger-car performance characteristics appropriate for the weight/brake horsepower ratios of the 1930's and 3.5 percent each of 300 and 200 lb/NHP trucks. On the basis of Normann's article in 1958 (*51*), it is legitimate to use the 1939 data. The fundamentals of passing behavior remained essentially unchanged. The higher performance vehicles of the 1950's resulted in slightly higher average speeds and in the capability (or tendency) to avoid very low safety margins.

Most passing maneuvers in the simulations required between 7 and 12 sec. This range agrees with values in

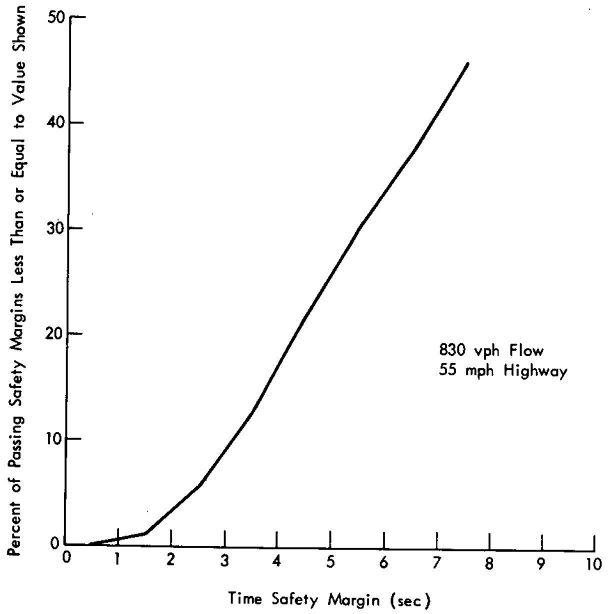

Figure 7. Time safety margins from simulation passes.

Refs. (*51*) and (*52*). The number of aborted maneuvers appeared slightly high (2.5 to 10 percent); however, some maneuvers were abandoned shortly after initiation and would probably not be interpreted as an aborted pass by observers. (The low frequency of aborts is based on qualitative statements by investigators and the observations by System Development Corporation for this project in 1973.) The distribution of small time safety margins compared well with those derived from the data (*50, 51, 52*). Subsequent runs, comparable with Ref. (*32*), confirmed the adequacy of time margin results as shown in Figure 7.

The simulation results also showed that all except a very few passing maneuvers were completed without overrunning the ends of the passing zones. A sizable fraction of passes was made by extending a pass in progress to include another impeding vehicle. An explicit comparison with Normann's work can not be made since Normann counted maneuvers involving "multiples." These were maneuvers in which either a vehicle passed more than one impeder, or more than one impeded vehicle passed the same impeder.

The number of vehicles passed in the simulation is compared with Normann's data (*50*) in Figure 8. The simulation was run with a passing zone ½ mi long together with the adjacent 1-mi sections at each end of the passing zone. Normann's curve is an average from several zones with various sight distances and adjacent geometrics. The simulations employed long sight distances comparable with the best zones in Normann's sample (*51*).

The range of simulation results in Figure 8 is the result of using a variety of geometrics in the 1-mi sections adjoining the passing zone. The characteristics were selected on the basis of general descriptions in Ref. (*51*). All the passing zones were 0-percent grade. The characteristics of the 1-mi sections adjoining the passing zone are given in Table 14.

As would be expected from traffic engineering considerations, the approaches to the passing zone have a strong influence on the number of vehicles passed. The simulation values are high at the lowest flow volume. This difference appears to be caused by the influence of sight distance and platooning. According to Ref. (*51*) the 1938 data at low flows contained contributions from zones with relatively low sight distances and low fractions of traffic platooned.

The influence of one adjustment in the simulation was tested in a comparison between the simulation results from numbered points 10 and 13 in Figure 8. In these tests, the approaches for 13 are the same as for 10. However, in 13 the simulation vehicles *never* reconsider the possibility of accepting an ongoing passing opportunity. This condition was achieved by setting a probability (PREC) in the simulation equal to zero for 13, so that vehicles were motivated to consider a passing opportunity only when they were first overtaking the impeder or when a new opportunity arose as a result of clearing an oncoming vehicle or entering the passing zone. The influence of PREC is strongest at low flows and in long passing zones. It was found, however, to have only a moderate influence under those conditions.

The value PREC = 0.2, from initial estimates, was retained. With a simulation review period of 1 sec, this value causes impeded vehicles to reconsider ongoing passing opportunities at stochastically determined intervals with a mean of 5 sec. All other parameters, also set from initial estimates, were left unchanged.

The next tests were made by comparing mean speeds from the simulation with those in the Highway Capacity Manual. In these tests, current vehicle performance characteristics were employed and attention was centered on a nearly ideal highway. The mean and standard deviation of desired speeds (85.48 and 9.47 ft/sec, or 58.28 and 6.46 mph, respectively) were selected, so that the 85th percentile of desired speeds was 65 mph. These values correspond closely to the case of a 70-mph average highway speed with a 65-mph speed limit, or alternatively a 65-mph average highway speed. The highway with 65-mph average highway speed would be expected to have about 10-percent passing sight distances less than 1,500 ft.

The initial series of simulation runs was conducted with 100-percent passenger vehicles on a highway with straight and level alignment. The results for these tests are shown in Figure 9. A fundamental difference is observed between the simulation results and the traffic behavior reported in the Manual. It is of interest to note that comparable results from the North Carolina State University simulation (*39*), also shown in Figure 9, exhibit a similar deviation from the Capacity Manual. The mean speeds from the simulation remain high at large two-way flow rates in comparison with the Manual values. In fact, the speed-flow rate relation from the simulation has the general character associated with two unidirectional lanes. (The intercepts in Figure 9 are average passenger car speeds in very light, free-flow traffic; in the simulation, they are also the mean desired speed.)

Series of variations were then explored to see if some nonideal features of geometrics or vehicle populations would explain the differences observed. First, the passing sight distance was reduced from 3,000 ft to 1,500 ft. This caused mean speeds to drop about 5 to 8 ft/sec from the previous results throughout the range 200 to 1,900 pcph (passenger cars per hour). Next, the following variations

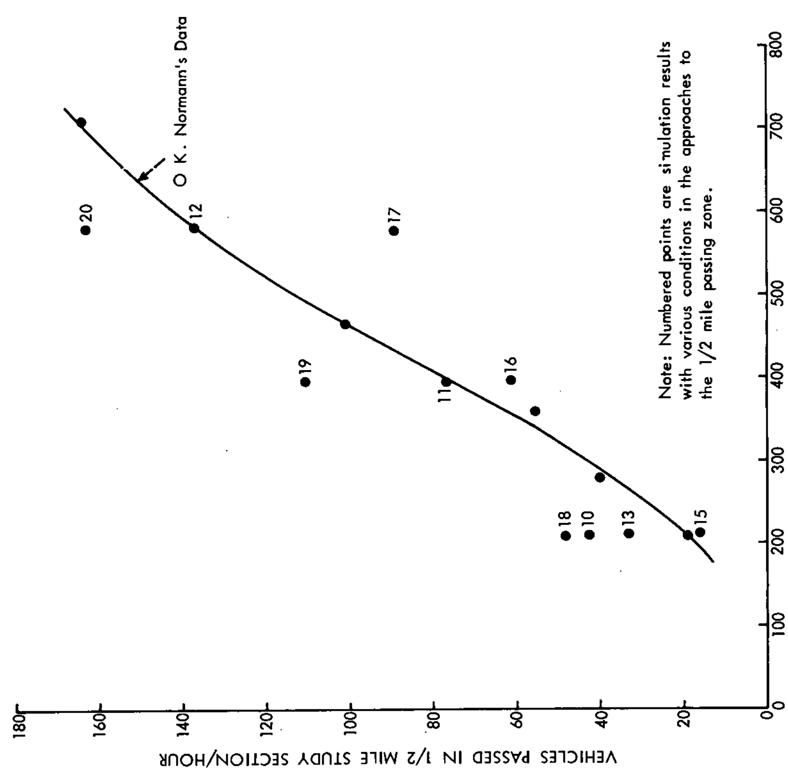

Figure 8. Vehicles passed—comparison of simulation results with Normann's data.

TABLE 14

CHARACTERISTICS OF APPROACHES TO PASSING ZONE USED IN SIMULATIONS FOR COMPARISON WITH NORMANN'S DATA

Identifying Numbers	Approaches to Passing Zone
10, 11, and 12	0% grade, 100% (5,280 ft) no passing
15, 16, and 17	0% grade, 1,000 ft of no passing
18, 19, and 20	3% grades up toward the passing zone, 100% no passing

were tested and found to produce very small effects on the mean speeds on 0-percent grade:

- Fourteen-percent low-performance trucks (400 lb/NHP) were added to the flows.
- Highly unbalanced flows were simulated.
- Buffer zones (in which traffic data are not collected) at each end of the simulation test section were lengthened and modified to include no-passing zones.
- A gentle horizontal curve was added in the simulated road test section to depress passing in the traffic curving to the right.
- The following and overtaking characteristics of the vehicle were made more conservative.

The foregoing tests were made to explore the possibilities that may have influenced the data summarized in the Manual. However, they did not provide an explanation for the differences between the simulation results and the Capacity Manual values.

The simulation results shown in Figure 9 strongly illustrate an anomaly that has interested engineers for years—namely that the results account for and duplicate a large number of well-established traffic characteristics. The anomaly was described by Arthur A. Carter (*54*) at a review meeting for FHWA-coordinated projects as follows:

> Why does the capacity of a two-lane, two-way roadway section apparently only rarely exceed 2,000 passenger cars per hour, total for both directions, (and then by only a few hundred), whereas, just by turning around the flow direction on one lane, the same strip of pavement operating one way can and frequently does handle 2,000 passenger cars per lane, or 4,000 passenger cars total (for instance, as one "barrel" of a divided highway), double the two-way operation total? (The summertime peak period one-way operation of the Maryland Chesapeake Bay Bridge, when still operating as a single structure, took advantage of this phenomenon.) Some authorities explain it by saying that the passing opportunities found on multilane highways up to relatively high volumes are necessary to permit full use of the available roadway. Yet moving flows of 2,000 passenger cars per hour per lane are regularly found on multilane facilities, with practically no passing occurring. Others feel that the close proximity of opposing direction traffic is the explanation, yet on four-lane undivided highways any such effect is much less. This is probably the most perplexing question that exists among the fundamentals of highway capacity. It is closely related to the "by-lane" capacities and service volumes question previously mentioned, and probably is a special case in that broader area.
>
> Currently, there appears to be a renewal of thinking among some engineers that it is a demand question—that the problem is that sufficeint demand never exists in both directions simultaneously on a two-lane facility. Their view is that if it did, then volumes of 2,000 passenger cars per hour could be attained in each direction simultaneously. Be that as it may, such volumes have never been reported from any two-lane facility in some 40 years of reporting, even in cases where a four-lane road is "necked down" to two at a bridge, tunnel, detour, or other bottleneck. The maximum on record is about 2,600 vehicles, total for both directions.
>
> Given the realities of the situation, there is probably little practical advantage to the designer or operating man in learning "why"; there would apparently be little that could be done to generally attain such volumes. But from the standpoint of bringing traffic flow theory and practice closer together, so that the former in the laboratory can substitute for the latter, it is all-important that such wide discrepancies between the two be explained.
>
> The goal here, then, would be to establish the ultimate maximum capacities of two-lane, two-way flow on roadways, capable of 2,000 passenger car per lane per hour operation when operated one way.

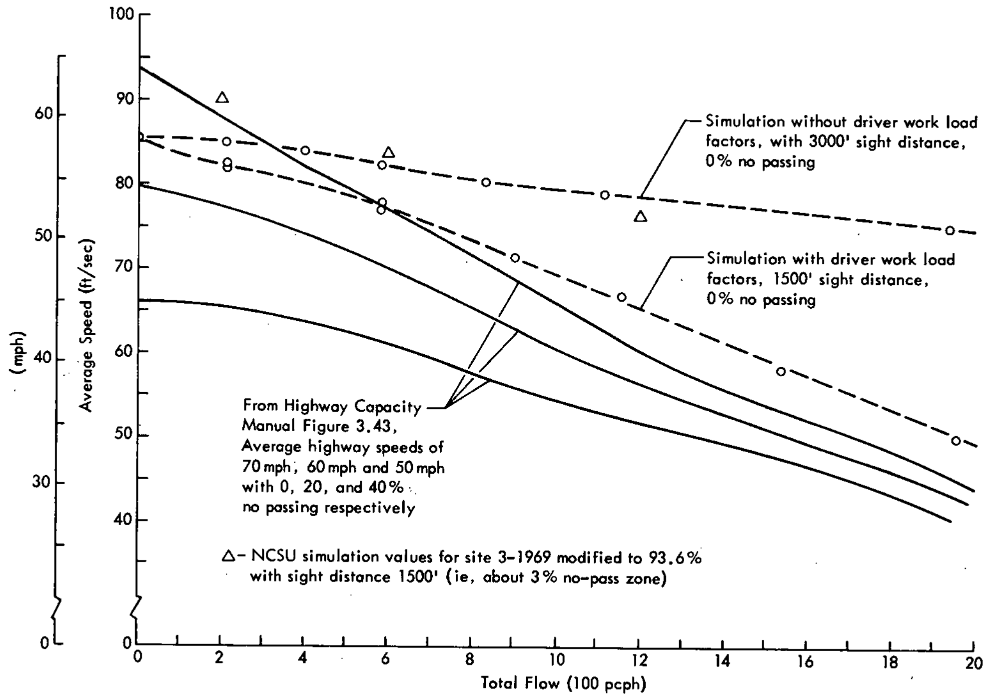

Figure 9. Mean speeds vs. two-way flow—comparison of simulation results and Highway Capacity Manual values.

After discussions with Carter and human factor experts at MRI, it was concluded that the reduced speeds were caused by driver workloads. Another possibility is that demand never reaches higher than 2,000 pcph in combined directions. Even if that possibility were a fact, it would not explain the depressed speeds. The speeds would vary with flow more in accord with the original simulation results.

The human factors explanation for reduced speeds is reasonable in view of other driver responses. With 1,000 vph in each direction, each driver encounters an opposing vehicle at average intervals of 1.8 sec. An opposing vehicle is an implicit rather than explicit hazard. However, drivers do slow for other implicit hazards if they are encountered frequently (examples are roadside developments, access points, and short sight distances). A distinction should also be made between multilane flows on undivided highways and two-lane, two-way flows. On the undivided, multilane facility, there is no expectation for opposing vehicles to encroach; on two-lane facilities encroachments add to the driving tasks. Finally, it is not uncommon to follow a driver who makes obvious speed reductions when opposing vehicles are encountered on a two-lane highway.

Logic was added to the simulation to account for the "encounter workload." The logic, which is an internal part of the simulation, keeps a separate, running average of the encounter frequencies for each direction of travel. The frequencies are used to modulate the desired speeds of vehicles already in the simulation. The parameters were adjusted to provide the mean speeds shown in Figure 9 for balanced passenger vehicle flows. The adjustments were made to provide maximum two-direction flows between 2,200 and 2,300 pcph. The 2,200- to 2,300-pcph flow was selected as a reasonable maximum for ideal conditions; it lies between the conventional 2,000 pcph and the maximum recorded value of 2,600 pcph. The speed-flow relationship shown in Figure 9 was considered to represent an ideal and was left above the maximum speed indicated in the Capacity Manual.

The encounter workload effects do not begin until two-way flow increases above 500 vph. The effects are small for flows slightly above 500 vph. The passing frequencies previously compared with Normann's data are affected very slightly.

Another type of workload factor, "passing workload," was also added to the simulation. The "passing workload" logic was based on the postulate that humans have an upper bound for nearly any task in multiple task jobs. It was considered likely that there was an upper limit on the frequency with which drivers would undertake passing maneuvers. The logic employed a separate running average of the passing workload in each direction. The running average was used to modulate desired speeds, primarily by modifying the standard deviation. The parameters initially selected have resulted in minor effects. It is questionable if logic for passing workloads is needed.

The simulation was validated by reproducing the over-all speeds measured for this project on California Route 152 near Pacheco Pass. The simulations contained an accurate representation of the highway alignment, including the sections adjoining the test length. The distribution observed on Route 152, 24-percent trucks and 4-percent recreational vehicles, represented the simulated vehicle population.

In these tests, the data collection cameras were placed in different locations for each of the 3 days that data were collected. The boundaries for the simulation data section were set in the corresponding locations in three runs. Equal rates of flows were used in all three simulations.

Figures 10, 11, and 12 show a comparison of the simulated speeds with the experimental data. It can be seen from these figures that the distributions from the simulation are more consistent than those from the observed data for the 3 days. Also, the range of speeds is slightly larger in the observed data than in the simulation results. The difference in range is caused by the wide variation in flow rates in the observed data. The observed rates, tabulated at 5-min intervals, typically varied ±40 percent from the hourly mean. This variation was larger than expected or obtained with the simulation headway generator.

The combined field data are in close agreement with the simulation results. The day-to-day differences in over-all speeds are not explained by variations in flow rates or vehicle populations. The unexplained variations are probably a reasonable measure of the differences that may be expected between field samples and the simulation under the best of conditions.

Simulation Results—Speeds and Flow Rates

The results from the simulation—as applied to various geometrics, vehicle populations, and flow rates—are shown in Figures 13 and 14. The variations received most emphasis are given in Table 15. Passenger-car mean speed was used to evaluate flow characteristics and equivalences. The operating speed is available in the simulation output. It has the advantage of great sensitivity to changes in the high service levels; however, the sample size for operating speeds is smaller and the basis for sample selection has some latitude.

Figure 13 shows the passenger-car mean speeds versus total flow for four conditions on zero grade. The data were from simulation runs with apssenger cars only and essentially balanced flows. The highest over-all mean speeds were on a highway with 0-percent no-passing, 1,500-ft sight distance, and 85th-percentile desired speed equal to 65 mph. With the same desired speeds, the over-all mean speeds were slightly lower for 59-percent and 80-percent no-passing. Under these conditions, the 59- and 80-percent no-passing highways provided results that were indistinguishable. Lower mean speeds were obtained with the 85th-percentile desired speed equal to 55 mph and 80-percent no-passing.

Figure 14 presents additional results from simulation runs in which the entire vehicle population consisted of passenger cars. All of these runs employed desired speeds with the 85th percentile equal to 65 mph. Again, the flows were nearly balanced. The over-all mean speeds up the grade were sensitive to grade magnitudes of 4 percent and greater. Variations in percent no-passing cause the expected effect on speed for grades of 4 percent and greater, but only in the flow range of 0 to 500 vph. The zero-flow intercepts are the mean speeds of the population traveling as isolated vehicles. The reduction in speeds with grade was due to passenger-vehicle performance characteristics combined with driver restraint in the use of power over extended periods of time. The basis for the driver restraint is detailed in Appendix B.

Simulated downgrade flows of passenger vehicles had speeds essentially equal to the zero-grade values. However,

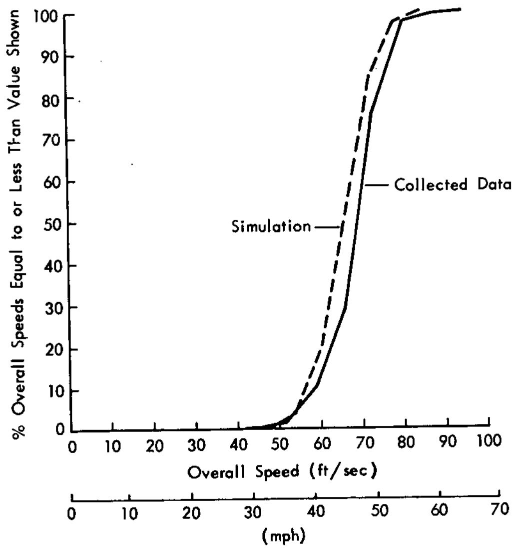

Figure 10. Comparison of over-all speeds—simulation and measured values 24 July 1973.

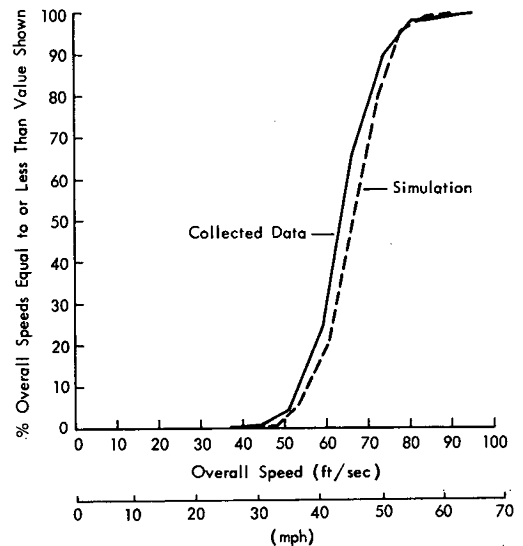

Figure 11. Comparison of over-all speeds—simulation and measured values 25 July 1973.

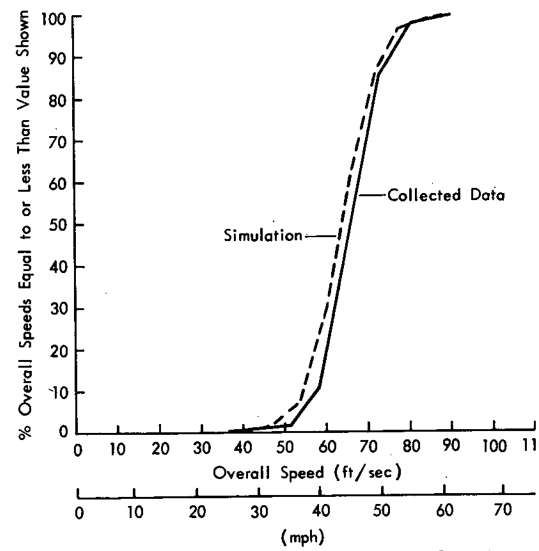

Figure 12. Comparison of over-all speeds—simulation and measured values 26 July 1973.

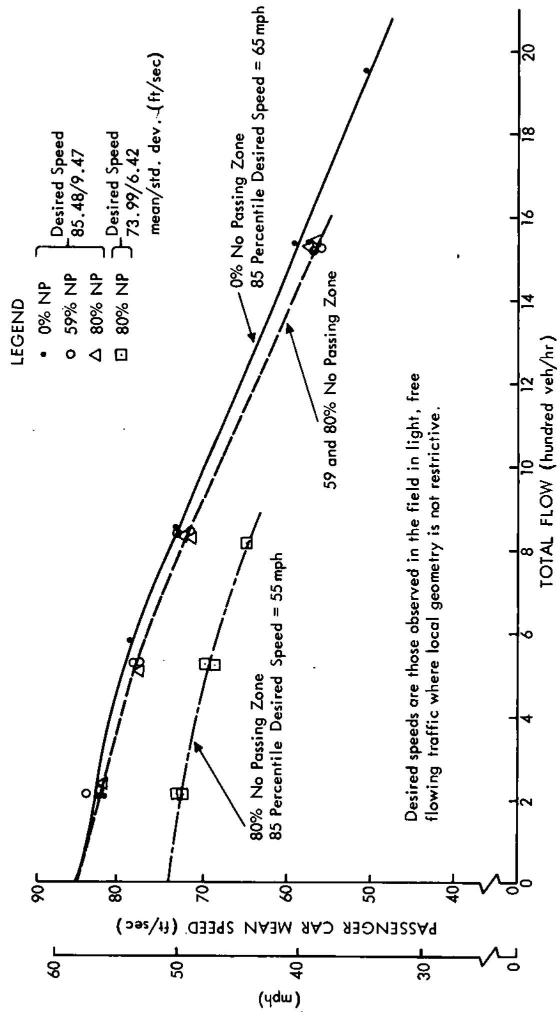

Figure 13. Passenger car over-all mean speeds on 0-percent grade—vehicle population 100 percent passenger cars.

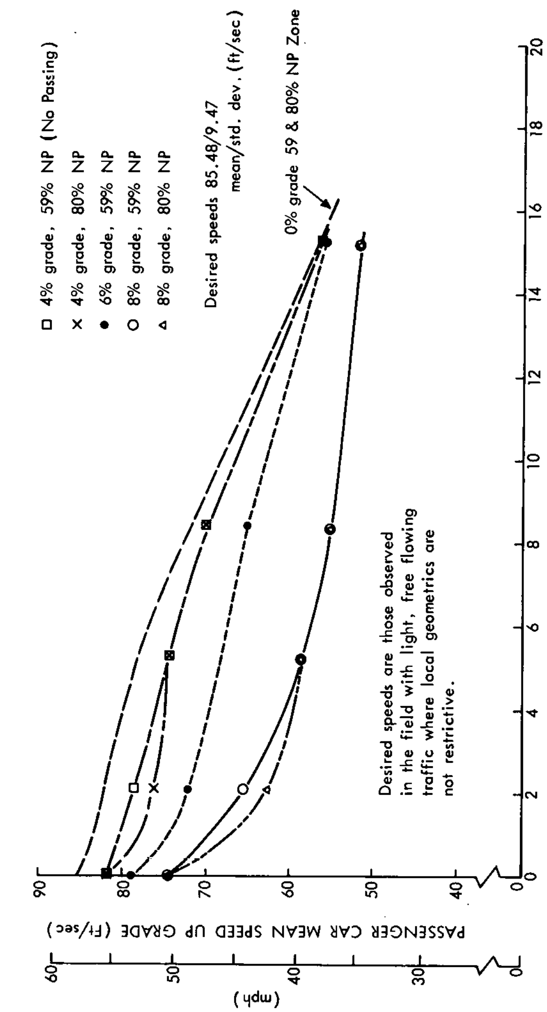

Figure 14. Passenger car over-all mean speeds up various grades—vehicle population 100 percent passenger cars.

the flows simulated for Figure 14 are on-grade. If a simulated upgrade vehicle was to be performance or preference limited on the grade, it entered the simulated road at the limiting speed. The simulated road was 25,120 ft long and had 2,000-ft buffer lengths at each end and a 21,120-ft (4-mi) section in which data were collected. The sequences and lengths of passing, no-passing zones were assembled stochastically using an analysis from Ref. (*1*).

The data in Figure 14 formed the basis for evaluating the effects of other vehicles added to the passenger-vehicle population. (The passenger-vehicle population itself was seen to have a greater sensitivity to extended grades than would have been expected.) Numerous simulation runs were made on the same extended grade geometrics used for Figure 14, but with 10 percent or 20 percent of a single type of low-performance vehicle added. The low-performance vehicles used in different runs included: the three truck types—400, 300, and 125 lb/NHP; the low-performance camper; and the low-performance travel-trailer combination. Trucks traveling downgrade used crawl speeds appropriate for the grade.

Simulation Results—Vehicle Equivalences

Passenger-car equivalences for the individual low-performance vehicle types were calculated using the passenger-car mean over-all speed from the mixed flow. This means that the procedure first determined, from Figure 14, what flow of passenger cars only would provide the same mean speed on the same road section. The passenger-car mean over-all speed from the mixed flow was located on the curve for the same grade and the flow corresponding to that point was the equivalent flow of passenger cars only. The equivalence for the single type of impeding vehicle was then calculated as E:

$E =$ (equivalent flow passenger cars only—passenger car flow in mix) / (flow of single impeder type)

It is emphasized that simulations with single types of impeders were run primarily to provide results for this simple type of evaluation. This is a major advantage of the simulation over dependence on field data wherein the vehicle population is not controlled and is frequently not accurately identified.

Figure 15 presents the equivalences versus the speed of the low-performance vehicle type. The relations in Figure 15 are similar to the curves in the "Highway Capacity Manual." Most importantly, the two curevs in Figure 15 indicate the type of nonlinearity suspected. For example, if 60-ft/sec vehicles replace 10 percent of a passenger-car flow, the 60-ft/sec vehicles are each equivalent to 15 passenger cars. However, if 20 percent of the passenger cars had been replaced, each of the slow vehicles would be equivalent to only 8.5 passenger cars. From an incremental standpoint, the second 10 percent were less disruptive to the flow than the first 10 percent. (The first 10 percent already have depressed speeds.) The equations currently employed to obtain truck factors with equivalences assume a linearity inconsistent with the simulation results.

Figure 15 and the foregoing example dealt with the case where different fractions of the same vehicle type were compared for effect. A similar and consistent nonlinearity was found for cases where two or more types of impeding vehicles are involved. Stated simply, the effect of the mixture is not predicted correctly from the effects of the individual types when they are combined using the current linear relation.

An alternative version of the truck factor equation was therefore derived. The intent was to establish a relation that would depend exclusively on the speed of the low-performance vehicle, would be applicable to a range of percentages, and would correctly combine and predict the influence of a mix of low-performance types. The following expression provided a starting point.

The truck factor currently employed is

$$F_T = 100/(100 - P_T + E_T P_T) \quad (10)$$

where:

P_T = percent trucks; and
E_T = equivalence of trucks.

The application of the truck factor is

$$Q_E = Q/F_T \quad (11)$$

where:

Q = the mixed volume; and
Q_E = the equivalent volume of passenger cars.

The source of the nonlinearities is suggested by engineering judgment and an application of Eqs. 10 and 11. Therefore, recast the current truck factor as

$$(1/F_T) = 1 + \frac{P_T}{100}(E_T - 1) \quad (12)$$

and consider the simplest case—where the total effect of a percentage of one type of truck (or recreational vehicle) is to be obtained by adding the percentage in small increments. For each increment, use the symbol r defined by

$$r = \frac{\delta p}{100}(E_T - 1)$$

where δp is an increment of the percentage to be added. When the first increment displaces the incremental number of passenger vehicles, the equivalent passenger car volume is given by

$$Q_{E1} = Q(1 + r)$$

The important nonlinear effect is seen in the addition of the second increment. The effective total flow before the addition of the second increment is Q_{E1}, not Q. Thus, the effective percentage of the second incremental addition is not δp but is $\delta p\ Q/Q_{E1}$. It follows that the addition of the second increment should result in the form:

TABLE 15

CHARACTERISTICS USED IN SIMULATION RUNS

Speeds

- Most runs with approximately 65 mph highway speed (in very light traffic the 85th percentile speed was 65 mph).
- Lesser number of runs with 55 mph highway speed.

Alignments

- Multiple mile grades of 0%, 2%, 4%, 6%, and 8%.
- Rolling terrain with grade lengths of 1,000 to 1,700 ft and magnitudes up to 7%.

Percent No-Passing

- On steady grades, 0%, 59% and 80%.
- On the rolling terrain, 46%.

Vehicle Populations

- Passenger vehicles only.
- Passenger vehicles with one type of truck or recreational vehicle.
- Passenger vehicles with the truck population identified by Wright and Tignor (46).
- The population observed at Pacheco Pass, i.e., 25% trucks which are predominantly 300 lb/NPH, and 6% recreational vehicles.
- The population observed on Canadian highways near National Parks (44) with 35% recreational vehicles and 3% trucks.
- The Pacheco Pass population with the 300 lb/NHP trucks replaced by a heavy modular house combination with the same 300 lb/NHP ratio.

$$Q_{E2} = Q\left(1 + r + \frac{r}{1 + r}\right)$$

In a similar fashion, the addition of the third increment should provide

$$Q_{E3} = Q\left(1 + r + \frac{r}{1 + r} + \frac{r}{1 + r + \frac{r}{1 + r}}\right)$$

Now recognize that r is an incremental and, in a mathematical sense, can be treated as a differential in limit processes. The differential form of the relationship is

$$d(Q_E/Q) = \frac{dr}{(Q_E/Q)} \quad (13)$$

which is integrated to provide

$$(Q_E/Q)^2 = 2r + \text{constant}$$

Since $(Q_E/Q) = 1$ when $r = 0$, the constant = 1, and the relationship sought is

$$(Q_E/Q) = (2r + 1)^{\frac{1}{2}} \quad (14)$$

so that the truck factor is $1/(2r + 1)^{\frac{1}{2}}$ and for the simple case of one type impeding vehicle

$$r = \frac{P_T}{100}(\nu - 1)$$

where P_T is the percent of the impeding vehicle type and ν is the equivalence kernel for the impeding vehicle type.

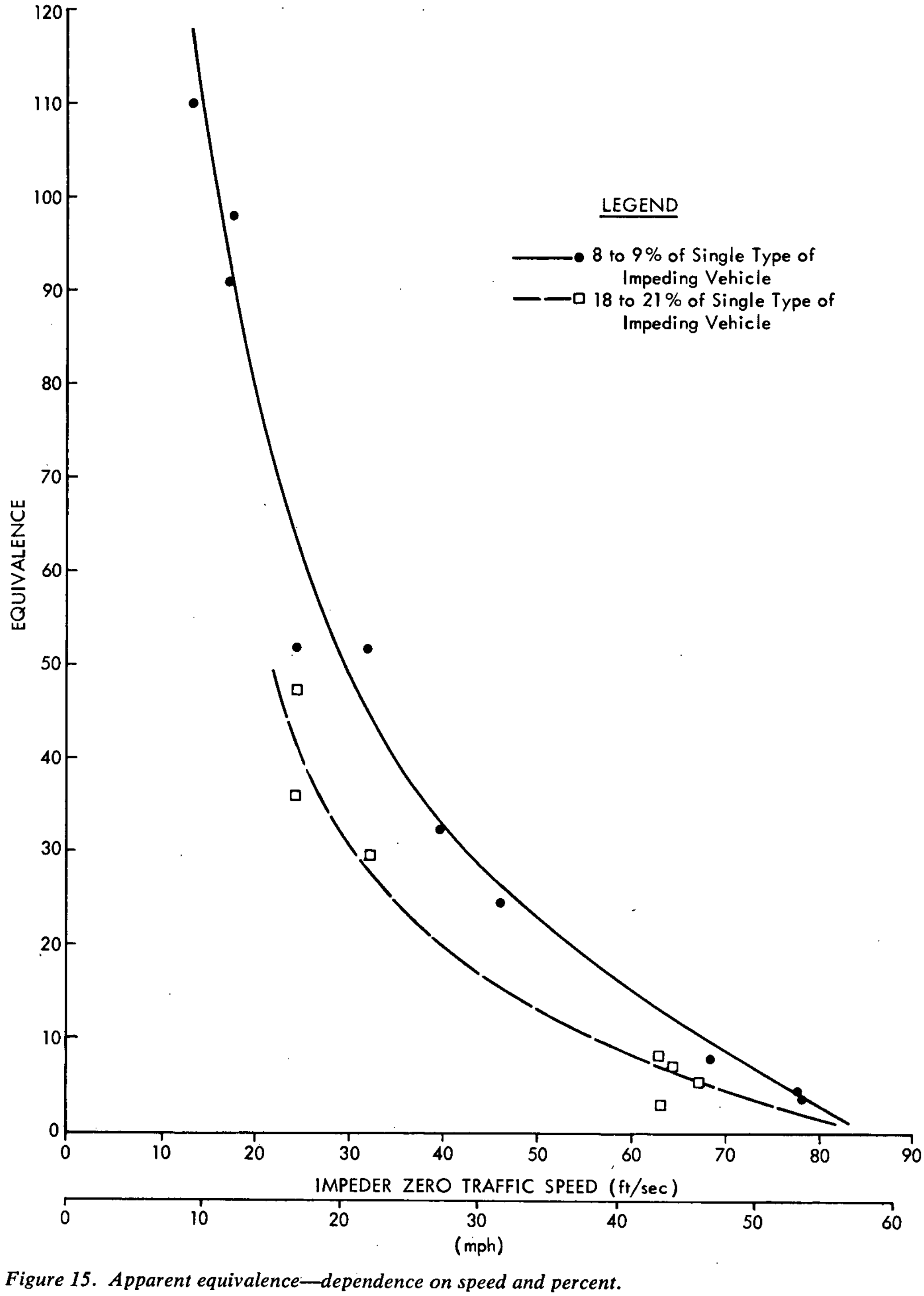

Figure 15. Apparent equivalence—dependence on speed and percent.

The equivalence kernel is a new and necessary concept; it replaces the equivalence E_T. The replacement is necessary because the equivalence kernel ν will always be employed in r and subsequently in a square root (see Eq. 14). However, as will be shown in the following, the equivalence kernels can be evaluated for individual vehicle types on grades and in rolling terrain; in this sense, they serve the same purpose as conventional equivalences. (Equivalence kernel values are like conventional equivalences only in the sense that they are used to construct a truck factor (see Eqs. 11, 14, and 15). The equivalent number of passenger cars is a nonlinear function of the equivalence kernel; conventional equivalences correspond directly to a number of passenger cars.)

In the more general case of n types of impeding vehicles, r would be obtained from

$$r = \sum_{i=1}^{n} \frac{P_i}{100}(\nu_i - 1) \qquad (15)$$

where ν_i is the equivalence kernel for the ith type, which occurs with percentage P_i.

For a flow with only one type of impeder present at percentage P, the equivalence kernel is obtained from Eq. 14 as

$$\nu = \frac{50}{P}[(Q_E/Q)^2 - 1] + 1 \qquad (16)$$

Eq. 14 is a fundamental relation. As shown later, it permits a usable evaluation of the passenger-vehicle flows that are the equivalents of mixed flows. The mixed flows can contain impeding vehicles in varying quantities and mixes. Eq. 15 provides the format to assemble r for a mix of impeding vehicles. Eq. 16 provides a format to evaluate ν for an impeding vehicle type when it is the single impeder type in the mixed flow Q.

Recognize that the ν (or the set of ν_i) are not equivalents; they have been defined as equivalence kernels. That is, the kernel(s) must be assembled and subjected to a nonlinear process in Eq. 14 before equivalence in the usual sense is quantified.

The simulation results for constructing Figure 15 were used to calculate ν using Eq. 16. The results are shown in Figure 16. The variance around the least squares fit in Figure 16 did not depend systematically on percent of impeders as noticed in Figure 15.

The fitted equation for equivalence kernels is

$$\nu = e^{[7.440436 - 0.08227925\ V]} \qquad (17)$$

where V is the impeder speed in ft/sec. Eq. 17 is applicable for flows that are nearly balanced on highways where the percent no-passing is 46 to 80 percent and where the 85th-percentile speed of passenger cars is about 65 mph in light, free-flowing traffic.

It is difficult to appraise the meaning of ν (equivalence kernel) values until they are applied in Eqs. 14 and 15. After application of these equations, it is possible to determine the apparent equivalence. Apparent equivalence is the value that would be derived from observation of the flow and by application of Eq. 10 or Eq. 12. The current equivalences in the "Highway Capacity Manual" are apparent values. The formal relationship can be written for a single type of impeding vehicle appearing as a percentage P of the flow. The relationship is obtained by equating the current (linear) and new (nonlinear) form of the truck factor:

$$1 + \frac{P}{100}(E_T - 1) = \left\{2\left[\frac{P}{100}(\nu - 1)\right] + 1\right\}^{\frac{1}{2}}$$

or

$$E_T = \left\{\left[\frac{2P}{100}(\nu - 1) + 1\right]^{\frac{1}{2}} - 1\right\}\frac{100}{P} + 1$$

where E_T is the apparent equivalence and ν is the equivalence kernel. This equation was used in conjunction with Eq. 17 to prepare Figure 17.

Figure 17 carries out the pattern noted in Figure 15. It emphasizes that, even with a single type of impeding vehicle, the apparent equivalence is not just a function of impeder speed but also depends strongly on percent of impeders in the flow. The advantage of the equivalence kernel lies in its relative insensitivity to percent of impeders. These findings and relationships were derived exclusively from the simulaton results.

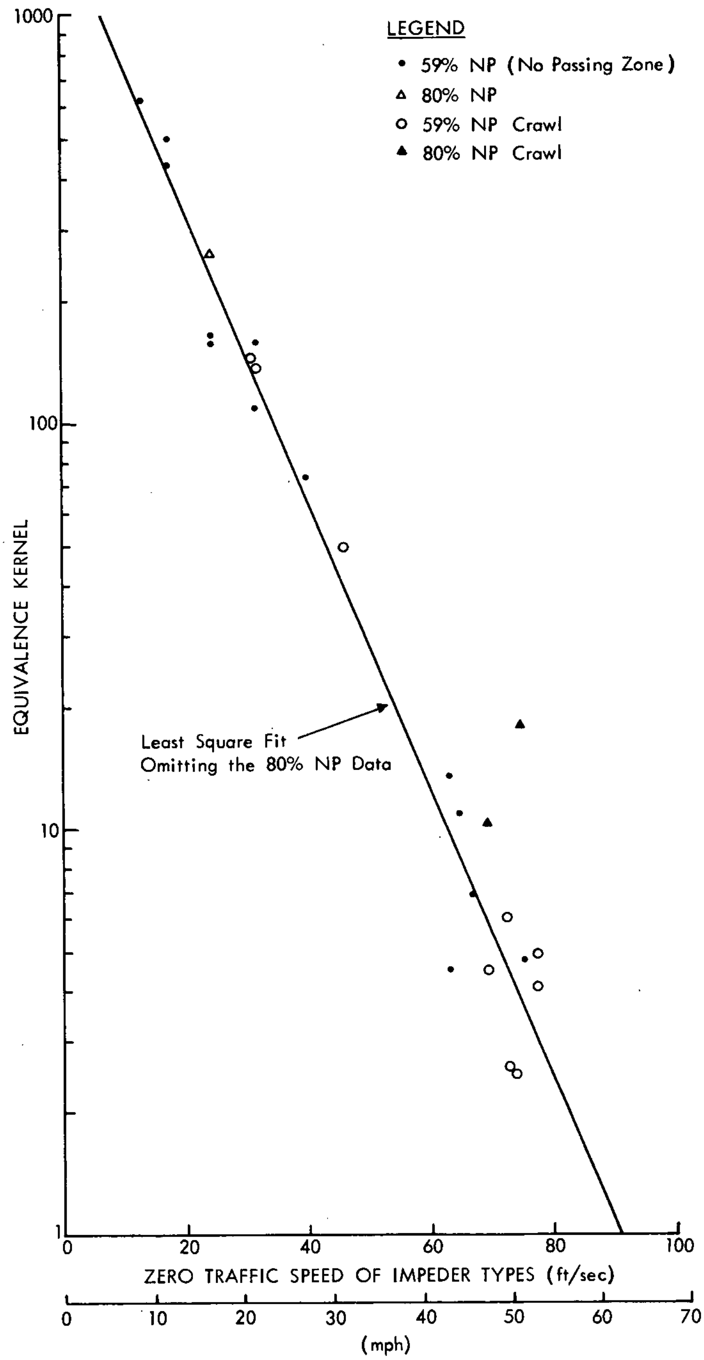

Figure 16. Equivalence kernel vs. speed—65-mph speed limit.

Other results from the simulation were used to further test the concept of an equivalence kernel and the associated equations. The additional tests employ simulation results including a mix of impeding vehicle types, rather than a single type, and cases of rolling terrain as well as steady grades. The tests involve the ability to predict passenger-car mean speeds (or equivalent passenger car flows) using

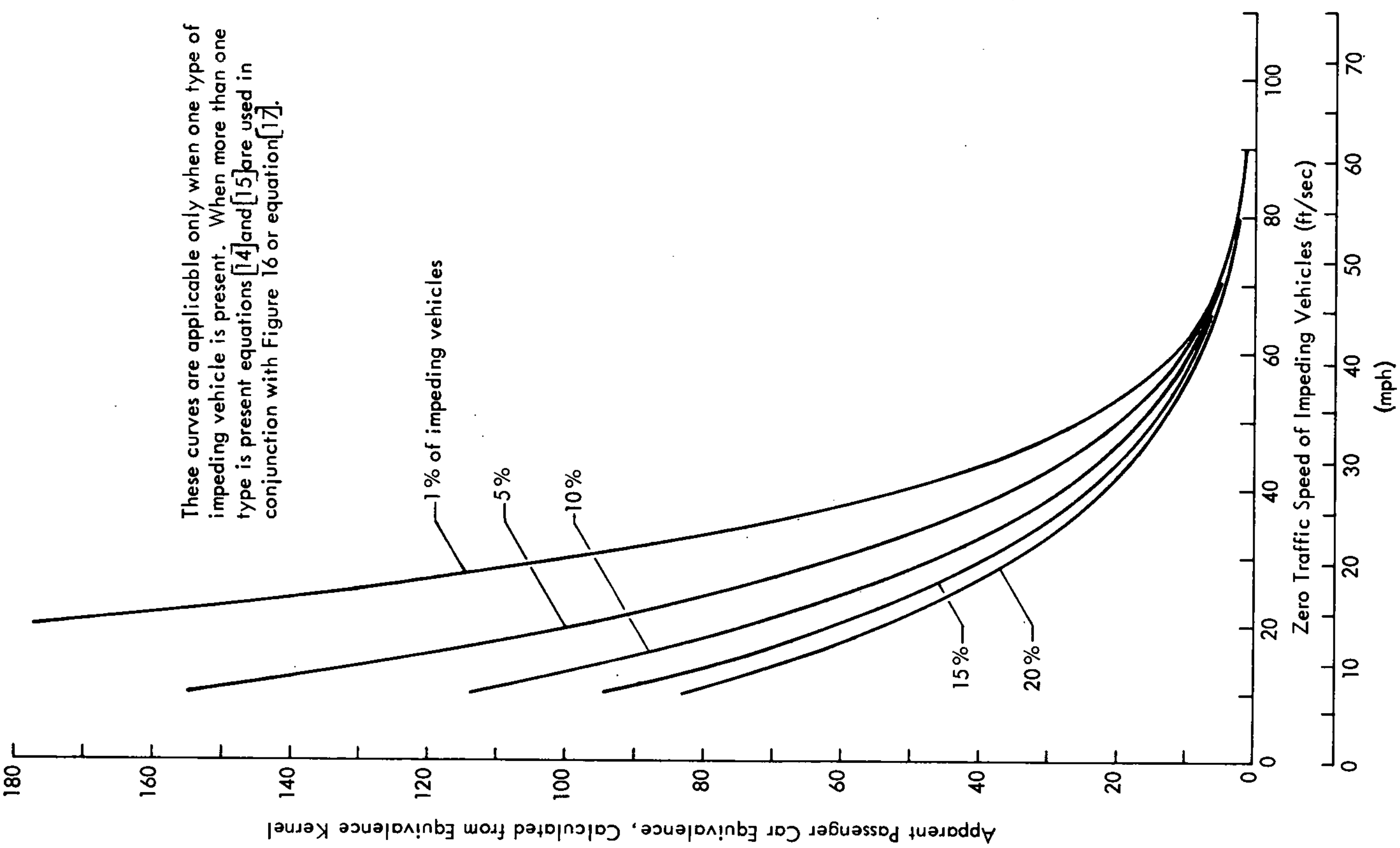

Figure 17. Apparent equivalences calculated from equivalence kernels.

Eqs. 14 and 15 together with Eq. 17 or Figure 16, and finally Figure 14. The procedure for prediction is as follows:

1. Estimate the mean speed of each impeding vehicle type over the terrain of interest, using the vehicle-performance equations and the mean speed of light, free-flowing traffic on sections with good geometrics as the desired speed. A computer subroutine can make this calculation and include the influence of horizontal curves and, for trucks, the influence of long downgrades where crawl speeds are used.
2. Use Eq. 17 or Figure 16 to obtain an equivalence kernel, ν_i, for each impeding vehicle type.
3. Apply Eq. 15 to obtain r.
4. Apply Eq. 14 to obtain the equivalent flow rate Q_E of passenger cars only.
5. Enter Figure 14 and read passenger-car mean speed versus Q_E. For long, steady upgrades, use the curve for the grade involved. For long, steady downgrades, or for rolling terrain, read the 0-percent grade curve.

The values calculated using this procedure are compared with simulation results in Figure 18. The excellent agreement of the data indicates that the estimation method provides useful results. There is a small systematic deviation (the estimated speeds below 65 ft/sec are consistently low by 5 to 8 ft/sec) that is not associated with grade, grade length, vehicle population, or the choice of 59- or 80-percent no-passing. However, this deviation should be considered in perspective. In similar tests employing the apparent equivalents from the linear form currently in use, absurdly high equivalent flows Q_E, and correspondingly low estimates of mean speed for the mixed flow, were obtained when mixes of impeding vehicle types were used.

It may be possible to obtain additional accuracy for the estimates by applying Eqs. 14 and 15 for successive elements of the vehicle population. The slowest elements of the vehicle population would be entered first into Eq. 15 and, after the result was used in Eq. 14, the passenger-car speed would be read from Figure 14. The next slowest vehicle elements of the population would be added in Eq. 15, provided their speed is below the last estimate of passenger-car mean speed, etc.

Several special simulation runs were made to appraise the effect of vehicle length. In the simulation model individual vehicle lengths are treated explicitly for their effect on the space occupied and for their effect on the passing maneuver. Both effects from increased length would seem to reduce over-all speeds and service. However, within the scope of runs made, vehicle length was found to be unimportant as shown by the following:

- The influence on traffic flow was essentially the same for the low-performance camper and low-performance travel-trailer combination. These vehicles had nearly equal performance characteristics and differed only in length. (Result is for noncongested traffic.)
- On rolling terrain, the 300-lb/NHP trucks in a heterogeneous population can be replaced by 300-lb/NHP modular-house combinations with only minor effect on the flow. The modular house had a significantly larger frontal area and was assigned an over-all length of 100 ft.

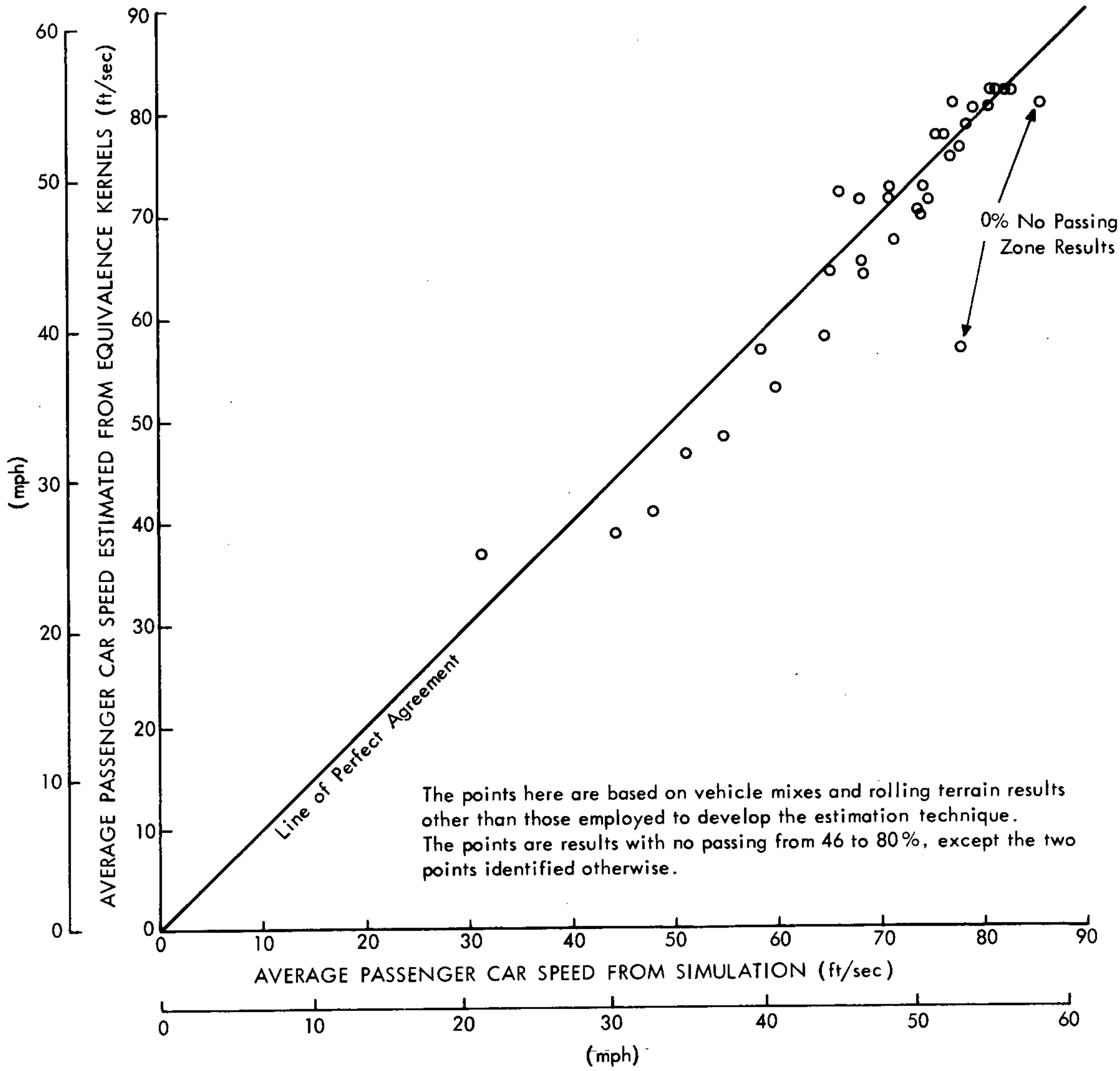

Figure 18. Passenger-car mean speeds—comparison of estimated values and simulation results.

Simulation Results—Safety and Service

The simulation output contains several items having safety and service related implications. These implications are discussed in following paragraphs.

Accident involvement rates were estimated by using simulation results in conjunction with Solomon's report (*57*), which presents involvement rates as a function of deviation from the mean speed. Local speed differences in the simulated flows were obtained from the histograms of overtaking events. These events were stratified on speed difference and number in the overtaking platoon. Equal involvement rates were assigned to the overtaking vehicles and to the overtaken vehicle. This assignment, which is conservatively low, provides the values given in Table 16.

An estimated average involvement rate for the entire flow was obtained as:

$$\bar{R} = \left[\sum_i N_i R_i\right] \Big/ \sum_i N_i$$

where:

$\bar{R}$ = estimated average involvement rate, vehicles/10^8 veh mi;

R_i = involvement rate for speed difference Δ_i (from Table 16); and

N_i = number of vehicles involved in overtaking events with speed difference Δ_i.

The results are shown in Figures 19 and 20. The symbol legend for Figures 19 through 29 are given in Table 17.

The results plotted in Figure 19 are identified with the general character of the vehicle populations. For passenger cars only, the involvement rate is nearly constant over the range of flows from light to approaching capacity. The populations with many recreational vehicles and a few trucks have involvement rates that are about 133 percent of the rates for flows with all passenger vehicles. With sizable fractions of low-performance trucks and truck populations, the involvement rates are about 175 to 250 percent of the rates for passenger cars only. However,

TABLE 16

ACCIDENT INVOLVEMENT RATES ASSIGNED ACCORDING TO OVERTAKING EVENTS IN SIMULATION FLOWS

Speed Difference, Δ_i (ft/sec)	Involvement Rate, R_i (Vehicles/10^8 Vehicle miles)
5	112
15	121
25	143
35	183
45	250
55	370
65	640
75	1,200

TABLE 17

SYMBOL LEGEND FOR FIGURES 19 THROUGH 29[1]

Symbol	Vehicle Population	One Way Flows (vph)	Grade (%)	% No. Passing
○	100% passenger cars		0	
•	100% passenger cars		±4,6,8	
●	20% low performance trucks	98-240	4	59
●	14-18% low performance trucks	110-262	-4	59
▲	29% trucks + 5% RV[2]	98-255	4	59
▲	26% trucks + 59% RV	109-257	-4	59
X	8.4% low performance trucks	98	6	59
X	9.0% low performance trucks	109	-6	59
X	30% trucks + 5% RV	95-250	6	59
X	26% trucks + 5% RV	108-250	-6	59
■	8.5% low performance trucks	95	8	59
■	8.7% low performance trucks	109	-8	59
■	8.5% typical trucks	97	8	59
■	8.7% typical trucks	106	-8	59
R	26% RV + 3% trucks	99-263	6	59
R	24% RV + 3% trucks	109-256	-6	59
R	26% RV + 3% trucks	98-260	8	59
R	24% RV + 3% trucks	109-253	-8	59
+	19% low performance truck	96-250	4	80
+	15% low performance truck	109-258	-4	80
▼	26% RV + 3% trucks	100-248	4	80
▼	24% RV + 3% trucks	109-261	-4	80
△	31% trucks + 3% RV	99	4	80
△	28% trucks + 4.6% RV	109	-4	80
(RV)	23% RV + 2.5% trucks	257-265	Severe rolling terrain	49
(TP)	28% trucks + 5% RV	100-265		49

1/ All results used here are from flows which would have free speeds with mean of 85.48 ft/sec (58.3 mph) and standard deviation equal to 9.47 ft/sec (6.46 mph).

2/ Recreation Vehicle

it should be noted that almost all of the situations with high involvement rates concern relatively light flows with sizable fractions of slow vehicles that significantly depress the mean speed. The most notable exception is the flow on a 4-percent upgrade with 0-percent no-passing zones (symbol △). The speed suppression, down from 85.48 ft/sec, is only moderate in this case because passenger cars and recreational vehicles are able to pass trucks without long delays.

The points plotted in Figure 19 are results from simulations of flows and vehicle populations observed in real world traffic. However, the particular volumes and populations were selected so that the truck and recreational vehicles would have a significant effect on the flow. As a result, there are no examples of flows in which a very low truck volume is combined with a high passenger car volume. Judging by the available results, a low truck volume would not cause a large increase in involvement rate. Passenger-car speeds would already be depressed by car volume, and the addition of slow trucks should have more moderate effects than those depicted in Figure 19.

Accident involvement rates were also estimated for flows in severe rolling terrain. The circled RV symbol is for a vehicle population with 23-percent RV (recreational vehicles) and 2.5-percent trucks; the circled TP symbol is for

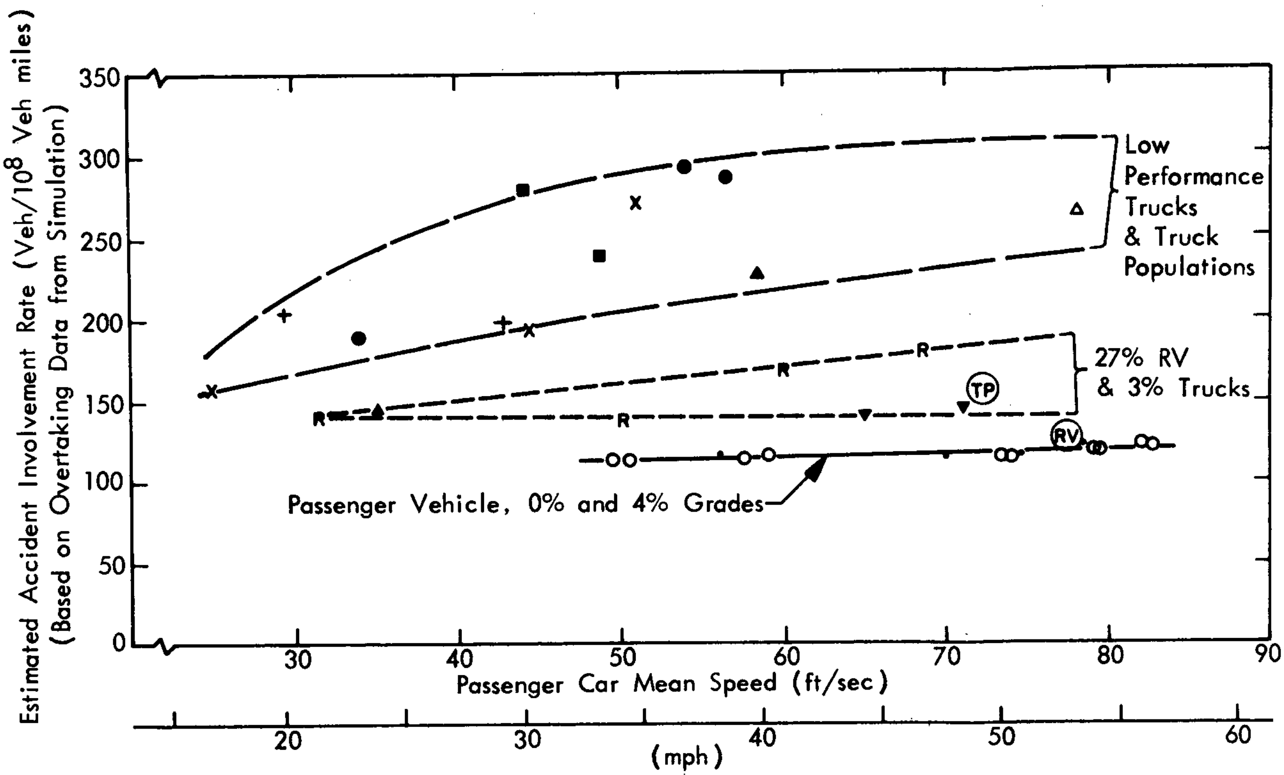

Figure 19. Estimated accident involvement rates in long, upgrade flows.

a vehicle population with 28-percent trucks and 5-percent RV. The estimated rates for rolling terrain are much lower than those for long grades where truck speeds remain low for long distances and times.

The estimated accident involvement rates for flows on long downgrades are shown in Figure 20. The estimates are influenced by trucks using crawl speeds on long downgrades of magnitude 4 percent and steeper. The —8-percent grades lead to the highest estimates (associated with the lowest crawl speeds) with lesser estimates for —6 percent and —4 percent. The —4-percent values are essentially equal to the estimates for flows with passenger cars only.

The potential for instabilities in the traffic flows has been evaluated by two measures, each addressing a different origin of instability. The first situation involves platoons of vehicles that overtake a slower vehicle. Some platoon leaders may be able to make flying passes; however, in many cases the platoon will be decelerated to the speed of the overtaken vehicle before an opportunity to pass occurs. Reported studies of platoon dynamics indicate that platoons frequently travel with speeds and headways resulting in marginal stability. The onset of serious instabilty (and rear-end accidents) is increased by the number of vehicles in the platoon and presumably by the severity of the decelerations.

The data on overtaking events from the simulations were used to construct instability potentials consistent with the situation described previously. The instability potential based on overtaking events is formed from the complete sample of the events as:

$$[\sum(N_p \cdot V_d)] \cdot E \text{ (vehicle (ft/sec)/veh mi)}$$

where:

N_p = number of vehicles in an overtaking platoon;
V_d = initial speed difference, overtaking platoon speed minus speed of overtaken vehicle, ft/sec; and
E = over-all average of overtaking events per vehicle mile.

Results for upgrade flows are shown in Figure 21. As would be expected, the instability potential is very low for very light flows with all passenger cars. At heavy passenger car flows approaching capacity, the potential is about four times the value for very light flows.

Flows with significant numbers of low-performance trucks exhibit potentials that are several times those for flows with passenger cars only. Flows with large numbers of recreational vehicles and a few trucks produce intermediate values. Less pronounced increases of instability potential are caused by trucks and recreational vehicles in rolling terrain, as shown in Figure 21 by the special symbols TP and RV. Again, the reader is cautioned that the mixed flow results displayed here are for relatively light flows of passenger cars having significantly depressed speeds because of the presence of sizable numbers of low-performance trucks. Flows in which speeds are already depressed by large passenger car flows should be less drastically affected by the addition of a few low-performance trucks.

The instability potential in downgrade flows is shown in Figure 22. On the —4-percent grades the potential with all

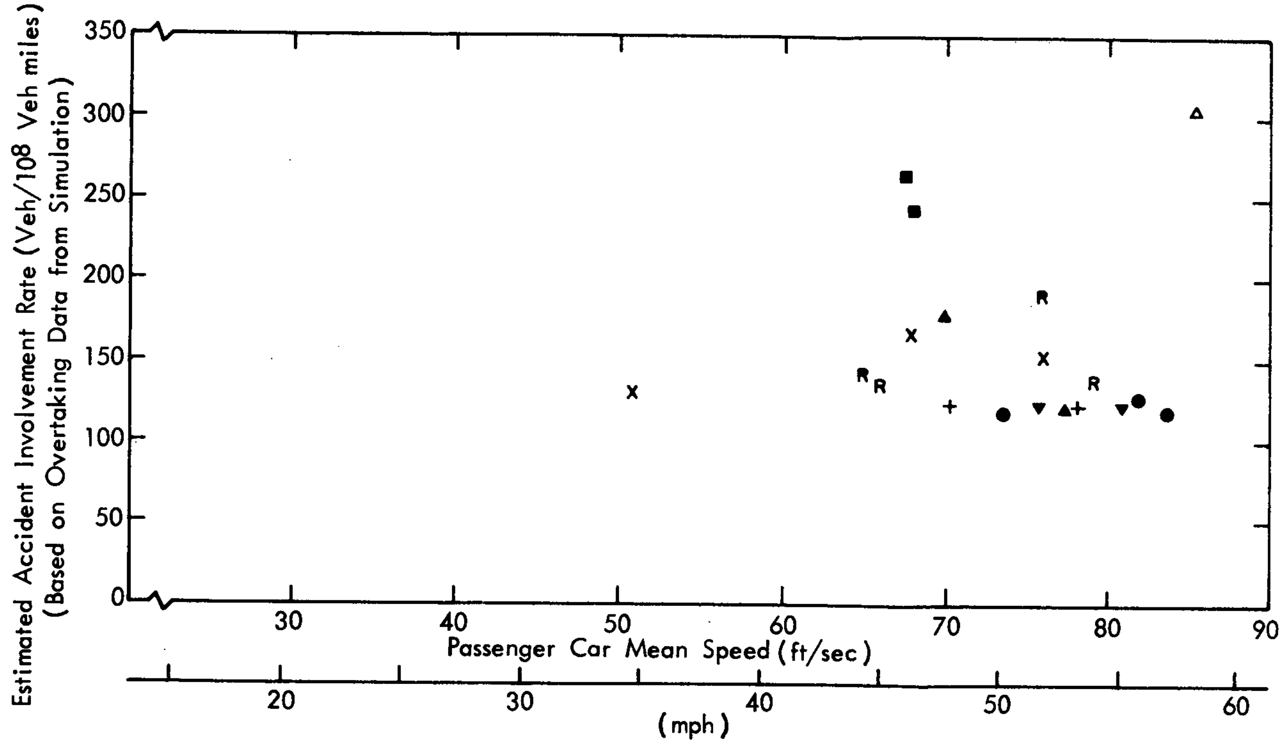

Figure 20. Estimated accident involvement rates in long, downgrade flows.

vehicle populations is essentially equal to the values for passenger cars only. The flows on —6- and —8-percent grades have markedly higher instability potentials.

A second trigger for instabilities concerns perturbations within otherwise undisturbed platoons. Two principal sources for perturbations are aborted passing maneuvers and leapfrog passes (i.e., passes of a platooned vehicle other than the leader). In both cases passing vehicles re-enter the platoon. Most of these maneuvers are performed by passenger cars. Figures 23 and 24 show the frequency of the perturbing maneuvers. The patterns are similar to those observed in the instability potential. Again, values for severe rolling terrain (not shown in Figure 23) lie only slightly above those for passenger cars only.

Acceleration noise * is frequently suggested as a measure of accident potential and depressed service. Figures 25 and 26 present the acceleration noise measured in simulation flows upgrade and downgrade. The patterns of values are similar to those found for instability potential.

The percent of time that passenger cars are unimpeded is a measure of service. The percents for upgrade and downgrade flows are shown in Figures 27 and 28. Notice in the upgrade flows that, for a given mean speed, the percent unimpeded is larger for flows with low-performance trucks than for flows with all passenger vehicles. This is, of course, a result of plotting against mean speed rather than total flow volume. When sizable numbers of slow vehicles are present, the mean speed is an average including periods of high-speed free travel and periods of very slow impeded travel. (The latter are the conditions giving rise to large speed differences and estimates of high accident involvement rates.) The same mean speed is achieved with all passenger cars at a higher flow rate and with a smaller range of speeds.

The analysis of the simulation results indicates that trucks, especially low-performance trucks, on long grades can elevate the accident involvement rates (involvements per vehicle mile) severalfold. The most serious situations are those in which sizable numbers of low-performance trucks impede flows that would otherwise travel at high speeds. Less serious situations should arise when the passenger-car flow rate is itself high enough to reduce over-all mean speeds. Here, a long grade is one that has an average gradient of 4 percent or more for more than ½ mi. The elevated accident rates for the upgrade flow would be expected on the upper part of the grade past the first ½ mi.

The analysis of the simulation results also indicates that low-performance trucks on long grades increase the likelihood that instabilities will occur in platoons of vehicles. The most serious situations with regard to instabilities should occur when the speed and number of impeding vehicles are sufficient to depress the over-all mean speeds of passenger cars below 30 mph in flows that would otherwise travel at high speeds.

Recreational vehicles on long grades also increase the estimated accident involvement rates and likelihood of

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$$\text{* Acceleration Noise} = \left\{ \left[\sum_{i=1}^{n} (a_i - \bar{a})^2 \right] \Big/ (n-1) \right\}^{1/2}$$

where:
a_i = the accelerations of individual vehicles during individual seconds of simulated time;
$\bar{a}$ = the average acceleration over all vehicle, sec; and
n = the total vehicle, sec.

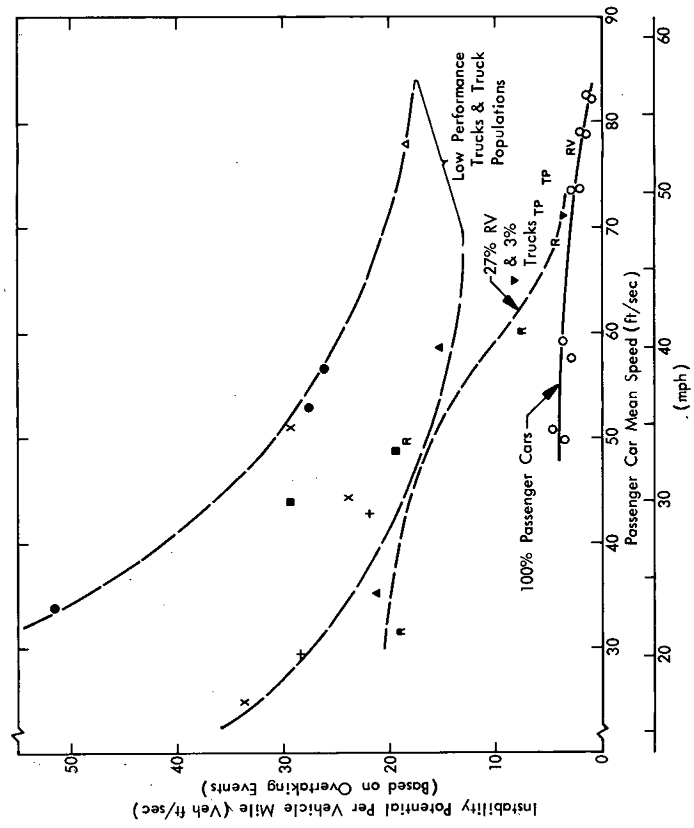

Figure 21. Instability potential per vehicle mile in upgrade flows (based on simulation results).

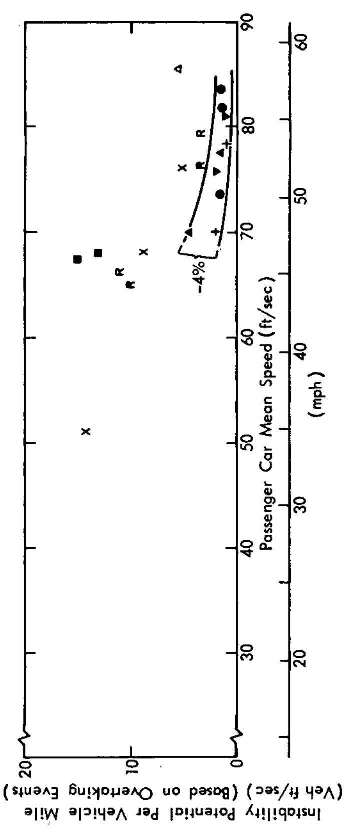

Figure 22. Instability potential per vehicle mile in downgrade flows (based on simulation results).

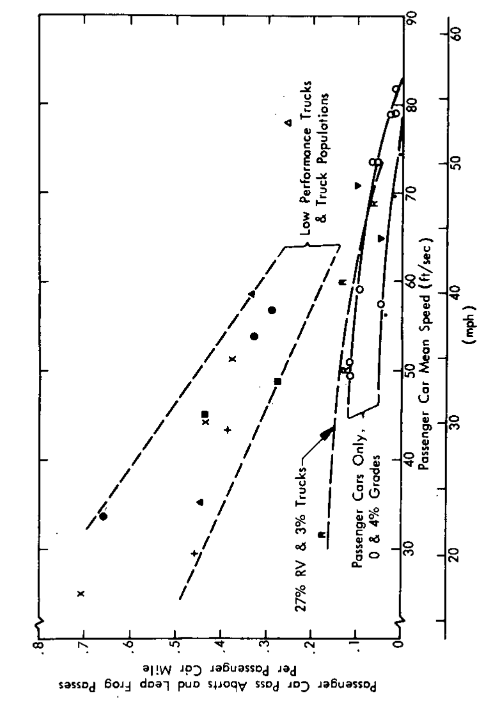

Figure 23. Passenger-car aborts and "leapfrog" passes per passenger car mile in upgrade flows (based on simulation results).

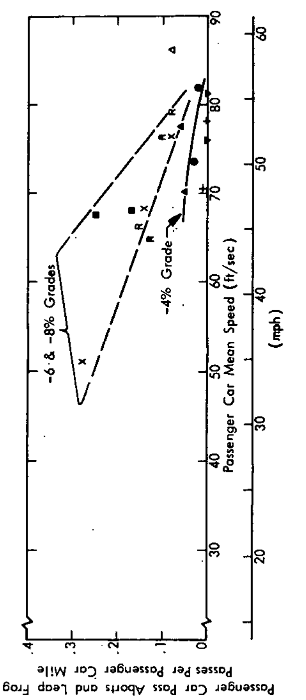

Figure 24. Passenger-car aborts and "leapfrog" passes per passenger car mile in downgrade flows (based on stimulation results; trucks use appropriate crawl speeds).

instabilities, but to a lesser extent than low-performance trucks.

Accident involvement rates are estimated to be elevated on long downgrades of over 4 percent, where trucks crawl to maintain speed control. In rolling terrain, both trucks and recreational vehicles increase the estimated accident involvement rates. However, the rate increase is much less than on the long grades.

The elevated accident rates on long grades are a result of the large difference in speeds of trucks and passenger cars. It is reasonable to expect that the situation could be improved by reducing the speed limit. The results based on

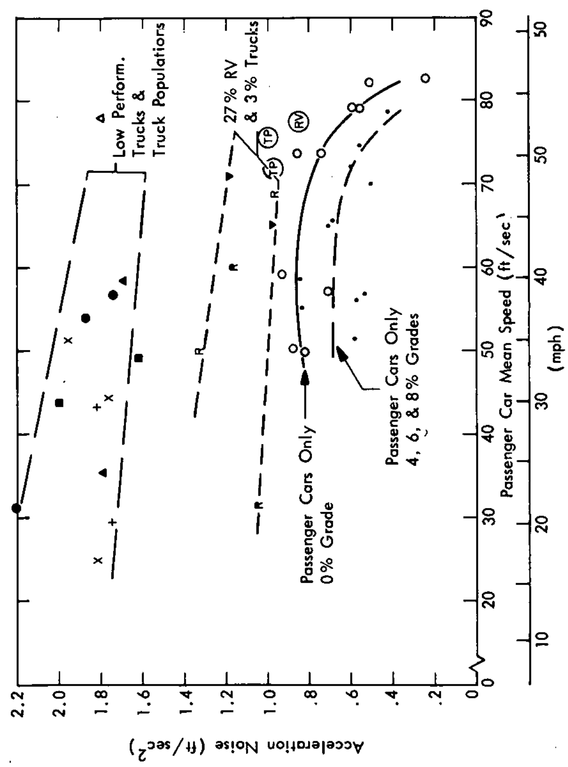

Figure 25. Acceleration noise in traffic ascending long grades (simulation results).

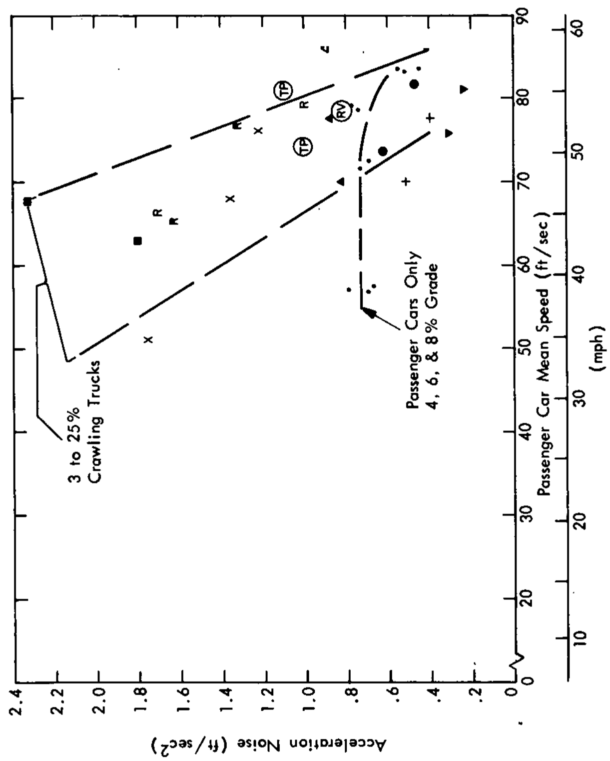

Figure 26. Acceleration noise in traffic descending long grades (simulation results).

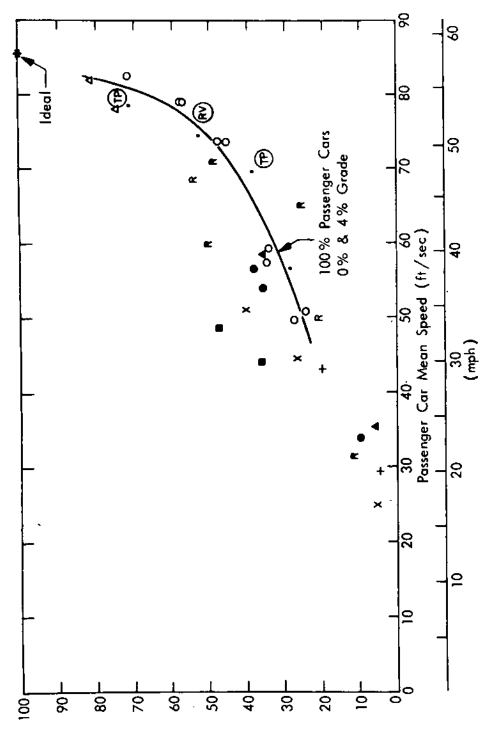

Figure 27. Percent of time passenger cars are unimpeded on upgrades (simulation results).

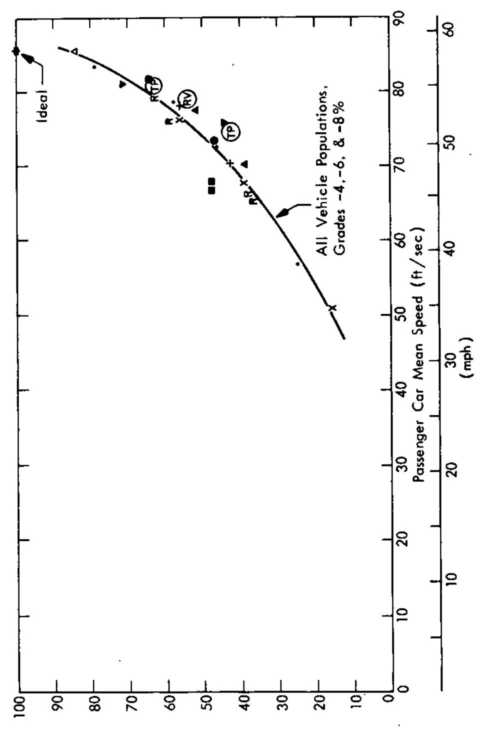

Figure 28. Percent of time passenger cars are unimpeded on downgrades (simulation results).

pairs of simulations with two different speed limits are given in Table 18. (The compared runs have the same grades, passing/no-passing configurations, and the same entering traffic; however, the drivers in the second run of each pair prefer to drive slower in response to a lowered speed limit.) The tabulated values indicate that only very small improvements in accident involvement rates are realized from a lowered speed limit in flows containing very few, low-speed vehicles. However, in the case of the sizable truck flow (31.9 percent) on the +4-percent grade, a large reduction in accident involvement rate is estimated. The instability potential shows a generally favorable response to the low-

TABLE 18

EFFECT OF REDUCED SPEED LIMIT ON ESTIMATED ACCIDENT INVOLVEMENT RATES AND INSTABILITY POTENTIALS

Run No.	One Way Flow (vph)	Vehicle Population	% No Passing	Grade	Mean Free Speed (mph)	Estimated Accident Involvement Rate (Vehicles/10^8 Vehicle-Miles)	Instability Potential (Vehicle·ft/sec)/(Vehicle-Mile)	(Aborts + Leap Frog Passes)/(Vehicle-Mile)
146	266	100% passenger car	49	Rolling	58.3	118.9	2.726	0.04
147	266	100% passenger car	49	Rolling	50.4	115.9 (-2.5%)	2.227 (-18.3%)	0.06 (+50%)
146	258	100% passenger car	49	Rolling	58.3	118.6	2.560	0.07
147	258	100% passenger car	49	Rolling	50.4	115.5 (-2.6%)	1.810 (-29.3%)	0.06 (-14%)
148	265	23.86% RV + 2.83% T	49	Rolling	58.3	123.1	2.967	0.05
149	265	23.90% RV + 2.83% T	49	Rolling	50.4	121.6 (-1.2%)	2.241 (-24.5%)	0.05 (0%)
148	257	22.74% RV + 2.33% T	49	Rolling	58.3	119.2	2.323	0.08
149	258	22.73% RV + 2.33% T	49	Rolling	50.3	118.3 (-0.8%)	1.965 (-15.4%)	0.08 (0%)
136	100	28.14% RV + 3.01% T	80	+4%	58.3	144.1	3.66	0.10
139	100	28.09% RV + 3.01% T	80	+4%	50.3	146.2 (+1.5%)	2.54 (-30.6%)	0.02 (-80%)
136	109	25.36% RV + 3.69% T	80	-4%	58.3	123.6	0.94	0.0
139	109	25.22% RV + 3.68% T	80	-4%	50.3	117.0 (-5.3%)	0.64 (-31.9%)	0.0 (0%)
137	248	24.36% RV + 3.61% T	80	+4%	58.3	141.3	8.18	0.05
138	250	24.26% RV + 3.58% T	80	+4%	50.3	134.6 (-4.7%)	7.03 (-14.1%)	0.06 (+20%)
137	261	23.56% RV + 2.87% T	80	-4%	58.3	124.1	1.85	0.0
138	263	23.61% RV + 2.86% T	80	-4%	50.3	118.6 (-4.4%)	1.88 (+1.6%)	0.02 (+)
115	98	31.93% T + 3.33% RV	59	+4%	58.3	229.3	15.28	0.34
142	98	31.83% T + 3.32% RV	59	+4%	50.3	145.2 (-36.7%)	12.08 (-20.9%)	0.32 (-6%)
115	109	28.37% T + 4.64% RV	59	-4%	58.3	124.2	1.50	0.06
142	109	28.3% T + 4.63% RV	59	-4%	50.3	116.5 (-6.2%)	0.97 (-35.3%)	0.01 (-83%)
				Effect of Change in Passenger Vehicle Population[a]				
115	98	31.93% T + 3.33% RV	59	+4%	58.3	229.3	15.28	0.34
155	97	31.94% T + 2.31% RV and more low performance passenger vehicles	59	+4%	58.3	160.7 (-29.9%)	12.81 (-16.2%)	0.26 (-24%)
115	109	28.37% T + 4.64% RV	59	-4%	58.3	124.2	1.50	0.06
155	109	28.37% T + 4.64% RV and more low performance passenger vehicles	59	-4%	58.3	126.8 (+2.1%)	1.80 (+20.0%)	0.03 (-50.0%)

a/ In all simulation runs except No. 155 the passenger car population was specified as 63% high performance, 27% medium performance, and 10% low performance. In Run No. 155 the population specification was inverted to provide 10% high performance, 27% medium performance, and 63% low performance.

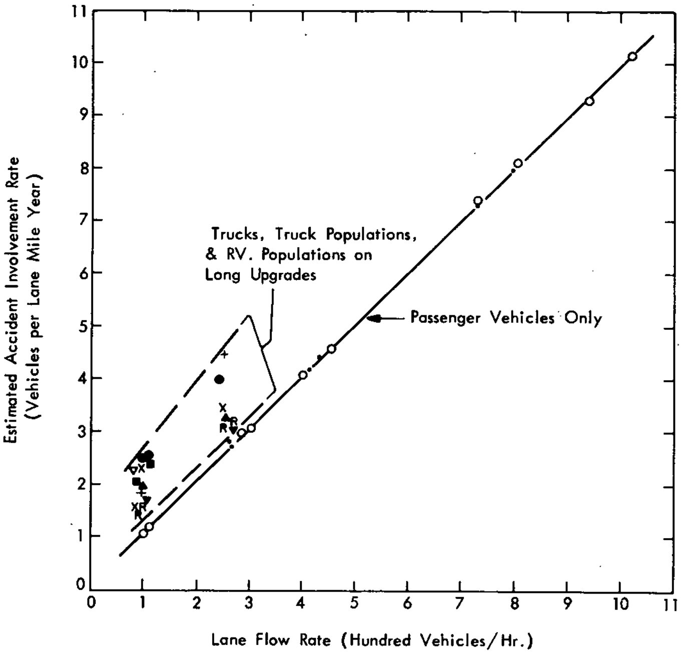

Figure 29. Estimated accident involvement rate vs. lane flow rate.

ered speed limit. On the basis of these results, it appears desirable to consider lower than normal speed limits for the few situations with elevated accident involvement rates. The situations are: (1) upgrades longer than ½ mi at 4 percent or greater, with sizable numbers of low-performance vehicles; and (2) long downgrades at more than 4 percent, with sizable numbers of vehicles using crawl speeds to maintain speed control.

The last four entries in Table 18 illustrate some of the effects of a drastic increase in the proportion of low-performance passenger cars. The estimated accident involvement rate for the upgrade flow is greatly reduced; the rate in the downgrade flow is not appreciably influenced. The increase in low-performance passenger cars also affected passenger-car mean speeds. The upgrade speed fell from 58.5 ft/sec (39.9 mph) to 54.2 ft/sec (37.0 mph), as might be expected. The downgrade speed was unaffected.

All of the accident and instability results have been presented on a vehicle-mile basis. This basis accounts for exposure at the simplest level. If accident involvement rate is obtained as involvements per lane mile year, the flow rate is likely to become the strongest correlate of involvement rate. This is shown in Figure 29 where the results used in Figure 19 are presented in alternative form.

Program Extensions and Availability

The simulation was run with a wide variety of passing/no-passing ratios, highway speeds, and vehicle mixes. However, results sufficient for generalization were obtained only for the 65-mph highway speed and 46- to 80-percent no-passing range. (In addition to debugging and development runs, over 100 hr of traffic and over 100,000 veh mi were simulated to obtain the results in this report.) A considerable effort was also devoted to developing and testing the encounter workload logic and the nonlinear form for the truck factor.

Within the scope of variables chosen as the most useful for generalization (i.e. 65-mph highway speed and no-passing range of 46 to 80 percent), it was concluded that the simulation model is suitable to extend the results to additional highway speeds, passing/no-passing ratios, and highly unbalanced flows. The simulation can be used also to depict flows at specific locations. A verified copy of the simulation source program and a sample run have been deposited with the Transportation Research Board, National Cooperative Highway Research Project. Detailed instructions for program use and interpretation are given in Appendix I.

TRAFFIC BEHAVIOR NEAR LOADS WITH OVERREGULATION WIDTH

In almost all states, 8 ft is the normal maximum width for buses and trucks. An 8.5-ft maximum is permitted in a few states, and a few special routes for 8.5-ft buses are currently in use. Loads having overregulation widths are described here as overwidths and require special permits. Mobile and modular houses, having widths of 10, 12, and 14 ft, constitute a large part of the overwidth traffic. These dimensions fill or exceed the lane widths of some facilities and, thus, have the potential to pose safety hazards or service reductions for other road users. However, it is questionable as to whether significant hazards or service reductions are realized. There are also questions concerning the efficacy of safety measures such as escort vehicles, warning signs, and warning lights. Data were collected in this project and summarized from a related project in attempt to answer these questions.

Data Collected in This Project

Data were collected on the behavior of traffic in the vicinity of 12- and 14-ft-wide mobile homes and modular houses by an observer riding in the cab of the towing vehicle. Comparable data were obtained for regulation width (8-ft) commercial units. The data were examined and summarized in general terms; a detailed analysis was not conducted because of the related extensive data collection and analysis subsequently performed under another contract (*37*).

Four trips were made with 12-ft-wide mobile homes, one trip with a 12-ft-wide modular house and one trip with a 14-ft-wide mobile home (mounted on a low-boy trailer) for a total mileage of 806 mi. Five trips were made with regulation width commercial units for a total mileage of 718 mi. One trip was made in Missouri and the remainder in California and Arizona. In this project the two-lane highways employed by the observed vehicles had 36- to 40-ft, fully paved cross sections with no shoulder delineation. (In the other project (*37*), two-lane highways with conventional cross sections were employed.)

Data were recorded on size and weight of the load; weight, horsepower, and transmission type of the towing tractor; age and experience of the driver; and kind of safety features employed (signs, flags, etc.). The following observations were made about the behavior of the load and the traffic encountered (most of the observations were recorded at 1-min intervals).

General Observations

1. *The Load*—Speed; mileage; lane occupied; number of vehicles passed; and number and cause of intrusions into adjacent lane.

2. *Other Traffic*—Count of vehicles platooned behind the load (the platoon was frequently not visible to the observer); count of vehicles platooned behind escort vehicles; lateral placement of overtaking vehicles (estimated relative to lane lines); lateral placement of oncomers (on two-lane highways); and estimate of speed change by oncomers.

Specific Observations

1. *12-Ft-Wide Mobile Homes and Modular Houses*—The 12-ft-wide units had no pronounced observable effect on neighboring traffic. The units were able to smoothly enter limited access, multilane highways even when the through lane traffic was fairly heavy. This is not surprising because the units, although large, are not severely performance limited at low and intermediate speeds.

On multilane highways, the 12-ft-wide units stayed in the right lane except to pass (or to avoid parked cars or other obstructions on the shoulder) and generally traveled with the left side of the trailer 18 to 24 in. inside their own left-lane boundary. This distance varied somewhat as the result of normal path drifting and sometimes by driver preference.

Overtaking traffic passing wide loads on multilane divided highways appeared to move left, but rarely to the extent of intruding into the adjacent lane or left shoulder. There was no evidence of deceleration by the passing traffic, but it moved back noticeably toward the center of its lane after passing the wide load.

On two-way highways, the paved surface was usually very wide (36 to 40 ft over-all) with no shoulder delineation. The wide load traveled with its left side 3 to 4 ft to the right of the centerline, and opposing traffic stayed well over in its lane. Same-way passing traffic was seldom delayed more than a few seconds because the width of pavement and rightward lateral placement of the wide load afforded excellent forward visibility. Passes were sometimes made "three abreast" when the opposing traffic and the wide load moved toward the pavement edges to accommodate the passer.

In general, opposing traffic was observed to move a foot or two toward the outside edge of the pavement as the wide load approached. However, deceleration (moderate) by opposing traffic was noted only very infrequently (two or three times in approximately 250 mi traveled).

On some trips, with closed-sided mobile homes, 15- to 25-mph winds were encountered. Head winds and tail winds did not cause the tractor load to crab. (As used here crab means that the rear-wheel paths were offset to the side of the tractor-wheel paths.) Broadside and quartering winds caused a 64-ft trailer to crab, so that the rear of the trailer was offset ½ to 1 ft. A lighter, 50-ft unit crabbed, so that the rear was offset about 1 ft. Estimates of offsets were difficult to make from the tractor cab. On one occasion, an open-sided mobile home (about 40 ft long) was followed in a quartering wind when the radio broadcast wind speed for the general area was 17 mph. From this unencumbered visual vantage point, it could be seen that the rear of the mobile home was 12 to 18 in. out of line with the center of the tractor. The displacement was steady (i.e., no tail wagging), so some of the crabbing might have been caused by improper alignment of the axles on the mobile-home frame.

Oncoming trucks on two-way highways did not produce noticeable aerodynamic disturbances. The most noteworthy disturbance observed was caused by the (oncoming) passage of three or four closely spaced campers. A fairly strong pulsating disturbance could be felt, and the driver had to make several short, rapid steering adjustments to retain control.

2. *Legal-Width Commercial Units*—As one might expect, the 8-ft-wide units had less effect on neighboring traffic than did the mobile homes and modular houses.

On the multilane divided highways, the trucks normally stayed in the right lane and ran with the left side of the trailer 2 to 3 ft inside the lane line. There was no hesitancy to pass slower trucks on grades. There was very little tendency to run on the shoulder (even very good shoulders) when slowed by long upgrades.

On two-way highways, the traffic was light; sight distance was good; and the trucks offered little impedance to passing. Slower trucks were frequently overtaken and passed, again with little time delay.

3. *14-Ft-Wide Mobile Home*—This unit was transported on a low-boy trailer as then required by the State of Arizona. Leading and following pilot cars were used.

The 14-ft-wide mobile home was long (73 ft) and somewhat difficult to maneuver through city traffic. No problems were encountered entering or exiting limited-access multilane highways, either from conflict with the traffic or from maneuvering on the ramps.

On multilane highways, the 14-ft-wide unit stayed in the right lane except when forced to intrude in the adjacent lane by cars parked on the right shoulder. (Advance warning of the parked cars was radioed from the leading pilot car.) The wide load traveled with its left edge about 6 in. to the right of the lane dividing line; 2 to 3 ft of the mobile home were overhanging the shoulder. Passing traffic, on the average, appeared to move farther left for the 14-ft-wide loads than for the 12-ft-wide loads. Again there was no evidence of speed changing by the passing traffic.

The 14-ft-wide unit traveled only a very short distance on two-way highway. In a 3-mi length of two-way highway, which was 40-ft wide over-all with no shoulder delineation, traffic appeared to respond to the 14-ft unit the same as it did to 12-ft wide loads.

During the entire trip, winds were calm and no aerodynamic disturbances were noted.

Data From the Literature

Data were collected in California on lateral placement and relative speed for passenger vehicles overtaking and passing 96- and 102-in.-wide buses on multilane and two-lane highways (*49*). Lateral placements were also observed for oncomers on two-lane highways. The multilane highways had 12-ft lanes; and the two-lane highways, 13-ft lanes. The bus speed was typically 50 to 55 mph.

When in the lane adjacent to the bus on a multilane highway, the mean lateral placement of overtaking passers was offset 1 to 1.5 ft to the left of its lane centerline. This shift from the centerline did not occur in lanes farther from the bus. On two-lane highways the lateral placements were about the same as for multilane, but the placement variances were significantly larger. Oncomers on two-lane highways traveled about 1 ft farther away than overtaking passers did.

The speeds of overtaking passers dipped slightly (1 to 3 mph) as the bus was passed. The location of the speed depression relative to the bus agreed with increased drag regions observed in companion wind-tunnel tests. It was concluded that the speed decrease is an aerodynamic effect rather than an indication of driver preference.

Data From FHWA-HUD Project

Two kinds of data were collected (*37*). The first was time-lapse photographs of traffic in the vicinity of wide loads (12- and 14-ft-wide mobile homes and modular houses). The photographing was conducted from inside the load, from the cab of the towing tractor, and from the escort vehicles. The photographic data were used to determine the speed, the lateral placement, and the lane-occupancy characteristics of traffic encountering the load. The second kind of data collected comprised counts of traffic events over timed intervals. Attention was concentrated on queuing and passing; occasional events, such as intrusions into an adjacent lane, were also recorded. The count data provide the basis for determining the temporal characteristics of queuing, overtaking, passing frequencies, etc.

The photographs and manual counts were then analyzed to obtain data on overtakers on multilane highways, overtakers on two-lane highways, oncomers on two-lane highways, and queuing. The data are summarized as follows. For detailed data tabulations, the reader is referred to Ref. (*37*).

1. *Overtaking on Multilane Highways*—The vast majority of overtakers made a lane change, with relatively small speed adjustment, instead of forming a queue. In the analysis of this set of data, the point of lane changing was taken as critical and two measures were calculated: the time to overtake at the current relative speed and the emergency deceleration required to avoid impact if the wide load began a stopping deceleration of 20 ft/sec². The results obtained are as follows:

Number in sample	169
Average wide load speed	49.9 mph
Average time to overtake	10.5 sec
Average emergency deceleration	14.3 ft/sec² (these decelerations are readily achievable under conditions when the wide load can attain 20 ft/sec²)

2. *Overtaking on Two-Lane Highways*—Contrary to behavior on multilane highways, driver response on two-lane roads is generally a deceleration preparatory to forming or joining a queue. Therefore, the point in the speed trajectory where a speed reduction was obvious was taken as critical. Time to overtake and emergency deceleration were calculated similar to the multilane highway case. This set of results includes the following:

Number in sample	57
Average wide load speed	48.6 mph
Average time to overtake	13.1 sec
Average emergency deceleration	11.8 ft/sec² (these decelerations are readily achievable under conditions when the wide load can attain 20 ft/sec²)

3. *Oncoming Traffic on Two-Lane Highways*—Three measures of interaction between the oncomers and the wide load were calculated. These were: final speed (average speed of oncomers at meeting); lateral displacement (average distance from highway centerline to outside edge of left-front tire of oncoming vehicles if a car or a pickup, and to outside edge of left-rear tire if a truck); and pavement margin (average remaining lane width available to oncoming vehicles, the distance from outside edge of oncomer lane to outside edge of right-front tire of oncomer or right-rear tire for trucks). The following results were based on data from 10 trips, 3 with 14-ft-wide houses, and 7 with 12-ft-wide houses.

	Passenger Vehicles	*Trucks*
Number in sample	269	50
Average speed of wide load	50.0 mph	49.5 mph
Average final speed	55.3 mph	50.0 mph
Average lateral displacement	4.19 ft	2.92 ft
Average pavement margin	1.37 ft	0.25 ft

4. *Queuing Observations*—Queuing data are summarized in the normalized form—vehicle minutes in queue/minute of travel by the wide load. On multilane highways, this normalized queue measure averaged about 0.05 (that is, a vehicle was in queue about 5 percent of the time). No multiple vehicle queues were observed. On two-lane highways, multiple queuing was common. The normalized queue measure averaged about 2.0 (that is, on the average, two vehicles were in queue behind the load).

On two-lane highways, mean queue length appears to increase with flow rate and with load width. There is no obvious effect of load length or the presence of a front escort. On occasion, a rear escort substantially increased the mean queue length.

The time spent in queue by individual vehicles is not directly available from the data. The photographs show that it was not uncommon for a vehicle to trail the wide load for 10 to 15 min. In one instance the photographer noted that the same car had been following for more than ½ hr.

Safety Implications

Lane placement perturbation implies increased hazard because displaced vehicles travel closer to other traffic or to the edge of the traveled way. The experiments with buses (*49*) show that overtakers and oncomers move laterally away from the bus when passing. Similar behavior was observed for traffic overtaking and meeting overwidth homes. On narrow, two-lane highways, use of the shoulder by oncoming traffic was frequently observed (*37*). Speed heterogeneity adds to driver workload and implies increased hazard.

On two-lane highways, overtakers are generally required to reduce speed either to pass or to join a queue. On multilane highways, overtaker speed changes are negligibly small.

Overtakers passing the buses were slowed temporarily by aerodynamic effects. This speed change adds to traffic heterogeneity but, more importantly, could cause reduced time margins in passing on two-lane highways.

Broadside and quartering winds cause crabbing and fishtailing of overwidth homes, which, in turn, cause lateral placement variations and increased workload for other traffic.

On multilane highways, overtaking traffic tends to close rapidly, before changing lane and passing, through a period when large (emergency) deceleration by the wide load would require near capacity braking by the overtaker to avoid impact. This dynamic interaction is less severe on two-lane highways where closure speeds were observed to be lower. There was also indication that the use of high intensity flashing lights on the rear of wide loads would tend to reduce the criticality of the overtaking trajectories.

Some escort vehicle operations also create increased workload for other traffic. In particular, the rear escorts occasionally travel close behind the wide load and cause hazardous multiple vehicle passing.

Implications for Delay to Other Traffic

Delay magnitude was not directly obtained in any of the data collection activities. Delay implications included in the speed and cost data of Ref. (*37*) are summarized as follows. (These data refer to the transporting of 12- and 14-ft-wide mobile homes and modular houses.)

- Delay to overtaking traffic on multilane highways is insignificant for the light-to-moderate range of flows observed. There is no queuing and only slight speed reductions in passing.
- Almost all overtaking traffic on two-lane highways experience significant delays. There was practically no unslowed passing, and the average queue of delayed vehicles was two.
- Oncoming traffic is delayed slightly, but insignificantly by virtue of temporary speed reduction at meeting with the wide load.
- Delay for overtakers on two-lane highways increases as the speed of the wide load decreases.
- Delay for overtakers on two-lane highways may be increased by the presence of escorts. In particular, rear escorts traveling too close behind the load may cause prolonged queuing by making it more difficult to pass.
- There is an apparent increase in delay to overtakers with increasing traffic flow.

The Modular-House and Mobile-Home Loads

Data were collected on the characteristics of the subject combinations in this project and in Ref. (*37*). The results are shown in Figures 30, 31, and 32. Figure 30 is a histogram of combination gross weights. The weight/net horsepower ratio is highly correlated with gross weight as shown in Figure 31. The weight/frontal area ratio is also highly correlated with gross weight as shown in Figure 32.

All but a few of the combinations have weight/NHP ratios under 200; they are distributed almost uniformly in the range 100 to 175 lb/NHP. The higher values are rare extremes. The frontal areas are larger than normal truck combinations.

The tractor and load samples in Figures 30, 31, and 32 are not the result of random sampling. They are the units for which data could be obtained in a sample selected to provide coverage of the following load an terrain types:

1. *Loads*—Mobile homes (12-ft wides, 14-ft wides, single unit, double unit); modular houses.
2. *Terrains*—Level, rolling, mountaineous.

In Figure 33 the performances of a light mobile home combination and a light truck are compared. The large frontal area of the mobile-home combination (solid lines in Figure 33) is seen to exact a penalty in high-speed perform-

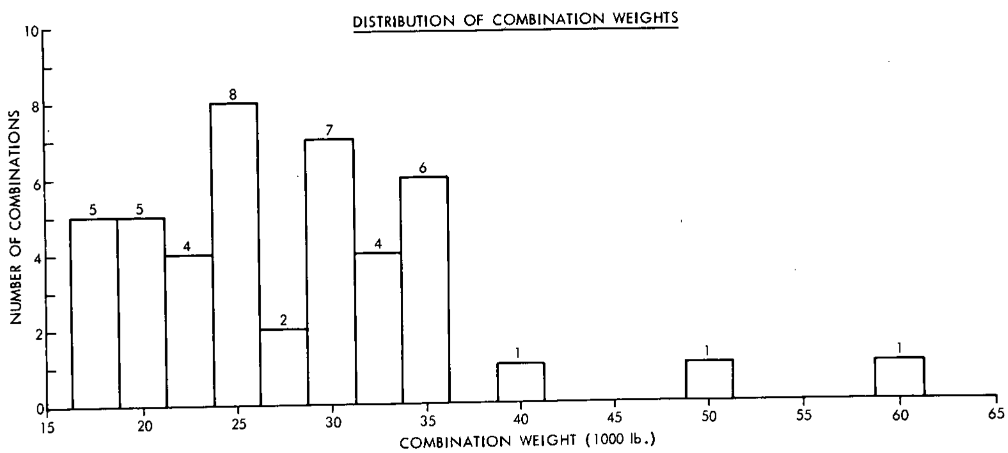

Figure 30. Gross weights of mobile-home and modular-house combinations.

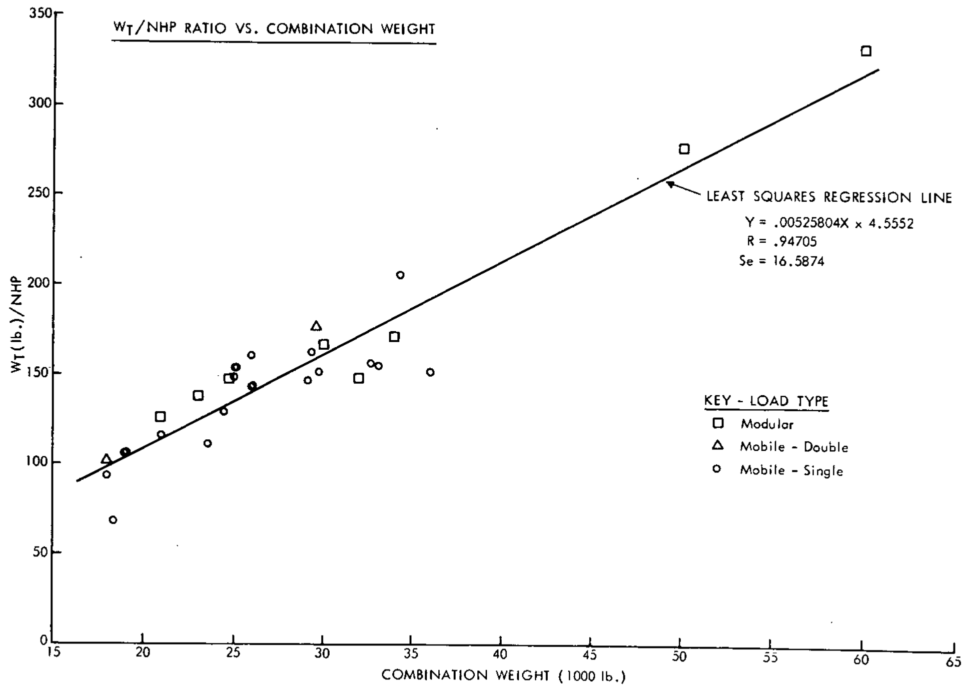

Figure 31. Weight/net horsepower ratios of mobile-homes and modular-house combinations.

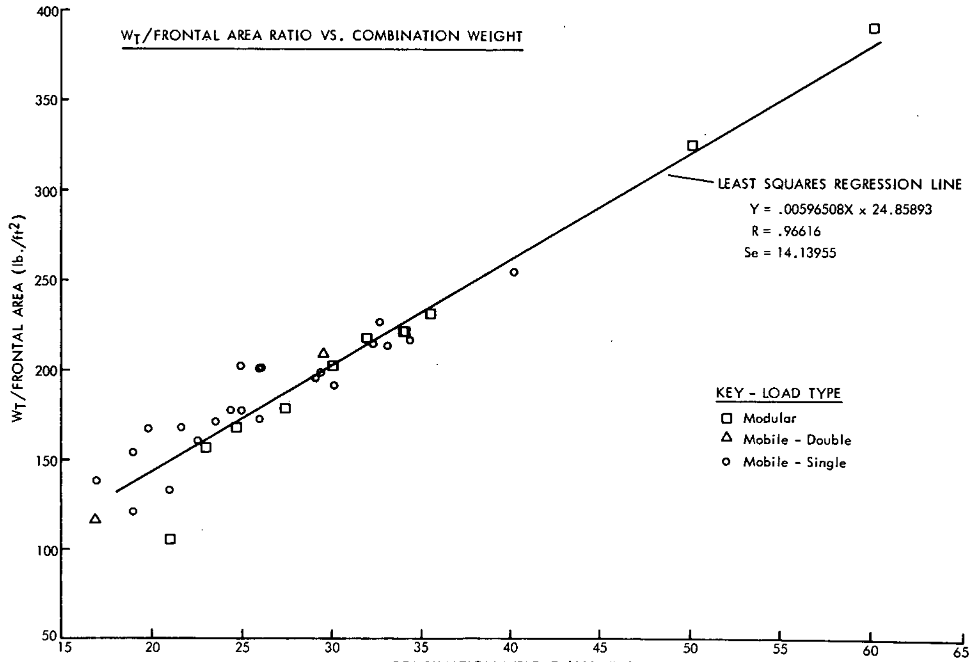

Figure 32. Weight/projected frontal area of mobile-home and modular-house combinations.

ance. A comparison of the calculations also made for a 175-lb/NHP mobile-home combination with those made for a 200-lb/NHP truck shows that the 175-lb/NHP mobile-home unit has better accelerations at low speed but slightly lower maximum speeds on moderate grades.

The performances of 300-lb/NHP units (note that this is an extreme value for the modular-house combinations) are compared in Figure 34. The large frontal area reduces the maximum speeds of the modular-house unit on moderate grades. The difference is about 6 mph on zero grade. On steep grades, the performances are essentially indistinguishable.

In the multilane flows in Ref. (*55*), and in the two-lane flows simulated here, the most severe effects of performance-limited vehicles occur in upgrade flows. Further, the influence on the flow (or equivalence) increases rapidly as vehicle speed drops. The mobile-home and modular-house combinations are unlikely to be the slowest vehicles on steep grades. They will be slightly more disruptive than indicated by their W/NHP ratio in level or gently rolling terrain. On two-lane highways, the speed reductions and stops for lateral clearance problems may outweigh the direct effects of performance limitations.

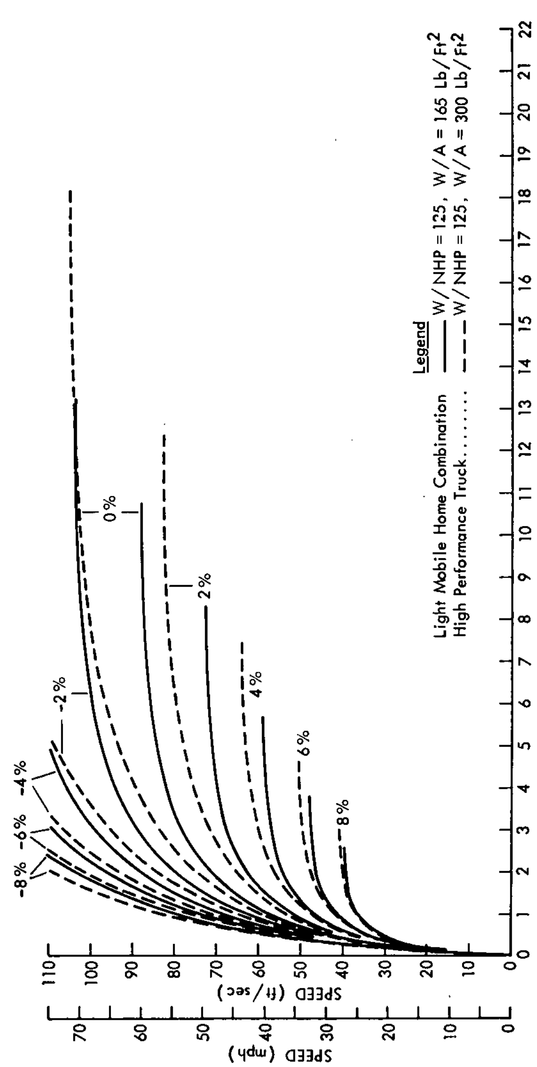

Figure 33. Calculated acceleration performance—comparison of a light, mobile-home combination with a high-performance truck.

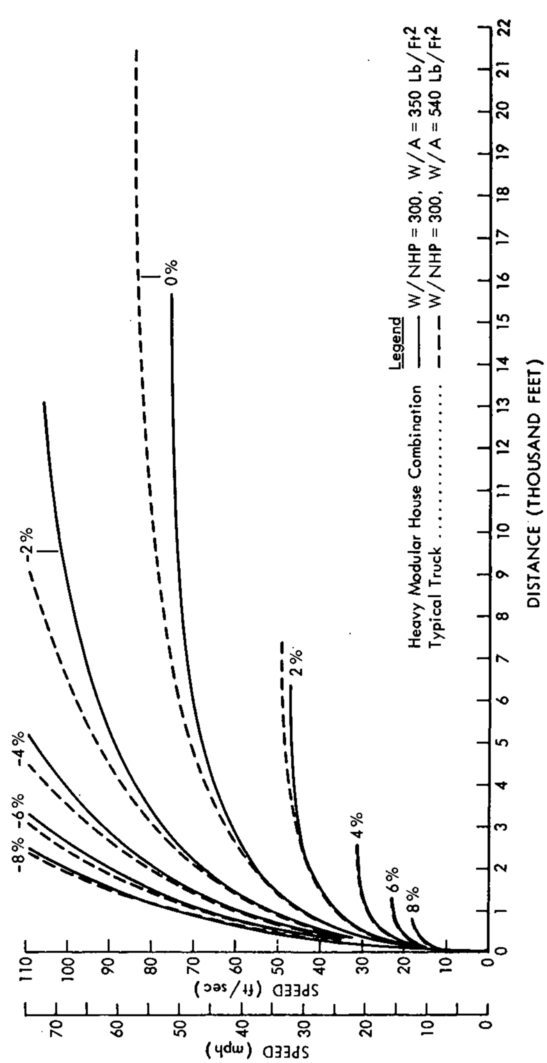

Figure 34. Calculated acceleration performance—comparison of a heavy, modular-house combination with a typical truck.

Relative Vulnerability of Mobile Homes and Modular Houses to Winds

The effects of winds were compared on mobile homes, modular houses, truck campers, travel trailers, and regulation width (8-ft) truck semitrailers. The comparison was made by estimating both the steady side wind required to overturn the units at standstill and the amount of crabbing that would be caused by a steady side wind of 20 mph.

The overturning wind speed was estimated using a moment balance about the wheels on the lee side. Two upsetting aerodynamic moments were included: that due to the "drag" force on the vertical windward side and that due to the "lift" force on the roof near the windward edge. (The drag force is the effect of overpressure on the vertical surface struck by the wind. The lift force (a lesser effect) acts upward on the roof and is the result of underpressure caused by air accelerating up and over the structure. The aerodynamic coefficients employed and the area on which the lift force acts are estimates based on results from wind-tunnel tests reported in Ref. (*60*). The referenced work deals with wind loads on rectangular architectural structures.) These upsetting moments are countered by the stabilizing moment of the weight acting vertically downward through the center of gravity.

The magnitude of crabbing was estimated using a moment balance about the hitch point (about the front wheels for the truck camper). The aerodynamic moment tending to cause crabbing was taken to be that due to the drag force acting on the vertical windward side. The countering moment is that due to the lateral force acting on the tires.

The aerodynamic drag force was assumed to act at the areal centroid of the vertical side. Its magnitude is

$$\text{Drag Force} = \tfrac{1}{2}\,\rho\, C_D A_D U^2$$

where:

ρ = air density = 0.075 lb/ft³ (sea-level standard);
C_D = drag coefficient = 0.90 (assumed);
A_D = area of side on which force acts; and
U = wind speed, ft/sec.

Inserting the values for ρ and C_D gives

$$\text{Drag Force} = 0.00225\, A_D\, U^2_{\text{mph}}$$

where U_{mph} is the wind speed in miles per hour.

The lift force was assumed to act uniformly over an area near the edge of the roof (3-ft wide on the mobile homes and 2-ft wide on the other units). Its magnitude is:

$$\text{Lift Force} = \tfrac{1}{2}\, \rho C_L A_L U^2$$

where:

C_L = lift coefficient = 0.40 (assumed); and
A_L = area over which force acts.

Thus,

$$\text{Lift Force} = 0.0010\, A_L U^2_{\text{mph}}$$

The lateral force acting on the tires was obtained from Ref. (*56*), where the lateral force is given as a function of the normal load on the tire and the slip angle (angle between the tire plane and the direction of motion and is equal to the estimated crab angle). The data are plotted for normal tire loads up to 2,000 lb, which do not cover the operating range for truck tires. Lateral forces for truck tires were estimated assuming that the *ratio* lateral load/normal load given in Ref. (*56*) for normal load equal 2,000 lb was applicable to trucks. (This is equivalent to the assumption that automobile and truck tires are similar and the truck tire is loaded to near capacity.)

The physical characteristics used to represent the five vehicle classes were obtained from Ref. (*43*) and some field observations. The following weight and dimensional data were used:

12- x 64-Ft Mobile Home	
Weight (without towing tractor)	14,000 lb
Length (excluding hitch frame)	61 ft
Length (over-all)	64 ft
Width	12 ft
Height (over-all)	11 ft
Height (pavement to bottom of box)	2 ft
Tread width (center-to-center spacing of the out board tires)	8 ft
Length (hitch point to center axle)	42
14- x 70-Ft Mobile Home	
Weight (without towing tractor)	18,000 lb
Length (excluding hitch frame)	67 ft
Length (over-all)	70 ft
Width	14 ft
Height (over-all)	11 ft
Height (pavement to bottom of box)	2 ft
Tread width (center-to-center spacing of the outboard tires)	8 ft
Number of axles	4
Length (hitch point to center axle)	47 ft
12- x 50-Ft Modular House	
Weight (house and trailer)	32,000 lb
Length (excluding hitch extension)	50 ft
Length (over-all)	52½ ft
Width	12 ft
Height (open side)	12½ ft
Height (pavement to bottom of box)	2½ ft
Tread width (center-to-center spacing of the outboard tires)	8 ft
Number of axles	3
Length (hitch point to center axle)	32½ ft
45-Ft Semitrailer	
Weight (with payload; without tractor)	60,000 lb
Length	45 ft
Width	8 ft
Height (over-all)	13½ ft
Height (pavement to bottom of box)	4 ft
Tread width (center-to-center spacing of the outboard tires)	7 ft
Number of axles	2
Length (fifth wheel to center of axles)	35½ ft
Truck—Camper	
Weight (camper and pickup)	7,900 lb
Length	15 ft
Wheelbase	12½ ft
Width	7½ ft
Height (over-all)	8 ft
Height (pavement to bottom of box)	1 ft
Tread width (center-to-center spacing of the outboard tires)	5 ft
28-Ft Travel Trailer	
Weight (without towing vehicle)	7,000 lb
Length (excluding hitch frame)	25 ft
Length (over-all)	28 ft
Width	7 ft
Height (over-all)	9 ft
Height (pavement to bottom of box)	1 ft
Tread width (center-to-center spacing of the outboard tires)	5 ft
Number of axles	1
Length (hitch point to axle)	20 ft

The following estimates for overturning winds were obtained:

Configuration	*Side Wind Required to Overturn (mph)*
12 x 64 mobile home	77
14 x 70 mobile home	82
12 x 50 modular house	104
45-ft semitrailer	146
Truck camper	114
Travel trailer	79

These results indicate that the mobile homes and travel trailers are equally susceptible to overturning; the truck semitrailer is very stable, and the modular house and camper are intermediate. The vulnerability of the mobile homes and travel trailers arises from their low density. Their large size results in large upsetting moments, whereas their light weight produces small stability moments. The modular house experiences approximately the same aerodynamic moments, but its larger weight (higher density) makes it more stable. In the comparisons, the semitrailer is assumed to be fully loaded. An empty trailer will be about as vulnerable to overturning as the mobile homes if the trailer attachment does not supply stabilizing reactions to roll.

It should be recognized that the previous estimates were made to compare relative susceptibilities to overturning. It is encouraging that the calculated winds fall in a range that seems reasonable. However, both the relative comparisons and the calculated winds are based on a simple analytical model that neglects several factors. The model does not include any stabilizing effect from attachment to a towing tractor, and there is no provision for the effects of gusts.

The towing attachment could supply torsional rigidity in roll, and the vertical reaction force could supply a stabilizing or destabilizing moment in roll. The attachment in mobile and modular houses has little torsional rigidity. To appraise the reaction force, data are required on the hitch height and the height of the trailer's center of gravity.

Wind gusts can produce monentary forces and moments as much as two or three times the steady values with wind sustained at gust speed (*61*). In addition to the increased aerodynamic forces, a gust could add momentum to a roll motion and increase the chance of upset. The importance of the latter effect depends partly on the suspension system characteristics.

The crabbing offset caused by a side wind of 20 mph was estimated. Crabbing offset is defined here as the sideward deviation of the rear of the unit from an in-line position behind the tractor. (For the truck camper, crabbing offset is the offset of the rear-wheel path centerline from the front-wheel path centerline.) A 20-mph direct side wind was estimated to cause steady crabbing offsets as follows:

Configuration	*Crabbing Offset (in.)*
12 x 64 mobile home	4
14 x 70 mobilc home	4
12 x 50 modular house	1½
45-ft semitrailer	Negligible
Truck camper	Negligible
Travel trailer	1¼

The mobile homes show the greatest tendency to crab in response to a steady side wind, a result that is not surprising. The 4-in. offset shown may seem small in view of popular opinion about mobile home crabbing. In this regard, it is noted that the 4-in. deviation represents a misalignment of only one-quarter degree; manufacturing tolerances on axle alignment could easily result in significant additional crabbing.

In conclusion, mobile homes are observed to be vulnerable to cross winds. Modular houses are affected to a lesser extent. The sensitivity of mobile homes stems primarily from their low density, which is not easily changed. Increasing the tread width would make the homes less susceptible to overturning, but would not appreciably affect crabbing.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

This chapter is divided into four sections. The first section explains how to estimate service levels for nearly balanced flows on a 65-mph highway with 46- to 80-percent no-passing. The second treats the problem of estimating vehicle populations. The third section presents the implications from the analysis and observation of wide loads, and the fourth describes how the simulation can be employed effectively.

ESTIMATION OF SERVICE LEVELS FROM SUMMARIZED SIMULATION RESULTS

The general procedure to provide an estimate of passenger vehicle over-all mean speed for essentially balanced flows on a 65-mph highway with 46- to 80-percent no-passing requires five steps:

1. Obtain for each truck and recreational vehicle type the zero-traffic speed through the highway section of interest in the direction of interest.
2. Read the equivalence kernel, ν, for each vehicle type from Figure 16 for the vehicle zero-traffic speed (or use Eq. 17).
3. Calculate the truck factor F_T from $F_T = 1/(2r + 1)^{\frac{1}{2}}$, where:

$$r = \sum_{i=1}^{n} \frac{P_i}{100}(\nu_i - 1)$$

Here P_i is the percentage of the ith vehicle type, and ν_i is the equivalence kernel of the ith type.

4. Calculate the equivalent passenger vehicle flow from $Q_E = Q/F_T$, where Q is the nearly balanced total flow, and Q_E is the equivalent total flow of passenger vehicles.
5. Enter Figure 14 with Q_E to read the estimated passenger vehicle over-all mean speed in the mixed flow. If the analyzed flow direction occurs up a grade, use the appropriate curve in Figure 14; if the flow occurs in rolling terrain or down a grade with crawling trucks, use the 0-percent grade curve.

Normally the zero-traffic speed of each type of impeding vehicle is required to begin the calculation of equivalent flows. These speeds can be obtained for trucks from the figures in Appendix E and for recreational vehicles from the performance equations. When the zero-traffic speed is known, the equivalence kernel is calculated from Eq. 17 or read from Figure 16. Tables 19, 20, and 21 have been provided to bypass the foregoing tasks. They summarize the zero-traffic speeds and equivalence kernels for rolling terrain and for long grades, and can be used to make calcu-

TABLE 19

ZERO-TRAFFIC SPEEDS (FT/SEC) AND EQUIVALENCE KERNELS, ν, IN ROLLING TERRAIN[a]

Vehicle: Simulation Type Number	Vehicle: Description	Site[b/] NCSU 3-1969, Direction One (Westbound) Overall upgrade: speed	kernel	NCSU 3-1969, Direction Two (Eastbound) Overall downgrade: speed	kernel	Pacheco Pass, Direction One (Eastbound) Overall upgrade: speed	kernel	Pacheco Pass, Direction Two (Westbound) Overall downgrade: speed	kernel
1	Truck, 400 Lb/NHP, 895 Lb/Ft^2	59.6	13.0	65.7	7.9	62.4	10.0	82.9	1.90
2	Truck, 300 Lb/NHP, 580 Lb/Ft^2	65.8	7.8	71.8	4.8	71.1	5.0	83.3	1.85
3	Truck, 125 Lb/NHP, 300 Lb/Ft^2	80.7	2.22	82.7	1.9	85.1	1.60	85.2	1.55
4	Low Performance Camper	78.5	2.70	80.3	2.3	80.5	2.30	83.9	1.78
5	Low Performance Travel Trailer Combination	81.4	2.15	83.6	1.8	84.6	1.65	85.1	1.58
6	Low Performance Motor Home	81.3	2.15	83.2	1.85	84.1	1.70	84.9	1.60
7	Medium Performance Camper	82.8	1.90	84.1	1.70	84.7	1.65	85.1	1.58
8	Nominal Motor Home	82.9	1.90	84.2	1.70	84.8	1.62	85.1	1.58
9	Medium Performance Travel Trailer Combination	83.2	1.85	84.5	1.65	85.3	1.55	85.3	1.55
10	High Performance Travel Trailer Combination	84.6	1.65	85.2	1.58	85.5	1.00	85.5	1.00
Alternate 2	Heavy Modular House Combination 300 Lb/NHP, 350 Lb/Ft^2	62.1	10.3	68.1	6.3				

a/ Values for passenger and Recreational Vehicles are based on driver restraint which limits long period performance demands to 70% of maximum available horsepower. All vehicles attempt to maintain a speed of 85.49 ft/sec.for this zero-traffic speed.

b/ The NCSU (North Carolina State University) site 3-1969 is a rugged rolling terrain with grade lengths of 1,000 to 1,700 ft and magnitudes up to 7%. The number of one direction traffic climbs the 7% grade. There are no downgrade crawl regions. The Pacheco Pass site is a less rugged rolling terrain with an overall upgrade of about 0.6% for eastbound traffic.

TABLE 20

STEADY, ZERO-TRAFFIC SPEEDS (FT/SEC) AND EQUIVALENCE KERNELS, ν, ON LONG GRADES[a]

Vehicle		Grade %									
Simulation Type Number	Description	0		2		4		6		8	
		speed	kernel	speed	kernel	speed	kernel	speed	kernel	speed	kernel
1	Truck, 400 Lb/NHP, 895 Lb/Ft^2	83.0	1.85	40.0	85.0	26.3	196.0	17.3	431.0	13.4	581.0
2	Truck, 300 Lb/NHP, 580 Lb/Ft^2	86.0	1.47	50.0	28.3	34.5	101.0	22.9	261.0	17.8	401.0
3	Truck, 125 Lb/NHP, 300 Lb/Ft^2	97.0	1.00	83.0	1.85	66.4	7.3	50.7	26.3	41.0	59.0
4	Low Performance Camper	81.9	1.05	72.4	4.40	62.9	9.7	53.4	21.5	43.9	48.0
5	Low Performance Travel Trailer Combination	93.6	1.00	80.3	2.30	67.0	7.0	53.7	21.3	40.4	61.0
6	Low Performance Motor Home	90.0	1.05	78.7	2.65	67.3	6.85	56.0	17.3	44.7	44.0
7	Medium Performance Camper	90.0	1.05	82.1	2.00	74.1	3.9	66.2	7.4	58.3	14.0
8	Nominal Motor Home	90.0	1.05	82.4	1.95	74.8	3.65	67.1	6.95	59.5	13.0
9	Medium Performance Travel Trailer Combination	93.6	1.0	84.6	1.65	75.7	3.5	66.7	7.05	57.7	15.3
10	High Performance Travel Trailer Combination	99.0	1.0	91.7	1.00	84.5	1.65	77.2	3.05	69.9	5.6

a/ The steady on-grade speeds for the passenger and recreational vehicles are based on driver restraint to 70% of maximum available horsepower.

TABLE 21

TYPICAL DOWNGRADE CRAWL SPEEDS AND ASSOCIATED EQUIVALENCE KERNELS FOR TRUCKS

Grade (Percent)	Crawl Speed (ft/sec)	Equivalence kernels ν
-4	73.25	4.2
-6	48.83	31.0
-8	36.63	85.0

lations for nearly balanced flows on 65-mph highways with 46- to 80-percent no-passing.

Table 19 gives values for a severe rolling terrain (the NCSU 3-1969 site) and a moderate rolling terrain (the Pacheco Pass site). At both sites there is a slight over-all grade causing different speeds and kernels in the opposing directions.

Table 20 provides zero-traffic speeds and kernels for portions of a long upgrade where speeds of performance-limited vehicles have stabilized. Normally, these values will apply to portions of the grade more than 0.6 mi from the foot. Such grades are likely to be bottlenecks and may warrant separate appraisal. If trucks use crawl speeds downgrade, that flow direction may also warrant appraisal. Table 21 gives typical zero-traffic speeds and equivalence kernels for the trucks crawling downgrade.

As an example, the truck factor is calculated for a flow in severe rolling terrain containing 10-percent trucks and 5-percent recreational vehicles plus utility trailers on a primary highway in a nonrecreational area. The percent of individual type vehicles is obtained from Table 10. The equivalence kernel values are taken from Table 19. (The most conservative (large) values of equivalence kernel were selected.) Table 22 contains the tabulations and calculations to obtain r as defined by Eq. 15. The sources for tabulated values are shown in the headings of Table 22. The value of r is obtained as the sum of contributions to r; i.e., the sum of the entries in column (H). The nonlinear truck factor is then obtained from r as:

$$F_T = 1/(2r+1)^{\frac{1}{2}} = 0.6914$$

If the mixed flow rate is approximately 300 vph in each direction, the equivalent two-way flow is 600/0.6914 = 868. The estimated mean speed of passenger vehicles is read from Figure 14 on the 0-percent grade curve as 69.6 ft/sec, or 47.5 mph.

ESTIMATION OF VEHICLE POPULATIONS AND PERFORMANCE

The data collected in this project and reported by other investigators indicate that flows on different facilities contain markedly different fractions of trucks and recreational vehicles. At present, the only way to determine the vehicle population on a facility is by direct observation. In the case of trucks, the problem is compounded by variations in the performance levels observed on different facilities. If this difference is not accounted for in calculations, sizable errors could be introduced in estimated speeds.

For the present and near future, the performance aspects of individual vehicle types can be based on the tables in Chapter Two. Two other facets of the problem facilitate estimates of vehicle populations. First, it is relatively easy to obtain practical estimates of the performance capabilities of local truck populations. And second, although the frequencies of individual recreational vehicle types differ from location to location, the distribution of performance capabilities is much the same in each environment.

Practical estimates of truck-performance characteristics can be made with simple spot speed measurements on a sustained grade. It is not difficult to find a grade with otherwise good geometrics where truck speed will be dictated by performance limits. The figures in Appendix E can be used to determine the requirements for data-collection sites. The required length of grade will depend in part on the entrance speeds at the grade foot. The distribution of truck weight/NHP ratios can be estimated from spot speeds of unimpeded trucks through the use of the curves in Figures E-1 through E-10.

The characteristics of the recreational vehicle population can not be estimated as well as those of trucks from simple speed measurements. However, it appears from available data that the distribution of performance capabilities is nearly the same within recreational vehicle populations containing different proportions of individual types. The similarity is due in part to the fact that different recreational vehcle types have somewhat similar ranges of performance capability, as shown in Table 23, where types with similar performance are grouped together. (For illustrative purposes, Table 23 merely regroups part of the results in Tables 19 and 20. Tables 19 and 20 should be employed for equivalency information on all the vehicle types and geometries studied.)

In view of the strong economic pressures currently felt it is likely that the vehicle population and its performance characteristics will change. The equations for performance prediction were developed not only for estimating the current characteristics but also to provide a means to update characteristics in future years. In fact, it may be desirable to project future characteristics if rapid changes occur. The performance equations appear adequate for future application. The problem lies in obtaining data on the horsepower, weight, and size of either the vehicles in use or vehicles being manufactured and sold. Publications, such as *Automotive Industries,* are reducing the amount of data pub-

TABLE 22

TABULATIONS AND CALCULATIONS TO OBTAIN *r* (NEEDED IN NONLINEAR TRUCK FACTOR)

(A) Vehicle No. (i)	(B) Type	(C) Percent in Category	(D) From Table 10 Fraction Within Category	(P) (C).(D) Percent in Population	(G) From Table 19 Equivalence kernel,	(H) [(G)-1]/100 Contribution to r
1	Low Performance Truck	10	.11	1.1	13.	.1320
2	Typical Truck	10	.48	4.8	7.8	.3264
3	High Performance Truck	10	.41	4.1	2.22	.05002
4	Low Performance Camper	5	.0494	.247	2.70	.004199
5	Low Performance Travel Trailer	5	.0248	.124	2.15	.001426
6	Low Performance Motor Home	5	.0060	.030	2.15	.000345
7	Medium Performance Camper	5	.2768	1.384	1.90	.012456
8	Nominal Performance Motor Home	5	.0340	.170	1.90	.001530
9	Medium Performance Travel Trailer	5	.2808	1.404	1.85	.011934
10	High Performance Travel Trailer	5	.1713	.8565	1.65	.005567
						r = 0.545877

TABLE 23

RECREATIONAL VEHICLES GROUPED INTO SIMILAR PERFORMANCE STRATA (TABULATED VALUES ARE EQUIVALENCE KERNELS)[1]

	Rolling Terrain				Sustained Grades				
	Severe		Moderate						
Vehicle Type	Overall Upgrade	Overall Downgrade	Overall Upgrade	Overall Downgrade	0%	2%	4%	6%	8%
Low Performance Camper	2.70	2.30	2.30	1.78	1.05	4.40	9.70	21.5	48.0
Low Performance Travel Trailer	2.15	1.80	1.65	1.58	1.00	2.30	7.00	21.3	61.0
Low Performance Mobile Home	2.15	1.85	1.70	1.60	1.05	2.65	6.85	17.3	44.0
Medium Performance Camper	1.90	1.70	1.65	1.58	1.05	2.00	3.90	7.40	14.0
Medium Performance Mobile Home	1.90	1.70	1.62	1.58	1.05	1.95	3.65	6.96	13.0
Medium Performance Travel Trailer	1.85	1.65	1.55	1.55	1.00	1.65	3.50	7.05	15.3
High Performance Travel Trailer	1.65	1.58	1.00	1.00	1.00	1.00	1.65	3.05	5.6
High Performance Camper	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.0

1/ The equivalence kernel values are applicable to nearly balanced flows on a 65 mph highway where percent no passing falls in range of 46 to 80%.

lished, and even in past years it was difficult to assemble the data in the form required to estimate performance characteristics.

LOADS WITH OVERREGULATION DIMENSIONS

Comparisons with the Truck Population

Mobile-home and modular-house combinations have weight/NHP ratios mostly in the range of 100 to 200, with a very few values up to 300 lb/NHP. On steep grades, that is 4 percent and over, they should be considered as light, medium, or heavy trucks, with performances nearly equal to trucks in the same weight/net horsepower range. On moderate grades (±2 percent), the mobile- and modular-house combinations will have maximum speeds about 5 to 10 mph lower than trucks. On steep downgrades the mobile- and modular-house combinations have the same problems of speed control as other trucks.

Implications from FHWA-HUD Study

The data collected in the FHWA-HUD study on the effect of mobile homes and modular houses on other traffic enable recommendations on operational guidelines. The following discussion refers to oversize mobile and modular housing of 12- and 14-ft widths and lengths as presently found on the highways (approximately 45 to 70 ft).

1. *Preferred Routing*—The oversize loads should be encouraged to use Interstate or other controlled access facilities, unlimited access divided, multilane undivided, and two-lane (two-way) highways in the listed order of preference. Delay to other traffic, hazard potential, and traffic interference in general were observed to be greater on two-lane and the lower quality divided highways. No unique difficulties were observed for average load transport on the Interstate and high quality divided highways.

Each state should compile a route system suitable for use by oversize homes and publish it in the form of a route map. Priority indications should be included to promote the use of high quality facilities. Routes with undesirable features (e.g., appreciable lengths of steep grade, unusual roadside obstacles, or narrow lanes) could be given a reduced priority rating to limit use by the oversize loads when better options are available.

2. *Speed Limits*—Mobile and modular houses should travel in the speed range 45 to 60 mph except where other traffic is restricted to lower speeds. Oversize homes traveling below the indicated speed range create greater delay and hazard for other traffic. Data were not obtained for speeds above the indicated range; but higher speeds are deemed undesirable from standpoints of structural integrity, tracking stability, braking, and lane changing.

The foregoing observations were made prior to the National 55-mph speed limit. The 55-mph limit should be applied to mobile and modular houses on highways with good cross sections and sight distances.

3. *Lighting and Signing*—Signing configurations in current use are generally satisfactory. A tentative, recommended signing standard is as follows:

a. A WIDE LOAD sign on the front of the towing vehicle at bumper level—The sign should be approximately 18 in. x 72 in. over-all and consist of 12-in. bold black letters on a yellow background.

b. A WIDE LOAD sign on the rear of the home approximately 6 ft above pavement level—The sign format should be as previously described.

Some states require oversize homes to have flashing amber lights mounted on the rear. These lights are ineffective because they are low powered, often dirty and invisible for all practical purposes. Objective warrants and specifications for warning lights can not be given. However, visibility requirements, in general, suggest that lights should be used on escort vehicles and on the roof of the towing cab on two-lane highways. The lights should be the high intensity, rotating beacon type commonly used by emergency vehicles.

4. *Escort Vehicles*—Escort vehicles perform useful functions, but also add to delay and interference with other traffic.

The primary function of a rear escort is to warn overtaking traffic of the presence of a large, slow vehicle. Rear escorts are frequently used on divided highways where they are not needed, and this practice should be discontinued. Rear escorts are desirable on two-lane highways with severely limited sight distances. However, on two-lane highways, the rear escorts were observed to increase the difficulties of traffic overtaking and atempting to pass the escort and load. Therefore, for two-lane highways with marginal or better sight distance, consideration should be given to the use of high-intensity lighting on the rear in lieu of rear escorts.

Front escorts serve a double purpose. They warn oncoming traffic of the approach of a large vehicle, and they assist the driver of the tow vehicle by advising him of roadside obstacles and by occasionally blocking oncoming traffic at a constriction, such as a narrow bridge. Both functions are necessary and warrant the use of escorts, but discretion is required. Instances were observed where front escorts were needlessly employed on high quality, two-lane highways. Consideration should be given to the use of warning lights in lieu of escorts in marginal situations. Also, front escorts should be required to have two-way radio communication with the driver of the towing unit.

In general, escort vehicles are effective in reducing delay and disturbance for both the oversize load and other traffic. Frequently, however, improper escort action causes disruptions and increased delay. It is recommended that training programs be made available and escort drivers be tested and licensed to instill an appreciation of the purpose and responsibilities of the escort function. The necessity for occasionally blocking traffic emphasizes the need for prudence and responsibility in the escort functions. The authority to block traffic is normally reserved for police and highway department personnel. If this authority is delegated to escorts, it is desirable that their procedure and equipment be consistent with state police practices.

EFFECTIVE EMPLOYMENT OF THE TWO-LANE SIMULATION

Program and Computer Compatibility

The program for simulating traffic on a two-lane, two-way highway was written in FORTRAN IV language and was run on a Control Data Corporation 6600. The Extended FORTRAN or FTN compiler was used to compile the program, and the compile option was chosen which optimized the program (i.e., OPT = 2). The object program could be loaded using 66,000 words (octal) and run in 52,000 words (octal) once it was loaded.

Although the program was not tested on any computer other than the CDC 6600, it was written (aside from two minor exceptions) with the aim of making it compatible with any FORTRAN IV compiler. Thus, the programming does not store more than 4 characters per word in alphanumeric format and does not knowingly use any features of CDC FORTRAN IV that are unique for the 6600. One of the exceptions is the random number function subprogram RAN, which involves the computer word format. This routine, which is only nine words long, will require modification if the program is to be run on a machine with word format (length and bit configurations) different from the 6600. The other exception pertains to the array VDNOR, which contains normal desired speed for individual vehicles. The fractional part of the value is used to store the time (in seconds) when the vehicle entered the analysis or test section of the road. This time is divided by 10,000 before it is stored. Before running the program on another machine, the user should determine whether or not it will be necessary to make this array double precision.

There is one other place in the program where numerical difficulties might arise if the program is run on a computer having fewer significant bits in its single precision word format than the CDC 6600. In calculating desired speeds dependent on horizontal curves, the program sometimes generates differences of nearly equal numbers. It may, therefore, be necessary to use double precision in this calculation on some computers.

Road Length and Simulated Time

The shortest road length employed was 2½ mi for a few runs in level terrain. The majority of runs were made with 4- or 5-mi lengths, including a ½-mi buffer at each end where simulation results are not collected. The ½-mi buffer lengths were marginal on steep grades where extensive platooning occurs.

Most runs were made with a warm-up time (during which data were not collected) of 6 min of simulated time followed by a test time of 40 or 60 min. The 40-min test times were used for flows over 800 vph. The initial placement of vehicles on the road (priming) is performed by program logic and appears to be satisfactory. Data collected during the first 20 and 40 min of test time indicate that the results are not disturbed by starting transients. These simulation times are recommended together with the 3- to 5-mi road length for adequate sample size and reasonable economy.

Computer Running Time

The computer program logic was designed and sequenced to minimize running time. Experience on the CDC 6600 indicates that the computer processes 1,500 to 1,700 vehicles through a review period in 1 sec of computer time. With 1-sec review periods, the ratio of simulated real time to computer time depends on the number of vehicles in the simulation simultaneously. With 100 vehicles, the ratio is 16; with 200, 8; etc. These time estimates include the computer time used for data entry, preparatory processing, data processing, and output.

Program Input

The program input is detailed in Appendix I.

Computer Program Availability

The listing of the source program is not included in this report in the interest of conserving space. (The program contains about 4,000 statements, which would list on about 65 pages.) A copy of the source program (card deck), however, has been delivered to NCHRP together with a sample input deck and output for the sample. The source deck was tested by compiling it and using the object program to run the sample case. The same sample run was made with the original program and compared for exact matching. (The random number starters were the same.)

Instructions for using and interpreting the simulation program are given in Appendix I.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

The conclusions drawn from the data collection activities of this research are as follows:

1. The acceleration capabilities of individual passenger vehicles and recreational vehicles are linear functions of speed and grade.
2. The acceleration capabilities of individual passenger and recreational vehicles can be estimated from their brake horsepower, gross weight, gear ratios, projected frontal area, and the general characteristics of the body shape.
3. Drivers of passenger and recreational vehicles restrict their demand for performance on long upgrades to about seven-tenths of the maximum available horsepower.
4. The physical data to estimate performance characteristics for the vehicle population are not available in a directly usable form.
5. The acceleration capabilities of individual trucks are nonlinear functions of speed and grade.
6. The acceleration capabilities of individual trucks can

be estimated from the ratios—weight/net horsepower and weight/projected frontal area.

7. Mobile-home and modular-house combinations have weight/net horsepower ratios in the range 100 to 200, with a very few as high as 300. On steep grades, they perform like trucks of the same ratio. On moderate grades (±2 percent), the maximum speeds of mobile-home and modular-house combinations are 5 to 10 mph less than the maximum speeds of conventional trucks with equal weight/net horsepower ratios.

8. The anomolously low capacities observed for two-lane, two-way highways are probably associated with driver responses to high frequency encounters with oncoming vehicles.

9. The simulation program developed in this project for two-lane, two-way traffic can be used to determine traffic speeds and characteristics with a realistic account of vehicle characteristics and highway geometries. Specifically, analyses of computed simulation results indicate that:

a. The truck factor currently used does not properly account for variations in the percentage of impeding vehicles and does not properly account for the combined effects of a mixture of impeding vehicle types.
b. A nonlinear form of the truck factor, together with equivalence kernel values, provides useful estimates of passenger-car speeds on a variety of geometries with several vehicle populations in essentially balanced flows.
c. The equivalence kernel value for an impeding vehicle is a function of its over-all speed on the geometries of interest in zero traffic.
d. The performance limitations of passenger vehicles, combined with driver restraint in the use of performance, cause reduced speeds on extended grades of 4 percent and more in flows with 100-percent passenger vehicles.
e. The lowest performance recreational vehicles and a 125-lb/NHP truck have similar equivalences in a wide range of geometrics. The truck outperforms the recreational vehicles slightly on grades less than 4 percent, and vice versa on steeper grades.
f. Loads with overregulation widths should be routed on Interstate highways whenever possible, with next priorities to multilane and high-design type, two-lane facilities.

On the basis of the foregoing conclusions, the following recommendations are made:

1. The nonlinear truck factor, Eqs. 14 and 15, should be adopted and employed for nearly balanced flows on 65-mph highways with 46- to 80-percent no-passing. The application of this factor employs Eq. 17 or Figure 16, or alternatively Tables 19 and 20.

2. The simulation should be exercised with lower average highway speed, lower percent no passing, and highly unbalanced flows to extend the range of summarized results. The simulation has been thoroughly debugged and can be applied with efficiency because the general form of the relationships is now known.

3. Traffic data (speeds, flow rates, and vehicle population) should be obtained under conditions of highly unbalanced flows, preferably where the daily pattern produces the major flow in each direction at different times of day.

4. The logic within the simulation that deals with speeds in horizontal curves should be modified to include the results from additional data (*59*). This is the only feature of the simulation that is believed to need adjustment.

5. A partial version of the simulation computer program should be assembled to calculate the speeds of trucks and recreational vehicles in zero traffic on user-specified geometrics. These speeds are needed to obtain the equivalency kernels for mixed flow estimates; they are also needed for estimates on multilane facilities. The current simulation program makes these calculations as a part of preliminary processing, since hand calculations using graphs, tables, and equations are very time consuming.

6. Vehicle characteristics needed for performance estimates in the future should be obtained in the registration process or in the initial registration for new vehicles.

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APPENDIX A

DETAILS OF PASSENGER, RECREATIONAL, AND UTILITY VEHICLE PERFORMANCE

This appendix contains a brief description of the vehicle performance tests and a detailed presentation of the data-reduction procedure and results.

EXPERIMENTAL PROGRAM

Field Tests

Tests of recreational vehicles and utility type commercial vehicles were conducted by Digitek Corporation under subcontract to Midwest Research Institute (MRI). The subcontractor provided a test report (*17*) describing the vehicle configurations, the test courses, and the data obtained. Selections of data from this report comprise part of the present description.

Three types of tests were conducted; namely, acceleration on level terrain, coasting on level terrain, and acceleration on a nominal 6.15-percent upgrade. The data were analyzed by MRI. Aerodynamic drag coefficients, rolling resistance coefficients, and acceleration-speed relationships were determined.

The following discussion covers the vehicle configurations and tests, the data analysis, and the performance parameters derived from the tests. Useful complementary data from the literature are also included.

TABLE A-1
GENERAL DESCRIPTION OF TEST VEHICLES

Identification	Test Weight (lb)	Maximum BHP at Engine rpm	Weight BHP	Transmission Type	Transmission Speeds Fwd.	Frontal Area (Ft²)a/
1970 Chevrolet sedan	4,606	300 - 4,800	15.35	Automatic	2	23.8
Sedan with travel trailer	6,045	300 - 4,800	20.15	Automatic	2	47.5
Sedan with utility trailer	7,608	300 - 4,800	25.36	Automatic	2	37.2
Sedan with boat on trailer	6,836	300 - 4,800	22.79	Automatic	2	35.0
1971 Chevrolet 3/4-ton pickup	5,405	300 - 4,800	18.02	Automatic	3	30.8
Pickup with camper shell	6,015	300 - 4,800	20.05	Automatic	3	41.1
Pickup with camper shell and travel trailer	7,454	300 - 4,800	24.85	Automatic	3	48.1
1970 Ford 1-ton step van	7,015	165b/ - 3,600	42.52	Manual	4	54.8

a/ Computed from enlarged calibrated frontal photographs and dimensional data.
b/ The Digitek test report gives net rating of 126 horsepower at 3,400 rpm. This was converted to maximum BHP (for consistency with the other configurations) using information from (18).

Vehicle Configurations

Pertinent characteristics on the eight configurations tested are given in Table A-1. Additional descriptive information is included as follows:

1. *1970 Chevrolet Impala Four-Door Sedan*—This vehicle was typical of family-type sedans in common use. It was equipped with V-8 engine, two-speed automatic transmission, power steering and disc brakes, and air conditioning—but no heavy duty or performance options. Vehicle mileage at the beginning of testing was approximately 27,800 mi. It was subjected to a thorough tune-up and inspection just prior to testing and was in excellent maintenance condition.

2. *1971 Field and Stream 15-Ft Travel Trailer*—This unit was selected as typical of light-weight travel trailers. It was a single-axle configuration with sleeping accommodations for six persons and featured cooking facilities and self-contained heating and plumbing. Its total weight was 1,439 lb, and its frontal area was 45.4 ft².

3. *U-Haul Utility Rental Trailer*—This unit was the familiar rental trailer used for furniture moving and similar activites. It was the heaviest of the three trailers tested at 3,002 lb (empty weight was 1,162 lb). Ballast weight consisted of steel shapes secured on the floor to provide a reasonable weight distribution and vertical coupler ball load (192 lb). Its frontal area was 33.6 ft².

4. *American Boat Trailer with 17-Ft Outboard Runabout*—This unit was representative of privately owned recreational boat/trailer combinations. The trailer was a well designed and matched single-axle unit providing excellent handling stability and control. Total weight was 2,230 lb, and frontal area with the boat was 33.1 ft².

5. *1971 Chevrolet ¾-Ton Pickup Truck*—This vehicle was a full-optional, luxury custom camper unit equipped with air conditioning, power steering and brakes, V-8 engine, 3-speed automatic transmsision, and heavy duty suspension. It was designed specifically for camper installations. Vehicle mileage at the beginning of testing was 10,400 mi, and the unit was thoroughly inspected and tuned prior to testing.

6. *Proline Expando-Type Camper Shell*—Typical of units of this type, this shell was of laminated aluminum/wood construction, well made and light weight (610 lb). The shell top was slightly above the cab; however, there was no over-cab volume.

7. *1970 Ford 1-Ton Step Van*—Representative of urban delivery vehicles, this unit was unique in this test series in its 6-cylinder, in-line engine and 4-speed manual transmission. At the beginning of the testing it had recorded only 4,100 mi and had been in service approximately 3 months.

Test Courses

Acceleration and coasting tests were performed on a section of Fourth Street just west of Rochester Avenue in the City of Ontario, Calif. The site was a newly developed street, constructed as an access road for the new Ontario Motor Speedway, and provided an almost perfectly level course nearly 2 mi in length, largely untraveled except during rush-hour periods. Runs were made in both eastbound and westbound directions to obviate wind and gradient variations. Site elevation was approximately 990 ft above sea level.

Grade acceleration tests were performed on a section of California Highway 138 near Wrightwood, Calif. The roadway provided a seldom used grade, averaging 6.15 percent over a distance of approximately 1.32 mi. Two curves of very large radius are included that should have had negligible effect on accelerations. Total elevation change was approximately 400 ft beginning at 4,100 ft above sea level. The roadway surface was macadam, well maintained, and free of irregularities.

Quantities Measured and Instrumentation

Vehicle distance, engine speed, and a time reference were recorded in each test. The test vehicles were fitted with onboard instrumentation equipment consisting of a light beam oscillograph recorder, power inverter, batteries, and time reference signal generator. Basic data channels consisted of a time reference channel with 10-cps square-wave reproduction; a vehicle engine, speed indication channel produced by an induction type, spark plug pulse transducer; and a vehicle distance channel triggered by a magnetic pulse type transducer fitted to a fifth wheel unit mounted on the rear of the vehicle.

Test Procedure

Prior to each test, the instrumentation equipment was checked, and environmental data were collected including dry-bulb and wet-bulb temperatures, wind direction and speed, and barometric pressure.

The level acceleration and coasting tests were made in a westbound and then eastbound sequence, at least two runs in each direction. Tests were made using the drive position for automatic-transmission-equipped vehicles with full-throttle application to the desired terminal speed (65 mph for single vehicles and 55 mph with trailers). At this point, the throttle was released, the transmission was immediately shifted to neutral, and the coastdown test was made to a speed of less than 20 mph or to the end of the course.

The procedures for the manual transmission 1970 Ford step van were basically identical except that starts were made in second gear, selected on the basis of preliminary tests showing a slight over-all acceleration time advantage. Normal shifts were made to third and fourth gears at predetermined engine speeds.

Procedures for grade testing were very similar to those used in the level acceleration runs. No less than two runs were made in each test configuration, and the runs were terminated either by achieving the desired maximum vehicle speed or by completing the measured course of 1.32 mi.

Instrumentation Difficulties

Difficulty was experienced in some of the tests with the time reference signal generator. A time trace was obtained on the oscillograph record, but the frequency is not accurately known. The tests affected involved the step van on both level and grade, the pickup truck on grade, and the pickup with camper shell and camping trailer on level.

In the case of the step van, the time reference trace is irregular, and Digitek marked the vehicle test data sheets (*17*) with the notation "use 1.12 correction factor on time reference." Inspection of the oscillograph records indicates that the distance and engine speed transducer pulses were counted over intervals less than 1 sec and that the notation means the pulse counts should be multiplied by 1.12 in calculating engine rpm and speed (feet per second). It further appears that the factor 1.12 was obtained by assuming that the chart speed was exactly equal to the expected nominal speed of 2.4 in./sec. The correction factor of 1.12 was used in reducing the data, although it is suspected that the factor should be somewhat larger (5 to 10 percent). This suspicion is based on oscillograms from tests of other vehicles (with the time reference signal generator working properly), wherein it is noted that chart speeds vary 5 to 10 percent from nominal. In calculating acceleration, the time reference enters to the second power, so that an error of 10 percent will produce an error of about 20 percent in the acceleration. Indications are that, if an error exists, it will cause calculated acceleration to be smaller than true acceleration.

In the case of the pickup truck on grade and the pickup with camper shell and camping trailer on level, the time reference trace is uniform, but the frequency is obviously about twice the desired value of 10 cps. There is no notation on the vehicle test data sheets (*17*), but there is a hand notation of 19.7 cps on the oscillograms. Again, this frequency is apparently based on nominal chart speed. The 19.7-cps figure was not used in the data reduction in this instance. Instead, a frequency was determined by examination of other tests for the vehicle configuration conducted when the time reference signal generator was working properly.

In summary, there is the possibility of error in acceleration calculated from the tests wherein time reference discrepancies were noted. The error, in all cases, probably causes calculated accelerations to be smaller than true accelerations. The magnitude of error for the step van may be as large as 20 percent, but is probably smaller for the configurations involving the pickup truck.

Data Reduction

Time histories of vehicle speed, distance, and engine speed were obtained from the oscillograph records and plotted by Digitek Corporation (*17*). The primary goal was to estimate aerodynamic drag and rolling resistance coefficients and acceleration speed characteristics. For this effort, estimates of vehicle acceleration were obtained directly from the oscillograph records rather than from the (smoothed) curves, because accelerations derived directly from the oscillograph records were much better behaved.

Aerodynamic Drag and Rolling Resistance Coefficients

The dynamic force balance for a coasting vehicle can be written as:

$$F_I + F_C + F_A + F_R = 0 \qquad \text{(A-1)}$$

where:

F_I = inertia force;
F_C = force due to chassis friction;
F_A = aerodynamic drag force; and
F_R = force due to rolling resistance.

The inertia force, F_I, is equal to Wa/g where W is the test weight of the vehicle, a its acceleration, and g the acceleration of gravity. The chassis friction force, F_C, results principally from transmission losses and was assumed to be negligible for vehicles coasting on a smooth, hard surface (*19*). Rolling resistance was assumed to be of the form (*20*):

$$F_R = (C_{RS} + C_{RV} V^2) W \qquad \text{(A-2)}$$

where C_{RS} and C_{RV} are constants and V is vehicle speed. There are arguments that favor considering F_R constant up to some critical speed (usually taken as 50 mph), above which it increases rapidly with V. However, most available data show F_R to increase moderately at lower speeds, and it was considered more realistic to use this form for F_R for the speed range covered in the experiments.

The aerodynamic drag force, F_A, can be expressed as:

$$F_A = \tfrac{1}{2} \rho A C_D V^2$$

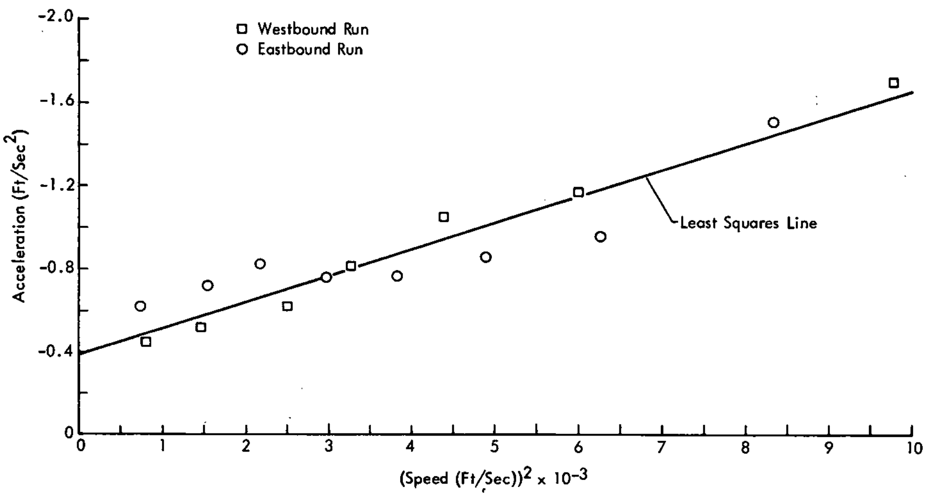

Figure A-1. Deceleration in coasting—Chevrolet sedan.

TABLE A-2

EXPERIMENTALLY DETERMINED COEFFICIENTS

Description	C_D	C_{RS}	On Level a_o (ft/sec²)	On Level V_M (ft/sec)	On 6.15% Grade a_o (ft/sec²)	On 6.15% Grade V_M (ft/sec)
Chevrolet sedan	0.549	0.0121	10.96	135	7.36	116
Sedan with travel trailer	0.586	0.0144	8.64	119	5.27	94
Sedan with utility trailer	0.932	0.0138	6.93	114	3.92	78
Sedan with boat on trailer	0.778	0.0107	7.87	117	4.86	84
Chevrolet pickup truck	0.588	0.0179	17.07	115	12.14	89
Pickup with camper shell	0.542	0.0174	14.47	107	10.79	86
Pickup with camper shell and travel trailer	0.628	0.0131	12.49	106	8.98	77
Ford step van	0.527	0.0157	8.69	90	6.97	63

where:

ρ = mass density of air;
A = reference area (the projected frontal area of the vehicle); and
C_D = nondimensional aerodynamic drag coefficient (constant at the high Reynolds numbers involved).

The dynamic force balance can now be written as

$$\frac{W}{g} a = C_{RS}W + (C_{RV}W + \tfrac{1}{2} \rho A C_D)V^2 \quad \text{(A-3)}$$

Pairs of values of a and V in coasting were obtained from the oscillograph records for the various vehicle configurations tested. (V was obtained by finding the distance traveled in 1 sec; acceleration, a, was estimated by differencing speeds obtained at 10-sec intervals.) Figure A-1 shows a plot of (W/g) a vs. V^2 for two runs made on the Chevrolet sedan. The linear dependence of acceleration on the square of the velocity, suggested by the force balance equation, is evident in Figure A-1. This dependence was also obtained for the other configurations tested.

Values were obtained for the expressions ($C_{RV}W + \tfrac{1}{2} \rho A_D C$) and C_{RS} by using a least-squares curve fit of straight lines to the data. It was not possible to separate C_{RV} and C_D using only the experimental data. However, it is known that the product $C_{RV}W$ is small compared with ½ ρ AC_D, so an average value, $C_{RV} = 0.65 \times 10^{-6}$, was assumed (*20*) that made it possible to estimate C_D. The value of C_D is relatively insensitive to the value of C_{RV} used. The values obtained for C_{RS} and C_D are summarized in Table A-2. They will be discussed later in this Appendix in conjunction with similar data obtained from the literature.

Acceleration and Speed Characteristics

A second goal of the experimental program was to investigate the relationship between acceleration capability and speed. Pairs of values of a and V were obtained (as previously described) for the acceleration tests on level terrain and on grade. The results for the sedan and the pickup truck are shown in Figures A-2 and A-3. These two plots indicate that the relationship between acceleration and speed is approximately linear. The same linear relationship was found for the other configurations tested; it was obtained earlier for passenger vehicles (*1*), and is typical of automobiles in general (*22*). There is some irregularity associated with gear shifting in the acceleration of the step van, but over-all the linear approximation appears quite good. On the basis of these multiple findings, the acceleration-speed relationship was written as:

$$a = a_0 \left(1 - \frac{V}{V_M}\right) \quad \text{(A-4)}$$

where:

a = acceleration;
V = speed;
a_0 = maximum acceleration (occurring at zero speed); and
V_M = maximum speed attainable.

The parameters a_0 and V_M were evaluated by least-squares curve fit to the experimental data. The results obtained are also included in Table A-2.

Correlation of Acceleration Capability on Level Road with Vehicle Attributes

The quantities a_0 (maximum acceleration) and V_M (maximum speed) completely define the acceleration capability of a vehicle configuration. It is desirable to formulate a_0 and V_M in terms of normally available attributes of the configuration.

Maximum Acceleration (Level Road)

In a previous analysis (*1*) it was determined that maximum acceleration for passenger cars can be satisfactorily expressed as a linear function of the inverse of the weight/horsepower ratio. The expression

$$a_0 = \frac{131.2}{W/\text{bhp}} + 5.093 \qquad \text{(A-5)}$$

was obtained by curve fitting data for 53 automobiles spanning the W/bhp range 12.5 to 42.8 (a_0 is in ft/sec², and W/bhp was obtained using the manufacturer's maximum rated brake horsepower).

The expression for a_0 is plotted in Figure A-4 with the data points from which it was derived. Maximum acceleration values obtained from the present tests on level road are also plotted and shown to be in unsatisfactory agreement with the simple W/bhp correlation. The chief objection is failure of the correlation to reflect the considerable difference between the sedan and the pickup configurations.

Acceleration capability depends on drive train gear ratios, transmission and engine characteristics, as well as W/bhp. Therefore, the maximum acceleration data on level road were correlated using a parameter reflecting these additional influences. The parameter is

$$\frac{r_1 r_2}{W/\text{bhp}}$$

where:

r_1 = first transmission gear ratio;
r_2 = rear-axle gear ratio;
W = vehicle gross weight, lb; and
bhp = manufacturer's maximum rated brake horsepower.

The correlation plot is shown in Figure A-5. Data are also included for six passenger cars. These data were obtained from tests reported in two issues of *Consumer Bulletin* (*21*).

Over-all, the data appear to be in good agreement. The apparently low value of the step van acceleration capability may be due in part to the uncertainty in the time reference raw data discussed earlier. An error of 20 percent (which is considered possible) would raise the maximum acceleration from 8.69 to 10.43 ft/sec², a value that is in better agreement with the other data.

The low acceleration capability of the one passenger vehicle from Ref. (*21*) may be due to traction limitations; this vehicle is lightly loaded on the rear axle in comparison with the other vehicles represented.

Somewhat better correlations for a_0 can be obtained by including tire size, engine rpm at rated horsepower, and torque converter maximum ratio at stall. However, the minor improvement is overshadowed by the increased complexity of the correlation parameter.

A least-squares curve fit to the data for the eight vehicle configurations tested in the project gives

$$a_0 = 0.86 + 31.38 \left(\frac{r_1 r_2}{W/\text{bhp}} \right) \qquad \text{(A-6)}$$

This expression can be used to predict the maximum acceleration capability of recreational vehicles and utility type commercial vehicles at essentially zero speed. The equation for a_0 was tested with data from the popular literature (*35*) on motor homes and large sport vans. It was found that a

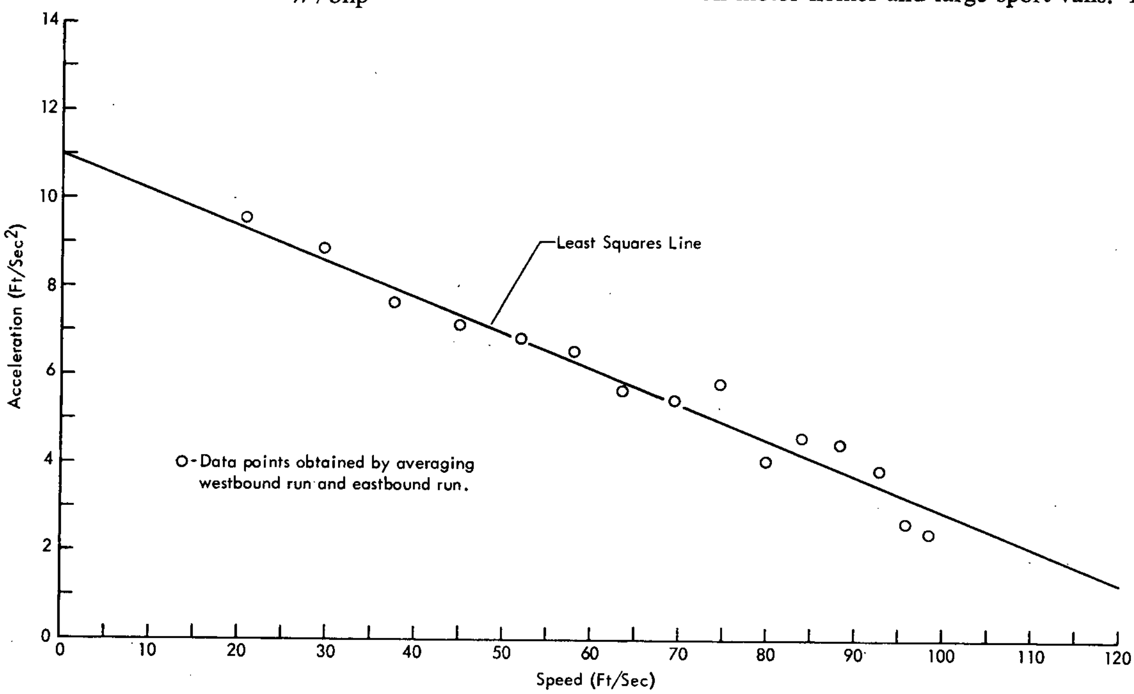

Figure A-2. Acceleration vs. speed for Chevrolet sedan on level terrain.

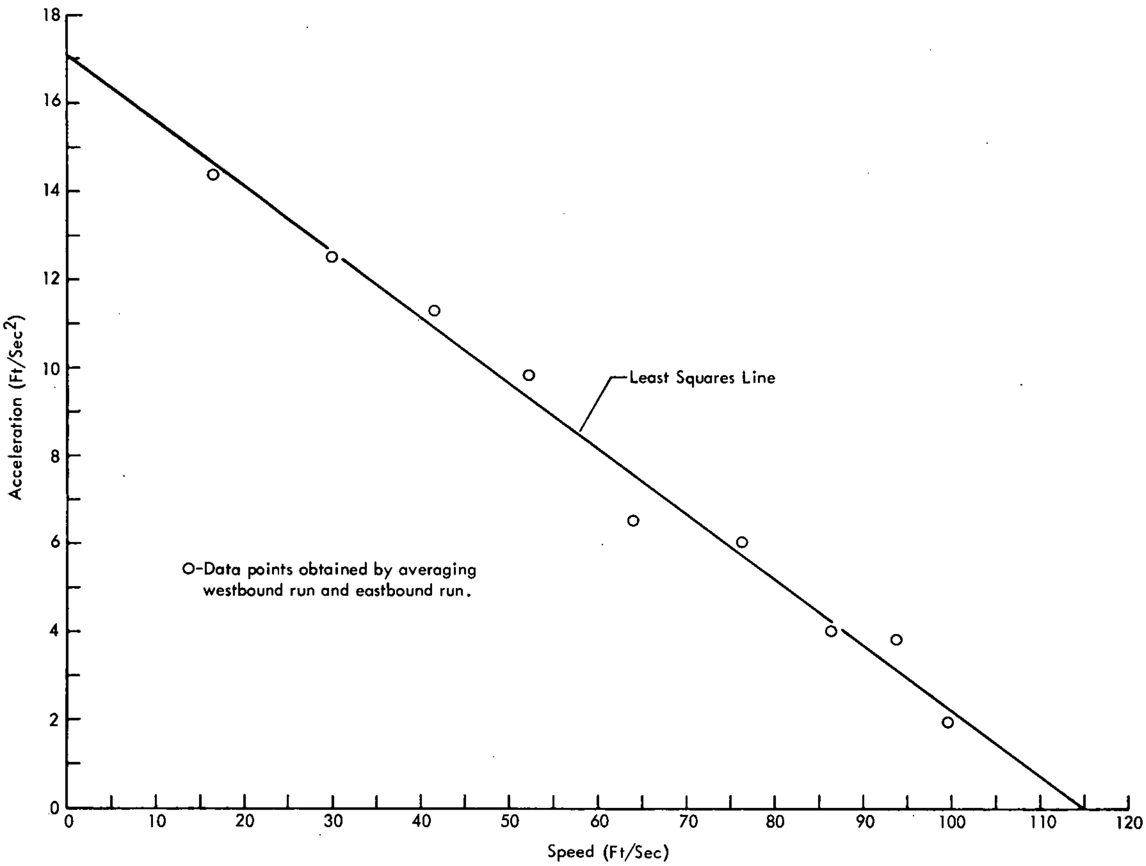

Figure A-3. Acceleration vs. speed for Chevrolet pickup on level terrain.

revision of the coefficients gave improved accuracy. The recommended expression for motor homes and large sport vans is:

$$a_0 = -0.6744 + 29.77 \left(\frac{r_1 r_2}{W/\text{bhp}} \right) \qquad \text{(A-7)}$$

Maximum Attainable Speed (Level Road)

In an earlier study (*1*), maximum speed was shown to be a function of W/bhp ratio, aerodynamic drag, and rolling resistance. Using experimental data for 53 passenger cars, the following relationship was obtained by least-squares curve fitting:

$$\frac{W}{\text{bhp}} = \frac{0.4683}{\alpha V_M{}^3 + \beta V_M} \qquad \text{(A-8)}$$

where:

W/bhp = weight-horsepower ratio as before, based on maximum rated brake horsepower;

V_M = maximum speed, ft/sec;

$$\alpha = \frac{1}{550}\left(\frac{1}{2}\,\rho\tau + C_{RV} \right)$$

$\beta = \frac{1}{550} C_{RS}$; and

$\tau = C_D A / W$.

The rolling friction coefficients were assumed from Ref. (*1*) to be $C_{RS} = 0.011$ and $C_{RV} = 0.65 \times 10^{-6}$. The observed and the fitted values of V_M for the 53 passenger cars are compared in Figure A-6. The straight line is the observed-equals-fitted line; the goodness of fit can be judged by the deviations of the data points from this line. Also shown in Figure A-6 are maximum speed values derived from the present tests on level road.

It is seen that the observed values from the present tests are low compared with the data for the 53 passenger cars. The following explanation is suggested. For the 53 passenger cars, the observed values were obtained by actually driving the test cars to their maximum speeds. The values shown from the present tests were obtained by extrapolating the linear acceleration speed approximation to zero acceleration. Although the linear approximation for acceleration is a good one, the true acceleration curve is probably slightly concave upward (i.e., small acceleration capability persists to higher speeds than predicted by the linear approximation). It is therefore concluded that the actual top speed of a vehicle is more accurately predicted by the curve fit from the previous work (*1*).

The maximum attainable speed is of less interest for its own sake than for its role in the acceleration speed formulation. It is recommended that the maximum speeds given by the linear fit in Figure A-6 *not* be used for V_M in the acceleration equation, because they will overestimate acceleration capability at all but very low speeds. The values from the present tests, hereafter referred to as pseudo-maximum speed $\bar{V}_M$ to avoid confusion, will give a more realistic estimate of acceleration capability throughout the range of practical driving speeds.

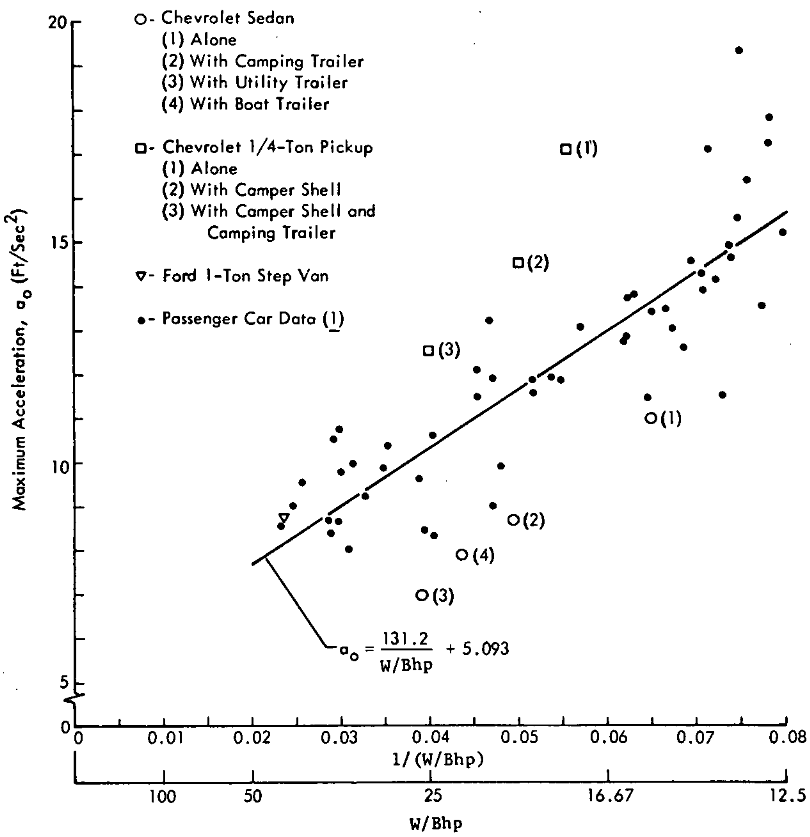

Figure A-4. Correlation of maximum acceleration with W/*bhp ratio.*

A predictive equation for $\bar{V}_M$ was obtained by fitting the expression:

$$\bar{V}_M = c_0 + c_1\sqrt[3]{1/[\alpha(W/\text{bhp})]} \qquad \text{(A-9)}$$

to the observed data. The functional form shown is obtained by neglecting the constant contribution of rolling resistance in a force balance at maximum speed. The correlation plot is shown in Figure A-7. The constants obtained by least-squares fitting are $c_0 = 34.54$ and $c_1 = 0.467$.

Comparison of Acceleration on Level Terrain and on Grade

If there were no difference in driver technique and transmission performance, the acceleration-speed curve on grade would be parallel to the curve for level terrain, but shifted by an amount depending on the magnitude of the grade. Thus, if a_{LV} = acceleration capability at speed V on level terrain, and a_{GV} = acceleration capability at speed V on grade, then:

$$a_{GV} = a_{LV} + \Delta a \qquad \text{(A-10)}$$

where:

$\Delta a = -Rg/\sqrt{1 R^2}$

g = acceleration due to gravity; and

R = percent grade expressed as a decimal with positive values implying upgrade (e.g., $R = 0.05$ represents a 5-percent upgrade).

Since R is generally small, the acceleration increment, Δa, can be satisfactorily simplified to $\Delta a = -Rg$.

The on-grade acceleration speed curves were found to be very nearly linear as was the case for level terrain. The on-grade and level terrain data can therefore be conveniently compared by means of the maximum acceleration, a_0, at zero speed and the slope, $a_0/\bar{V}_M$, of the curve.

For this comparison it is necessary to correct the experimental results for the effect of altitude. The level terrain tests were conducted at an altitude of 990 ft; the on-grade test, at an average altitude of 4,310 ft. All results were, therefore, corrected to sea level conditions. The corrections are of two kinds: a horsepower adjustment and an aerodynamic force correction. The horsepower adjustment is:

$$\text{hp at altitude} = \text{hp at sea level} \times (1 - 0.04 \times 10^{-3}\, E)$$

where E is elevation in feet. The correction to aerodynamic force originates from the density variation with altitude:

$$\text{aerodynamic force at altitude} = \text{aerodynamic force at sea level} \times (1 - 0.006887 \times 10^{-3}\, \text{E})^{4.255}$$

These two corrections were employed as follows. Since the maximum acceleration, a_0, occurs at zero speed, the aerodynamic force is irrelevant and the horsepower correction is made by assuming that maximum acceleration is directly proportional to power available. Thus

$$a_{0SL} = a_{0A}\left(\frac{1}{1 - 0.04 \times 10^{-3} E}\right) \quad \text{(A-11)}$$

where:

a_{0SL} = maximum acceleration adjusted to sea level; and
a_{0A} = maximum acceleration measured at elevation E.

The slope of the acceleration speed curve was corrected by adjusting the pseudo-maximum speed, $\bar{V}_M$, obtained by extrapolating the measured accelerations. Recall that the slope is equal to the negative of the maximum acceleration divided by $\bar{V}_M$. The form of the adjustment required for $\bar{V}_M$ was obtained from an energy balance at maximum speed:

$$550 \text{ bhp } \eta = \tfrac{1}{2} \rho C_D A \bar{V}_M{}^3 + O_L \quad \text{(A-12)}$$

where:

bhp = maximum rated brake horsepower;
η = fraction of bhp available at the drive wheels;
ρ = air density, lb-sec²/ft⁴;
C_D = aerodynamic drag coefficient;
A = frontal area, ft²; and
O_L = all other energy losses, primarily chassis and rolling.

Now, the energy balance for sea level and altitude conditions is:

$$550 \text{ bhp}_{SL}\, \eta = \tfrac{1}{2} C_D A \rho_{SL} \bar{V}^3{}_{MSL} + O_L$$
$$550 \text{ bhp}_A\, \eta = \tfrac{1}{2} C_D A \rho_A \bar{V}^3{}_{MA} + O_L$$

The subscript SL refers to sea level and A to altitude. Assume that η, C_D, A, and O_L are independent of altitude and maximum speed to obtain

$$\bar{V}_{MSL} = \left\{\frac{1}{\rho_{SL}}\left[\frac{550\,\eta}{\tfrac{1}{2} C_D A}(\text{bhp}_{SL} - bhp_A) + \rho_A \bar{V}^3{}_{MA}\right]\right\}^{\frac{1}{3}} \quad \text{(A-13)}$$

The quantities C_D, A, and $\bar{V}_{MA}$ are known from the tests. Also, $\rho_{SL} = 0.002378$ lb-sec²/ft⁴ (standard sea level density), bhp_{SL} = maximum rated brake horsepower, and $\eta = 0.4683$ from (*1*). Then, $\bar{V}_{MSL}$ can be calculated using

$$\text{bhp}_A = \text{bhp}_{SL}\,(1 - 0.04 \times 10^3 E)$$
$$\rho_A = \rho_{SL}\,(1 - 0.006887 \times 10^{-3} E)^{4.255}$$

Values for maximum acceleration corrected to sea level conditions are given in Table A-3. The decrement, $\Delta a_{0SL} = a_{0SL}$ on grade — a_{0SL} on level, ideally would be equal to —Rg, which, in the present case, is —1.98 ft/sec² for the 6.15-percent upgrade. Most of the tabulated values are seen to be in reasonable agreement with the ideal or expected value. The slightly larger (negative) value of —3.10 for the pickup may be due in part to the time reference uncertainty discussed earlier. For instance, an error of —5 percent in the acceleration measured on grade would bring this value to $-3.10 + 14.67 \times 0.05 = -2.37$. The small (negative) value of —0.63 for the step van may also be due in part to the time reference uncertainty. For this configuration an error as large as —20 percent is considered

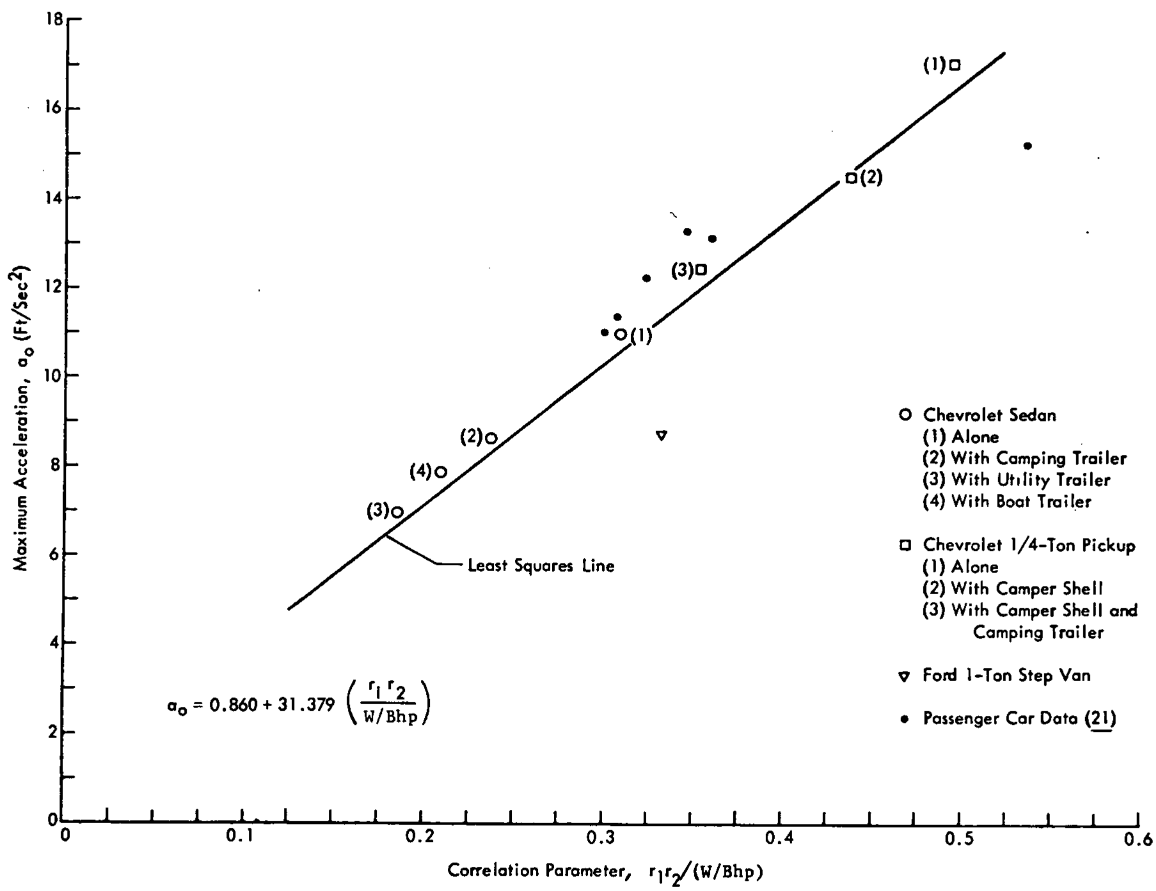

Figure A-5. Correlation of maximum acceleration with gear-ratio-weight horsepower parameter.

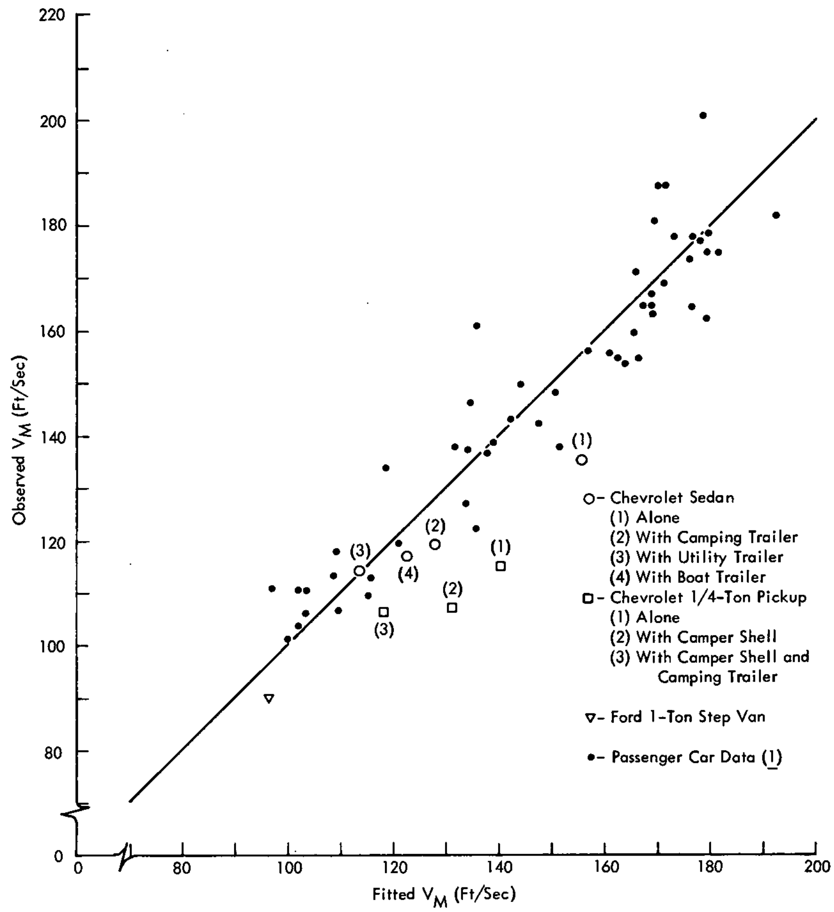

Figure A-6. Comparison of observed and fitted maximum speeds.

possible in both the level and on-grade values, which would change the value of Δa_{0SL} to $-0.63 \times 1.2 = -0.76$ ft/sec^2.

It appears that the vehicles with automatic transmissions (sedan and pickup) have maximum accelerations on grade slightly less than the expected value. Conversely, the step van with manual transmission exhibits a maximum acceleration on grade that is larger than the expected value, similar to that observed for larger commercial units with manual transmissions.

Values for extrapolated maximum speed $\bar{V}_M$ corrected to sea level conditions are given in Table A-4. The expected value for Δ slope is zero, so the tabulated values directly indicate deviations from the expected value. A negative value for Δ slope means acceleration capability decreases less rapidly with speed on grade than on level. The data in Table A-4 show over-all good agreement between expected and actual values. The vehicles with automatic transmission all show somewhat better acceleration capability at high speed than expected. The step van with manual transmission shows slightly reduced capability at high speeds.

In summary, it appears that, for vehicles with automatic transmission, a satisfactory approximation for on-grade acceleration capability can be obtained by decreasing the level capability by the amount *Rg*. The result, so obtained, is shown for the Chevrolet sedan in Figure A-8, and is typical of all of the configurations with automatic transmission. The vehicle with manual transmission (step van) appears to have on-grade acceleration capability somewhat better than expected. In this case, a better approximation would be obtained by reducing the acceleration speed curve by ½ *Rg*. The result obtained for the step van is shown in Figure A-9.

Rolling Resistance

The coasting tests provide some information on the magnitude of the rolling resistance. Rolling resistance is usually written in the form $\mu_R W$, where μ_R is the rolling resistance coefficient and W is gross weight of the vehicle. The form of μ_R is the subject of some controversy. One widely accepted approach expresses μ_R as

$$\mu_r = C_{RS} + C_{RV} V^n \qquad \text{(A-14)}$$

where C_{RS} and C_{RV} are constants and V is vehicle speed. The value $n = 2$ is used extensively on the basis of some fairly old experimental data (*20*).

More recently it has been suggested (*23*) that μ_R is constant up to a critical speed (generally accepted as 50 mph), after which it increases rapidly with speed. Other experimental data (*24*) show μ_R growing with speed at an increasing rate depending on tire type.

No evidence of a marked change was observed in resistance near 50 mph and, therefore, the form of Eq. A-15 is used.

$$\mu_R = C_{RS} + C_{RV} V^2 \qquad \text{(A-15)}$$

The value $C_{RV} = 0.65 \times 10^{-6}$ (for V in ft/sec) was used in this project. Least-squares curve fits of the data provided the estimates for C_{RS} given in Table A-2.

The estimated values of C_{RS} are in essential agreement with Ref. (*20*), which gives a value $C_{RS} = 0.011$ (for tire inflation pressure of 25 psi). They also agree with the values shown in Figure 2 of Ref. (*24*), which average about 0.0125.

From Table A-3 it can be seen that the constant part of the rolling resistance coefficient is larger for the pickup truck and step van than it is for the passenger vehicle. This could be due to the fact that the trucks were equipped with 8-ply tires and the sedan wih 4-ply tires.

TESTS OF POSTAL VEHICLES

Additional data on the acceleration capability of utility type commercial vehicles were obtained from reports on a safety study of postal vehicles (*25*). Acceleration tests conducted on the 10 vehicles described in Table A-5 were reported in the form of speed/time curves. Acceleration-speed relationships were obtained by differencing the speed-time curves; example relationships are shown in Figures

TABLE A-3

MAXIMUM ACCELERATION CORRECTED TO SEA LEVEL CONDITIONS

Description	Level a_{OA}	Level a_{OSL}	On 6.15% Grade a_{OA}	On 6.15% Grade a_{OSL}	Δa_{OSL} a/
Chevrolet sedan	10.96	11.41	7.36	8.89	-2.52
Sedan with travel trailer	8.64	9.00	5.27	6.37	-2.63
Sedan with utility trailer	6.93	7.22	3.92	4.74	-2.48
Sedan with boat on trailer	7.84	8.16	4.86	5.87	-2.29
Chevrolet pickup truck	17.07	17.77	12.14	14.67	-3.10
Pickup with camper shell	14.47	15.07	10.79	13.04	-2.03
Pickup with camper shell and travel trailer	12.49	13.00	8.98	10.85	-2.15
Ford step van	8.69	9.05	6.97	8.42	-0.63

a/ $\Delta a_{OSL} = a_{OSL}$ on 6.15% grade - a_{OSL} on level (ideally equal to -1.98 ft/sec²).

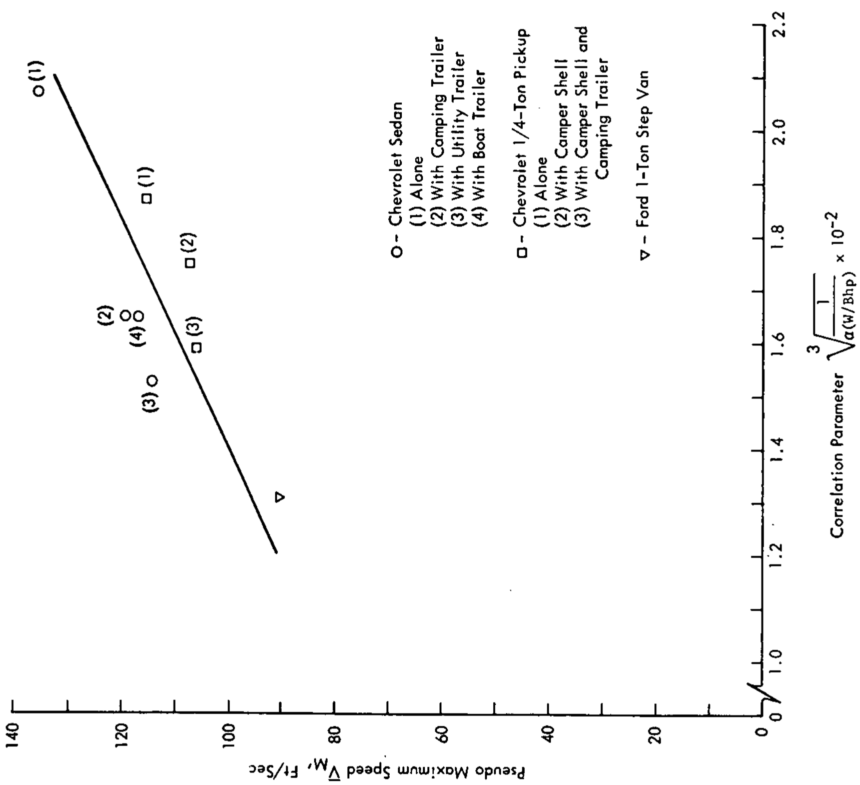

Figure A-7. Correlation of pseudo-maximum speed on level terrain.

A-10 through A-12. The relationships appear to be approximately linear for all except the 5-ton International Harvester unit (Fig. A-12), which was not considered further. Least-squares curve fits for the other vehicles produced the results given in Table A-6.

The acceleration parameters in Table A-6 were compared with the correlations determined from the tests of the recreational and utility vehicles. The transmission ratio, r_1, and the rear-axle ratio, r_2, are not available for the postal vehicles; therefore, the product, $r_1 r_2 = 8.78$, applicable for the Chevrolet pickup, was tentatively selected as typical of vehicles in this general class. The good correlation obtained for maximum acceleration is shown in Figure A-13. Vehicle 5 was in marked disagreement with the other vehicles using $r_1 r_2 = 8.78$. It was noted that this vehicle was equipped with a 2-speed powerglide transmission, so the value $r_1 r_2 = 4.75$ obtained for the Chevrolet sedan was used, giving the result shown.

For the correlation of pseudo-maximum speed, it was necessary to estimate the frontal area, A, and the aerodynamic drag coefficient, C_D. The frontal area was assumed to be equal to 90 percent of the product of width times height.

The drag coefficient was estimated using related available data and engineering judgment. The values used are given in Table A-7.

The correlation plot of pseudo-maximum speed is shown in Figure A-14. The postal vehicle data are seen to be in fairly good agreement with the least-squares curve fit (solid line in Fig. A-14) obtained for the recreational and utility vehicles. Since the postal vehicle tests extend the range of observed data, a line was fitted to the complete data set in Figure A-14 (broken line). The equation for this line is

$$\bar{V}_M = 10.28 + 0.60 \sqrt[3]{\frac{1}{\alpha\ (W/\mathrm{bhp})}} \qquad \text{(A-16)}$$

It appears to fit the over-all data better and is recommended for use as the predictive equation for $\bar{V}_M$.

TABLE A-4

PSEUDO-MAXIMUM SPEED ($\bar{V}_M$) CORRECTED TO SEA LEVEL CONDITIONS [a]

Description	Level		On 6.15% Grade		Slope[b/]		
	V_{MA}	V_{MSL}	V_{MA}	V_{MSL}	Level	On Grade	Δ Slope[c/]
Chevrolet sedan	135	137	116	131	-0.0833	-0.0679	-0.0154
Sedan with travel trailer	119	120	94	104	-0.0750	-0.0613	-0.0137
Sedan with utility trailer	114	115	78	90	-0.0628	-0.0527	-0.0101
Sedan with boat on trailer	117	118	84	98	-0.0692	-0.0599	-0.0093
Chevrolet pickup truck	115	117	89	107	-0.1519	-0.1371	-0.0148
Pickup with camper shell	107	109	86	102	-0.1383	-0.1278	-0.0105
Pickup with camper shell and travel trailer	106	107	77	92	-0.1215	-0.1179	-0.0036
Ford step van	90	91	63	76	-0.0995	-0.1108	0.0113

a/ Speeds in feet per second.
b/ Slope of acceleration-speed curve - $a_{OSL}/\bar{V}_{MSL}$
c/ Δ slope = slope for level - slope for 6.15% grade (ideally equal zero).

ESTIMATION OF AERODYNAMIC DRAG

In this section, the results of the tests conducted under the contract are compared with other experimental data. The intent is to scrutinize the new data and combine them with the other data to provide guidelines for estimating aerodynamic drag coefficients for passenger cars, vehicle-trailer combinations, and utility type commercial units.

Vehicles Without Trailers

The drag coefficient, C_D, of 0.549 measured for the 1970 Chevrolet sedan appears realistic, although slightly larger than for comparable body shapes. In Ref. (*19*), C_D obtained for a 1965 coupe (not further identified) from coasting tests was 0.48 for the standard car with all vents and windows closed and 0.52 for the standard car with all vents and windows open. Wind-tunnels tests of a 1955 Ford (*26*) and a 1965 Ford (*27*) gave, respectively, $C_D = 0.479$ and $C_D = 0.48$. Another wind-tunnel test of a 1965 Ford Galaxie sedan gave $C_D = 0.53$ (*28*). Coasting tests of a 1970 Dodge Polara, 4-door hardtop gave $C_D = 0.50$ (*24*).

The somewhat larger value obtained for the Chevrolet sedan is probably because of a combination of a real difference in C_D, experimental error in measuring speed change per unit time, and error in the correction made for rolling resistance (recall that only approximate values for rolling resistance dependence on speed are currently available).

The value $C_D = 0.588$ obtained for the pickup truck is reasonable. To the best of one's knowledge, no other data for pickup trucks are available for comparison. It is probable that the increase in C_D over that for the sedan is caused by air turbulence induced by the relatively open structure of the pickup. Increased drag has also been observed with open convertibles (*20*), probably for the same reason.

The pickup equipped with the camper shell has $C_D = 0.542$, which is less than that for the pickup alone. This reduction in drag coefficient is undoubtedly the result of reduced turbulence caused by the streamlining effect of the camper shell. Although the drag coefficient is lower, the product of drag coefficient times frontal area is larger than that for the pickup. Thus, for a given speed, the drag force on the pickup with camper shell is larger than the force on the pickup alone.

The drag coefficient of 0.527 obtained for the Ford step van appears low. There may be some error in C_D because of uncertainty about the time scale in the raw data noted earlier. Indications are that, if there is some error, its effect would be to give low values for C_D, and its magnitude is less than 20 percent. However, the agreement of the step van results in the previous correlations suggests that $C_D = 0.527$ is realistic. Also, the value agrees fairly well with measured values for Volkswagen vans (*29*), which bear resemblance to the step van. The measured value of 0.527 has, therefore, been accepted, recognizing the possibility that it may be somewhat low.

Methods are needed for estimating aerodynamic drag coefficient C_D for use in calculating vehicle performance capability. A procedure for passenger cars, based on wind-tunnel data from tests of 141 different vehicles, is provided by White (*2*). It consists in determining a "drag rating" from consideration of the important aerodynamic features of the vehicle. Drag coefficient is determined from the empirical relation $C_D = 0.16 + 0.0095 \times$ drag rating. The method is comprehensive, but at times gives low values. For instance, $C_D = 0.436$ is estimated for a Ford Galaxie, whereas $C_D = 0.53$ was obtained in Ref. (*28*). The Chev-

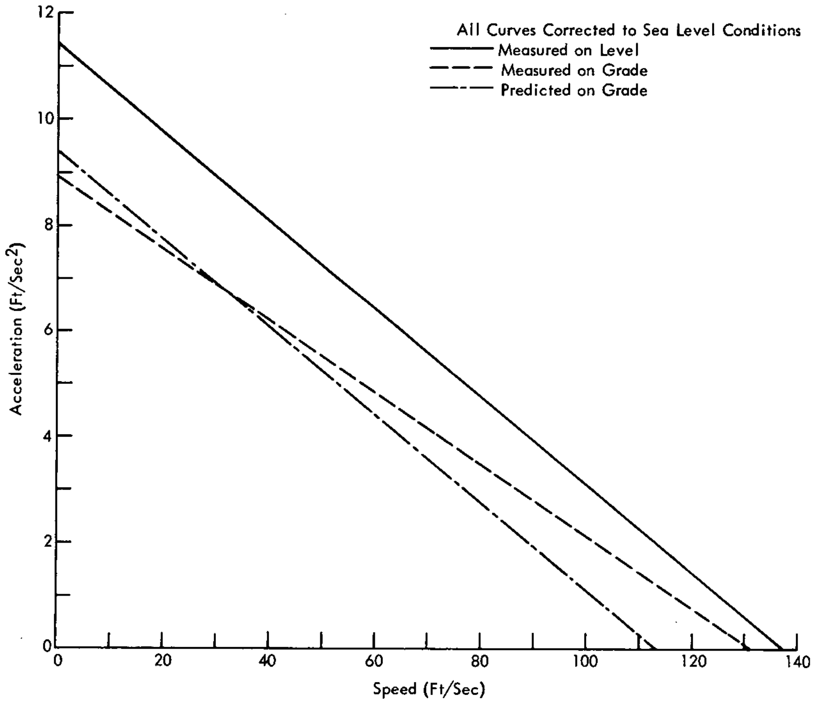

Figure A-8. Chevrolet sedan accelerations on level terrain and on grade.

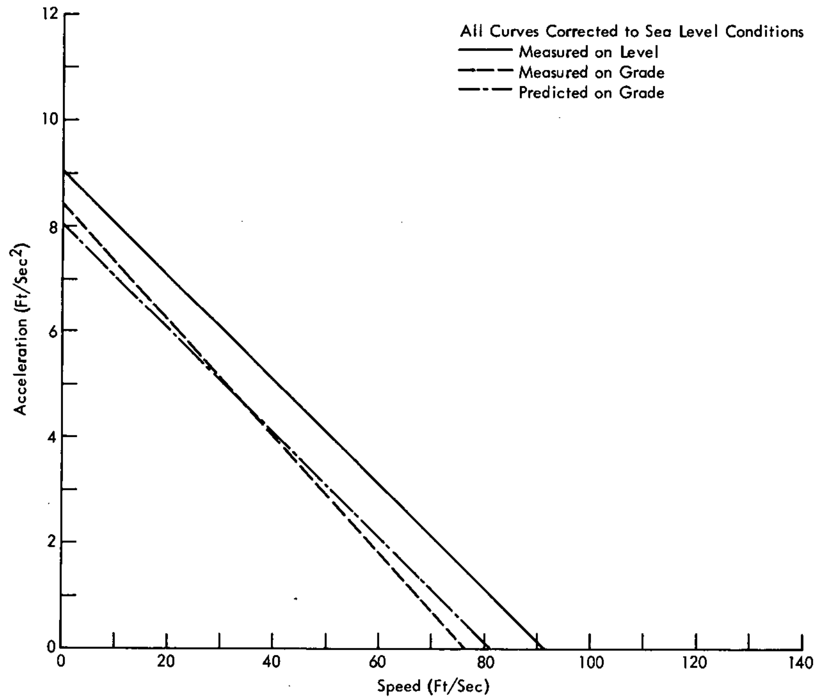

Figure A-9. Ford step van accelerations on level terrain and on grade.

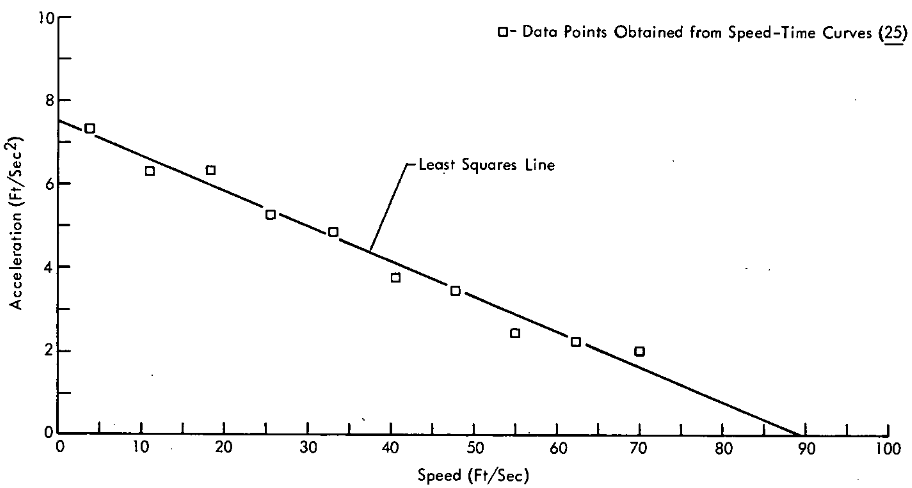

Figure A-10. Acceleration characteristics of Dodge 1-ton postal vehicle.

TABLE A-5

POSTAL VEHICLE CHARACTERISTICS

Identification	Test Weight (lb)	Maximum Rated Bhp	W/Bhp	Transmission Type	Transmission Speeds Forward
1/4 Ton International Harvester (1967)	3,155	93.4	33.8	Automatic	3
1/2 Ton International Harvester (1966)	4,470	140.8	31.8	Automatic	3
1/2 Ton Jeep (1965)	3,580	72.0	49.7	Automatic	3
1/2 Ton Dodge (1967)	3,920	140.0	28.0	Manual	3
1/2 Ton Chevrolet (1968)[a/]	3,440	155.0	22.2	Automatic	2
1 Ton Dodge (1966)	5,170	140.0	36.9	Manual	4
1 Ton Chevrolet (1968)	5,500	150.0	36.7	Automatic	3
1-1/2 Ton Ford (1968)[a/]	5,080	140.0	36.3	Manual	4
2 Ton Chevrolet (1966)	7,140	170.0	42.0	Manual	4
5 Ton International Harvester (1965)	9,785	196.7	49.8	Manual	4

a/ Units equipped with experimental aluminum bodies.

TABLE A-6

ACCELERATION CAPABILITY PARAMETERS OF POSTAL VEHICLES

Identification	Maximum Acceleration (ft/sec^2)	Pseudo Maximum Speed (ft/sec)
1/4 Ton International Harvester (1967)	7.84	89
1/2 Ton International Harvester (1966)	9.09	97
1/2 Ton Jeep (1965)	5.90	69
1/2 Ton Dodge (1967)	9.89	96
1/2 Ton Chevrolet (1968)	7.94	99
1 Ton Dodge (1966)	7.47	89
1 Ton Chevrolet (1968)	8.47	87
1-1/2 Ton Ford (1968)	7.48	75
2 Ton Chevrolet (1966)	6.16	78

TABLE A-7

ESTIMATED AERODYNAMIC PARAMETERS OF POSTAL VEHICLES

Identification	C_D	A (ft^2)
1/4 Ton International Harvester (1967)	0.60	26.6
1/2 Ton International Harvester (1966)	0.60	44.0
1/2 Ton Jeep (1965)	0.60	44.3
1/2 Ton Dodge (1967)	0.55	44.1
1/2 Ton Chevrolet (1968)	0.60	44.6
1 Ton Dodge (1966)	0.60	54.5
1 Ton Chevrolet (1968)	0.53	51.2
1-1/2 Ton Ford (1968)	0.58	46.4
2 Ton Chevrolet (1966)	0.60	62.6

rolet tested in the present work gave $C_D = 0.53$, but application of White's method gives 0.407. Conversely, the estimated value of 0.436 for the Volkswagen sedan is slightly larger than the 0.40 shown by Schlicting (*29*). Over-all, it appears that White's method of estimating C_D for passenger cars is the best currently available, but should be used with discretion and supplemented by measured data whenever possible. Very little aerodynamic data are available for campers and utility commercial vehicles. The drag coefficients given in Table A-2 are typical of vehicles in this class and may be regarded as average values. The procedure in Ref. (*2*) can be used to estimate the effect of configurational variations. The procedure is based primarily on passenger-car data; however, its application to utility type vehicles gives results reasonably consistent with Table A-2.

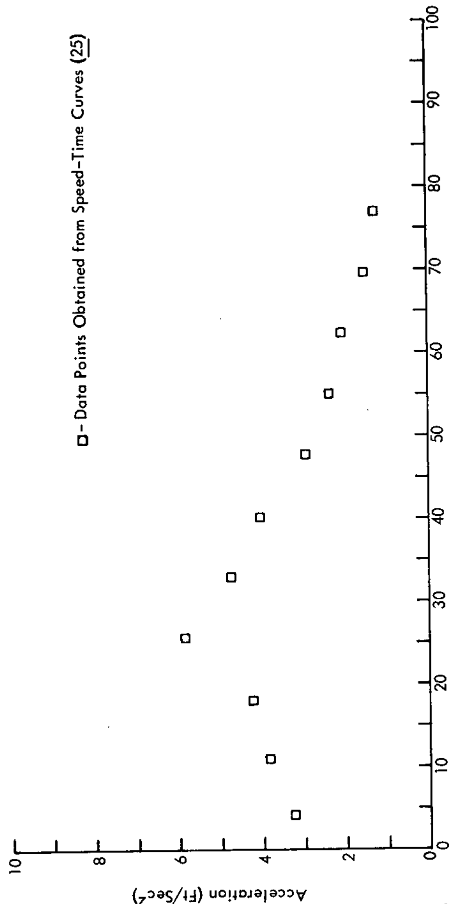

Figure A-12. Acceleration characteristics of International Harvester, 5-ton postal vehicle.

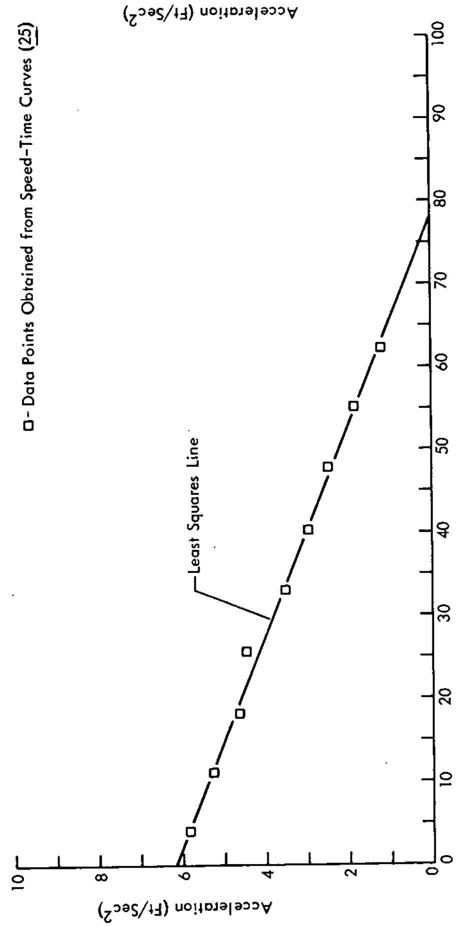

Figure A-11. Acceleration characteristics of Chevrolet 2-ton postal vehicle.

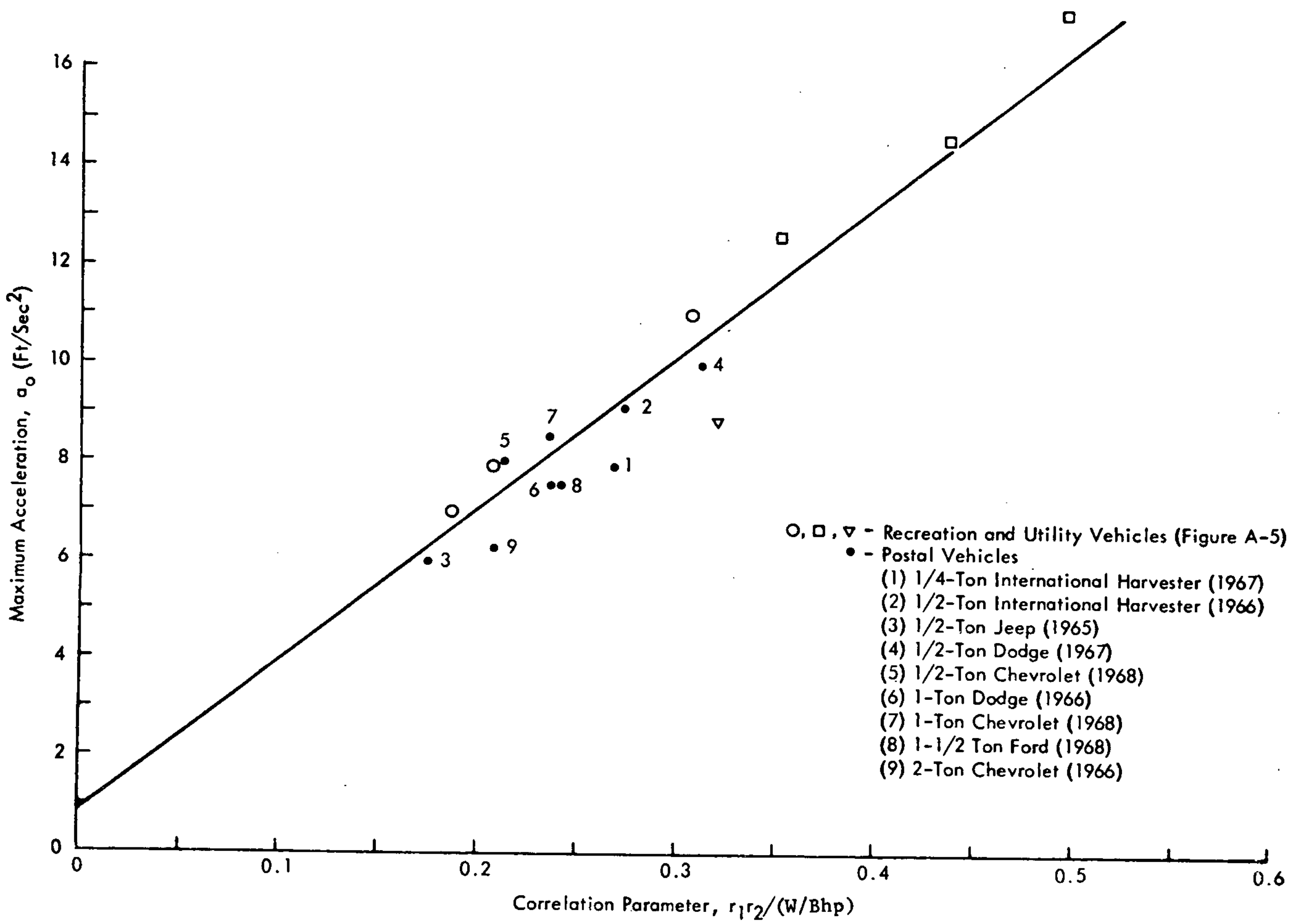

Figure A-13. Correlation of maximum acceleration for postal vehicles.

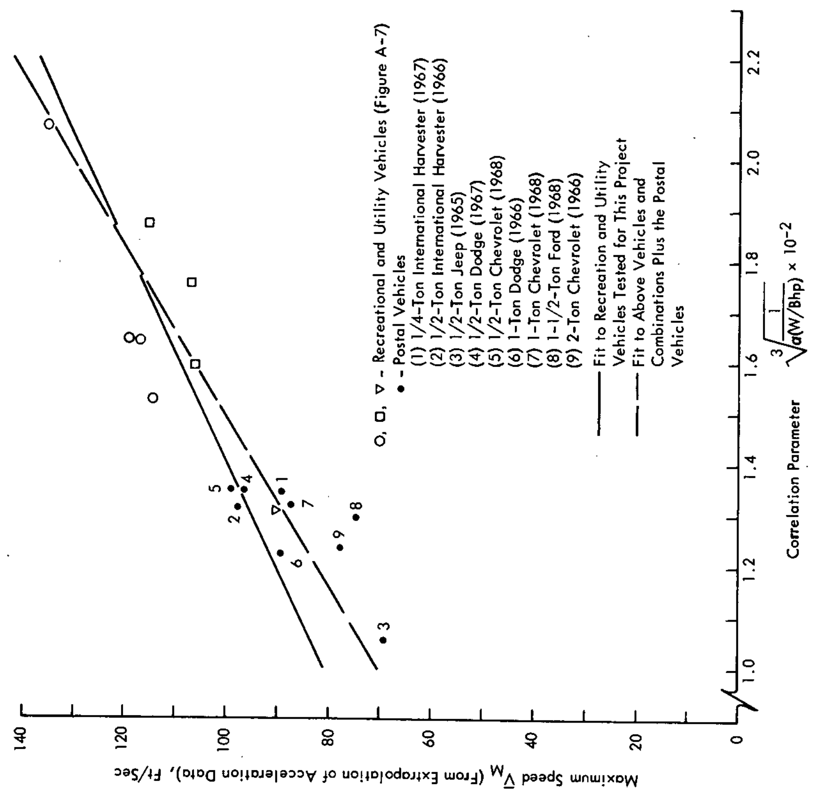

Figure A-14. Correlation of maximum speed including postal vehicle values.

TOWING VEHICLE-TRAILER COMBINATIONS

The aerodynamic drag coefficients derived from the project tests are given in Table A-8 and should be used in conjunction with the projected frontal areas of the assembled combination. The values are appropriate for trailers that increase the frontal area in combination.

It was thought that the aerodynamic drag of combinations could be analyzed to obtain a more basic understanding of combination drag. However, an analysis of the data derived from the project tests and from the literature, together with several conceptual models, showed that, from the data available, it was not possible to discern any fundamental relationships that would improve the ability to predict C_D for other combination geometries.

TABLE A-8

DRAG COEFFICIENTS, C_D, FOR VEHICLE-TRAILER COMBINATIONS

Configuration	C_D
Passenger car with travel trailer having beveled or rounded leading edges	0.59
Pickup or camper with travel trailer having beveled or rounded leading edges	0.63
Passenger car with trailer and boat	0.78
Passenger car or pickup truck with flat front utility trailer	0.93

APPENDIX B

DRIVER USE OF PERFORMANCE CAPABILITY IN PASSENGER AND RECREATIONAL VEHICLES

The characteristics of the vehicle population were established from project test results and from information in the literature. Subsequently, data were received in a private communication from A. Werner, Department of Civil Engineering, University of Calgary. The data had been collected in a project for the Alberta Department of Highways and included the speeds observed for specific vehicle types near the tops of very long grades. Analyses of the data performed at MRI indicate that drivers of passenger and recreational vehicles restrict their demands to about seven-tenths of the available horsepower in long, upgrade pulls. It is likely that a similar restraint is used in cruising on level and rolling terrains.

In order to place this finding in perspective, it is necessary to recall that most passenger-car engines develop maximum horsepower at engine speeds over 4,000 rpm. The maximum performance in a car with automatic transmission will usually require not only full throttle but also depression through a detent to hold the transmission in a lower than normal ratio. Engine noise is likely to be objectionable, even in well-insulated vehicles, and in some cases cooling capacity may be exceeded in prolonged demands for maximum available power. Lastly, most automobile engines are not built for prolonged operation at maximum horsepower. This is in contrast to the intercity truck engines that are usually rated conservatively, operate at lower engine speeds, and are designed for extended operation at maximum rated conditions.

The analysis leading to these conclusions was based on the vehicle types and characteristics found in the literature, combined with the performance equations from Appendix A. The characteristics of the original vehicle types are given in Table B-1, and are based on the use of maximum available horsepower.

The data collected on Canadian grades indicated that drivers in the postulated vehicle population were using less than maximum available horsepower at the observed elevations. Calculations were made to estimate what fraction of available power was being used.

Table B-2 shows, in the original vehicle types, the fraction of maximum available brake horsepower required to maintain the observed speeds. These values were calculated by varying bhp in the performance equations. The speed assigned to specific type performance strata assumes that the measured speed distribution for a particular type was normal. The assigned speed was the mean for the performance strata represented.

At this point in the analysis, there were two indications that drivers would limit a continuous demand to 0.65 to 0.70 of the maximum available power. First, the average of all calculated fractions for the 9-percent grade is 0.685. Second, the Canadian data included a controlled car-trailer test on the 9-percent grade, which indicated that 0.67 of the available horsepower was used.

A question was then posed. If drivers do limit the continuous power to something like 0.67 of the maximum available, what modifications of the original vehicle types would be indicated by the data? Tables B-3 and B-4 were constructed to determine the types of modifications attending the assumption that drivers used 0.67 of maximum available bhp on long upgrades.

The data in Table B-3 show that the required changes in performance characteristics are not drastic. It can be seen from Table B-4 that the low- and medium-performance passenger cars exhibit consistency with respect to fractional brake horsepower use. The high performance passenger car is apparently not limited by the driver preference and performance combination. The original passenger car perform-

TABLE B-1

ORIGINAL VEHICLE TYPES WITH PERFORMANCE BASED ON CHARACTERISTICS IN THE LITERATURE

Vehicle Type	% of Type	Weight/Bhp	Sea Level Performance: Maximum Acceleration a_o (ft/sec²)	Sea Level Performance: Pseudo Maximum Speed, $\bar{V}_M$ (ft/sec)
Passenger				
Low Performance	10	45.0	8.0	92
Medium Performance	27	23.6	9.25	105
High Performance	63	14.8	16.5	137
Travel Trailer Combination				
Low Performance	10	60.0	5.0	92
Medium Performance	80	32.5	8.8	102
High Performance	10	19.0	13.0	113
Campers[a]				
Low Performance	10	42.0	7.8	92
Medium Performance	56	22.0	15.0	105
Motor Homes				
Low Performance	15	52.5	6.0	95
Nominal Performance	85	32.9	10.0	98

a/ The high performance campers, 35% of type, are represented by medium and high performance passenger car types.

TABLE B-2

FRACTION OF AVAILABLE BRAKE HORSEPOWER USED BY ORIGINAL VEHICLE TYPES TO MAINTAIN OBSERVED SPEEDS

(Performance corrected for altitude)

Vehicle Type	Scott Lake Hill, Grade = 3.5%, Elevation = 4,600 ft: Fraction	at mph	Storm Mountain, Grade = 5.6%, Elevation = 5,560 ft: Fraction	at mph	Suwapta Pass, Grade = 9%, Elevation = 6,200 ft: Fraction	at mph
Passenger						
Low Performance	0.70	42.6	0.76	36.2	0.74	22.2
Medium Performance	0.70	50.4	0.72	42.6	0.71	28.7
High Performance	0.48	60.9	0.49	53.5	0.45	37.5
Travel Trailer Combination						
Low Performance	0.61	32.4	0.70	22.9	1.00	16.2
Medium Performance	0.55	41.2	0.60	34.0	0.70	24.5
High Performance	0.51	49.9	0.58	45.1	0.57	32.9
Campers						
Low Performance	0.48	34.0	0.56	27.7	0.65	17.1
Medium Performance	0.40	42.1	0.41	35.7	0.42	24.4
Motor Homes						
Low Performance	0.68	37.0	0.73	25.0	0.92	16.2
Nominal Performance	0.54	41.7	0.64	36.2	0.69	24.1

ances and population representations are best supported by available data and performance tests. The weight/bhp representation for the travel-trailer combinations is also strongly supported.

On the basis of these findings, it was concluded that passenger-car and recreational-vehicle drivers will limit their sustained demands for performance to seven-tenths of the maximum available brake horsepower. Revisions of the vehicle-performance characteristics were then made to reflect the evidence from the observed speeds on grades. Major emphasis in the revisions was placed on the values from the 9-percent grade. Brief comments on these revisions are made as follows:

1. For passenger vehicles, the original low- and medium-performance vehicles are in close agreement with the 7/10 value. The high-performance strata appear to be limited by other considerations. No revisions were made.

2. In the travel-trailer combinations, the low- and medium-performance characteristics on the 9-percent grade are close to those evaluated from manufacturing and survey data. The low-performance characteristics indicated by the grade data lie slightly above the original estimates. The grade-indicated values were adopted for the low and medium combinations. However, it should be recognized that the extremely rugged geometrics on the Canadian highways may deter use of the lowest performance combinations found elsewhere. The high-performance combinations may not have employed speeds that were so strongly dictated by performance. The characteristics adopted were a compromise between the original estimates and the grade-indicated values.

TABLE B-3

ORIGINAL VEHICLE CHARACTERISTICS COMPARED WITH CHARACTERISTICS TO MAINTAIN SPEEDS ON 9-PERCENT GRADE WTH 67-PERCENT MAXIMUM BRAKE HORSEPOWER

Vehicle Type	Original Characteristics: W/Bhp	Original: a_o (ft/sec²)	Original: $\bar{V}_M$ (ft/sec)	Revised Characteristics: W/Bhp	Revised: a_o (ft/sec²)	Revised: $\bar{V}_M$ (ft/sec)
Passenger						
Low Performance	45.0	8.0	92	40.7	8.75	94.75
Medium Performance	23.6	9.25	105	22.3	9.75	106.8
High Performance	14.8	16.5	137	22.0	11.36	121.2
Travel Trailer Combination						
Low Performance	60.0	5.0	92	40.2	6.18	103.7
Medium Performance	32.5	8.8	102	31.1	9.16	103.3
High Performance	19.0	13.0	113	22.3	11.19	107.6
Campers						
Low Performance	42.0	7.8	92	43.3	7.59	91.18
Medium Performance	22.0	15.0	105	35.1	9.72	91.34
Motor Homes						
Low Performance	52.5	6.0	95	38.2	8.49	101.74
Nominal Performance	32.9	10.0	98	31.9	10.32	98.6

3. On the 9-percent grade, the low-performance camper is in agreement with characteristics selected from manufacturing data. The distribution of characteristics for campers was not well defined from the literature. The medium performance camper on the 9-percent grade exhibits lower performance than estimated from the literature. The medium-performance characteristics selected were a compromise between those indicated by the grade data and those from the literature. The speed data for campers and cars also indicate that the high-performance campers,

34 percent of type, can be represented by the medium- and high-performance passenger cars in the ratio two medium-performance to one high-performance car.

4. On the 9-percent grade, the low-performance motor home has better performance than estimated from the literature. The low-performance characteristics selected are a compromise. Again, the rugged character of the Canadian geometrics may deter low-performance units found elsewhere. The nominal motor home characteristics were in agreement and were not changed.

5. The final characteristics for passenger and recreational vehicles are given in Table B-5. The maximum acceleration and speed with 7/10 brake horsepower are also shown. In this table, the fractional horsepower characteristics were obtained by applying correction factors to the full horsepower values. The fractional horsepower maximum accelerations are 0.73 of the full horsepower values; the maximum speeds have been multiplied by 0.9. The factors for the individual types vary over a small range; however, the factors 0.73 and 0.9 are recommended and have been used in the simulation.

The validity of the fractional horsepower constraint was reviewed by examining the results in conjunction with speed measurements reported by Williston (*36*). Figure B-1 shows measured and calculated speeds for passenger cars on a 5-percent grade. The high performance passenger car (analytical model) would be capable of maintaining a 70-mph speed on the 5-percent grade using 0.7 of available brake horsepower. The information in Williston's report is not sufficient to make a formal statistical test. However, a comparison tends to support the fractional horsepower concept and the performance characteristics selected. Williston also measured the speeds of panel and pickup trucks. This category is similar to the campers used in the analytical model, as shown in Figure B-2.

A final test of reason was made using the two-lane, two-way simulation. General observation suggests that passenger-car performance is normally not a significant constraint to flows in rolling terrain. Therefore, the simulation was run with and without the seven-tenths of available horsepower restraint for traffic on rolling terrain with grades up to 6 to 7 percent and lengths up to 3,000 ft. (The North Carolina State University test site 3-1969 was used.) Percent no-passing was about 46 percent. Also, recall that simulation drivers can, if not otherwise restricted, use maximum horsepower in making passes and in accelerating toward their desired speeds.

With the 7/10-horsepower restraints, the passenger-car mean speed was reduced 0.70 ft/sec from 81.58 to 80.88 ft/sec. Operating speed was reduced 1.58 ft/sec from 89.21 to 87.63 ft/sec. Other features of the flows such as passes, overtaking events, and acceleration noise also exhibited very small changes. These changes are in line with general observations.

TABLE B-4

FRACTION OF REVISED AVAILABLE BRAKE HORSEPOWER USED TO MAINTAIN OBSERVED SPEEDS

(Brake horsepower revised to provide observed speed on 9% grade with 0.67 of available Bhp utilized.)

	Sites					
	Scott Lake Hill Grade = 3.5% Elevation = 4,600 ft		Storm Mountain Grade = 5.6% Elevation = 5,560 ft		Sunwapta Pass Grade = 9.0% Elevation = 6,200 ft	
Vehicle Type	Fraction	at mph	Fraction	at mph	Fraction	at mph
Passenger						
Low Performance	0.63	42.6	0.69	36.2	0.67	22.2
Medium Performance	0.66	50.4	0.68	42.6	0.67	28.7
High Performance	0.48	60.9	0.49	53.5	0.67	37.5
Travel Trailer Combination						
Low Performance	0.41	32.4	0.47	22.9	0.67	16.2
Medium Performance	0.53	41.2	0.57	34.0	0.67	24.5
High Performance	0.60	49.9	0.68	45.1	0.67	32.9
Campers						
Low Performance	0.49	34.0	0.58	27.7	0.67	17.1
Medium Performance	0.64	42.1	0.65	35.7	0.67	24.4
Motor Homes						
Low Performance	0.50	37.0	0.53	25.0	0.67	16.2
Nominal Performance	0.52	41.7	0.62	36.2	0.67	24.1

TABLE B-5

FINAL CHARACTERISTICS FOR PASSENGER AND RECREATIONAL VEHICLES

			Performance at Sea Level Conditions			
			Full Bhp		Approximately 0.7 Bhp	
Vehicle Type	% of Type	Length (ft)	Max. Acceleration (ft/sec^2)	Pseudo Max. Speed (ft/sec)	Max. Acceleration (ft/sec^2)	Max. Speed (ft/sec)
Passenger						
Low Performance	10	18	8.0	100.0	5.84	90.0
Medium Performance	27	18	9.5	110.0	6.94	99.0
High Performance	63	18	14.0	135.0	10.22	121.5
Travel Trailer Combination						
Low Performance	10	36	6.2	104.0	4.53	93.6
Medium Performance	80	36	9.2	104.0	6.72	93.6
High Performance	10	32	12.0	110.0	8.76	99.0
Campers						
Low Performance	10	19	7.6	91.0	5.55	81.9
Medium Performance	56	19	10.0	100.0	7.30	90.0
Motor Homes						
Low Performance	15	26	7.0	100.0	5.11	90.0
Nominal Performance	85	22	10.4	100.0	7.59	90.0

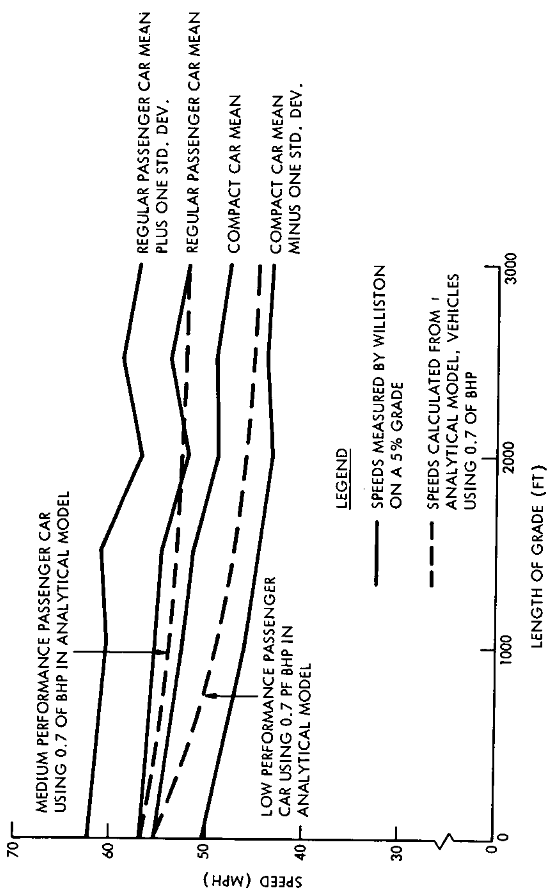

Figure B-1. Comparison of calculated and measured speeds of passenger cars on a 5-percent grade.

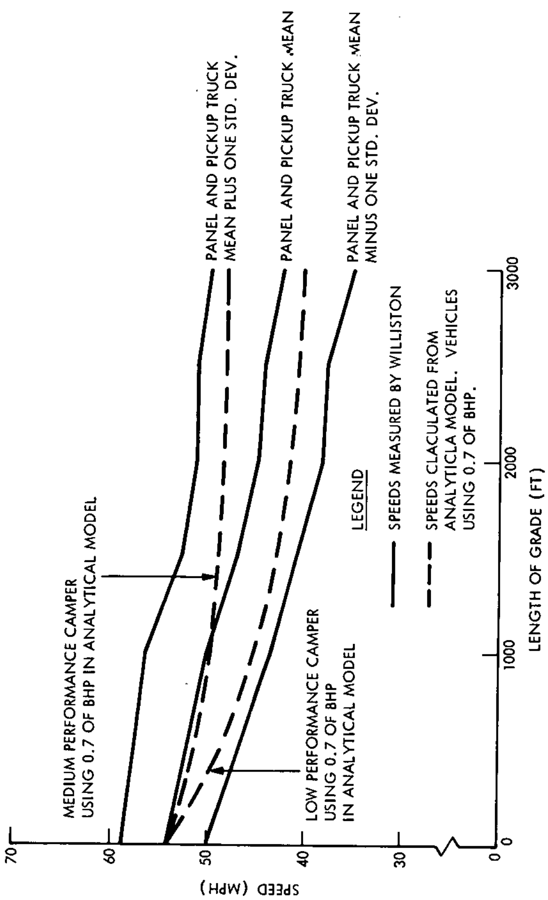

Figure B-2. Comparison of calculated and measured speeds of campers and panel and pickup trucks on a 5-percent grade.

APPENDIX C

COMMERCIAL VEHICLE ACCELERATION AND SPEED MAINTENANCE CAPABILITY

BACKGROUND

Several techniques and associated results are currently in use to predict commercial vehicle performance. In Huff and Scrivner (*3*), a simple analytical formulation is used in conjunction with vehicle tests to describe the acceleration and deceleration of a heavy truck (392 lb/NHP) on grades. In Firey and Peterson (*4*), coasting test results are used in an analytical formulation to produce performance curves for a variety of weight/power ratios, vertical curves, and grades. Their work takes explicit account of gear shift delays, but does not identify separate power losses. The SAE-recommended practice (*5*) treats the losses in detail, but does not account for the influence of gear shifts. Smith (*6*) describes a comprehensive investigation and proprietary computer program that calculates performance with a detailed account of vehicle characteristics and driver decisions.

The technique and results sought here should account for important vehicle characteristics and shift delays. The results in Firey and Peterson (*4*) would be satisfactory if they possessed more complete information and included a better account of the losses. Instead, their techniques and results are based on lumped losses for rolling, chassis, and aerodynamic effects. Further, the deceleration due to these losses does not change with vehicle speed in their account, a feature leading to overestimates of maximum speeds on level terrain and downgrades. In spite of these limitations, the results in Ref. (*4*) are useful, especially on upgrades and crest vertical curves.

CURRENT APPROACH

The approach adopted here centered on the following major undertakings:

1. Development of a comprehensive analytical model including individual losses, shift delays, and driver decisions.
2. Development and application of the model with a computer program.

3. Examination and adjustment of the loss coefficients by comparisons with published test results.
4. Design and verification of a simplified version of the comprehensive model for convenient application.

The features employed in the comprehensive model and computer program are:

1. The full throttle acceleration equation is based on the forms in the SAE "Truck Ability Prediction Procedure" (*5*).
2. The equation describing coasting deceleration is also based on the forms in Ref. (*5*) with an appropriate reduction of the chassis (drive train) losses.
3. Individual gear ratios are treated explicitly, with a transmission selected according to general practice as described in Ref. (*7*).
4. Engine-performance characteristics (NHP vs. RPM) can be specified in addition to rated characteristics.
5. The effects of engine inertia are included.
6. Starts in advanced gear ratios and skip shifts are utilized when they provide the best acceleration performance.
7. A distinction is made between rated gross weight and operating gross weight.
8. Traction limits can be specified and employed.
9. Acceleration and deceleration sequences are calculated for constant grades specified by the user.

BASIC ACCELERATION EQUATIONS FOR TRUCKS AND BUSES

These equations are based on the forms and coefficient values in Ref. (*5*) and are employed in the comprehensive model. Changes and additions have been made or are recommended based on comparisons with test data reported in the literature.

Horsepower-Limited Acceleration

The acceleration limited by horsepower is:

$$A_p = C_{pe} C_1 \Big/ \left[\frac{W}{(\mathrm{NHP})_s}(1 + C_e)\, V \right] - (C_2 + C_3 V)/(1 + C_e) - C_{de} C_4 V^2 \Big/ \left[\frac{W}{A}(1 + C_e) \right] - C_5 R_i \Big/ \left[\frac{W}{W_R}(1 + C_e) \right] - g\,(\sin\alpha)/(1 + C_e) \quad \text{(C-1)}$$

where:

A_p = horsepower-limited acceleration, ft/sec^2;
C_{pe} = horsepower correction factor for elevation = $1 - 0.00004E$ (for gasoline engines);
E = elevation, ft;
C_1 = 17693.5;
W = gross weight of vehicle or combination, lb;
$(\mathrm{NHP})_s$ = net horsepower at sea level conditions;
V = speed of vehicle or combination, ft/sec;
C_e = correction factor for engine inertia, defined later;
C_2 = 0.2445;
C_3 = 0.44×10^{-3} (the value corresponding to Ref. (*5*) would be 1.982×10^{-3}; comparisons with coasting and acceleration tests indicate that 0.44×10^{-3} is more representative);
C_{de} = correction factor for elevation effect on aerodynamic drag = $(1.0 - 0.000006887\ E)^{4.255}$;
C_4 = 0.0228 (this value is 72 percent of the one in Ref. (*5*) and appears more in accord with results of wind-tunnel and performance tests);
A = projected frontal area, ft^2;
C_5 = 3.5387×10^{-3};
R_i = the speed ratio (engine speed/vehicle speed) in the i$^{\text{th}}$ gear ratio, rpm/(ft/sec);
W_R = rated gross weight for vehicle or combination, lb;
g = acceleration due to gravity, 32.17 ft/sec^2;
α = angle of incline, positive upgrade (percent grade = $100 \times \tan\alpha$);

In the equation for A_p, the terms on the right-hand side account for the influences of weight/horsepower ratio, rolling losses, aerodynamic drag, chassis friction losses, and local grade. The account of engine inertia, C_e, has been added to the formulation given in Ref. (*5*). The value to be used for C_e is based on relations between engine displacement and inertia given in Ref. (*6*).

For diesel engines and in-line gasoline engines with four stroke cycles,

$$C_e = \frac{R_i^2}{W}\left[0.04388 + 1.101 \times 10^6 \frac{(\mathrm{NHP})_s^2}{(P\,S_r)^2} \right]$$

For V-type gasoline engines with four stroke cycles,

$$C_e = \frac{R_i^2}{W}\left[0.04388 + 0.826 \times 10^6 \frac{(\mathrm{NHP})_s^2}{(P\,S_r)^2} \right]$$

where:

P = net mean effective pressure at rated conditions, psi; and
S_r = engine speed at rated conditions, rpm.

Traction-Limited Acceleration

The traction-limited acceleration is determined by the basic relations involved, the appropriate coefficients from Ref. (*5*), and the test results from Ref. (*10*). Traction-limited acceleration is given by:

$$A_t = g\,(\sin\alpha_t - \sin\alpha) - f_R C_3 V - C_{de} C_4 V^2/(W/A) \quad \text{(C-2)}$$

where:

A_t = traction-limited acceleration on a grade of slope angle α at speed V, ft/sec;
α_t = slope angle on which incipient spin-out occurs at very low speed; typical values of $\sin\alpha_t$ are 0.22 for single-unit trucks and combinations with two drive axles, and 0.12 for combinations with one of three tractor axles driving (see Ref. (*10*); and
f_R = fraction of gross weight carried by nondriving axles under maximum acceleration. Estimated typical values are 0.48 for single-unit trucks, 0.65 for tractors with two drive axles, and 0.80 for tractors with one of three axles driving.

Coasting Acceleration

During gear shifts it is assumed that the chassis friction is 15 percent of its full-power value. The coasting acceleration is:

$$A_c = -C_2 - C_3 V - C_{de} C_4 V^2/(W/A) - (0.15) C_5 R_i/(W/W_R) - g \sin \alpha \qquad \text{(C-3)}$$

Starting Acceleration

A start is assumed to be made in speed ratio R_0 with engine speed of S_0 rpm. It is assumed that 80 percent of the full throttle torque at S_0 can be delivered to the follower element of the clutch. The starting acceleration at zero speed is then

$$A_s = (0.8) C_{pe} C_1 (R_0/S_0)/[W/(NHP)_0] - C_2 g \sin \alpha \qquad \text{(C-4)}$$

where $(\text{NHP})_0$ = sea level, full-throttle horsepower at engine speed S_0.

In the calculations performed for presentation in this report, the engine speed $S_0 = 800$ rpm has been used. R_0 has been taken as the lowest speed ratio that is not traction limited, or the next higher ratio if it provides an over-all faster start.

COMPARISON WITH TEST RESULTS

Calculated and test results are compared here in figures depicting acceleration versus speed. Although accelerations obtained from test results using geometrical or numerical differentiation may introduce some error, comparisons made in an acceleration versus speed plot can be more informative than comparisons using integrated (raw) data such as speed versus time.

Figures C-1 and C-2 show acceleration values obtained from the comprehensive computer program. Figure C-1 shows for a specific truck the accelerations achieved in each gear ratio on a zero grade with engine speeds in the normal operating range. The short dashes of negative acceleration are the decelerations resulting in speed losses occurring during gear shifts in an acceleration sequence. The sequence, as calculated, consists of a powered acceleration, a drop to a deceleration during shift, a speed loss during this deceleration, a rise again for the powered acceleration in the next gear, etc. Comparison with smoothed test results requires an averaging procedure, as shown in Figure C-2, wherein each dashed line of constant acceleration was obtained as the net speed change divided by the time in a gear ratio *and the following shift.* The powered acceleration values repeated in Figure C-2 for comparison point out the importance of the role played by the shift delays and the concurrent decelerations.

Preliminary results were calculated from the comprehensive computer program for comparison with the test results reported by the Western Highway Institute (*8*) and the Road Research Laboratory (*9*). These initial comparisons showed that certain features of the acceleration sequence required refining.

The calculated accelerations for the 400-lb/NHP vehicle were found to lie below the values from both reference sources. The 300-lb/NHP data were in better correspondence. The 200-lb/NHP case was good, but the calculated values for 100 lb/NHP lie at the upper bound of the observed values.

It appeared that some of the power losses, especially those influencing heavy units, were overestimated. The candidates for adjustment were: the shift time, the rolling losses, the chassis losses, and the aerodynamic losses. Each of these factors is discussed next.

In Ref. (*8*), the shift time is not given directly. Instead, the time reported is measured from the beginning of the shift until the same speed is achieved in the next gear ratio. Similar values from the results of the computer program bracket those reported, except in the lowest ratio shifts where the computed values are slightly smaller. (The comparisons were made with the 10 speed ratios in the real world tests since the analytical trucks had 9 ratio transmissions.) The literature provides no justification for reducing the actual shift times below the 1.5 sec employed in the calculations, so no change was made.

The rolling losses appear in Ref. (*5*) as two terms. When treated as a retarding force, one term is independent of speed and the second depends linearly on speed. The literature on the two coefficients is reviewed in Ref. (*10*) and compared with the results of the two tests. The comparisons and results indicate that the constant term in the SAE procedure (*5*) may be slighly low. However, the literature indicates that the term containing speed may be only 22 percent of the SAE value. A reduction in the speed-containing term was indicated by two considerations: (1) specific measurements of the term and (2) a consequent improved agreement with over-all performance measured by other investigators in field tests. Therefore, the SAE coefficient was reduced to 22 percent of its published value in subsequent calculations.

The chassis losses were compared with the recommendations in Ref. (*6*), which are based on an extensive series of transmission tests. In Ref. (*6*), the chassis losses are incorporated as a transmission efficiency. The highest full throttle efficiencies are 92 percent for a pickup truck and 90 percent for a 4 x 2 tractor (four wheels with two driving; i.e., a two-axle tractor with one drive axle). An efficiency of 86 percent is recommended for a 6 x 4 tractor, which is a very prevalent type. The basic forms of the chassis losses are different in Ref. (*6*) and in Ref. (*5*); however, the losses in Ref. (*5*) are equal to those in Ref. (*6*) under a set of reasonable conditions. The conditions of equality are obtained with: (1) the techniques of Ref. (*6*) applied with 90-percent transmission efficiency and (2) the SAE expressions (*5*) applied with rated weight/NHP equal to 280. If the SAE form is applied with rated weight/NHP greater than 280, the chassis losses will be greater than those in Ref. (*6*) with a 90-percent transmission efficiency. Since there appeared to be little justification for making a significant reduction in the chassis loss coefficient as used in Ref. (*5*), no change was made.

The SAE value for the aerodynamic drag force was known to be high from a previous comparison with test data. Drag force is normally expressed as $\frac{1}{2} \rho V^2 C_D A$ where ρ is atmospheric mass density, V is the speed, A is the frontal area, and C_D is the drag coefficient. The drag

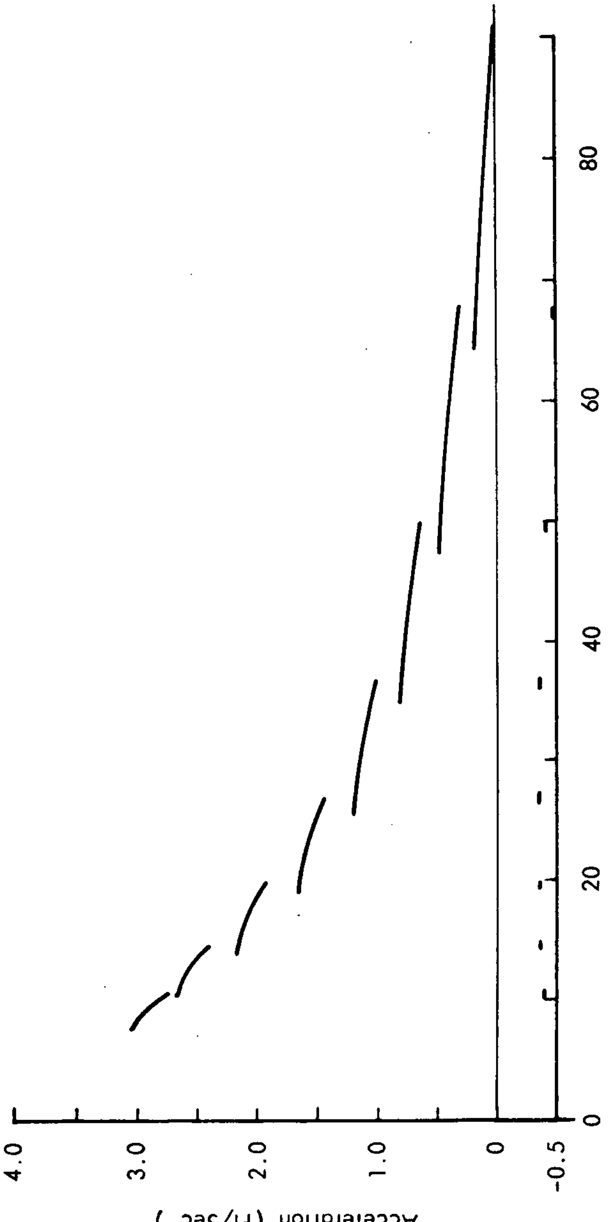

Figure C-1. Calculated acceleration in individual gear ratios and decelerations in shifts, zero grade, 300 lb/NHP.

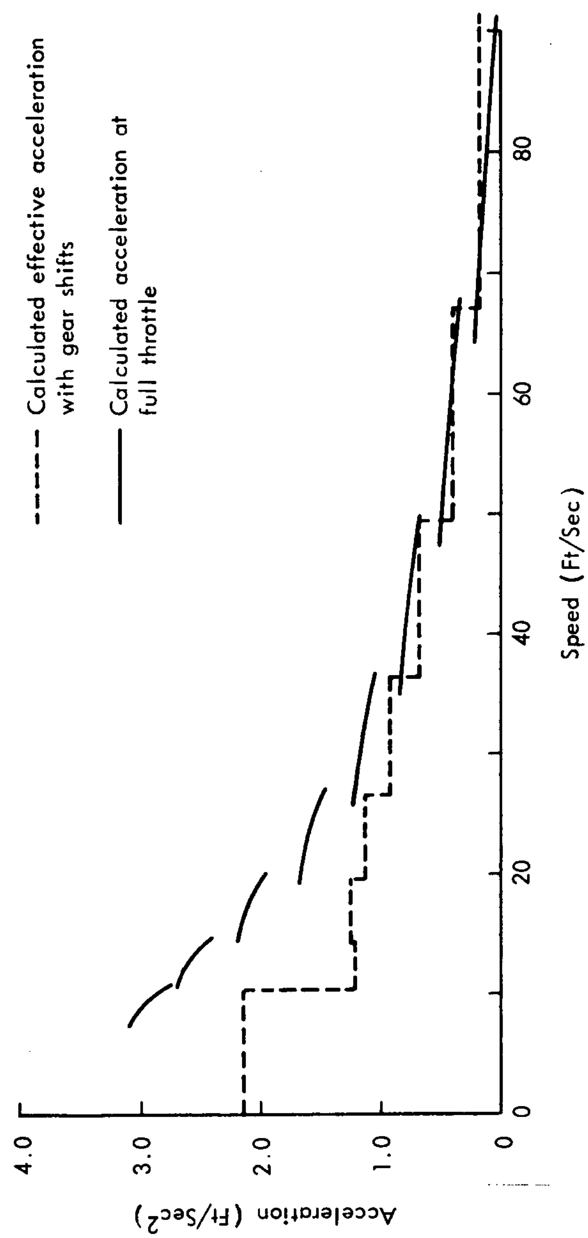

Figure C-2. Calculated effective acceleration in individual gear ratios with effects of gear shifts included, zero grade, 300 lb/NHP.

force given in Ref. (*5*) is equivalent to a C_D of 0.825. The best information now available (*11*) indicates that the aerodynamic coefficient should be reduced to about 72 percent of the value published in Ref. (*5*). The comparison is shown in Table C-1.

In summary, it appears justifiable to reduce two of the original SAE coefficient values. The coefficient for rolling loss (force) proportional to speed was reduced to ⅔ of its published value. The aerodynamic loss coefficient was reduced to 0.72 of the published value. However, this latter change would not influence the comparison because an increase was required in frontal area to match the trucks tested. A program correction was also made concerning engine inertia, which had been underestimated through a numerical coefficient error. The correction to larger inertias tends to reduce the magnitudes of both accelerations and decelerations.

The performance calculations were repeated with the revised coefficients. The results are shown in Figures C-3 through C-6. The 400-lb/NHP results were improved and in essential agreement with the Road Research Laboratory results. The 300-lb/NHP results were improved, especially

TABLE C-1

C_D VALUES FROM REF. (*11*)

Configuration	C_D	Fraction of SAE Value
Cab or tractor and square front body or trailer	0.687	0.833
Cab or tractor and body or trailer with rounded vertical corners	0.585 to 0.605	0.710 to 0.734
Cab or tractor and body or trailer with rounded vertical and top corners	0.521 to 0.542	0.632 to 0.658

at high speed. The 200-lb/NHP and 100-lb/NHP results remained satisfactory.

The performance bounds, as given in Ref. (*8*), for the 400-lb/HP vehicle was obtained by extrapolation, and may be slightly high. The highest ratio in the trucks tested was 310/HP. The tested trucks covered the range 100 to 300 lb/HP. (It appears that brake rather than net horsepowers were recorded. Therefore, since the brake horsepower is approximately 1.1 times net horsepower, the weight/power ratios from Ref. (*8*) should be multiplied by 1.1 to approximate a conversion to net horsepower.)

Additional analysis was made of the accelerations for the

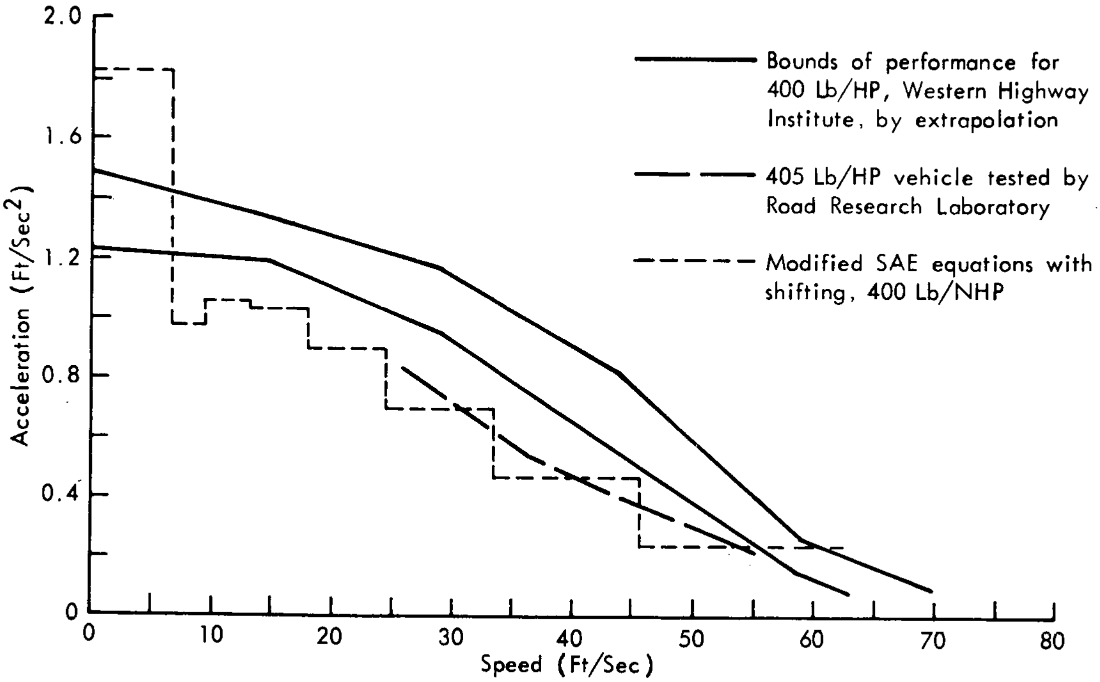

Figure C-3. Acceleration on zero grade, 400 lb/NHP.

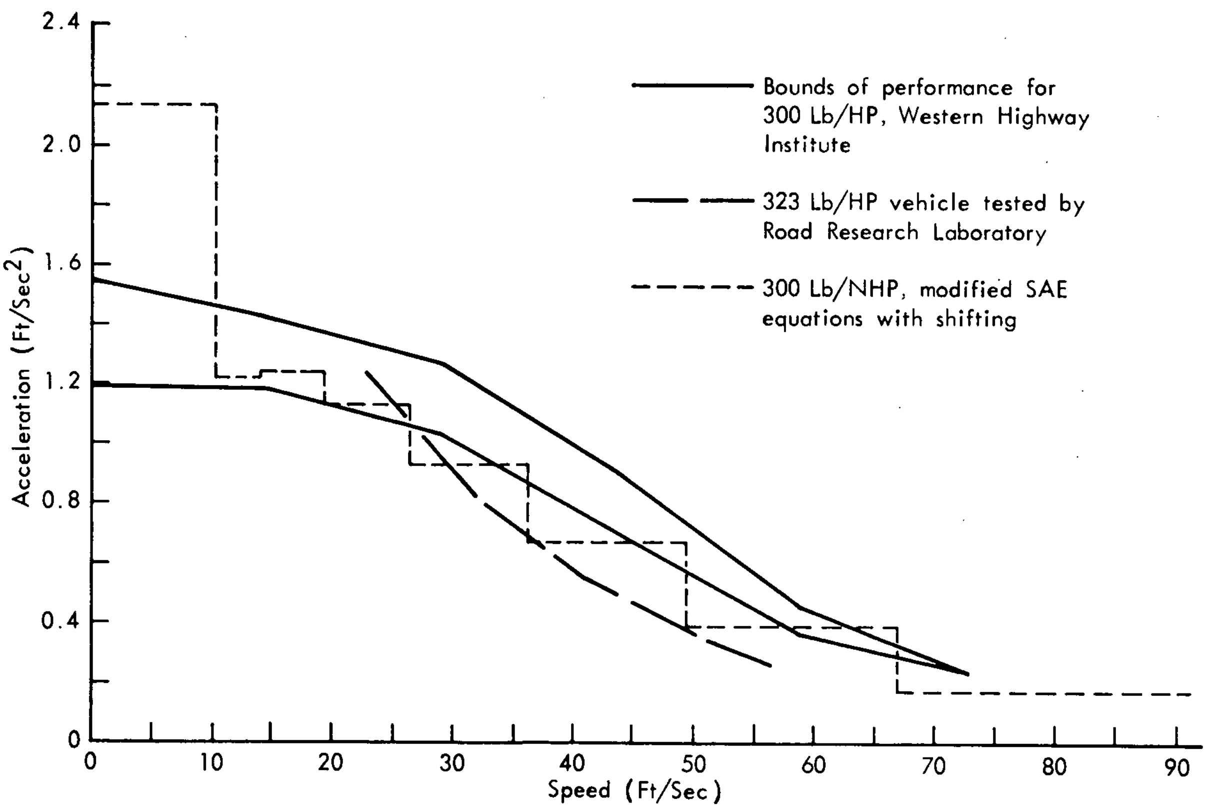

Figure C-4. Acceleration on zero grade, 300 lb/NHP.

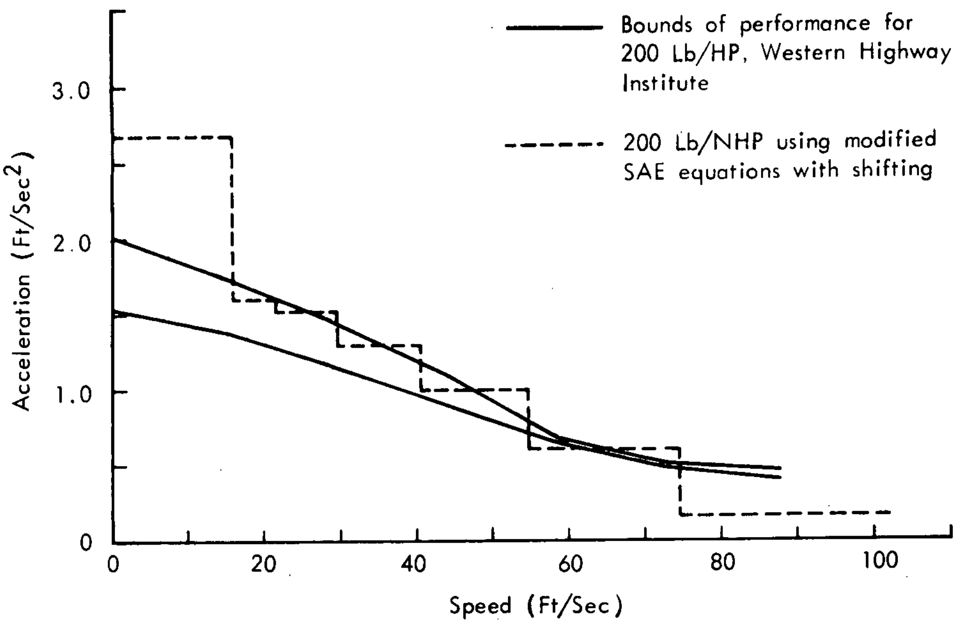

Figure C-5. Acceleration on zero grade, 200 lb/NHP.

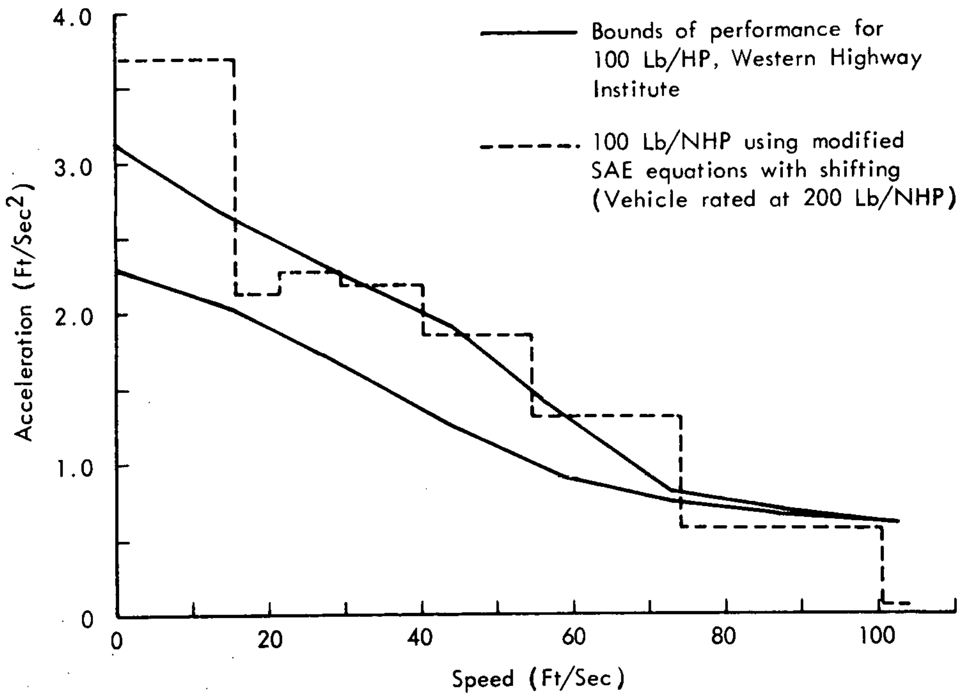

Figure C-6. Acceleration on zero grade, 100 lb/NHP.

lowest performing trucks. Further comparisons with data on individual facets of performance indicated that the equation coefficients and computational procedure are properly adjusted, but some of the reported data for 400-lb/HP vehicles may be too high. There are three potential explanations for the differences. First, it is noted that almost all of the tested vehicles, in Ref. (*8*), with high weight/power ratios had two-cycle engines. The inertia of such an engine will be overestimated in the computations based on its horsepower, and this will incorrectly depress the accelerations in lower gear ratios. Second, the analysis assumes that there is an absolute maximum engine speed, while real governors permit speed overshoot. Such overshoot could significantly improve acceleration. The third possibility involves human factors. Drivers of heavily loaded, low-performance trucks may be motivated to make shifts with less delay.

It is more conventional to compare vehicle performance using values that are directly measured or integrated in calculations. Figures C-7 through C-10 show the speed-distance relations for acceleration from a standing start. The calculated results are from the same computations used in Figures C-3 through C-6. The agreement is seen to be good.

RECOMMENDED PROCEDURES

For general calculations, satisfactory results will be obtained if the SAE equations with shift delays and adjusted coefficients as developed here are used, and the rated weight/horsepower is set equal to 200 or 250 lb/NHP. This choice will slightly increase the calculated accelerations for the 300- and 400-lb/NHP vehicles. An additional small reduction in the aerodynamic drag term might also be appropriate since the calculated maximum speeds for the heaviest vehicles appear slightly low in view of the character of the curves derived from Ref. (*8*).

DISCUSSION OF GRADE EFFECTS

The results in this section were obtained with the same 300-lb/NHP vehicle, coefficients, and logic used for Figures C-4 and C-8.

The simplest adjustment for grade effects, one's first intuitive choice, would be to take the zero-grade performance and add (algebraically) the acceleration component due to gravity. That is, simply subtract $g \sin \alpha$, where g is the acceleration due to gravity and α is the angle of the incline, positive upgrade. Another approach is to repeat the sequence of calculations leading to acceleration-speed plots, including the effects of gravity in each step of the sequence. The two procedures lead to quite different results, as shown in Figure C-11.

If Figure C-11 is read from left to right, the sequence is the calculated performance from a standing start on the 4-percent grade. If Figure C-11 is entered at the right and scanned to the left, the sequence is the calculated deceleration of the truck entering the 4-percent grade at high speed. (The two sequences were calculated separately.) The difference in results from the two procedures is caused by a change in the relative importance of shift delays and subsequent decelerations on the grade. The simple adjustment for the gravity component underestimates the effective low speed acceleration obtained as outlined in the discussion of Figures C-1 and C-2. The simple adjustment also overestimates the decelerations after the high-speed entry to the grade.

The important factor involved in this change in effective acceleration is the fraction of time the engine is usefully employed for acceleration. On steep upgrades there is an effect due to sizable speed losses during shifts. The large speed loss may cause the engine to operate below its normal operating speed and power in the next gear ratio. However, for engines normally employed and typical transmission characteristics, this effect is less important than the fraction of time the engine is applied. On zero grade the full-throttle acceleration in one of the low-gear ratios requires only a short time to reach maximum engine speed, and the time for shifting constitutes a large fraction of the

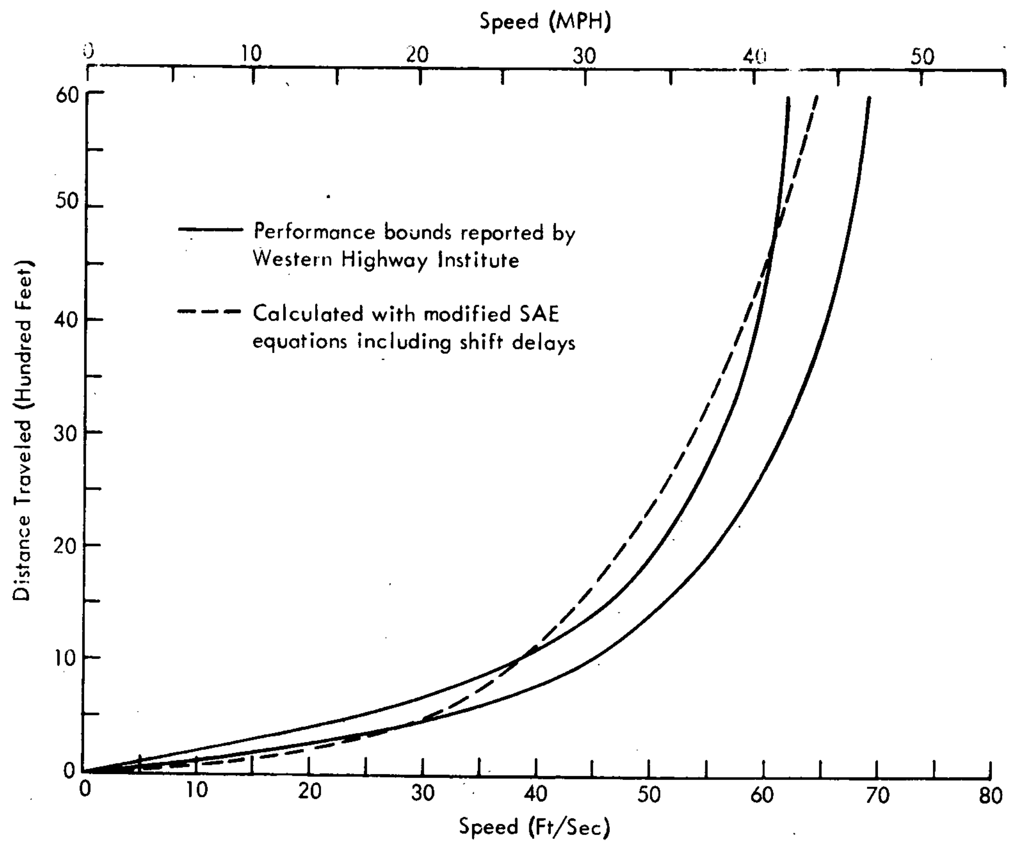

Figure C-7. Speed distance from a start, zero grade, 400 lb/NHP.

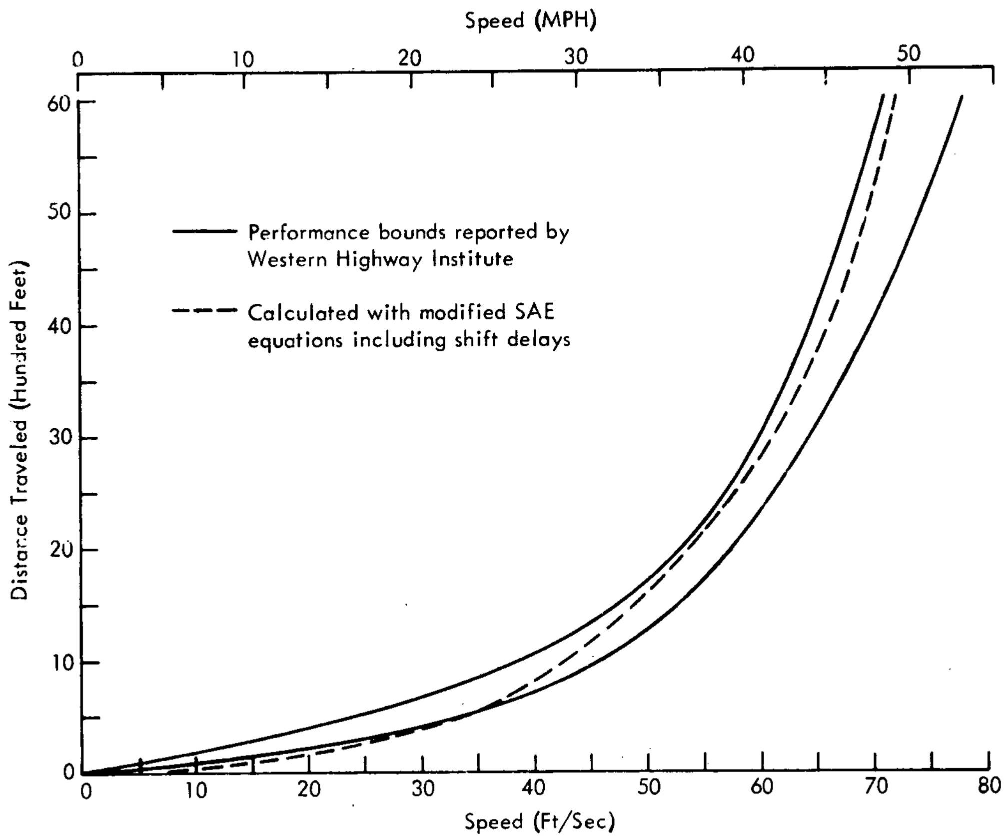

Figure C-8. Speed distance from a start, zero grade, 300 lb/NHP.

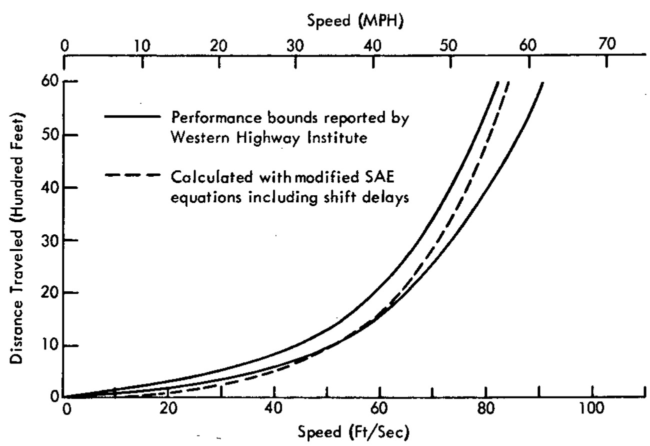

Figure C-9. Speed distance from a start, zero grade, 200 lb/NHP.

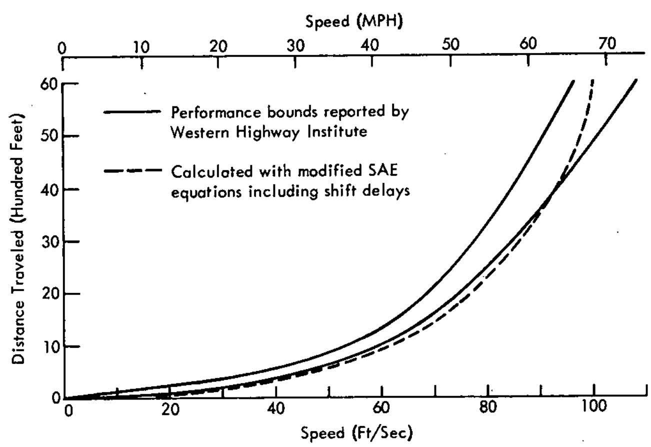

Figure C-10. Speed distance from a start, zero grade, 100 lb/NHP.

total time. On upgrades in the same gear ratio the vehicle acceleration will be lower, so that a longer fraction of the total time will be spent under power.

The equilibrium condition in Figure C-11 is one with an indicated positive acceleration. This situation occurs because the equilibrium condition is at maximum governed engine speed (and maximum operative horsepower) in the fourth-gear ratio. The vehicle speed is governor limited at that point. A shift to the next higher gear ratio would result in a negative acceleration and loss in speed.

A comparison (see Fig. C-12) for an 8-percent grade shows generally the same differences, with more serious discrepancies between values calculated sequentially for the grade and the results of a simple adjustment for the gravity component. The simple adjustment would incorrectly indicate that the truck could not start and accelerate on the steep grade.

The simple adjustment procedure is also inaccurate for downgrades, as shown in Figure C-13. The benefits from the 4-percent downgrade are not fully realized.

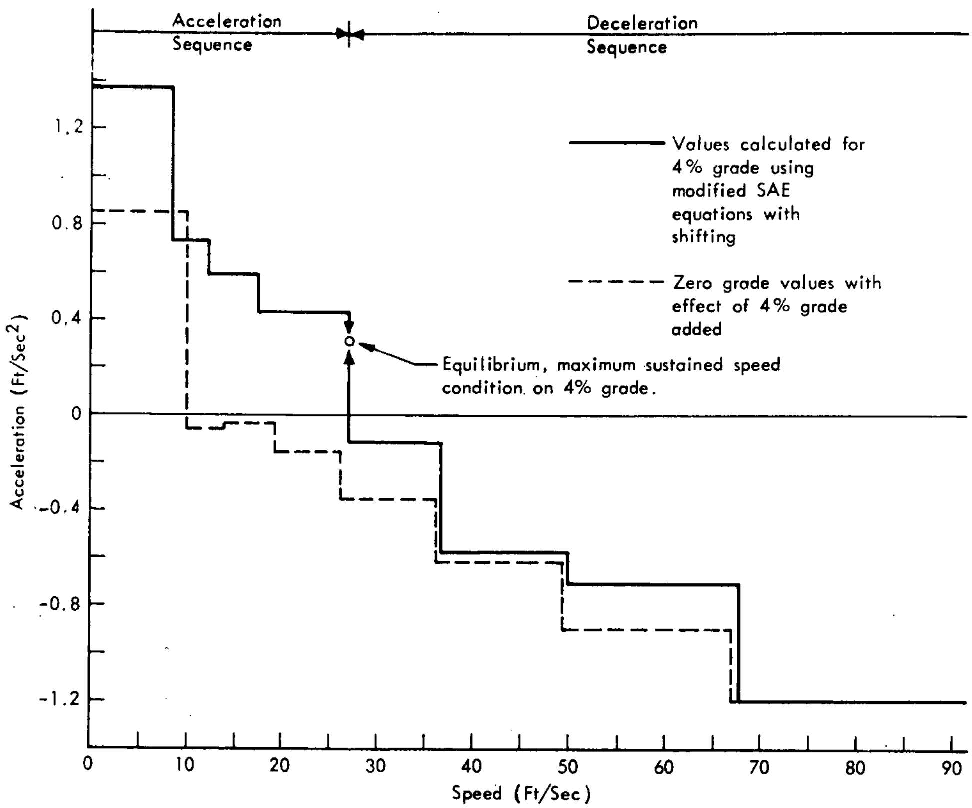

Figure C-11. Acceleration and deceleration to sustained conditions on 4-percent grade, 300-lb/NHP vehicle.

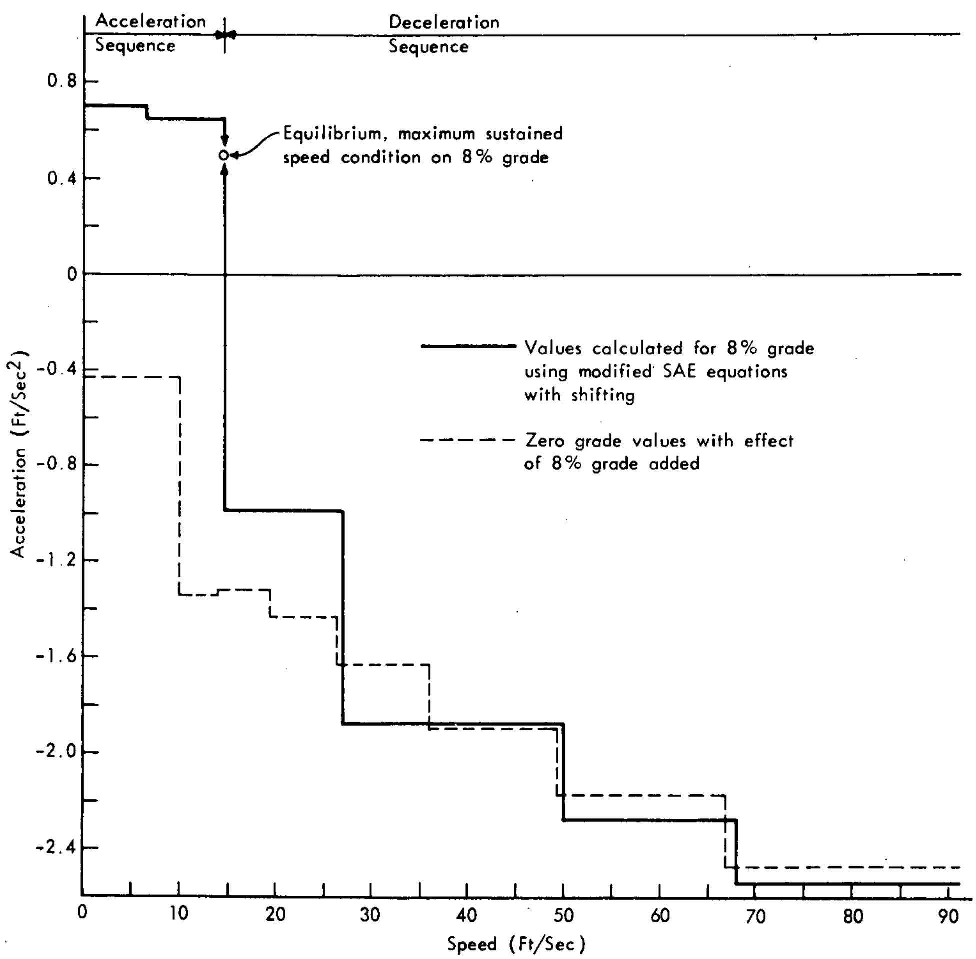

Figure C-12. Acceleration and deceleration to sustained conditions on an 8-percent grade, 300-lb/NHP vehicle.

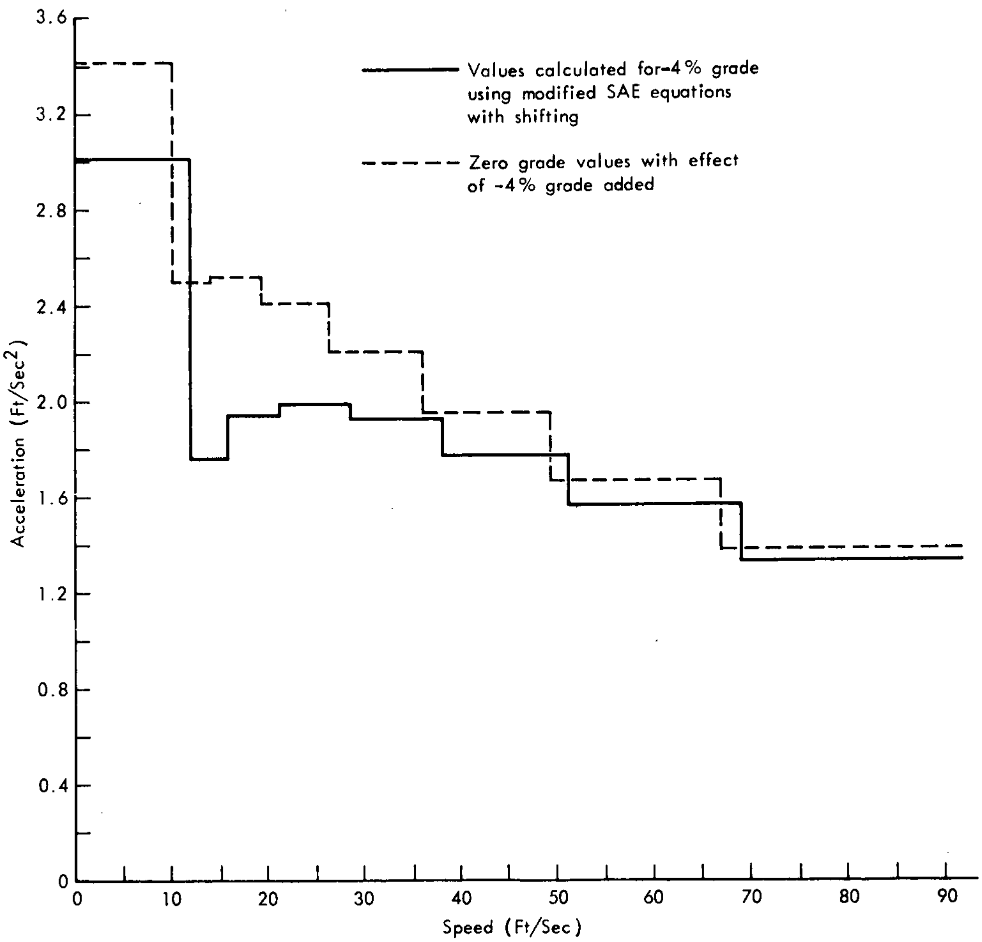

Figure C-13. Acceleration down a —4-percent grade, 300-lb/NHP vehicle.

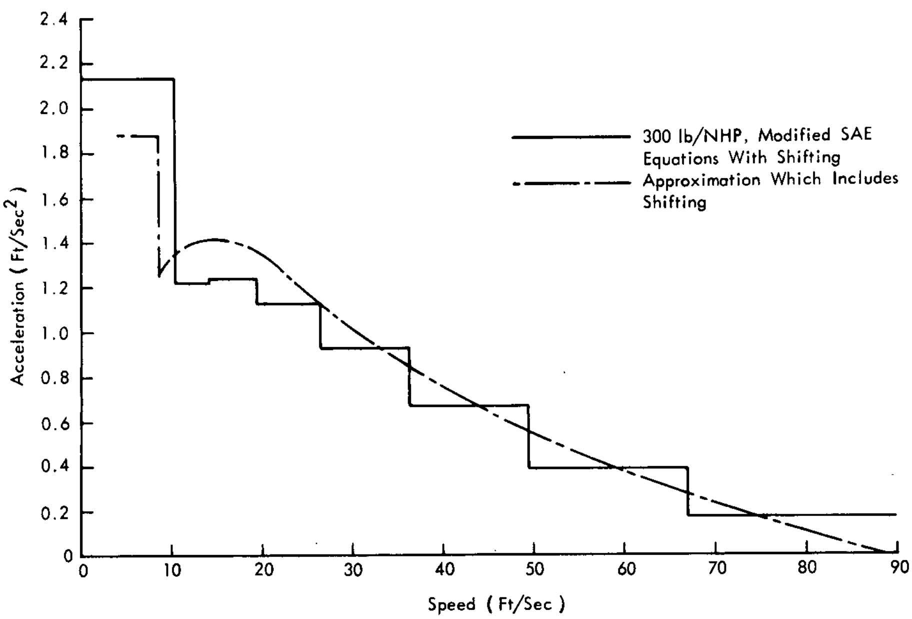

Figure C-14. Approximate correction for gear shift delays, zero grade, 300-lb/NHP vehicle.

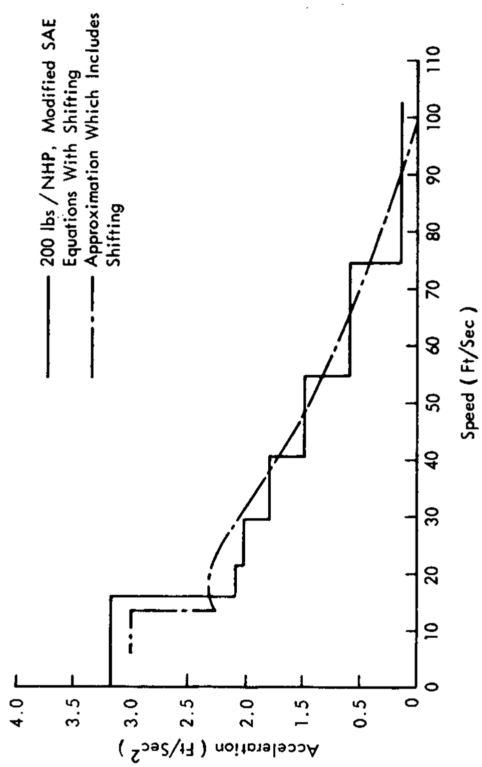

Figure C-15. Approximate correction for gear shift delays, zero grade, 200-lb/NHP vehicle.

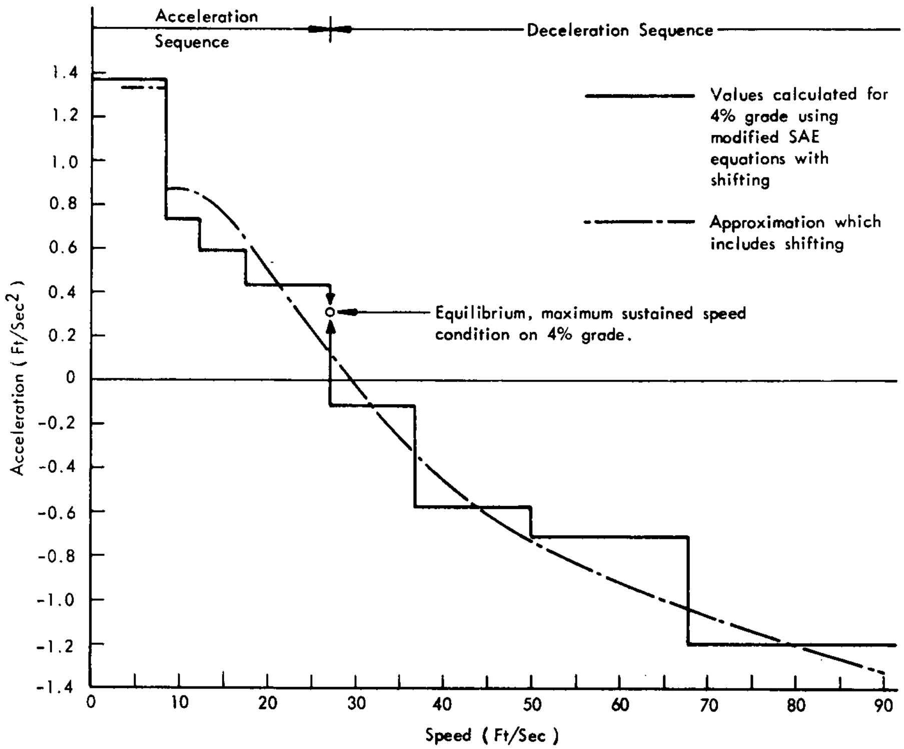

Figure C-16. Approximate correction for gear shift delays, 4-percent grade, 300-lb/NHP vehicle.

APPROXIMATE CORRECTION FOR GEAR SHIFT DELAY

Because of the important influence of gear shift delays in determining on-grade performance, an approximation to account for these delays was developed. The approximate form accounting for gear shift delays is derived in Appendix D. The result is an expression for effective acceleration, A_e:

$$A_e = \left[\frac{\eta V}{\eta V + S_u t_s (\bar{A}_u - \bar{A}_c)} \right] \bar{A}_u \qquad \text{(C-5)}$$

where:

η = a parameter dependent on the range of engine speeds normally employed; typical values range 0.33 to 0.43; 0.4 is recommended;

V = vehicle speed, ft/sec;

$\bar{A}_u$ = minimum of $\bar{A}_p$, the power-limited acceleration, or $\bar{A}_t$, the traction-limited acceleration, ft/sec^2; the bar indicates the use of average available net horsepower;

S_u = one times the sign of A_u (which can be either + or −);

t_s = actual time to shift gears, sec;

$\bar{A}_c$ = acceleration in coasting, ft/sec^2; the bar indicates the use of an average ratio for the coasting chassis losses.

When the vehicle speed is less than or equal to V_1—when the vehicle is in the starting gear ratio—the product ηV should be replaced by V_1. Approximations for V_1 are given in Appendix D.

The equation for A_e has been employed to calculate values for comparisons with the results from the comprehensive computer program, as shown in Figures C-14 through C-16.

The value of η used for the illustrated approximations (0.43) was based on the range of normal operating engine speeds. It appears that slightly improved results would be obtained by averaging with the next lower transmission ratio ($\eta = 0.355$). However, a typical value $\eta = 0.4$ should be satisfactory for most heavy trucks.

The performance characteristics in Appendix E have been calculated with the simple equation for effective acceleration. The equations employed were based on: $\eta = 0.4$; $V_1 = 10$ ft/sec; engine inertia and chassis losses for a 200-NHP engine; average available net horsepower equal to 0.94 of rated maximum net horsepower; and standard sea level conditions.

APPENDIX D

AN APPROXIMATE CORRECTION FOR GEAR SHIFT DELAYS

In general, each gear ratio is used in conjunction with a shift. A smoothed acceleration relation will take into account the acceleration with power applied, the acceleration (deceleration) during shifts, and the time in each condition.

The effective acceleration equation can be written to include an account of shift delays:

$$A_e = \frac{\Delta V}{t_p + t_s} \tag{D-1}$$

where:

A_e = effective acceleration;
ΔV = total net speed change in one ratio;
t_p = time with full-throttle engine (or traction-limited power applied); and
t_s = time for gear shift.

However,

$$t_p = (\Delta V - t_s \bar{A}_c)/\bar{A}_u$$

where:

$\bar{A}_u$ = minimum of $\bar{A}_p$ or A_t;
$\bar{A}_p$ = average acceleration during full throttle in the gear ratio;
A_t = traction-limited acceleration; and
$\bar{A}_c$ = average coasting acceleration during shifts.

Therefore,

$$A_e = \left[\frac{\Delta V}{\Delta V + t_s(\bar{A}_u - \bar{A}_c)}\right] \bar{A}_u \tag{D-2}$$

ΔV will have the sign of $\bar{A}_u$ and a magnitude approximated by ηV, where η = (maximum engine speed in the operating range/minimum engine speed in the operating range) — 1.0 —typical values will be 0.33 to 0.43—and V = vehicle speed. Thus,

$$A_e = \left[\frac{\eta V}{\eta V + S_u t_s(\bar{A}_u - \bar{A}_c)}\right] \bar{A}_u \tag{D-3}$$

and S_u is one times the sign of $\bar{A}_u$ (which can be either + or —).

The approximation $\Delta V = \eta V$ is not applicable in the starting gear ratio. In this case, ηV should be replaced by V_1 where V_1 = maximum speed (ft/sec) in the starting gear ratio. The value of V_1 is approximated by

$$V_1 = \frac{\left[0.8138\, C_1 \Big/ \dfrac{W}{(\mathrm{NHP})_s} - 2100\, C_5\right]}{C_2 + g(\alpha_s + 0.05)} \tag{D-4}$$

where α_s is the slope angle of grade on which a normal start should be possible. C_1, C_2, C_5, W, $(\mathrm{NHP})_s$, and g were defined in Appendix C.

It remains to determine suitable forms for the average accelerations $\bar{A}_p$ and $\bar{A}_c$. Since the intent is to provide a simple, but accurate, performance prediction, it is appropriate to use expressions employing average values for engine characteristics and the like. In particular, the average engine power available can be written as the product of the maximum power, $(\mathrm{NHP})_s$, and a factor f_p, which typically ranges from 0.90 to 0.96. Likewise, the average engine speed, S_a, can be taken as

$$S_a = S_r \frac{(\eta + 2)}{2(\eta + 1)} \tag{D-5}$$

Thus, $\bar{A}_p$ and $\bar{A}_c$ can be found from A_p and A_c, which are maximum values, by replacing $(\mathrm{NHP})_s$ by $f_p(\mathrm{NHP})_s$ and R_i by S_a/V in the equations given in Appendix C.

APPENDIX E

SPEED-DISTANCE RELATIONS FOR COMMERCIAL VEHICLES

Figures E-1 through E-10 present speed versus distance for five trucks using maximum available power in acceleration and deceleration. The values were calculated with the modified SAE performance equations and the simple approximation for gear shift delays.

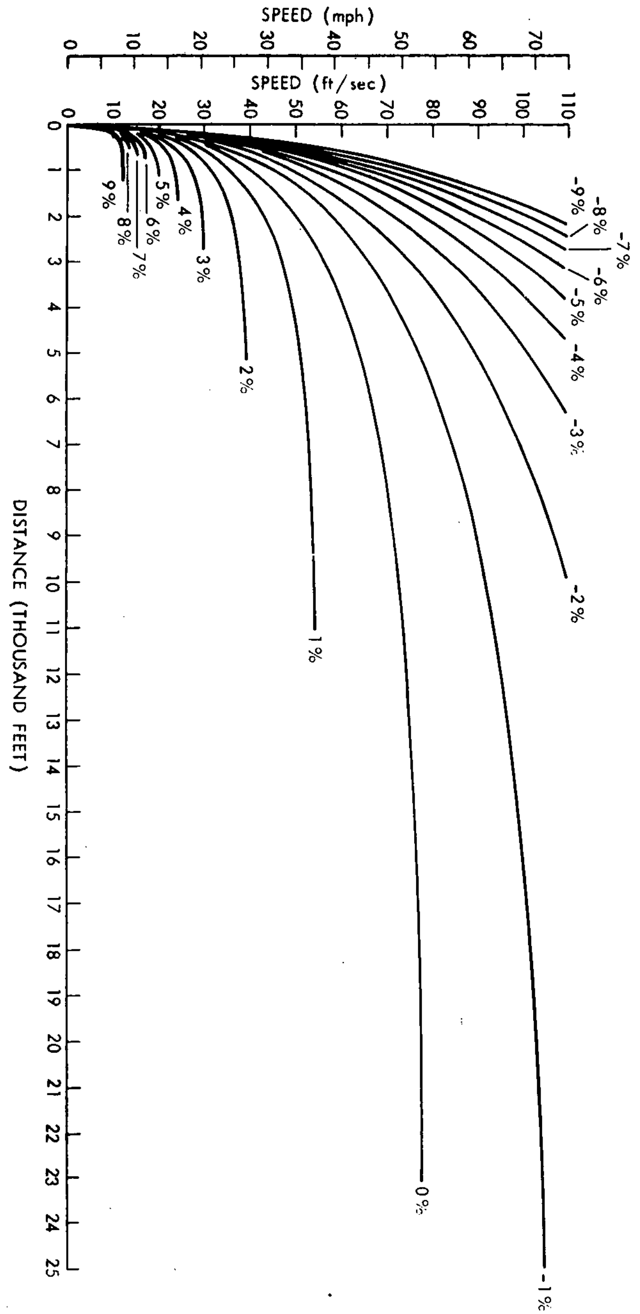

Figure E-1. Speed vs. distance in acceleration, 400 lb/NHP, 720 lb/ft².

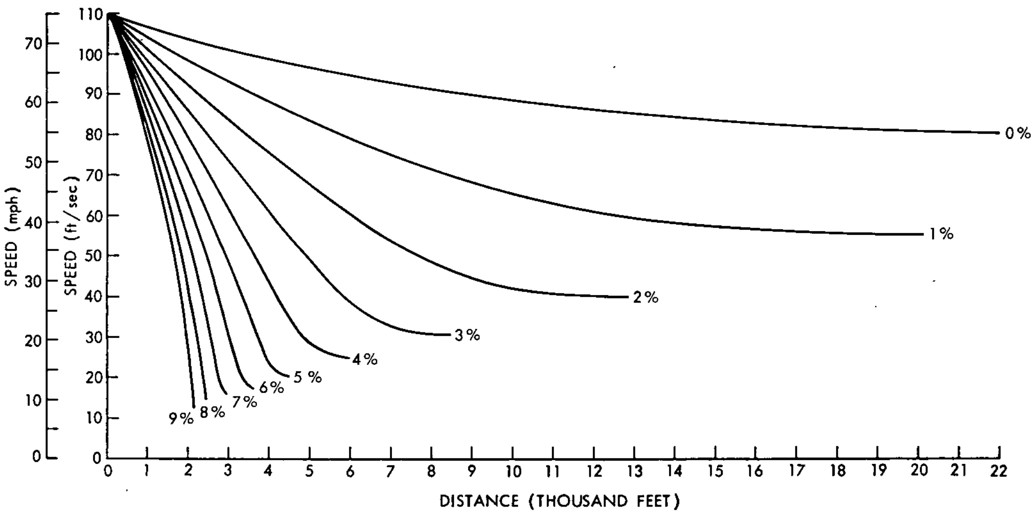

Figure E-2. Speed vs. distance in deceleration, 400 lb/NHP, 720 lb/ft².

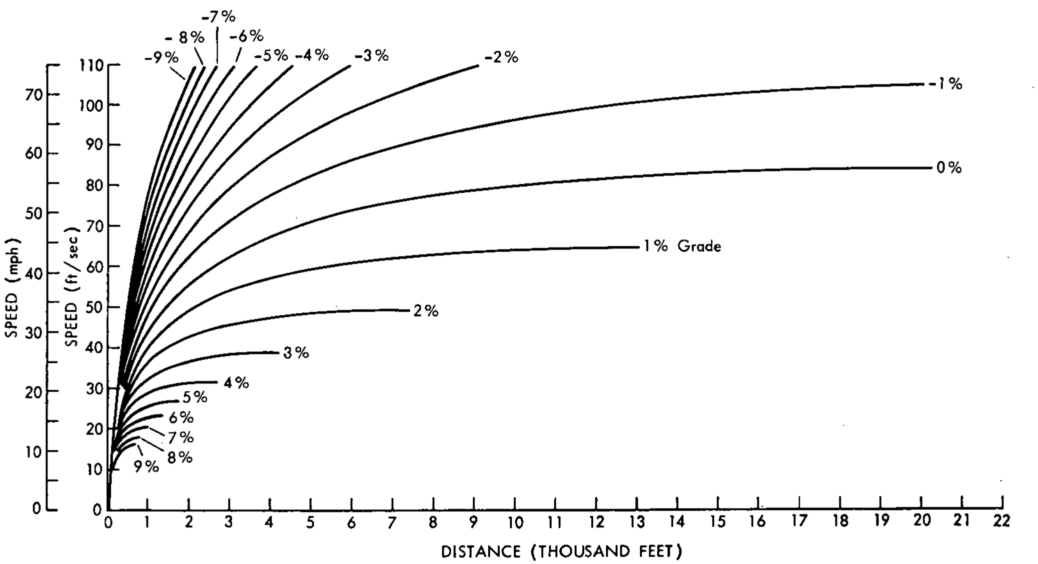

Figure E-3. Speed vs. distance in acceleration, 300 lb/NHP, 540 lb/ft².

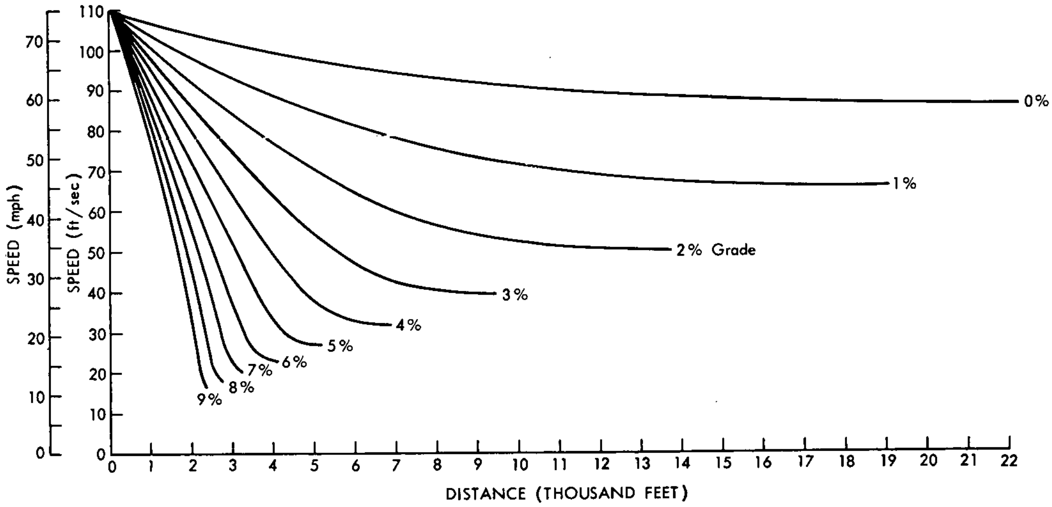

Figure E-4. Speed vs. distance in deceleration, 300 lb/NHP, 540 lb/ft².

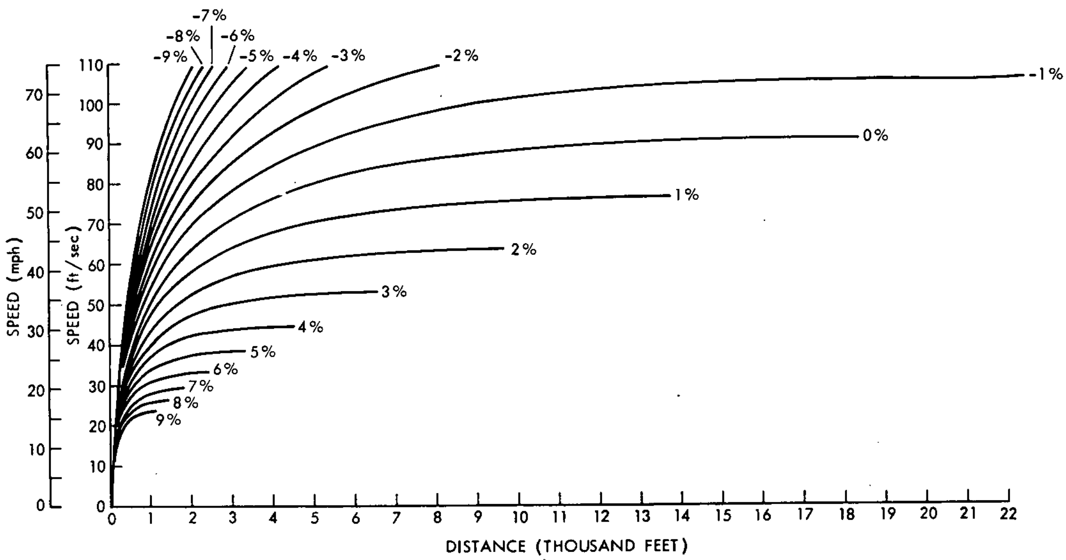

Figure E-5. Speed vs. distance in acceleration, 200 lb/NHP, 360 lb/ft².

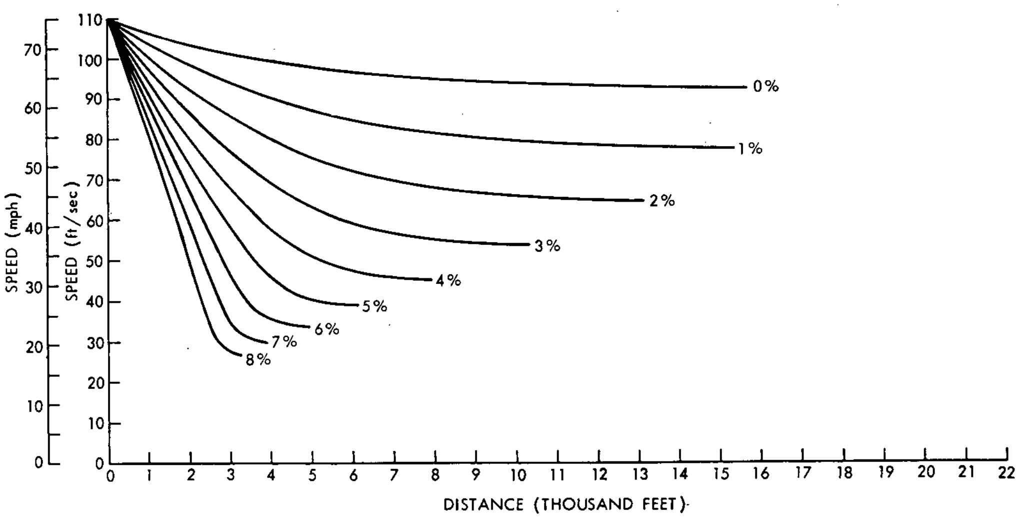

Figure E-6. Speed vs. distance in deceleration, 200 lb/NHP, 360 lb/ft².

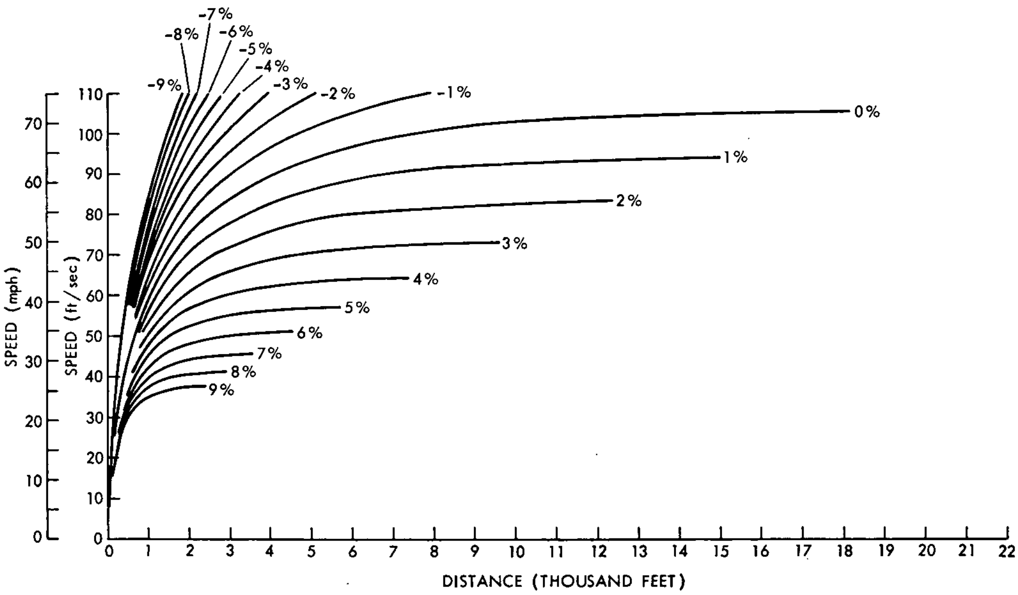

Figure E-7. Speed vs. distance in acceleration, 125 lb/NHP, 300 lb/ft².

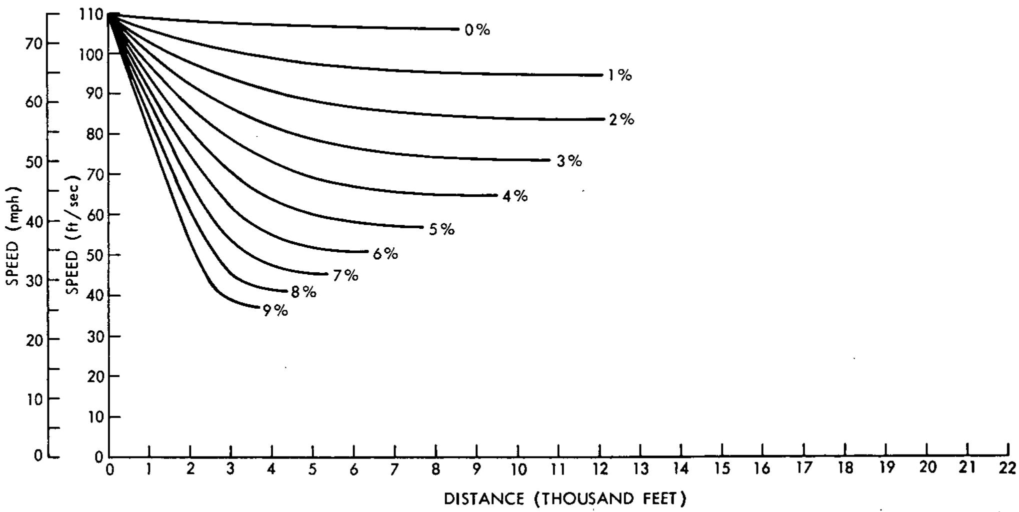

Figure E-8. Speed vs. distance in deceleration, 125 lb/NHP, 300 lb/ft².

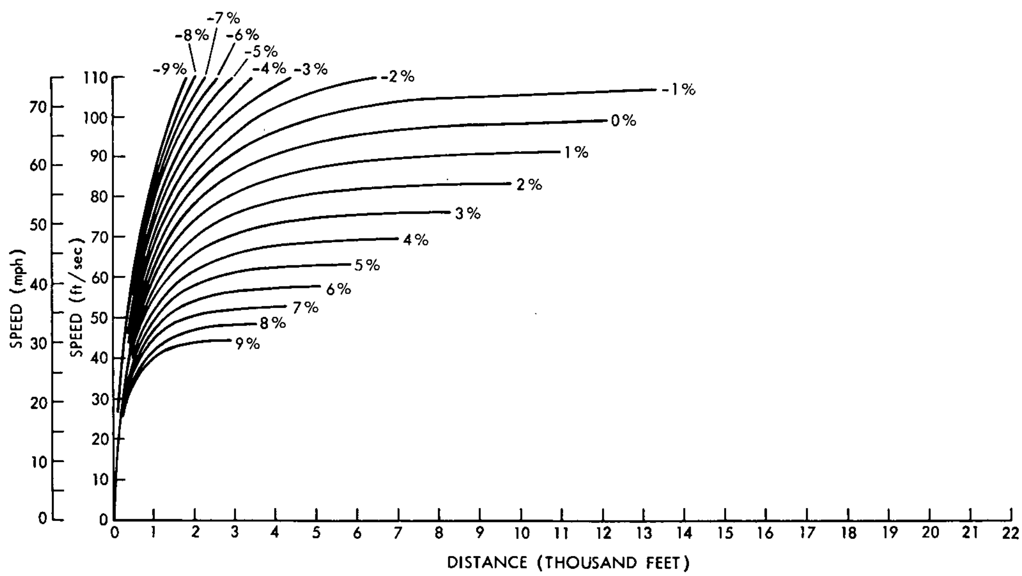

Figure E-9. Speed vs. distance in acceleration, 100 lb/NHP, 180 lb/ft².

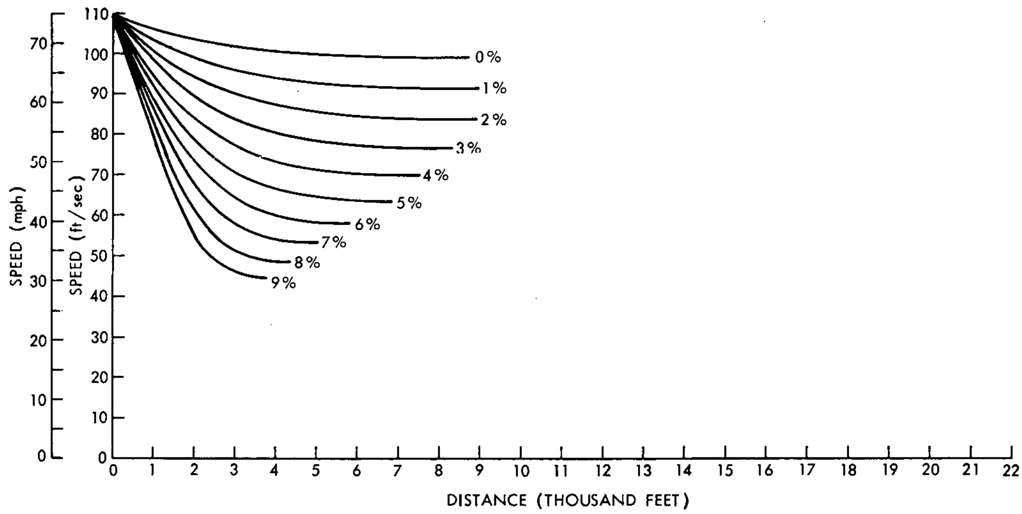

Figure E-10. Speed vs. distance in deceleration, 100 lb/NHP, 180 lb/ft².

APPENDIX F

PASSING BEHAVIOR AND TRAFFIC DATA COLLECTED BY THE SYSTEM DEVELOPMENT CORPORATION

INTRODUCTION

Under a subcontract, the System Development Corporation located data-collection sites, collected and reduced traffic data, and performed preliminary data sorting and analysis. The subcontract work is reported in Ref. (*42*).

Two types of data were sought on highway sections with significant grades. The first was the distribution of over-all speeds through the section. Second, additional details of passing behavior were sought to supplement the information in the literature. In particular, data were needed to determine if the acceptance of passing opportunities depends on the local grade, the vehicle types involved, and the positions of the vehicles in a platoon. Sites were sought where the detailed passing behavior could be obtained within the section used for over-all speed measurements. The detailed passing data would then be obtained in a well-defined traffic environment.

DATA-COLLECTION SITES

Sections were sought with the following attributes:

1. Three or more miles of two-lane highway with significant grades.
2. Passing zone(s) with considerable lengths of no-passing zones adjacent.
3. Essentially uniform design speed and cross section, including adjacent highway sections.
4. Absence of major intersections or roadside developments.
5. Flow rates which, in conjunction with the geometrics, would motivate frequent passing attempts.
6. Vehicle populations containing significant fractions of trucks and recreational vehicles.
7. Vantage point(s) near passing zones from which data could be recorded photographically.
8. Tree cover insufficient to block data collection by aerial photography.

Data were collected on California Route 27, Topanga Canyon Boulevard (one passing zone) and on California Route 152 near Pacheco Pass (two passing zones).

At the Topanga site, the 1,000-ft passing zone was near the top of a 5-percent grade extending for 1 mi with no reasonable passing regions. The road contained numerous curves with radii from 130 to 200 ft. The asphaltic pavement had 12-ft lanes and partly paved, variable-width shoulders. The road is rural, but is near an urban area and probably does not carry long distance traffic.

The test section west of Pacheco Pass was 2½ mi long and contained three passing zones. Data were collected at two of the zones, which were 1,200 and 2,000 ft long. The road had a slight over-all grade of 0.4 percent up to the east with several short grades from −2.4 to 3.0 percent, which were 1,000 to 1,700 ft long.

The two instrumented passing zones had saddle shaped vertical alignment and horizontal curves at each end of both zones. The horizontal curves in the test section had radii from 1,200 ft to 2,500 ft. The small radius horizontal curves appeared to limit the speeds of most passenger

TABLE F-1

TYPES OF DATA COLLECTED AND REDUCED BY SYSTEM DEVELOPMENT CORPORATION

Test Location	Data Type	Hours Collected and Reduced
Topanga	Overall Speed	5:17
(Site 1)	Pass Maneuvers	10:30[a]
Pacheco	Overall Speed	8:59
2,000 ft zone (Site 2)	Pass Maneuvers	1:56
1,200 ft zone (Site 3)	Pass Maneuvers	3:09

a/ Only part of these pass maneuver data were reduced.

vehicles. (This judgment was based on a two-way tour of the section and observation of traffic for about 1 hr.) East of the test section, a steep grade (about 5 percent) required west-bound trucks to use downgrade crawl speeds. West of the test section, the vertical and horizontal alignment was similar to that in the test section. The pavement was asphaltic with 12-ft lanes and partly paved, variable-width shoulders.

The speed limit was 65 mph, which was the standard in the state at the time of data collection for this highway type.

DATA COLLECTED AND ANALYZED

The data collected and reduced by the subcontractor are given in Table F-1. Aerial photographic data were also taken but not reduced.

The subcontractor reduced the data from projected film images. The locations in the data on passing opportunities and maneuvers were deduced from markers placed along the road in view of the camera. (Markers were located to have minimum visibility to drivers.) The passing opportunity and maneuver data were collected for both directions of travel; the over-all travel speeds were obtained for one direction.

The data were sorted to supply the following:

- Flow rates (two directions).
- Vehicle types (one direction).
- Over-all speed histograms (one direction).
- Platoon sizes (one direction, from over-all speed stations).
- Numbers of passes by individual vehicles (one direction).
- Number of vehicles passing individual impeders (one direction).
- Types of vehicles passing and being passed (one direction, from over-all data).
- Speeds of platoon leaders entering and leaving passing zones (two diretcions).
- Types of vehicles leading platoons at passing zones (two directions).
- Platoon sizes at passing zones (two directions).

The data on the acceptance of passing opportunities were sorted and stratified to identify the effect of leader speed, the effect of passing sight distance, the influence of direction of travel, the influence of the passing zone site, and the influences of vehicle types and positions in the platoon.

The data were sorted into subsets at each site-direction to investigate the influences of vehicle types and positions in the platoon. The pass opportunities in the base subsets had the following attributes:

- Two or more vehicles were in the platoon.
- The potential passer was in platoon position No. 2; i.e., immediately behind the platoon leader.
- The potential passer was a normal size passenger car, pickup, or Jeep.
- The platoon leader was one of the previous vehicle types.
- Opportunity to pass begins as a result of entering the zone, clearing an opposing vehicle, or clearing another passer.

Other subsets had the attributes:

- Potential passer was in a platoon position greater than two.
- Potential passer was a van or camper.
- Potential passer was a bus or truck.
- Potential passer was a motorcycle.
- Lead vehicle was a van or camper.
- Lead vehicle was a truck or trailer combination.

These data were analyzed at Midwest Research Institute; the results and conclusions are discussed in the body of this report.

APPENDIX G

MACROSCOPIC FLOW DIAGRAM AND DESCRIPTION FOR THE SIMULATION

INTRODUCTION

This appendix presents a macroscopic flow diagram and a brief description of the main elements in the simulation. The flow diagram is shown in two parts. Figure G-1 shows the preparatory elements. Figure G-2 presents the elements in the loop used to process individual vehicles and to provide final output. The purposes and contents of the major routines are described in the following sections.

MAJOR SUBROUTINES IN PREPARATORY ELEMENTS

Subroutine ERASE clears arrays that will accumulate counts and data during the simulation for use in calculating final output values.

Subroutine REED reads and prints the input data.

Subroutine PRØCI processes the input data for program use and stores it. This includes the calculation of approach regions, curve speeds, and the insertion of nominal values for road regions not influenced or specified. This routine also calculates the maximum speed for each vehicle type on zero grade. The logic then selects the lesser of the average desired speeds or the performance-limited speed as the speed for the vehicle type on ideal geometry. PRØCI also calculates the table of coefficients that will be used to select the time headways between vehicles entering the simulation, and sets four dummy vehicles just off the ends of the simulation road.

Subroutine ØPUT assembles and prints a summary of the input data specifications and a numerical description of the road geometrics.

Subroutine PRIME places vehicles on the road prior to the beginning of simulation. The placements are made in approximate accord with the specified flow rates, desired speeds, vehicle-performance characteristics, and road geometrics. The logic employed uses subroutine ZERØ (called by PRIME), which integrates each vehicle type along the road in each direction. During the integration, the isolated vehicle has a desired speed equal to the mean value (mean desired speed is based on the "free flow" speeds having known dependence on design speed and/or speed limit in sections without restrictive geometrics); driver preferences on acceleration are observed, and vehicle-performance capabilities are included with the influence of local grades. Speed reductions are made, if necessary, at horizontal curves. Trucks slow in downgrade crawl regions. The density with which a vehicle type appears on a road is proportional to its flow rate and inversely proportional to its speed. This relationship is used to place the initial vehicles on the road in PRIME, using speed calculated by ZERØ. The over-all speed for each isolated type-direction is also obtained and is retained as the zero-traffic speed. (The zero traffic speed for a vehicle type is similar to the mean desired (free flow) speed except that the speed suppression associated with sharp horizontal curves and grades is also included (see Chapter Two).)

It should be noted that the priming employed will place too few, high-performance vehicles initially on the road. (The priming does not account for speed reductions due to traffic.) The vehicles constrained by performance limitations will be primed at about the correct rate.

Subroutine VGEN uses a stochastic process to select the time headway between successive vehicles entering the simulation road in a direction of travel. The routine is used in the preparatory processing to select the times of entry for the first vehicles entering in each direction. VGEN also determines the type of the vehicle that is to enter. Note that the same random number is used to select the time headway and the type of vehicle. The correlation is imposed so that vehicles with low type indices enter with large headways in front of them. These vehicles are the low-performance types. The correlation tends to perpetuate the entering platoons.

The program is designed to accept a zero flow rate in the number two direction. The test on SFLØ(2) is a part of the associated logic. If TNTRY(2) is set equal to 10^6, there will be no atempt to enter a vehicle in the number two direction until one million seconds (277.7 hr) of simulation time have been calculated. No vehicles will be primed in the number two direction with SFLØ(2) = 0.

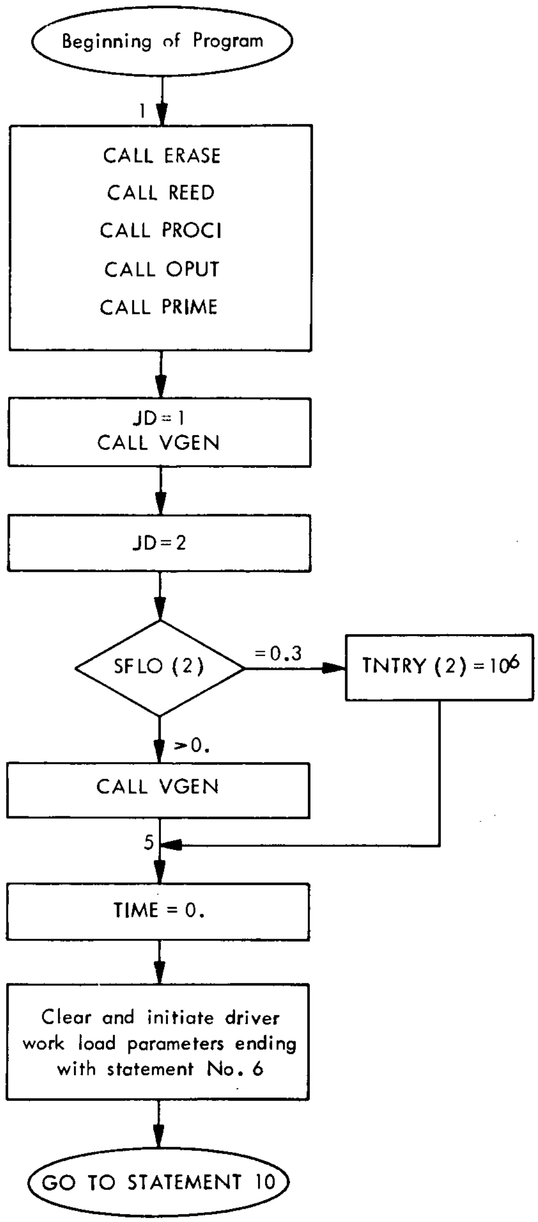

Figure G-1. Simulation preparatory logic.

MAJOR SUBROUTINES IN SIMULATION PROCESSING

The diagram in Figure G-2 is arranged to display the processing of a simulation vehicle and the generation of output. The initial entry to this loop from the preparatory logic is made at statement No. 10, which is near the end of the loop (lower right side of figure).

It is convenient to think of processing a simulation vehicle beginning at statement No. 21. Prior to this step, a small table has been prepared of the three vehicles immediately in front and the two immediately behind the vehicle to be processed. Also, several subscripted variables for the vehicle in process have been placed in unsubscripted form for efficient computing. IP is the subscript for the vehicle in process and KSIP is the state of the vehicle at the beginning of the review period. The test on KSIP is

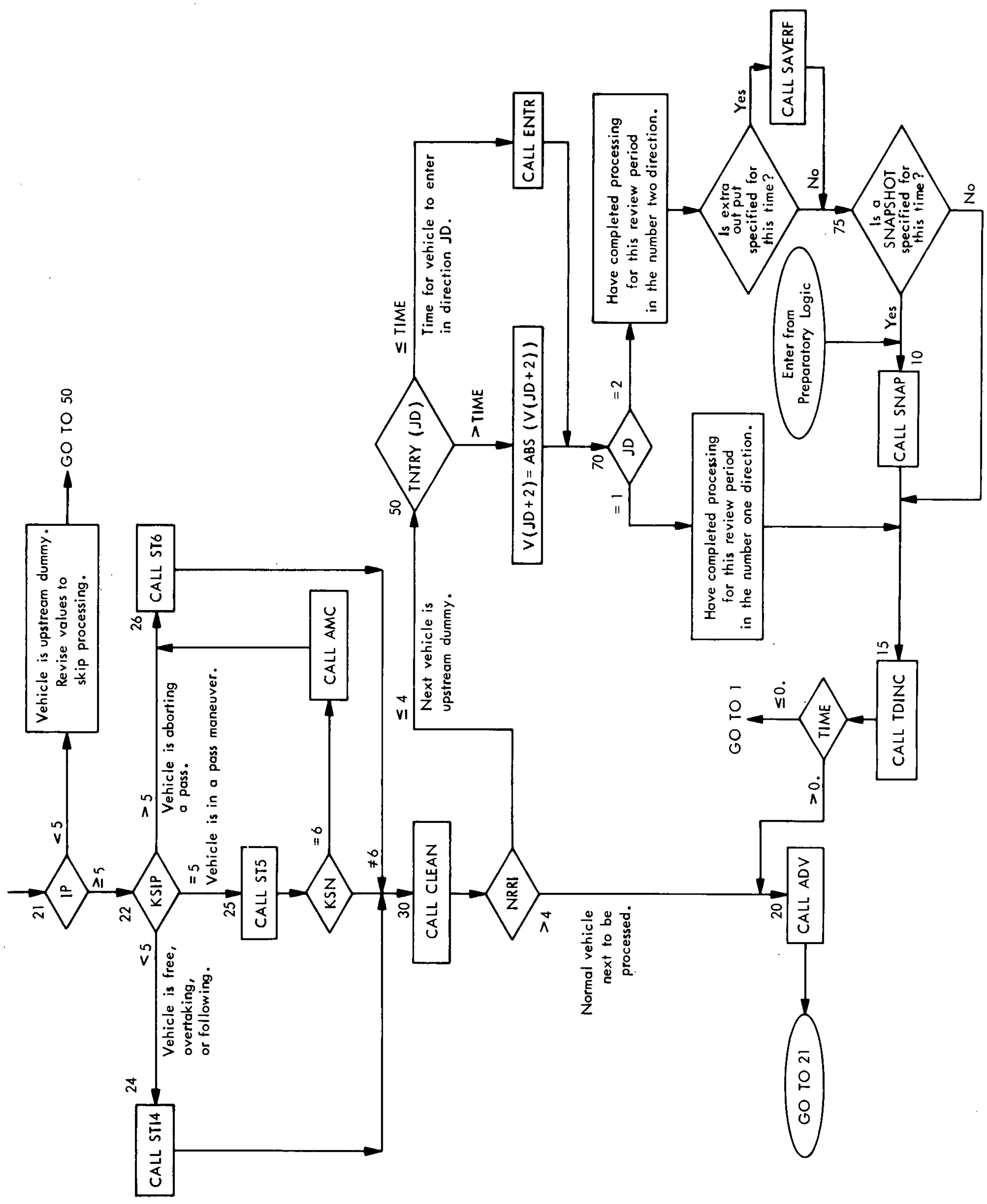

Figure G-2. Simulation processing loop.

used to direct processing to one of three major routines described as follows.

Subroutine ST14 processes vehicles in states 1 through 4. The states are: (1) unimpeded, (2) overtaking an impeder, (3) following an impeder, or (4) following an impeder closely. After ST14 locates the immediate leader in the normal lane, a call to subroutine SPD is used to determine the new speed at the end of the review interval. For unimpeded vehicles, the leader may not be an influence due to a large gap or sight distance limits. Otherwise, the new speed is based on the most restrictive constraint due to leader influence, desired speed (normal), desired speed altered by horizontal curvature or crawl zone, performance limit on local grade, driver preference on acceleration bounds, or constraint on acceleration if being passed. SPD also determines changes in state between 1, 2, 3, and 4.

Subroutine ST14 continues with tests on passing for vehicles in states 2, 3, or 4. The main elements are:

1. Motivation to consider a pass dependent on:
   a. Occupancy of passing zone at end of review period.
   b. A threshold of performance ability.
   c. Entry into passing zone in this review period.
   d. Clear oncoming vehicle during this review period.
   e. Still overtaking impeder (in state No. 2).
   f. Pass a stochastic test to reconsider an ongoing passing opportunity.
   g. Impeder projected to require more than 5 sec to reach end of passing zone.
   h. Next oncoming vehicle not a follower in a platoon.
2. Motivation to consider a pass dependent on absence of blocks to passing, including:
   a. A passer to the rear, which will overtake vehicle in process within 5 sec.
   b. A passer is beside vehicle in process or concluding a pass in front of vehicle in process.
   c. A pass abort is in progress in front of, beside, or behind the vehicle in process.
   d. Two other vehicles are currently passing impeder which would be passed by vehicle in process.
   e. Truck is currently passing impeder which would be passed by vehicle in process.
   f. There is a lack of suitable return gaps in front of immediate impeder and second impeder ahead.
   g. Another vehicle is passing the impeder in a maneuver that has a safety margin of 6 sec or less.
   h. The distance to the impeding vehicle is greater than 350 ft.

If the vehicle in process is not motivated to consider a pass or is blocked from passing, the processing in ST14 is completed. Otherwise, the logic continues with tests and calculations to reach a decision on initiating a pass. The main elements are:

1. Type of constraint on pass:
   a. Oncoming vehicle in sight.
   b. End of pass zone in sight.
   c. Sight distance limitation.
2. Factors influencing acceptance probability:
   a. Position in platoon.
   b. Negotiating or approaching curvature to the right.
3. The stochastic decision on acceptance:
   a. Employs foregoing factors.
   b. Is dependent on leader speed.
   c. Is dependent on passing opportunity distance (oncomer in sight) or sight distance.

If a decision to pass is reached, subroutine ST14 continues with calculations and decisions designed to provide input for the pass maneuver and to reduce absurd pass attempts that would arise primarily from performance limitations. The main calculations and decisions are as follows:

1. Calculations:
   a. A preferred upper bound on the speed in the pass is based on normal desired speed and local restraints due to horizontal curves; or, crawl regions for trucks.
   b. Estimated time required to pass is based on gain required to clear impeding vehicle; nominal acceleration that may be used by vehicles being passed; initial speed differences; passing accelerations due to preference associated with upper bound on speed, or performance limitations on local grade; and a 2-sec period for vacating the opposing lane.
   c. Estimated passing time available is based on closure rate and distance to constraining feature (oncomer, end of pass zone, or sight distance limit), and passer lead distance at end of pass.
3. Decisions:
   a. Pass is declined if estimated time-to-pass equals or exceeds 52 sec for a truck, or 30 sec for other vehicles.
   b. Pass is declined if estimated time margin (passing-time-available minus time-to-pass) is less than 2 sec when the oncoming vehicle is not in sight. Pass is declined when margin is less than 3 sec with oncomer in sight.
   c. If the time margin is small (2 to 4 sec for oncomer not in sight and 3 to 6 sec when oncomer is in sight), the decision to pass is recast using the same random number in conjunction with probabilities appropriate for marginal situations. The decision depends on the constraint on the pass, the availability of unused acceleration capability, and the leader speed.

If the final decision is to pass, the vehicle in process is marked with the new state (No. 5). The pass maneuver actually begins in the next review period.

Subroutine ST5 processes vehicles that are engaged in a passing maneuver. The logic determines if there is a vehicle ahead that is also in the passing lane (opposing direction lane) and may, therefore, influence acceleration and speed of the vehicle in process. Subroutine SPD is then used to calculate speed at the end of the review interval based on:

1. Influence of lead vehicle (if any) in passing lane.
2. Acceleration preference based on the speed upper bound for the pass maneuver.
3. Performance capability on the local grade.

In alternate (even-numbered) review intervals, the projected time margin is recalculated. The calculation includes the effects of the new field of view. (The end of the passing zone or an oncoming vehicle may have come into view.)

The results are used in the logic controlling decisions to abort or continue the pass. The decision to abort the pass is reached under the following conditions:

1. The passer is not yet committed to pass and time margin becomes less than zero without oncoming vehicle in sight. (If the passer is committed to pass when the time falls below the listed value, the restraints on acceleration and maximum speed are removed. However, the passer may still be limited by performance or by a leader in the passing lane.)
2. The passer is not yet committed to pass, and the time margin becomes less than 2 sec with an oncoming vehicle in sight. (If the passer is committed to pass when the time margin falls below the listed value, the restraints on acceleration and maximum speed are removed. However, the passer may still be limited by performance or by a leader in the passing lane.)
3. A leader in the passing lane is aborting a pass around the same impeder.
4. The pass is failing; i.e., because of preference limits, performance limits, or leader interference, the passer is not gaining on the impeding vehicle.
5. The time to pass increases to 52 sec or more for passers that are trucks or 30 sec or more for other vehicle types.

Subroutine ST5 also recalculates the stage of the pass at the end of the review period. The stages are:

1. Not yet committed to pass.
2. Committed to pass but not yet drawing ahead of the impeder.
3. Drawing ahead of impeder but not yet clear of impeder.
4. Just clear of impeder and making a decision about passing the next vehicle in the normal lane.
5. Just clear of impeder and beginning an exit from the passing lane that will require two review periods.
6. Exiting from passing lane with one more review period to completion.

Subroutine ST5 processes vehicles in stage 4 when a decision is made to extend or conclude the pass maneuver. Extension requires that the next impeder be within 200 ft, that the initial speed difference ensure a short time to pass, that another passer will not provide a serious delay, and that the return gap is adequate after any passer ahead is accommodated. The final decision to extend the pass is based on a stochastic test with probability dependent on projected time margin and new impeder speed.

In stages Nos. 5 and 6, the passer vehicle responds to a leader in the normal lane rather than in the passing lane.

If the decision is reached in ST5 to abort a pass, the processing is transferred to subroutine AMC, which stands for abort maneuver calculation. The logic in AMC calculates three items: the time, if any, before the vehicle in process can start to vacate the passing lane; the position relative to the impeder where the lane change will begin; and, last, the speed of the aborting vehicle when the lane change will begin. The calculations employ the initial positions and speeds of the aborting vehicle and the impeder that was being passed. Large decelerations (18 ft/sec^2) are projected for the maneuver if required to establish a negative speed relative to the impeder. The vehicle is then processed by subroutine ST6 for the same review period in which the abort decision was made.

Subroutine ST6 processes vehicles in state No. 6; i.e., vehicles aborting a pass. This is the only maneuver not subject to revisions as the simulation time advances. Instead, the aborting vehicle is held in the calculated position relative to the impeder where it will begin the lane change. It is so retained in the passing lane until the calculated time has elapsed. During the subsequent lane change the aborter vehicle responds to the impeder as a leader and also responds to road geometrics.

Subroutine CLEAN is employed on the vehicle in process after exit from one of the main processing routines described earlier. CLEAN does some bookkeeping and calls other routines to store data generated and to remove vehicles that have left the simulation road length. CLEAN revises pointers in accord with passes and aborts and assigns and recovers the extra subscripted variables required by vehicles in states Nos. 5 and 6. CLEAN also begins the preparations for processing the next simulation vehicle.

If a normal vehicle (not a dummy) is to be processed next, subroutine ADV completes the preparation for processing and the main loop is entered at statement No. 21 in Figure G-2.

If the next vehicle is a dummy, it is not processed, but the subroutine simply indicates that processing is complete in the direction JD of travel for the current review period.

If the test on TNTRY(JD) in Figure G-2 indicates that a vehicle is scheduled to enter the simulation, the entry is performed by ENTR. ENTR contains logic that reduces spurious transients. If TNTRY(JD) is equal to TIME, it means that the vehicle was scheduled to enter in the current review period. ENTR attempts to enter the vehicle (already selected as to type and desired speed) at midinterval. The initial speed is tried as the lesser of desired speed or entering speed as defined in the input data. If this entry speed would violate leader-follower relations, a lesser speed in accord with leader-follower relations is calculated. If this lesser speed is equal to or greater than the leader speed, it is used and the new vehicle is entered. If the calculated speed is less than the leader speed, the new vehicle is held for the next review period. (The important point is to not enter any vehicle, especially a low-performance vehicle, with a speed lower than it would normally have.)

In the next review interval, TNTRY(JD) will be less than TIME, indicating that the vehicle should have entered in a previous review period. ENTR will attempt to enter the vehicle at the beginning of the review period, and failing that, at midinterval. After the vehicle is entered in the simulation, subroutine ENTR calls VGEN, which selects the time interval until the next vehicle should be entered. The next entry time, TNTRY(JD), is obtained by adding the selected time interval to the time when the previous vehicle was designated to enter.

When JD = 2 in the test at statement No. 70, it means that both directions of flow have been processed and simulation for the review interval is complete. Tests are then made for two types of output specified by the input data.

The first test determines if the collected data are to be summarized at the current simulation time. If so, subroutine SAVERF is called. This routine writes all the current data values into an intermediate file for later recall and processing. The second test determines if the current status of the simulation flows is specified to be printed at this simulation time. If so, the organization of data and printing is done by subroutine SNAP. This provides a snapshot of the current status of every vehicle in the simulation.

Subroutine TDINC increments direction of processing and, when JD has been equal to 2, simulation time is incremented. TDINC sets up the tables and values required for processing vehicles in the next direction. It also tests for completion of the specified simulation time. If the specified time has been reached, TDINC calls FPUT, which processes the collected data and prints summaries for the entire simulation test time. As a control the value of TIME is then set to zero, so that the next test will transfer to statement No. 1. This transfer is made to process data that may have been stored by SAVERF. The stored data are processed and printed by calls to FPUT after the intermediate file has been read.

APPENDIX H

SUMMARY OF TABLES AND EQUATIONS USED IN THE SIMULATION

TIME HEADWAYS OF ENTERING VEHICLES

The entering time headways are based on Schuhl's distribution where the probability that a headway is less than or equal to t is given by

$$P(h \leq t) = 1 - \gamma e^{-(t-\epsilon)/t_1} - (1-\gamma) e^{-t/t_2} \quad \text{(H-1)}$$

The parameters γ, ϵ, t_1, and t_2 were initially assigned values from Ref. (*38*). Subsequently, the parameter t_2 was revised to satisfy the specified flow rate. The parameters used are:

$$\gamma = 0.115\, v$$
$$\epsilon = 1.0$$
$$t_1 = 2.5$$
$$t_2 = \frac{36}{v} + 2.03615 - 0.45906\, v/(1 - 0.115\, v)$$

where v is lane flow rate (100 veh/hr) and time t is in seconds. This form is suitable for $v \leq 7.5$ 100 veh/hr. At higher specified flow rates, a simple exponential distribution is used. In the simulation, a table of $1 - P(h \leq t)$ is calculated and used with a random number to assign entering headways.

Ref. (*39*) presents values for the Schuhl parameters based on measurements made in rolling terrain.

GRADES

The local grade at position x in the simulation is obtained with

$$\alpha = \alpha_0 + \alpha_1(x - x_{\alpha 0}) \quad \text{(H-2)}$$

where:

α_0 = percent grade at $x_{\alpha 0}$;
α_1 = rate of change of grade, %/ft; and
x = position, i.e., distance along simulated highway measured in direction of travel for which grade (sign) applies.

The parameters α_0 and α_1 vary from grade region to region. Also, with $\alpha_1 \neq 0$, the normal parabolic sag ($\alpha_1 > 0$) and crest ($\alpha_1 < 0$) vertical curves are accurately represented.

PASSING SIGHT DISTANCES

The passing sight distance at x, within a sight distance region, is obtained with

$$s = s_0 + s_1(x - x_{s0}) \quad \text{(H-3)}$$

where:

s_0 = passing sight distance at $x = x_{s0}$, ft;
s_1 = rate of change of sight distance with position, ft/ft; and
x = position, i.e., distance along simulated highway measured in direction of travel for subject sight distance.

If the foregoing value is less than specified minimum sight distance, the specified minimum is used.

NORMAL DESIRED SPEEDS

Each vehicle is assigned a desired speed selected stochastically from a truncated normal distribution. The mean desired speed and the standard deviation of desired speeds are part of the mandatory input data.

The individual assignments are made by linear interpolation in Table H-1 with a generated random number.

If the random number is <0.001349898 or is >0.998650102, another random number is generated and used. If specified in the input data, a bias value (ft/sec) will be added algebraically to the desired speed according to the vehicle category.

DESIRED SPEEDS IN HORIZONTAL CURVES

The distributions of desired speeds in horizontal curves depend on the curve geometrics. The relations used are

TABLE H-1

DESIRED SPEED VS. RANDOM NUMBER

Random Number	Speed (Standard Deviations from the Mean)
0.001349898	- 3.0
0.006209665	- 2.5
0.022750132	- 2.0
0.066807201	- 1.5
0.158655254	- 1.0
0.308537539	- 0.5
0.500000000	0
0.691462461	0.5
0.841344746	1.0
0.933192799	1.5
0.977249868	2.0
0.993790335	2.5
0.998650102	3.0

based on an analysis of speed measurements and lateral accelerations reported in the literature (*40, 41*). In horizontal curves obviously influencing speeds, the distribution of speeds is essentially normal in the accumulative range 1 percent to 99 percent. The calculated distribution for a specific curve in the simulation is based on a maximum speed and a minimum speed for the curve. Both the maximum and minimum, U_{max} and U_{min}, are based on the lateral acceleration. The equation for both U_{max} and U_{min} (ft/sec) is

$$U = -\frac{184321\ a_1}{2d + 1.6} + \left[\left(\frac{184321\ a_1}{2d + 1.6}\right)^2 + \frac{184321\ (a_0 + e)}{d + 0.8}\right]^{1/2} \tag{H-4}$$

where:

U = speed which vehicle would employ in horizontal curve due to constraints imposed by the curve, ft/sec;
d = curvature, deg/100 ft;
e = superelevation, ft/ft; and
a_0, a_1 = coefficients for U_{max} and U_{min}, which depend on the speed range as given in Tables H-2 and H-3.

In the solution for U_{max}, the coefficients for the lowest speed range (0 to 100 ft/sec) are used first. If the calculated U_{max} exceeds the range, 100 ft/sec, the next higher range is tried, etc. The same procedure is used in the separate solution for U_{min}. In either case, a calculated value falling within the range is the solution, and the associated traction demand coefficient is equal to $a_0 - a_1 U$.

The values in Tables H-2 and H-3 are a part of the simulation computer program. Experience to date with the simulation indicates that Table H-2 should be revised. Table H-4 gives suggested values. The values in Table H-4 represent dry pavement conditions. On wet pavement, drivers must make smaller traction demands at speeds below 75 ft/sec to avoid frequent skids.

In the simulation, an individual vehicle in a curve has a curve desired speed proportional to its normal desired speed. The normal desired speed is the algebraic sum of a mean speed, V_{dm}, and a deviation from the mean.

TABLE H-2

COEFFICIENTS a_0 AND a_1 FOR U_{max}

Speed Range (ft/sec)	a_o	a_1
0 - 100	0.5	0
100 - 135	1.857143	0.013571
> 135	0.025	0

TABLE H-3

COEFFICIENTS a_0 AND a_1 FOR U_{min}

Speed Range (ft/sec)	a_o	a_1
0 - 55	0.29	0.0048182
> 55	0.025	0

TABLE H-4

ALTERNATIVE VALUES OF a_0 AND a_1 FOR U_{max}

Speed Range (ft/sec)	a_o	a_1
0 - 60	0.75	0
60 - 95	1.99284	0.020714
> 95	0.025	0

$$V_d = V_{dm} + f \cdot \sigma$$

where the deviation $f\sigma$ is a part of the total range of six standard deviations. In the curve the same vehicle has a curve-limited desired speed V_{dc} given by

$$V_c = V_{cm} + f\ \sigma_c \tag{H-5}$$

where $V_{cm} = (U_{max} + U_{min})/2$, and $\sigma_c = (U_{max} - U_{min})/6$. The curve desired speed is applied only if it is smaller than the normal desired value.

DESIRED SPEEDS IN APPROACHES TO CURVES AND CRAWL REGIONS

A transition region is supplied for approaches to horizontal curves and downgrade crawl zones. (Only trucks and designated recreational vehicles respond to downgrade crawl restraints.) The transition supplies a nearly constant deceleration from the normal desired speed to the curve or crawl desired speed. The calculated approach speed is the mean; the standard deviation used in approach is the value for the curve or crawl region. The approach region starts upstream a distance z_0 given by

$$z_0 = (V^2_{dm} - V^2_{cm})/(2\,A_a) \qquad \text{(H-6)}$$

where:

V_{dm} = mean of normally desired speeds, ft/sec;
V_{cm} = mean of desired speeds in curve or crawl region, ft/sec; and
A_a = average deceleration in approach (a positive quantity; the value 3.5 is used in the computer program), ft/sec^2.

The mean desired speed in the approach region is given by

$$V_{am} = V_{dm}\,[(1 - c_1 x_0 + c_2 x_0^2) + (c_1 - 2c_2 x_0)x + c_2 x^2] \quad x_0 \leq x \leq x_c \qquad \text{(H-7)}$$

where:

x_0 = position where approach region begins = $x_c - z_0$;
x_c = position where actual curve or crawl region begins;
$c_1 = -A_a/V^2_{dm}$; and
$$c_2 = -2\left[\left(\frac{V_{cm}}{V_{dm}} - 1\right)\frac{A_a}{(V^2_{dm} - V^2_{cm})}\right]^2$$

The coefficients $(1 - c_1x_0 + c_2x_0^2)$, etc., are calculated once in initial proecssing and retained for use by each simulation vehicle.

UPPER BOUND ON SPEED IN PASS MANEUVERS

Vehicles appraising a pass opportunity or conducting a pass maneuver do so with an upper bound on the speed during the maneuver. The upper bound for a vehicle depends on its normal desired speed and on local geometrics that may influence desired speed. The upper bound is the lesser of the values calculated from the following expressions:

$$V_{u1} = 1.167\,V_d + 15 \qquad \text{(H-8)}$$

$$V_{u2} = 1.167\,V_c \qquad \text{(H-9)}$$

where:

V_d = normal desired speed, ft/sec; and
V_c = local desired speed due to curve, crawl region, or an approach to these features, ft/sec.

The upper bound is not only a limit, but may also influence accelerations used. Frequently, the upper bound is not reached during the maneuver. Vehicles that are committed to pass and face an unacceptable safety margin abandon the restraint on maximum speed.

ACCELERATIONS PREFERRED BY DRIVERS

Speed data in Ref. (*12*) indicate that drivers may prefer to use accelerations less than vehicle capability to approach their desired speeds. Analysis of the data in Ref. (*12*) leads to the equation:

$$A_p = 1.2 + 0.108\,(V_d - V),\ (V_d - V) > 0 \qquad \text{(H-10)}$$

where:

A_p = preferred acceleration, ft/sec^2;
V_d = desired speed, ft/sec; and
V = current speed, ft/sec.

In a pass maneuver, V_d is replaced by the upper speed bound for the maneuver. At the conclusion of a pass maneuver, if the speed is higher than the desired value, decelerations of 1.2 ft/sec^2 are used. If the vehicle's desired speed is set by a horizontal curve or crawl region, decelerations up to 4 ft/sec^2 are employed.

LEADER-FOLLOWER INTERACTION

The speed of a vehicle following or overtaking a leader may be dictated by the leader-follower interaction. The speed for the end of the review interval is based on conditions at the beginning of the interval. The equation is

$$V_{nl} = \left(\frac{\alpha_1 + \alpha_2\,G}{\alpha_3 + \alpha_4\,G}\right)V_l + \frac{\alpha_5 + \alpha_6\,G}{\alpha_7 + \alpha_8\,G} \qquad \text{(H-11)}$$

where:

V_{nl} = new speed for vehicle in process based on interaction with leader, ft/sec;
V_l = leader speed, ft/sec;
G = gap between front of vehicle in process and rear of leader, ft (in the simulation, the leader has been processed; so the position of the leader for this calculation is adjusted by subtracting the leader's speed times the length of the review period);
$\alpha_1 = 0.775$; $\alpha_2 = -0.000656$; $\alpha_3 = 1.0$; $\alpha_4 = 0.00236$; $\alpha_5 = -1.31$; $\alpha_6 = 0.3077$; $\alpha_7 = 1.0$; and $\alpha_8 = 0.0013$.

For close following, the sign of α_2 is reversed. The criteria to enter close following (state 4) are:

1. Speed of the follower is not more than 8 ft/sec greater than leader speed.
2. Desired speed of follower is more than 10 ft/sec greater than current speed of leader.
3. (Follower acceleration capability) + (speed advantage)/25 $\geq$ 1.0 ft/sec^2 for trucks and $\geq$ 2.0 for passenger cars and recreational vehicles.

Vehicles in close following (state 4) remain in that state until they pass or until, because of performance limits or desired speeds, they drop back further than calculated for normal following. When the calculated value of V_{nl} is smaller than $V_l - 3$, the value, $V_l - 3$, is used—except V_{nl} is never less than zero.

VEHICLE ACCELERATION PERFORMANCE

Each passenger car and recreational vehicle type has an acceleration capability that is a function of speed and local grade.

$$A = P_0 - P_1 V - 32.17(\alpha/100) \qquad \text{(H-12)}$$

where:

P_0 = maximum acceleration at zero speed, ft/sec^2;
$P_1 = P_0$/(maximum speed on zero grade);
V = current speed; and
α = local grade in percent.

For passing and accelerating toward desired speeds, the values P_0 and P_1 are based on full available horsepower. If specified in input, values based on partial horsepower are employed in other situations. The value with partial horsepower has the same form

$$a = p_0 - p_1 V - 32.17(\alpha/100) \qquad \text{(H-13)}$$

With seven-tenths of full horsepower,

$$p_0 = 0.73\, P_0$$

V_{max} on zero grade = 0.9 of the full-power value

thus,

$$p_1 = \frac{0.73}{0.9} P_1$$

When a passenger car or recreational vehicle accelerates toward its desired speed, the performance limit on acceleration is calculated as A from Eq. H-12. The value of A is used as the performance limit, providing acceleration, a, from Eq. H-13 is greater than zero. When acceleration, a, from Eq. H-13 becomes less than or equal to zero, it is used as the limiting value. This procedure permits accelerating passenger cars and recreational vehicles not otherwise constrained to use maximum available horsepower, but not for extended time periods.

The acceleration capability of trucks is calculated with

$$A_e = \left[\frac{0.4\,V}{0.4\,V + 1.5\,S_p(\bar{A}_p - \bar{A}_c)}\right] \bar{A}_p,\ V \geq 10 \text{ ft/sec} \qquad \text{(H-14)}$$

$$A_e = \left[\frac{10}{10 + 1.5\,S_p(\bar{A}_p - \bar{A}_c)}\right] \bar{A}_p,\ V < 10 \text{ ft/sec} \qquad \text{(H-15)}$$

where:

TABLE H-5

VALUES OF P_{44} (D) AND S_0 (D)

D(feet)	P44(D)	S_o(D) $V_\ell > 44$	$V_\ell \leq 44$
100	- 0.065	- 0.004500	- 0.005591
200	- 0.052	↓	↓
300	- 0.	↓	↓
400	- 0.	↓	↓
500	- 0.	↓	↓
600	0.00	- 0.004500	- 0.00591
700	0.0133	↓	↓
800	0.0265	↓	↓
900	0.0398	↓	↓
1000	0.0530	- 0.004500	- 0.005591
1100	0.0731	- 0.004142	- 0.007773
1200	0.0933	- 0.003784	- 0.009955
1300	0.1134	- 0.003426	- 0.012136
1400	0.1335	- 0.003068	- 0.014318
1500	0.1716	- 0.003324	- 0.019432
1600	0.2098	- 0.003580	- 0.024546
1700	0.2479	- 0.003835	- 0.029659
1800	0.2860	- 0.004441	- 0.034773
1900	0.3596	- 0.005727	- 0.030938
2000	0.4333	- 0.007364	- 0.027103
2100	0.5069	- 0.009000	- 0.023267
2200	0.5805	- 0.010306	- 0.019432
2300	0.6250	- 0.010875	- 0.016398
2400	0.6695	- 0.011114	- 0.013364
2500	0.7140	- 0.011352	- 0.010329
2600	0.7585	- 0.011591	- 0.007295
2700	0.7781	- 0.010909	- 0.006869
2800	0.7977	- 0.010228	- 0.006443
2900	0.8173	- 0.009546	- 0.006017
3000	0.8369	- 0.008864	- 0.005591
3100	0.8433	- 0.008455	↓
3200	0.8496	- 0.008045	↓
3300	0.8560	- 0.007636	↓
3400	0.8623	- 0.007227	- 0.005591
3500	0.8691	- 0.007074	↓
3600	0.8761	- 0.006921	↓
3700	0.8829	- 0.006767	↓
3800	0.8898	- 0.006614	- 0.005591

V = vehicle speed, ft/sec;

S_p = one times the sign of $\bar{A}_p$ (which can be either + or −);

A_e = effective acceleration, including a correction for gear shift delays of 1.5 sec, ft/sec²;

$$\bar{A}_p = \left[\frac{15145\, C_{pe}}{(W/\text{NHP})V} - 0.2445 - 0.00044\, V - \frac{0.0228}{(W/A_f)} V^2 C_{de} - 32.17\,\alpha\right] \Bigg/ \left[1 + \frac{14080}{(W/\text{NHP})V^2}\right] \qquad \text{(H-16)}$$

$$\bar{A}_c = \frac{-222.9}{(W/\text{NHP})V} - 0.2445 - 0.00044\, V - \frac{0.0228}{(W/A_f)} V^2 C_{de} - 32.17\,\alpha \qquad \text{(H-17)}$$

and

C_{pe} = altitude correction factor for net horsepower;

W = gross weight, lb;

NHP = net horsepower;

C_{de} = altitude correction factor for aerodynamic drag;

A_f = projected frontal area, ft²; and

α = percent grade/100.

PROBABILITIES FOR PASS OPPORTUNITY ACCEPTANCE

With an oncoming vehicle in sight, the fraction of opportunities accepted is given by:

$$P_0 = [P_{44}(D)] + (V_l - 44)[S_0(D)] \qquad \text{(H-18)}$$

where:

$P_{44}(D)$ = fraction of acceptances when leader speed is 44 ft/sec and the passing opportunity distance is D, ft;

V_l = leader speed; and

$S_0(D)$ = rate of change of acceptance with leader speed; values of $S_0(D)$ are distinct for leader speeds greater than 44 and less than 44 ft/sec.

Table H-5 gives the values of $P_{44}(D)$ and $S_0(D)$.

When an oncoming vehicle is not in sight, the fraction of pass opportunities accepted depends on leader speed and passing sight distance. The equation is:

$$P_s = [P_{41}(D_s)] + (V_l - 41)[S_s(D_s)] \cdot F_s(D_s) \qquad \text{(H-19)}$$

where:

$P_{41}(D_s)$ = fraction of opportunities accepted when leader speed is 41 ft/sec and passing sight distance is D_s, ft;

V_l = leader speed, ft/sec;

$S_s(D_s)$ = rate of change of acceptance with leader speed at sight distance D_s; values of $S_s(D_s)$ are distinct for leader speeds greater than 41 and less than 41 ft/sec; and

$F_s(D_s)$ = factor to account for the enhanced probability of acceptance in the first 400 ft of a passing zone; for leader speeds less than 41 ft/sec, the value of $F_s(D_s)$ is always 1.0.

Table H-6 gives the values of $P_{41}(D_s)$, $S_s(D_s)$, and $F_s(D_s)$.
In the simulation, the value of D or D_s is rounded to the nearest 100 ft and the appropriate equation is used with the tabular values.

FACTORS FOR PASS ACCEPTANCE PROBABILITIES

Table H-7 gives the factors employed on the basis of information in the literature and on the basis of the analysis of data collected in this project.

PASSING TIME AVAILABLE

The passing time available is calculated with either a linear or quadratic equation. The linear equation is

$$T_a = D/V_c \qquad \text{(H-20)}$$

D = a distance—passer's length—50 + 0.2 V_l, and the distance is measured from front of the impeder to front of oncoming vehicle if it is in sight; or, failing that, to end of pass zone if in sight; or, failing that, to limit of passing sight distance, ft;
V_l = impeding leader speed, ft/sec; and
V_c = initial closure speed (this is the sum of impeder and oncomer speeds if oncomer is in sight; otherwise, V_c is the speed of the impeding leader).

The linear form is used if the anticipated acceleration of the impeder is zero or negative. The quadratic form is used if the anticipated acceleration of the impeder, A_i, is greater than zero. Time available, T_a, is the smallest positive solution of the following equation.

$$T_a^2 + \frac{2V_c}{A_i} T_a - \frac{2D}{A_i} = 0 \qquad \text{(H-21)}$$

TIME REQUIRED TO PASS

The time required to pass is calculated as an estimate. The expressions were derived from the analysis of a large number of calculated passing events using a variety of passenger, recreational, and commercial vehicles. The expressions used depend on the type of vehicle passing, the gain required to pass, and the acceleration used by the impeder.
For passenger cars and recreational vehicles, the linear form is

$$T_p = C_p/B_p,\ A_i \leq 0 \qquad \text{(H-22)}$$

where, for G ≤ 25,

$C_p = 17.57418 + (18.6044/\beta) + 4U + 2G$;
$B_p = (9.3022/\beta) + 2U$;
G = gain required, the distance from rear of passer to nose of impeder, ft;
A_i = impeder's acceleration;
$\beta = 0.30 + (1/A_0)$, sec²/ft;
A_0 = initial acceleration set by preference or performance, ft/sec²; and
U = speed advantage, the passer's current speed minus speed of impeder, ft/sec.

If $G > 25$ ft, the forms for β, B_p, and C_p are:

$\beta = 0.125 + (1/A_0) - 0.05/A_0^2$;
$B_p = (19.04/\beta) + 2U$; and

TABLE H-6

VALUES OF P_{41} (D_s), S_s (D_s), AND F_s (D_s)

D_s (feet)	$P_{41}(D_s)$	$S_s(D_s)$ $V_l > 41$	$S_s(D_s)$ $V_l \leq 41$	$F_s(D_s)$ $V_l > 41$
100	- 0.1907	0.	0.0	0.600
200	- 0.1430		- 0.00635	
300	- 0.0953		- 0.01318	
400	- 0.0477	↓	- 0.02068	
500	0.0000	- 0.00000	- 0.02818	↓
600	0.0477	- 0.001735	- 0.03477	0.600
700	0.0953	- 0.003468	- 0.04136	0.602
800	0.1430	- 0.005201	- 0.04757	0.603
900	0.2009	- 0.006934	- 0.05379	0.606
1000	0.2587	- 0.008667	- 0.06000	0.610
1100	0.3166	- 0.010587		0.612
1200	0.3744	- 0.012507		0.617
1300	0.4323	- 0.014427		0.623
1400	0.4901	- 0.016347		0.630
1500	0.5480	- 0.018267		0.636
1600	0.5837			0.642
1700	0.6194			0.653
1800	0.6551			0.666
1900	0.6908	↓		0.680
2000	0.7265	- 0.018267		0.700
2100	0.7622	- 0.017732		0.720
2200	0.7979	- 0.017199		0.743
2300	0.8336	- 0.016667		0.772
2400	0.8693	- 0.016135		0.808
2500	0.9050	- 0.015603		0.850
2600	0.9169	- 0.015452		0.900
2700	0.9288	- 0.015301		0.980
2800	0.9406	- 0.015150		1.000
2900	0.9525	- 0.014997		
3000	0.9644	- 0.014844		
3100	0.9763	- 0.014692		
3200	0.9881	- 0.014540		
3300	1.0000	- 0.014388		
3400		0.013948		
3500		0.013511		
3600		0.013074		
3700	↓	0.012637	↓	↓
3800		- 0.012200	- 0.0600	1.000

TABLE H-7

FACTORS FOR PASS ACCEPTANCE PROBABILITIES

Situation	Factor
One or more other platoon member(s) between the potential passer and the platoon leader	0.52
Potential passer is approaching or in a curve to the right	
No oncoming vehicle is in sight	0.50
Oncoming vehicle is in sight within 5,000 ft	0.00

$C_p = 83.81 + (68.57/\beta) + 4U + 2G$.

The linear form neglects impeder acceleration and is used if the impeder acceleration is less than or equal to zero. If the impeder acceleration, A_i, will be greater than zero, the solution is obtained as the smallest, real, positive solution of a quadratic.

$$T_p^2 - [(B_p/A_i) + 4]\,T_p + [(C_p/A_i) + 4] = 0 \qquad \text{(H-23)}$$

For trucks and buses, the time to clear the impeder is calculated and 2 sec are added to obtain the time to pass. The linear form for the time to clear is:

$$T_c = (G - C_c)/(B_c + U),\ A_i \leq 0 \qquad \text{(H-24)}$$

where, for $G \leq 50$ ft,

$B_c = 1/[0.248(\gamma - 0.4)(|\alpha|/100) + 0.082 + 0.0615\ \gamma]$;
$C_c = -2.9\ \gamma B_c$;
$\gamma = (1/A_0) - 0.05/A_0^2$;
A_0 = initial acceleration to be used by the truck, ft/sec²;
$|\alpha|$ = magnitude of local grade, percent; and
G = gain required to clear (this is the distance from rear of passer to front of impeder), ft.

If $G > 50$ ft, the form for γ is unchanged. The forms for B_c and C_c are:

$$B_c = 1/[0.248(\gamma - 0.4)(|\alpha|/100) + 0.0348 + 0.035\ \gamma]$$
$$C_c = -(2.36 + 5.2\ \gamma)B_c$$

If the impeder acceleration, A_i, will be greater than zero, the time to clear is the smallest, real, positive solution of a quadratic.

$$T_c^2 - 2\ [(B_c + U)/A_i]\ T_c + 2(G - C_c)/A_i = 0 \qquad \text{(H-25)}$$

The speed during a pass maneuver may reach the upper bound set by driver preference and road geometry. A test is made for this possibility, and, if the passer's projected speed is excessive, the estimated pass maneuver is revised to account for the upper bound.

For passenger and recreational vehicles, the time to reach the upper-bound speed is calculated as:

$$T_{uv} = (11\ \Gamma + 1.95\ \Gamma)/(1.04 - \Gamma) \qquad \text{(H-26)}$$

where:

$\Gamma = (V_u - V)/[(p_0 - 0.3217\ \alpha)/p_1 - V]$
V_u = upper-bound speed for maneuver, ft/sec;
V = current speed of passer, ft/sec;
p_0 = maximum acceleration of passer on zero grade, ft/sec²;
p_1 = rate of change of acceleration ability with speed, (ft/sec²)/(ft/sec); and
α = local grade, percent.

The maneuver is recalculated if the time to pass is more than 3 sec longer than the time to reach the upper-bound speed. The gain accomplished by the passenger or recreation vehicle, when the upper-bound speed is reached, is calculated with

$$G_{uv} = [(T_{uv} - 1.6)/(\beta - 4.4)]/0.105 + T_{uv}\ [U - 0.5\ A_i T_{uv}] \qquad \text{(H-27)}$$

For trucks, the time to reach the upper-bound speed is given by

$$T_{uv} = (V_u - V)\{1.0 + (V_u - V)[0.026 + (\alpha/100)(0.2158 + 0.005694\ \alpha)]\}/A_0 \qquad \text{(H-28)}$$

where:

V_u = upper-bound speed for maneuver, ft/sec;
V = current speed of passer, ft/sec;
α = local grade, percent; and
A_0 = initial acceleration used, ft/sec².

The maneuver is recalculated if the time to clear, T_c, is more than 1 sec larger than T_{uv}. In this case, the gain accomplished by the truck, when the upper-bound speed is reached, is calculated with

$$G_{uv} = (B_c + U - 0.5\ A_i T_{uv})T_{uv} + C_c \qquad \text{(H-29)}$$

The remaining calculations for the revised values are similar for all vehicle types. The time to pass is obtained from

$$T_p = T_{uv} + T_b + 2 \qquad \text{(H-30)}$$

where:

T_{uv} = time to reach upper-bound speed, sec;
T_b = time to clear impeder after reaching upper-bound speed, sec; and
2 = time to vacate the opposing lane, sec.

The additional time to clear the impeder, T_b, is linear if the impeder will not be accelerating.

$$T_b = (G - G_{uv})/(V_u - V_{im}),\ (V_u - V_{im}) \neq 0 \qquad \text{(H-31)}$$

where V_{im} = speed of impeder at time $T_{uv} = V_i$ in this case. And, the possibility of passing is abandoned if $(V_u - V_{im}) \leq 0$. If the impeder will be accelerating, the value of T_b is obtained as the smallest, positive, real root of a quadratic.

$$T_b^2 - 2\ [(V_u - V_{im})/A_i]\ T_b + 2(G - G_{uv})/A_i = 0 \qquad \text{(H-32)}$$

where $V_{im} = V_i + A_i T_{uv}$, $A_i > 0$. If there is no real positive solution, the pass is not possible within the speed constraint, and the possibility of passing is abandoned.

INFLUENCE OF DRIVER WORKLOADS

Within the simulation, the desired speeds of vehicles are influenced by two types of driver workloads. They are: (1) the work associated with encountering opposing vehicles; and (2) the work associated with passing maneuvers. The workloads are evaluated separately for the two directions of travel and are updated in running averages each 10 review intervals.

The mean desired speed within the simulation is $\bar{V}_e$, which is continually recalculated as

$$\bar{V}_e = \bar{V}_d(C_{mo} + C_{em1}E + C_{em2}E^2 + C_{pm1}P + C_{pm2}P^2) \qquad \text{(H-33)}$$

where:

$\bar{V}_d$ = input mean desired speed, ft/sec;
E = encounter workload opposing vehicles encountered per sec; and
P = passing workload, the fraction of time spent in pass and abort maneuvers.

If $\bar{V}_e$ is greater than $\bar{V}_d$, it is replaced by $\bar{V}_d$. The values for E and P are obtained for the j and k directions of travel from the ongoing simulation using

$$E_j = Q_k(1 + V_j/V_k)/3600 \qquad \text{(H-34)}$$

and

$$P_j = \frac{(\text{number of passes + aborts})_j/(\text{veh mi})_j}{(\text{travel time for 1 mi})_j} \qquad \text{(H-35)}$$

where:

Q_k = flow rate in k direction, veh/hr;
V_j = average speed in j direction flow, ft/sec; and
V_k = average speed in k direction flow, ft/sec.

A similar form is used for the standard deviation of desired speeds:

$$\sigma_e = \sigma_d(C_{so} + C_{es1}E + C_{es2}E^2 + C_{ps1}P + C_{ps2}P^2) \quad \text{(H-36)}$$

where σ_d = input standard deviation of desired speed, ft/sec.

The coefficient values currently in the simulation are listed in Tables H-8 and H-9. The passing workload coefficients are set to produce slight effects for the flow simulated. The encounter workload coefficients start to produce an effect when the opposing flow causes encounters at a rate greater than 0.15/sec.

The computer program constrains the effective mean desired speed to $\bar{V}_e \geq 47.5$ ft/sec. A similar constraint for the standard deviation insures $\sigma_e \geq 3.5$ ft/sec.

TABLE H-8

COEFFICIENTS IN WORKLOAD EQUATION AFFECTING MEAN DESIRED SPEED

Coefficient	Value
C_{mo}	$1.375 - (15.75 + 0.375\ \sigma_d)\bar{V}_d$
C_{em1}	$-2.5 + (105. + 2.5\ \sigma_d)/\bar{V}_d$
C_{em2}	0
C_{pm1}	0
C_{pm2}	$(1050. - 300\ \sigma_d)/\bar{V}_d$

TABLE H-9

COEFFICIENTS IN WORKLOAD EQUATION AFFECTING STANDARD DEVIATION OF DESIRED SPEED

Coefficient	Value
C_{so}	1.0
C_{es1}	0
C_{es2}	$-2.2039 + 5.5096/\sigma_d$
C_{ps1}	0
C_{ps2}	$-100. + 350/\sigma_d$

APPENDIX I

INSTRUCTIONS FOR USING AND INTERPRETING THE SIMULATION

This appendix presents details of the data elements and formats required to run the simulation. The input requirements are followed by descriptions of the simulation output and its interpretation. A brief, general description of the simulation is also provided prior to giving the data details. The listing of the source program is not included here in the interest of conserving space (program contains about 4,000 statements, which would list on about 65 pages). However, a copy of the source program (card deck) has been submitted to NCHRP together with a sample input deck and output for the sample. (See Foreword for availability of source program.)

GENERAL INFORMATION

The simulation moves vehicles individually in both directions on a length of two-lane, two-way highway. With input data, the user specifies the geometrics of the highway, the performance characteristics of the vehicle types, and the flow rates and vehicle populations in each direction.

Several techniques are used to reduce spurious transients and to account for the characteristics of the highway adjoining the ends of the simulated lengths of highway. The user specifies the time to be simulated as the sum of two values—a warm-up time and a test time. The warm-up time is used to avoid transients that may ensue when the simulation begins. Data are collected and analyzed only during the test time.

The length of highway simulated includes a buffer at each end. The buffer length is specified by the user. Data are collected and analyzed only for the simulated length between the buffers. In the buffers, the road geometrics are specified and the simulation logic is applied just as it is elsewhere.

The user specifies an upper bound on the speed with which each vehicle type can enter the simulated length. Specifications are separate for each direction. This control is used to represent the influence of geometrics in sections adjoining the simulated length. If traffic is entering after an upgrade, the bounds can represent the performance limits. A speed bound may also arise from a sharp horizontal curve or from a steep downgrade on which commercial vehicles crawl. Higher than normal speeds may be specified where traffic enters on or after a moderate downgrade.

Individual vehicles enter the simulation road length based on stochastic tests with a Schuhl time-headway distribution. The logic employed preserves the platoons generated, but without creating spurious entrance transients.

INPUT DATA

The data consist of items that the traffic engineer-investigator is most likely to have. In particular, it is anticipated that the program user will have a unidirectional coordinate system from highway plans or an inventory. The No. 1 direction in the simulation should correspond to the direction of increasing values in the available coordinate system. All input data use the No. 1 direction coordinate value to define positions. Note, however, that the coordinate system in the simulation must be zero at the end of the simulation road where No. 1 direction traffic enters.

Mandatory Deck

The mandatory deck must be present and must be correctly sequenced in the order presented. Individual card formats and contents are described as follows.

Comment Cards (Minimum of Two Required)

Field	1-4	5-76
Format	I4	18 A4
Content	RUN NO.	Alphanumeric note for run identification

For all but the last comment card the field 1-4 must contain a positive integer. On the final comment card the field 1-4 must be empty.

Card No. 1

Field	1	2	3-6	7-10	11-20	21-30	31-40	41-50
Format	I1		I4	I4	F 10.0	F 10.0	F 10.0	F 10.0
Content	1	empty	ISNAP	NSNAP	TWRM	TTES	DELT	TSP

where:

ISNAP = number of seconds between sets of snapshot output;
NSNAP = number of successive snapshot outputs in each set;
TWRM = time simulation is to run before data collection begins, min;
TTES = time simulation is to run while data are collected, min; total time = TWRM + TTES;
DELT = length of review interval, sec; the simulation has been run only with DELT = 1; and
TSP = measure of pass suppressing influence upstream of a curve to the right, sec. The distance equivalent is equal to 2. * TSP * VEAN, where VEAN is the mean desired speed. The value TSP = 5. has been used. The digit, 1, in field one is not read; it is punched to assist in keeping the deck sequenced correctly.

Card No. 2

Field	1	2-10	11-20	21-30	31-40	41-50	51-60
Format	I1		F 10.0	F 10.0	F 10.0	F 10.0	F 10.0
Content	2	empty	RL	XBUF	SMIN	SNØM	PREC

where:

RL = total simulation road length, ft;
XBUF = length of buffers at each end of simulation road, ft; the start and finish lines are set in XBUF from the ends of the RL-long road; over-all measures are made between the start and finish lines; space data are collected only between the start and finish lines;
SMIN = minimum forward sight distance, ft;
SNØM = nominal forward sight distance, ft; and
PREC = probability that simulation driver will reconsider starting a pass during one review period. The value 0.2 has been used with 1-sec review periods. (Driver's are always motivated to consider a pass when they enter a passing zone or when they clear an opposing vehicle.)

Card No. 3

Field	1	2	3-8	9-14	15-20	21-26
Format	I1		F 6.4	F 6.4	F 6.4	F 6.4
Content	3	empty	SFLØ (2)	SFLØ (1)	RE	RP

where:

SFLØ (1) = specified flow rate in No. 1 direction, VPH;
SFLØ (2) = specified flow rate in No. 2 direction, VPH;
RE = control for encounter workload; any negative number will cause logic to *not* apply the encounter workload; empty field will cause logic to use encounter workload; and
RP = control for passing workload, defined similarly to RE.

Card No. 4

Field	1	2	3-80
Format	I1	II	13 F 6.4
Content	4	1	FRC (1, KVT), KVT = 1, 13

where FRC (1, KVT) = specified fraction of flow in No. 1 direction, which is of vehicle type KVT.

Card No. 5

Field	1	2	3-80
Format	I1	I1	13 F 6.4
Content	5	2	FRC (2, KVT), KVT = 1, 13

where FRC (2, KVT) = specified fraction of flow in No. 2 direction, which is of vehicle type KVT.

Card No. 6

Field	1	2	3-8	9-14	15-20	21-26	27-32	33-38
Format	I1		F 6.4	F 6.4	F 6.4	F 6.4	F 6.4	F 6.4
Content	6	empty	VEAN	VSIG	VBI (1)	VBI (2)	VBI (3)	SIGSM
			39-44	45-50	51-56			
			F 6.4	F 6.4	F 6.4			
			SIGBG	FPO	FPI			

where:

VEAN = specified mean desired speed, ft/sec;
VSIG = standard deviation of desired speeds, ft/sec;
VBI (1) = bias to be added algebraically to desired speeds for trucks (KVT = 1-3), ft/sec;
VBI (2) = bias to be added algebraically to desired speeds for recreational vehicles (KVT = 4-10), ft/sec.
VBI (3) = bias for passenger vehicles (KVT = 11-13), ft/sec;
SIGSM = lower limit of desired speed for sample used in operating speed calculation; value is in standard deviations from the unbiased mean;
SIGBG = upper limit of desired speed for sample used to calculate operating speed; value is in standard deviations from the unbiased mean;
FPO = factor to be used on maximum acceleration to account for the horsepower restraint; the value is 0.73 for 7/10 power (see Appendix B for explanation); an empty field will cause the default value 1.0 to be used; and
FPI = factor to be used on maximum, zero-grade speed to account for horsepower restraint. The value is 0.90 for 7/10 power (see Appendix B for explanation). An empty field will cause the default value 1.0 to be used. The fractional power restraint is applied to passenger cars and recreational vehicles.

Card No. 7

Field	1	2	3-80
Format	I1	I1	13 F 6.4
Content	7	1	VENTR (1, KVT), KVT = 1, 13

where VENTR (1, KVT) = an upper bound on the speed with which a vehicle of type KVT can enter the simulation traveling in the No. 1 direction.

Card No. 8

Field	1	2	3-80
Format	I1	I1	13 F 6.4
Content	8	2	VENTR (2, KVT), KVT = 1, 13

where VENTR (2, KVT) = an upper bound on the speed with which a vehicle of type KVT can enter the simulation traveling in the No. 2 direction. Card No. 8 is the last card of the mandatory deck.

Optional Data Cards

The following optional cards may be in any order. The card type is determined by the computer program from the letter entered in field position 2.

Random Number Starters

Field	1-2	3-20	21-60
Format	A2		4I10
Content	RN	empty	NSRAND (N), N = 1, 4

where:

NSRAND (1) = starter for random number generation used to select entering headways and vehicle types in the No. 1 direction flow;
NSRAND (2) = starter for random number generation used to select entering headways and vehicle types in the No. 2 direction flow.
NSRAND (3) = starter for random number generation used to select desired speeds for entering vehicles in both directions; and
NSRAND (4) = starter for random number generation used to make stochastic decisions on pass initiation and pass extension.

If no RN card is used, default values 5555555 are used. This number is appropriate for the word length of the CDC 6600 computer.

Grade Data

Field	1-2	3-5	6-10	11-20	21-60
Format	A2	I3	I5		4 F 10.0
Content	GD	J	MJGD (1)	empty	XGDN (J), G0 (J), G1 (J), X (J)

where:

J = the sequence number of this grade definition region counting in the No. 1 direction;
MJGD (1) = the total number of grade regions (dimensioned for a maximum of 30, one-way);
XGDN (J) = the position coordinate value of the beginning of this grade region measured in the No. 1 direction, ft;
G0 (J) = the grade at XGDN (J) for traffic traveling in the No. 1 direction, percent;
G1 (J) = the grade at X (J) for traffic traveling in the No. 1 direction, percent; and
X (J) = the position coordinate of the end of this grade region measured in the No. 1 direction, ft.

The grade data need be entered only for the No. 1 direction of travel. Program logic supplies the data for the No. 2 direction. Continuous grades can be entered with grade discontinuities between regions. Or, vertical curves can be specified through the difference in G0 (J) and G1 (J) values. If grade data are entered, they must be supplied for the entire simulation road length of zero to RL. If no grade data are entered, a default value of zero is used for the entire road.

Passing, No-passing Zone Data

Field	1-2	3-5	6-10	11-15	16-20	21-30	31-40
Format	A2	I3	I5	I5	I5	F 10.0	I10
Content	PS	JD	MLP (1)	MLP (2)	KPZ	XPZØ (KPZ)	JPS (KPZ)

where:

J = direction of travel for this zone data, 1 or 2;
MLP (1) = total number of zones, passing plus no-passing, in the No. 1 direction;
MLP (2) = total number of zones in the No. 2 direction;
KPZ = sequence number of this zone, counting in the direction of travel, from the appropriate end of the road;
KPZØ (KPZ) = position of beginning of zone where beginning is based on direction of travel, but position is expressed in No. 1 coordinates, ft; and
JPS (KPZ) = code for type of this zone. The code is 1 for passing; −1 for no-passing.

If passing, no-passing data are entered, they must be specified for the entire road in both directions. If data are not entered, the default is used as 100-percent passing zone in both direction.

Horizontal Curve Data

Field	1-2	3-5	6-10	11-15	16-20	21-30	31-40
Format	A2		I5		I5	F 10.0	F 10.0
Content	CV	empty	MJCV (1)	empty	KCV	XCVN (KCV)	RCUR (KCV)

Field	41-50	51-60
Format	F 10.0	F 10.0
Content	SCUR (KCV)	ACUR (KCV)

where:

MJCV (1) = total number of horizontal curves (counted one direction);
KCV = sequence number of this curve counted in the No. 1 direction;
XCVN (KCV) = position where this curve begins for traffic in No. 1 direction; position is in No. 1 direction coordinates, ft;
RCUR (KCV) = radius of this curve, ft;
SCUR (KCV) = superelevation; and
ACUR (KCV) = angular change in alignment in curve, deg. It is measured as positive for No. 1 traffic turning to the right, negative turning to the left.

Horizontal curve data are entered only for the No. 1 direction and then only for the nontangent sections. The program logic calculates approach sections for each direction if the curve will affect speeds. Otherwise, an approach section will be lumped with the curve itself for the flow turning to the right. This information is used in the simulaton to reduce (but not eliminate) passing in the region and direction affected. Very small changes in alignment should not be entered as curve data to avoid spurious reduction of passing in one direction.

The computer program is dimensioned for a total of 60 regions associated with horizontal curves. Each curve has the potential of using up to three regions in each direction, for a total of six per curve. In one direction, the regions would be: (1) an uninfluenced region upstream, (2) an approach region, and (3) the curve itself. Therefore, the maximum number of horizontal curves normally admissible will be nine or ten. The program logic assigns the regions based on the input data dealing only with the curves proper in one direction.

Crawl Regions

Field	1-2	3-5	6-10	11-15	16-20	21-30
Format	A2	I3	I5	I5	I5	F 10.0
Content	CW	JD	MJCW (1)	MJCW (2)	KCW	XCWN (KCW)

Field	31-40	41-50	51-60
Format	F 10.0	F 10.0	F 10.0
Content	CW2 (KCW)	CWO (KCW)	SCWL (KCW)

where:

JD = direction of flow for which these data apply; JD = either 1 or 2;
MJCW (1) = total number of input crawl regions in No. 1 flow direction;
MJCW (2) = total number of input crawl regions in No. 2 flow direction;
KCW = sequence number of this input crawl region in the JD direction; count is made in the JD direction;
XCWN (KCW) = beginning of the steady crawl region (beginning is in the sense of traffic moving in the JD direction); the location is in No. 1 direction coordinates, ft;
CW2 (KCW) = end of this steady crawl region; end is in the sense of JD traffic flow; location is in No. 1 direction coordinates ft;
CWO (KCW) = mean crawl speed in this region, ft/sec; and
SCWL (KCW) = standard deviation of crawl speeds in this region, ft/sec.

The input specifies only the regions in which steady crawl speeds are used by trucks (and recreational vehicles if specified elsewhere). The program logic adds approach regions and uninfluenced regions as required. Dimensioning will permit a total of 12 or 13 crawl regions specified in input.

If no data are entered, the default used contains no crawl regions.

Passing Sight Distances

Field	1-2	3-5	6-10	11-15	16-20	21-30	31-40
Format	A2	I3	I5	I5	I5	F 10.0	F 10.0
Content	ST	JD	MLS (1)	MLS (2)	KSG	XSGØ (KSG)	SGTO (KSG)
			41-50	51-60			
			F 10.0	F 10.0			
			SGTF (KSG)	XSGF (KSG)			

where:

JD = direction of travel, 1 or 2, for which these data apply;
MLS (1) = number of input sight regions for No. 1 direction;
MLS (2) = number of input sight regions for No: 1 direction;
KSG = sequence number of this input region; count is made in the JD direction;
XSGØ (KSG) = location where this sight region begins; beginning is based on the travel direction, JD; location is based on the No. 1 direction coordinate, ft;
SGTO (KSG) = passing sight distance at beginning of region, XSFØ (KSG), ft;
SGTF (KSG) = passing sight distance at end of region, XSGF (KSG), ft; and
XSFG (KSG) = location where this sight region ends. Ending is based on travel direction JD. Location is based on the No. 1 direction coordinate.

Sight distance data need be entered only for regions where sight distances differ from the nominal value, SNØM, which is input on mandatory card 2. Program logic assigns regions of nominal value where input is lacking. Also, simulation logic selects minimum sight distance, SMIN, on card 2, where specified sight distance would be less. Dimensioning allows a total of 60 sight regions for both directions combined and considering both input and assigned regions.

Vehicle Characteristics, Trucks and Buses

Field	1-2	3-5	6-20	21-30	31-40	41-50
Format	A2	I3		F 10.0	F 10.0	F 10.0
Content	VC	KVT	empty	WØHP (KVT)	WØA (KVT)	FLG (KVT)
			51-60	61-70		
			F 10.0	F 10.0		
			CPE (KVT)	CDE		

where:

KVT = code number for vehicle type; KVT = 1, 2, and 3 for trucks and busses;
WØHP (KVT) = weight/net horsepower, lb/NHP;

WØA (KVT) = weight/projected frontal area, lb/ft^2;
FLG (KVT) = length over-all, ft;
CDE (KVT) = factor correcting horsepower to local elevation; and
CDE = factor correcting aerodynamic drag to local elevation.

It is recommended that vehicles be coded so that the lowest performance type is 1, next higher performance is 2, etc.

All vehicle types for which a fraction of the flow are specified (mandatory cards 4 or 5) must be defined. Failure to provide a definition will cause the program to waste a small amount of computer time. However, program execution will cease without excessive, nonproductive running when indexed storage is exceeded.

Vehicle Characteristics, Recreational and Passenger Vehicles

Field	1-2	3-5	6-15	16-20	21-30	31-40	41-50
Format	A2	I3		I5	F 10.0	F 10.0	F 10.0
Content	VC	KVT	empty	KCWLF	PO (KVT)	SP1	FLG (KVT)

where:

KVT = code number for vehicle type; numbers 4 through 10 are for recreational vehicles or combinations; numbers 11 through 13 are for passenger vehicles;
KCWLF = control number; if set >3, the vehicle types up to and including KCWLF will respond to downgrade crawl zones, similar to trucks; if field is blank, the default value 3 causes just trucks and busses to respond to downgrade crawl zones;
PO (KVT) = maximum acceleration using maximum available horsepower, ft/sec^2;
SP1 (KVT) = pseudo-maximum speed on zero grade using maximum available horsepower, ft/sec; and
FLG (KVT) = length, over-all, ft.

It is recommended that vehicles be coded so that the lowest performance type is 4 for recreational vehicles and sucuessively higher performance types are 5 through 10. The lowest performance passenger vehicles should be type 11. Sucecssively higher performance types should be 12 and 13.

Failure to define a type specified on mandatory cards 4 or 5 will cause expenditure of a moderate amount of unproductive computer time. Program execution will cease because of exceeding indexed storage.

Extra Final Output

Field	1-2	3-20	21-80
Format	A2		6 F 10.0
Content	EØ	empty	TØ (N), N = 1, 6

where TØ (N) = specification for simulated time (min) after test data collection begins when data will be summarized, analyzed, and printed. Specified values increase for fields to the right. Any number of times, as high as six, may be entered.

The input applies only to versions of the main program containing the option for extra final output. If no data of this type are entered, the simulation results will be analyzed only for the entire simulation test time.

SIMULATION OUTPUT AND INTERPRETATION

There are four types of output, all of which are printed: (1) direct reflection of the input data cards; (2) a condensed summary of the road, vehicles, and flows specified by input; (3) "snapshots" of the status of all individual vehicles on the road at specified times during the simulation; and (4) summarized simulation results. Each type of output is described, as follows, together with its value and interpretation.

Input Reflection

The instructions to print each input card are located after the instruction to read. The print format is an expansion of the card format. This output provides a permanent record of what was run and permits an examination for data errors or omissions. This output could be removed by eliminating the write statements in subroutine REED. This initial output is headed by all the comments. Subsequent outputs repeat the first comment card.

Input Summarization

The condensed summary of input includes:

- The times to be simulated.

- Specified flow rates in each direction for each vehicle type by vph and fraction of directional flow.
- The upper bound on entry speeds for each vehicle type in each direction.
- Specified desired speeds as the minimum, average, and maximum.
- Vehicle characteristics including the coefficients used for acceleration and performance with full horsepower.
- Length.
- Maximum speed with full horsepower on 0-percent grade.
- For trucks and busses, the Wt/NHP and Wt/Area.

The condensed summary of input also includes a table of road characteristics that are essentially in the form they are employed by the simulation. The table is oriented so that the reader sees a normal right-hand traffic configuration with the No. 1 direction increasing on the right and the No. 2 direction (oncoming) on the left. Two columns refer to the No. 1 direction only; they are the grade (%) and grade rate of change (%/ft) that are signed for the No. 1 direction of travel. The following items are presented separately for each direction of travel: location, pass/no-pass zone code, passing sight distance, curve speed, and crawl speed.

Each line in the table corresponds to a position on the road. The No. 1 and No. 2 direction coordinates are both shown. The code for the pass/no-pass zones is 1 for a pass zone in the direction indicated, and is —1 for a no-pass zone. The passing sight distance is for the direction of travel indicated.

Where curve speed is over 200 ft/sec, neither curvature nor approach to a curve is a factor in the speed preferred by drivers. The location where speed first becomes less than 200 is the beginning of the approach to the curve where some unimpeded drivers' speeds will begin to be influenced. (The local speeds shown are the desired mean for the population.) In the horizontal curve itself, the curve speed will be constant. Where a minus sign is attached to the curve speed, it indicates curvature to the right or an approach to curvature to the right for the direction shown. Acceptance of passing opportunities will be reduced in the negatively signed regions. The curve speed may be coded as —202; this indicates an approach or curvature to the right with geometrics that will not influence desired speeds.

Where crawl speed is over 200 ft/sec, neither a crawl region nor the approach to a crawl region is a factor in the speed preferred by drivers. The crawl speed is less than 200 ft/sec and is variable in the approach to a crawl region. In the crawl region, crawl speed is constant and less than 200 ft/sec. The printed crawl speed is the mean for the vehicles responding. Normally, only trucks respond; recreational vehicles can be made to respond through input data.

Snapshots

The third type of output is the system snapshot presenting the location, speed, and status of each vehicle on the simulation road at a specified simulation time. The number of seconds since the simulation started is printed.

The snapshots are arranged to depict the normal right-hand, two-lane highways with the data for individual vehicles shown in correct sequences. The data for an individual vehicle are presented on either one or two lines. The second line is required only if the vehicle is engaged in a pass or is aborting a pass. The headings and interpretations for the top line are:

POS = position, expressed in No. 1 coordinates irrespective of direction of travel, ft;
SPD = current speed, ft/sec; a negative sign may be attached to the value to indicate that this vehicle has been passed by a same-direction vehicle during the last review period;
D SPD = normal desired speed, ft/sec;
ACEL = acceleration used during last review period, ft/sec^2;
VEH = vehicle type code, 1 through 13;
INDX = subscript for normal data associated with vehicle; and

STATE = code number for current state, where:

1 = unimpeded by other vehicles;
2 = overtaking another vehicle; speed difference is still greater than eight, ft/sec;
3 = following an impeding vehicle;
4 = following an impeding vehicle closely because of desire and ability to travel faster;
50MN = engaged in passing an impeding vehicle; the last two digits are the subscript for extra data carried in this state; and
60MN = engaged in aborting a pass; the last two digits are the subscript for extra data carried in this state.

The headings and interpretations for the second line apply only to vehicles passing or aborting a pass. The interpretations, which may depend on STATE are:

LTSPD = for a vehicle passing, this is the highest speed the driver is willing to reach during the pass maneuver, ft/sec; for a vehicle aborting a pass, this is the distance in back of impeder where return to normal lane will begin, ft;
TMAR = for a vehicle passing, this is the projected time margin at pass completion as most recently calculated (calculation is based on next oncoming vehicle if it is in sight; if not, calculation is based on end of passing zone; if zone end is not in sight, calculation is based on limit of passing sight distance); for a vehicle aborting a pass, this is the time remaining before the aborting vehicle will clear the rear of the impeding vehicle, sec;
OC = this is the general index, INDX, of the next oncoming vehicle; and
IMP = this is the general index, INDX, of the vehicle being passed or was being passed.

STAGE for passing maneuvers = code number, where:

1 = not yet committed to pass (that is, by decelerating at 18 ft/sec^2 the passer could avoid drawing ahead (nose to nose) of the impeding vehicle);
2 = committed to pass, but not yet abreast of impeder;
3 = ahead of impeder;
4 = clear of impeder (in this stage the passer makes a decision, partly stochastic, to pass or not pass the next impeder, if any. The decision to pass the next impeder is a pass extension, and the next stage assigned would be based on the status relative to the new impeder);
5 = a value only appearing internally for passers (stage 5 is assigned when the decision is made not to extend the pass in stage 4; the stage 5 vehicle begins to conclude the pass maneuver; two review periods remain until the vehicle clears the opposing lane); and
6 = concluding the pass maneuver. One more review period required to clear the opposing lane.

STAGE for abort maneuvers = code number, where:

1 = not yet clear of impeding vehicle;
2, 3, & 4 = not used;
5 = clear of impeding vehicle; two review periods remain before clear of opposing lane; and
6 = one review period remains before clear of opposing lane.

Four dummy vehicles appear in each printed snapshot. The dummies are not processed or moved. Two are 50-ft upstream of the ends of the simulation road, and two are 400 ft beyond the ends of the simulation road. They are assigned speeds (unexercised) and states minimizing the road end effects for other vehicles.

The snapshots also contain five data values on a line directly below the headings. These values, listed left to right, are as follows:

The value, 0;

CM(1) = factor for mean desired speed in the No. 1 direction, which accounts for the effects of driver workloads due to encountering vehicles and passing vehicles;
CM(2) = factor for mean desired speed in the No. 2 direction, otherwise like CM(1);
CS(1) = factor for deviation of desired speeds in No. 1 direction, which accounts for the effects of driver workloads due to encountering vehicles and passing vehicles; and
CS(2) = factor for deviation of desired speeds in No. 2 direction, otherwise like CS(1).

Summarized Results

The summarized simulation results are printed on 10 pages. The results are calculated from data generated by the simulation during the test time only, and for flows that occur in the test length between the buffer sections at each end of the simulation road. Two types of data are generated and processed: space data and over-all data. Space data include all values generated in the flows on the test section. These data include vehicle miles traveled; accelerations used; and events such as overtakings, passes, and aborts. The over-all data are the over-all travel times and speeds. The over-all measurement for a vehicle begins when it leaves the entrance buffer and enters the test section, and ends when the vehicle leaves the test section and enters the exit buffer length. Time headways are also measured at the entrance to and exit from the test section; the entrance location is considered a "start" line; the exit position, a "finish" line.

Results are presented for individual vehicle types, codes 1 through 13, or for the categories of trucks, recreational vehicles, and passenger cars, depending on data type. Most results are presented separately for each direction of travel, but some are given also for the directions combined.

Page 1 contains total flow rates measured at finish lines, flow rates and average speeds from space data, and operating speeds from the over-all speeds of a selected sample of passenger cars. (Only vehicles of the two highest performance passenger car types are admitted to the sample, and then only if their desired speeds fall within the specified range. The measurement of operating speeds are in accord with definitions in the "Highway Capacity Manual"; see also Chapter Two of this report for a description of speeds.) The flow rates from space data are given for individual vehicle types and for vehicle categories. The measured flow rates are compared with specified flow rates in a dimensional form (vehicles per hour) and fractional form (fraction of directional flow).

The flow rates from space data provide the best measure of flow and vehicle population. This is especially true for very slow vehicles that may be in the test section influencing the flow there for a long time without crossing the finish line.

Page 2 presents over-all speed results. The averages and standard deviations are given for vehicle categories and for the population combined. The desired speeds are also presented to assist in detecting variations due to stochastic assignments in a finite sample.

Page 2 also contains two reference speeds important to the concepts of speed and delays. One reference speed is the average to be expected, in the absence of other traffic on a level, tangent road. The average speed on the level, tangent geometrics is the lesser of (1) performance-limited maximum speed on ideal geometrics, or (2) the mean free flow (desired) speed for the vehicle type. Recreational and passenger vehicles will use fractional power for the maximum speed if the input data so specify. The second reference speed is the zero-traffic average speed. It is calculated and presented for each vehicle type by simulating the vehicle movement along the simulation road without any other traffic. The isolated vehicle uses the mean desired speed for its type in the calculations. The difference between the speed on level, tangent geometrics and the zero-traffic speed indicates, for each vehicle type, the effect on speed on curves and grades. The average speed obtained in the simulation reflects the additional effects due to other traffic.

The travel times and delays presented on page 3 contain the concepts previously discussed. The total delay (sec/mi) can be attributed to nonideal geometrics plus the presence of other traffic on those geometrics. The reference time for calculation of delay is the travel time expected for a driver who attempts to drive at the mean free flow speed for the facility, but on tangent and level geometrics with no traffic. The total time delay is obtained from:

Total Time Delay = (over-all travel time from the simulation)—(travel time for isolated vehicle on tangent, level geometrics)

The time delay due to nonideal geometrics is obtained from:

Geometric Delay = (travel time for isolated vehicle on this road)—(travel time for isolated vehicles on tangent, level geometrics)

The delay due to traffic is obtained from:

Traffic Delay = (total time delay)—(geometric delay)

Over-all speed histograms are presented on page 4. The speed strata (ft/sec) are: 0 to 12; 12 to 120 in increments of 6; and over 120. The resutls are for the vehicle categories of trucks, recreational vehicles, and all. Results are presented for the separate directions and for the directions combined. Two printed pages are required for the data.

The time margins in passes and pass aborts are presented on page 5. The time margins in passes are based on the oncoming vehicle if it is in sight; or, failing that, on the end of the pass zone if it is in sight; or, failing that, on the passing sight distance. The time margins for pass aborts are the projected pass margins when the abort was begun. Thus, they are not a measure of the situation criticality when the abort maneuver was completed.

The data on passes and pass aborts are presented on page 6, together with platoon leader data at finish lines and the percent of time vehicles are unimpeded. The data passes are shown both from a driver's standpoint (passes/vehicle mile) and from an observer's standpoint (passes/lane mile or passes/road mile). The results are shown for the directions separately and combined, and for vehicle categories. The values presented are passes started, passes aborted, pass extensions, leapfrog passes, and number of vehicles passed. Here, a pass start is counted when the initial affirmative decision is reached. Pass extensions occur during a pass in progress when the decision is reached to pass an additional vehicle. A pass is counted as a leapfrog type when, at the conclusion, the passer reenters the normal lane between two vehicles that are platooned or have a time headway of less than 5 sec. For the count of vehicles passed, the vehicle category shown is for the passer.

The data on platoon leaders at finish lines show the relative frequency that each vehicle category appears as a platoon leader. Isolated vehicles are not counted as platoon leaders.

The percent of time unimpeded is presented for each vehicle category. It is a measure of the service level for the geometry and flow simulated.

Time headways and platoon data are presented on page 7. The time headways are measured at the start and finish lines in each direction. The histograms are stratified in 1-sec intervals from 0 to 5; in 5-sec intervals from 5 to 20; and over 20.

The platoons are evaluated at the finish line in each direction. Platoons are classified by size in increments of one from 1 to 10 and a class for 11 and greater. Isolated vehicles are counted as platoons of size, 1, to complete the description of traffic crossing the finish lines. The isolated vehicles are not counted as platoon leaders. Platoon leaders must be in state 1 (i.e., unimpeded) or in state 5 (passing) with a time headway equal to or greater than 5 sec. Follower members of platoons must be in state 2, 3, 4, or 6 (i.e., overtaking, following, or aborting a pass); or, if in state 5 (passing), have a time headway of less than 5 sec.

The overtaking events on page 8 are classified by number in the overtaking platoon and by the initial speed difference between overtaking and overtaken vehicles. The overtaking events are evaluated when the leader of the overtaking platoon first responds to the vehicle being overtaken. The initial response may occur when speed and separation values first combine to cause a response, or it may occur when the overtaken vehicle first comes into view. (Sight distance is the passing distance that should be appropriate to this application.) The potential criticality of the overtaking events should increase with the speed difference and the platoon size.

Page 8 also contains the overtaking event rates in units appropriate to both the driver viewpoint (events/veh mi) and to the observer (events/lane mi).

The overtaking events are classified on page 9 by the number in the overtaking platoon and by the initial acceleration used by the overtaking platoon leader. The acceleration classes are: greater than zero, and 0 to —25 in increments of —5 ft/sec^2. This classification will indicate the large criticality associated with high overtakng speeds and short sight distances. Criticality of events increases with platoon size and with the magnitude of the deceleration used initially.

The acceleration noise for the flows are also presented on page 9. The values are calculated from the accelerations used in each review period by each vehicle within the test section and test time.

APPENDIX J

SUMMARY OF FINAL REPORT ON CONTRACT NO. DOT-FH-11-7989, "ECONOMIC EVALUATION OF MOBILE AND MODULAR HOUSING SHIPMENTS BY HIGHWAY"

This appendix contains a summary of the work conducted under Contract No. DOT-FH-11-7989 for the U.S. Department of Transportation, Federal Highway Administration. The summary was prepared by assembling selected excerpts from the final report for the contract (*37*).

GENERAL INTRODUCTION

Objectives

The ultimate mutual objective of the parties involved in the transportation of mobile and modular homes—that is, the U.S. Government, the state governments, mobile and modular builders and shippers, and the general public—is to establish acceptable regulations regarding shipment over the highways of these homes. These regulations should ensure safe transportation at reasonable costs. To this end, the objective of this research project was to obtain the data needed to reach rational decisions regarding such regulations, to analyze these data, and to make recommendations based upon the analyses, all in a timely fashion.

Scope

Our intent in the project was to identify factors in the highway movement of mobile and modular housing concerned with safety, inconvenience and cost. To do this, we first obtained data in four distinct ways. Then, after analysis of these data, conclusions were reached and recommendations made addressing specific questions which deal with increasing the safety, minimizing the inconvenience, and imposing only reasonable costs upon the purchasing and motoring publics.

The major data collection effort was associated with obtaining traffic data—data concerning movements of other traffic in the vicinity of wide loads (12- and 14-wide mobile homes and 12-wide modular homes). The data were collected photographically, supplemented by visual operations and manual counts of such things as queue lengths and passes. Our crews rode with wide loads, photographing from the cab, from the rear of the house, or from an escort vehicle. About 12,000 miles were logged on 63 trips in most parts of the country, on all kinds of highways and terrain, and under a variety of controlling state regulations. The films were then reduced by image measuring techniques. Over 25,000 frames of film were thus analyzed and the data were coded for computer processing. Speed-distance profiles were obtained, as well as other features of the vehicle maneuvers.

Two types of analyses were made of these data. One type concerned safety-related measures. Included here were considerations of relative speeds between vehicles, the time remaining before overtaking at which a motorist saw and responded to the wide load (by changing lanes or decelerating), usage of the shoulder by oncoming traffic, etc. The other type of analysis determined the costs imposed on the motoring public. These costs included incremental operating costs associated with fuel and tire consumption, delay, and added air pollution. Delay measurements also provided a measure of inconvenience to the motoring public. In addition to these data, we also recorded a number of incidents observed during these trips.

A second data collection effort was the conducting of motorist interviews. Almost 3,000 drivers were stopped on the highways, both divided and two-lane, of six states and a short interview conducted. The procedure was designed to optimize the chances that the motorists had recently passed a wide load. They were asked questions concerning delays and safety hazards, with wide loads not being specifically mentioned until the end of the interview. Then, the motorists were asked to complete and return a questionnaire in which they could compare wide loads with other classes of vehicles on the highways.

Thirdly, we obtained extensive cost and related data from common and private carriers of mobile and modular homes. This was done by on-site interviews at about two dozen locations around the country. Also, hard data were obtained on such factors as circuitous routing, costs of permit acquisition, delays enroute, etc.

Fourth, we obtained data from the states. This effort involved three steps—first by mail, second by telephone interview, and third (in a few states) by personal interview. Information was sought of state officials concerning permit office operations; costs to the states of issuing permits, enforcing regulations, etc.; permit and regulation policies and philosophies; and particular regulation problems within the state.

After assembling and combining all of these data, a number of questions regarding movements of wide loads were addressed. Among the topics were the following:

(1) The need for permits;
(2) The use of multiple-trip permits;
(3) Permit costs;
(4) Permit reciprocity;
(5) Advisability of divisible loads;
(6) The use of divided highways vs two-lane highways;
(7) Reasonable speeds for wide loads;
(8) Rear lighting;
(9) Advisability of escorts, front or rear;
(10) 12-Wides vs 14-wides on (a) divided highways, (b) two-lane highways with good sight distance and wide

lanes, and (c) two-lane highways with marginal sight distance and narrow lanes;

(11) Mobile vs modular movements;

(12) Particular safety hazards such as frequent tire failures, and improperly equipped or operated escort vehicles; and

(13) Other regulatory questions such as signing, flagging, etc.

Project Limitations

The research project covered a large number of facets of the cost and safety implications of wide load transportation. However, it is important to clarify certain areas which were outside the scope of the contract and of the study.

Aside from activities associated with the literature survey, the project did not encompass accident studies. We did not review accident statistics nor were accident investigations conducted. Accidents are too rare to provide reasonable samples, and most accident reports are not adequate to answer questions concerning causation.

It was not the intent of this project to examine wide loads in comparison to normal size loads or other types of vehicles. The only comparisons made in this regard were associated with the motorist surveys. From the beginning, it was implicitly assumed that wide loads are, and will continue to be, using the highways. Therefore, the intent of the project was to compare various alternatives and examine the parameters involved in their movement.

Likewise, certain costs involved in the transportation of wide loads were not examined in depth in this project. The study did not concern itself with cost elements common to all trucking, or even those costs which apply uniformly to mobile and modular home transportation. The present study was confined to incremental costs which arise within and between states as a result of complying with the particular regulations of the states.

Finally, there were many vehicle characteristics which were not examined in detail. The scope of the project did not include such items as the aerodynamic characteristics of mobile homes, stability considerations concerning their movements, the mechanical and other properties of the towing vehicle and how they relate to handling properties, or analyses of construction practices of mobile homes as they might relate to transportation.

EFFECTS ON OTHER TRAFFIC

Method

An important part of the present research was to identify and measure the effect on other traffic of the highway shipment of 12- and 14-wide mobile homes and modular houses. Collection and analysis of these data was the objective of the task discussed in this section.

Two kinds of data were gathered. In a major effort, time-lapse photographs were obtained of traffic in the vicinity of the wide loads. The photographing was alternately conducted from inside the load, from the cab of the towing tractor and from escort vehicles. The photographic data were used to determine the speed, lateral placement and lane occupancy characteristics of traffic encountering the load.

The second kind of data collected was counts of traffic events over timed intervals. Attention was concentrated on queuing and passing; occasional events such as intrusions into an adjacent lane were also recorded. The count data provide the basis for determining the temporal characteristics of queuing, overtaking and passing frequencies, etc.

The photographic and count data were reduced separately. The major effort concerned obtaining measurements from the film, then processing these by computer to obtain speed-distance profiles.

The reduced data were analyzed and measures relating to risk, traffic safety, and inconvenience were developed. Values of these measures obtained under various traffic conditions corresponding to a number of differing state regulations were compared. Cost implications were also deduced from the data.

Results

After the filmed data were reduced and analyzed, a number of measures were defined and examined which are measures of relative risk or hazard. Despite the rather large amount of filmed data, the samples' sizes for individual combinations of parameters such as load width, speed, escort and signing configurations were not exceedingly large. Also, the habits of individual drivers vary greatly, so the variances in the measures on individual trips were large. Because of these two factors we were generally unable to establish with statistical confidence, differences in driver behavior as affected by various load parameters. However, there were a number of consistent trends observed which are both reasonable and important.

Overtakers on divided highways tended to react in a less hazardous manner if the wide load had a speed closer to their own. Overtaking motorists reacted most cautiously, not to a wide load, but to a rear escort vehicle carrying a very high intensity flashing beacon. The relatively low intensity flashers used on the rear of some wide loads were generally ineffective. No differences whatsoever could be noted with 14-wides carrying such flashers and only a slight tendency towards safer behavior with 12-wides carrying flashers. No trends could be observed between the approaches of motorists to 12-wide loads vs 14-wide loads.

Overtaking traffic on two-lane highways demonstrated the same general trends as that on divided highways. The measures of risk indicated that the safer approaches were made when the wide load had a higher speed. Motorists also approached 14-wide loads more cautiously than 12-wide loads. They also tended to approach escort vehicles with high intensity beacons very cautiously. However, no difference could be found in motorists' approaches to wide loads as opposed to their approaches to a normal automobile traveling at wide load speeds. Neither could any trends be found between modular and mobile movements. One finding did have statistical significance. Although the sample size was small, a load traveling at 58 mph elicited responses from overtakers which yielded the highest margin of safety.

As opposed to the trends concerning overtakers, the findings regarding oncoming traffic were generally statistically significant. It was determined that the lateral displacement from the centerline of oncoming vehicles tends to increase as the lane width increases. Vehicles also tend to move further to the right for 14-wides than they do for 12-wides or for automobiles. No significant effect could be observed on motorists' lateral displacements passing a wide load that could be related to the presence or absence of a leading escort. However, motorists often tended to move to the right as they passed an escort vehicle, perhaps as much or more than in passing a wide load. Automobiles tend to move to the right further than trucks and to decrease their speed more than do trucks.

On 10-ft lanes, all trucks observed used some of the shoulder in approaching a 14-wide load. To a lesser extent trucks had a tendency to edge onto the shoulder in passing 12-wide loads on 10-ft lanes or 14-wide loads on 12-ft lanes. Putting this in proper prospective, however, trucks were also noticed to occasionally edge onto the shoulder in passing cars and escort vehicles on 11-ft lanes. They generally did not use the shoulder in passing 12-wide loads or escort vehicles on 12-ft lanes or greater. Passenger vehicles also tended to use part of the shoulder in passing a 14-wide load on a 10-ft lane, but not to do so otherwise. No effect could be found concerning shoulder usage which was related to the presence or absence of a leading escort.

Queuing behind a wide load on two-lane highways is a common phenomenon, with one or more vehicles in queue over half the time. The queue length is dependent on traffic volume. Available data do not allow clear assessment of other variables on queue length, although the presence of a rear escort appears to enhance queuing.

MOTORIST OPINION AND ATTITUDE SURVEYS

Survey Procedure

The intent of this task was to determine, in an unbiased fashion, the attitudes and opinions of the motoring public toward mobile homes. A carefully structured survey instrument was prepared and procedures developed to determine how the motorists compared mobile homes with other types of highway vehicles.

Interviews were conducted in six states—Oregon, Idaho, Nebraska, Indiana, New Hampshire, and Florida. In each state the interviewing was carried out in coordination with the appropriate state officials. Generally speaking, motorists were randomly selected from the traffic stream and flagged to an interview station. All types of vehicles were eligible for selection, including semis, motorcycles, etc.

The sites were selected in cooperation with the traffic engineers and permit officers of the states. The intent was to select highways which carried relatively high mobile home traffic. In that way we could maximize the possibility that the motorists being interviewed had recently passed a wide load.

Interviews were conducted both on divided highways and on two-lane roads. Of the six states, divided highway interviews were carried out in all but Nebraska. Two-lane highway interviews were conducted in all of these states except Florida.

The survey instrument was developed in coordination with the Federal Highway Administration. A two-step interview technique was employed. Part A was a personal interview of the driver carried out on site. This interview typically required about 2 min to complete. Part B consisted of a mail-back questionnaire which the drivers were asked to complete and mail using a furnished, post-paid envelope. The survey teams recorded the passage of wide loads during the interview periods.

Survey Results and Conclusions

A total of 2,952 motorists were interviewed, 1,097 on divided highways and 1,855 on two-lane highways.

Only rarely did a motorist who had recently passed a wide load suggest, without prompting, that he had encountered delay or a safety hazard at that time. Again, without prompting, motorists did not rank mobile homes extremely high as problem vehicles—trucks, campers, other cars, and farm equipment were more commonly mentioned.

When drivers who had recently passed a wide load were specifically queried about that experience, less than one in 10 on divided highways, and less than one in five on two-lane highways, recalled any problems.

When motorists were pointedly asked to rate mobile homes against other types of vehicles, they tended to place them at the top of the list in terms of hazards, impedances, and problems in general. Also ranking nearly as high on the list were trucks, campers, farm vehicles, and cars pulling trailers.

Motorists who normally drive on two-lane highways tended to be more tolerant of their driving environment, when compared to persons who normally drive on divided highways, except for mobile homes.

There were many geographic differences among the drivers and their opinions, relating directly or indirectly to mobile homes. Drivers in Florida tended to be older than others. Trucks and pickup trucks were more common in Idaho and Oregon, and, on two-lane highways, single unit and semi trucks were most common in Nebraska. Drivers from Indiana were most vocal concerning delays, hazards and mobile homes. New Hampshire drivers were least likely to express concerns. Drivers in the Northwest were most likely to complain about campers and cars pulling trailers. Nebraska drivers were troubled by farm equipment and, along with Indiana drivers, by mobile homes on two-lane highways. Trucks were a particular concern on divided highways to drivers in Indiana and Florida and, on two-lane highways, to New Hampshire drivers. The latter were also bothered by small passenger vehicles on divided highways.

ANALYSIS OF COSTS TO HIGHWAY USERS

Any vehicle, by its presence on the highway, has the potential of influencing the progress of other vehicles. That is, its presence could cause other drivers to change speeds, change lanes, be delayed, etc. These influences could be especially pronounced if the vehicle in question is extraordinarily large, or moving slower than other traffic, or both.

There are several traffic flow effects induced by other vehicles, which are quantifiable in terms of ultimate costs. One of the most obvious is a speed change. When a driver changes speed for a period of time, two phenomena occur which give rise to incremental costs. First, by driving at a constant speed which is different from the unimpeded or free speed, the motorist incurs incremental fuel, oil and tire costs, a change in the emission of air pollutants, and a change in travel time. Any of these quantities could be positive or negative depending on whether the affected speed is lower or higher than the unimpeded speed. The affected speed would be lower than the unimpeded speed if, for example, the motorist becomes a part of a queue; but it could become higher while, for example, the motorist is passing the impeding vehicle. The second phenomenon is the speed change cycle per se. That is, decelerating and later accelerating (or vice versa) results in additional consumption of fuel, oil, and tires and increases the emission of air pollutants.

The other common maneuver with which costs can be associated is a lane change. The major cost incurred in this maneuver is increased tire wear.

It was determined that the consumption of oil and modified depreciation and maintenance expenses were either insignificant or inappropriate for inclusion in this cost analysis. Therefore, the final results are based on consumption of fuel and tires, delay time, and air pollution.

The following general comparisons were observed between multilane and two-lane trips:

- Dollar costs imposed on other traffic were much smaller on multilane than on two-lane highways.
- On two-lane highways dollar costs were frequently negative (i.e., an implied net saving resulting from reduced speed). On multilane highways, costs were always positive.
- Incremental pollutant emissions precipitated by the wide loads were an order of magnitude larger on two-lane than on multilane highways.
- Time delay costs were much higher on two-lane than on multilane highways.

The following effects of configuration parameters were detected at 0.01 significance:

On Multilane Highways

- The slow 12-wides induced larger total costs than the fast 12-wides.
- The 14-wides induced larger total costs than the 12-wides.
- A rear escort induced larger total costs than no escort.

On Two Lane Highways

- Time delay costs induced by slow 12-wides were larger than those induced by fast 12-wides.
- The slow 12-wides induced larger incremental air pollutant emissions than the fast 12-wides.
- The 14-wides induced larger incremental pollutant emissions than the 12-wides.
- Of the escort options, a front escort or two escorts induced the largest incremental emissions. The no-escort case was next in severity and the rear-escort case was least severe.

EXAMINATION OF COSTS TO SHIPPERS AND/OR CARRIERS AND STATES

Every state has regulations or policies pertaining to the movement of overdimensional cargoes such as mobile homes. Compliance with oversize regulations contributes to the carrier's costs. Also, regulations vary from state to state and, as a result of variance, give rise to further incremental costs to carriers and shippers. This study examines these costs. Assessing the cost of compliance calls for analyzing each state's regulations, determining differences in regulations between states, and assigning costs of complying with the regulations and variances.

Additionally, the existence of state overdimension or permit regulations brings about a cost burden to the states. States must provide for issuance of oversize permits and enforcement of attendant regulations. Therefore, examination of the costs to the states of providing for and enforcing carrier compliance is also in order.

A four-element approach was developed to fulfill the requirements of this task. The elements are: (1) a detailed analysis of existing state regulations which affect the transportation of overdimensional mobile and modular homes, (2) the determination of variances in regulations between adjacent states, (3) the development and application of cost data which relate to regulations and variances in regulations, and (4) the determination of costs to the states of issuing permits and enforcing pertinent regulations. The approach is discussed further in Section V-B.

Items (1) and (2) resulted in a listing of current regulations too voluminous to reproduce in this summary. Items (3) and (4), the cost considerations, are summarized below.

Cost Burden to the States

Despite the large size of some permit issuing agencies, accurate cost information is difficult to obtain. In most states, issuance of oversize and overweight permits is a function of a division of the state highway department. While cost records of the highway department are available, interviews with state officials indicate that few states maintain an accounting system which treats permit processing as an independent cost center.

The accounting system used in California relates permit revenues to expenses on a cost recovery basis. In 1971, the State of California issued 109,921 transportation permits. Typical among these issuances in terms of procedures and issuance costs were overdimension permits for mobile homes. On a per issue basis, costs are:

Labor	$3.01
Operating Expense	0.72
Overhead	1.47
Total	$5.20

Connecticut does not charge a fee for overdimension permits and, therefore, cannot relate revenue to expense. However, in December 1971, a cost study of the oversize permit issuing activity was conducted by the state. Results show the average cost of permit issuance was $3.54. Again, mobile home permit issuances are typical in terms of procedures and costs. The permit director stated that if Connecticut were to charge a fee for permits, an accounting system would be required at an estimated additional cost of $1.50 per issue, raising the total to $5.04.

Despite a lack of hard evidence, 15 other state permit directors were willing to estimate the cost of issuing a permit. Their approximation ranged from $2 to "more than $10." Of those, 12 were in the range of $3 to $5.

Enforcing regulations relating to overdimension shipments is usually (if not always) part of a larger activity. Most often, responsibility for enforcing overdimension regulations is assigned to the agency responsible for enforcing weight laws of the state. Thus, enforcement costs are often buried within the budget of the larger agency. Interviews with numerous state police officials yielded no estimates regarding what fraction of a trooper's workday might be devoted to these particular enforcement activities. Two permit officials (who were also charged with enforcement responsibility) both estimated $1.50 as the cost per permit to their states of enforcing overdimension regulations.

Cost of Regulations to Shippers and Carriers

The most notable characteristic of costs to mobile home shippers and carriers brought about by permit and transportation regulations is their variability from trip to trip. The cost of regulations can range from a small fraction of basic line-haul charges to several times the cost of transportation only. However, for shipment of a 12-wide mobile home (excluding modules) an average distance, the cost of complying with regulations is typically $50 to $100. Compliance costs increase for modules primarily because of higher permit charges, and for 14-wides because of a combination of greater volumes of regulations and more stringent requirements for transportation.

Costs of compliance with regulations are ultimately paid by the consumer. Those costs are either added on to the price of the home or absorbed in the transportation costs. During the intermediate steps before final delivery to the consumer, compliance costs which are added on to the price of the home are borne by the shipper, and those costs absorbed in the transportation charges are borne by the carrier. For the most part, only minor costs (up to several dollars) are absorbed in transportation charges, while costs of greater than several dollars are added to the carrier invoice and paid by the shipper.

SAFETY HAZARDS

Introduction

In the course of collecting traffic data, our engineers traveled on 59 trips with mobile or modular homes, logging approximately 12,000 miles. These trips included all types of highways, in most parts of the country. They involved approximately 40 drivers working for a number of private and common carriers, and the wide loads were manufactured by a score of companies. With one exception, the movements were all initial movements. Since for the most part, the same drivers make both initial and secondary moves, we believe our experiences were typical of wide-load movements in general. For example, our experience with flat tires was probably not unusual as evidenced by the fact that most drivers carry four or five spare tires with them.

In the course of our observations, we noted a number of hazardous situations. Some of these resulted in property damage, either to the load or to another vehicle. Some of the incidents were considered not related to the wide load, and others were related only in an indirect fashion.

Many of the problems relate to the manufacture of the home, as typified by our tire experience. Several others illustrate problems which can arise when escort vehicles are used ineffectively. Finally, some of the problems are inherent with the routing of oversize loads on highways with marginal capabilities of handling them.

Summary

The incidents taken individually would not be too meaningful for research purposes. But, because there were so many, and because several of them had common characteristics, we believe that they do have importance as indicators of problem areas.

In 12,000 miles of travel, we observed six incidents involving the wide-load movement and resulting in property damage. (Two other incidents were observed not directly involving the wide load.) Of the six, only two would be classified as "reportable," with the others either resulting in too little property damage or occurring on private property. To our knowledge, however, none of the six were reported.

Three of these six incidents were the direct result of improper escort operation. They would not have occurred if the escort driver had properly carried out his duties or if there had been no escort.

Tires were a recurring problem. We averaged a flat tire for every 706 miles of travel. In addition, we lost an entire wheel from one modular shipment. It appears that the tires may be overloaded, considering their quality. This is a problem area worthy of additional study.

Strong or gusty winds are a particular problem with which mobile home drivers must contend. Despite the industry's concern with winds, numerous state regulations concerning wind limits, and driver caution (usually), many turn over or other wind-caused accidents occur yearly, according to BMCS officials. Further study is probably warranted here, also.

CONCLUSIONS IN THE FHWA-HUD REPORT

The collection, analysis, and evaluation of data from many sources has illuminated a number of problems relating to highway transportation of mobile and modular housing. These problems occur, in part, because of the inherent effects of moving such loads and, in part, because of the nonuniform regulations adopted by the several states concerning these movements.

Reviewing the problems encountered by the public, the carriers, and the states indicates that a number of conclusions can be drawn. These conclusions are summarized here.

Traffic Safety

- Reported accident rates and severities involving mobile and modular homes are similar to those involving other commercial vehicles (trucks).
- Slow moving wide loads create more traffic impedances and initiate driver responses of a more hazardous nature than do faster moving wide loads.
- Traffic disruptions and impedances caused by wide-

load movements are more frequent and severe on two-lane highways than on divided highways.

• The use of escort vehicles does not measurably reduce hazardous reactions of other motorists to the wide-load movement; some situations, such as passing on two-lane roads, are worsened by the presence of escorts.

• On two-lane roads, motorists approach 14-wide loads with more caution than 12-wides. Motorists are also more likely to encroach upon the shoulder in passing such loads. No other differences could be found that were attributable to the load width, per se.

• Few vehicles encroach upon the shoulder when passing 12-wide loads on 12-ft lanes, but shoulder usage increases as the load width increases and as the lane width decreases.

• Queuing behind a wide load on two-lane pavements is rather common; queue length is highly dependent on traffic volume, but not measurably dependent on other variables except that the presence of a rear escort may intensify queuing.

• The low intensity, flashing, warning lights presently used on the rear of some wide loads have no effect on motorists' responses; evidence indicates that high intensity flashers on escort vehicles do elicit early driver responses.

MOTORISTS' OPINIONS AND ATTITUDES (SECTION III)

• Only rarely did a motorist who had recently passed a wide load suggest, without prompting, that he had encountered a delay or safety hazard at that time. Neither did he spontaneously rank mobile homes extremely high as problem vehicles—trucks, campers, other cars, and farm equipment were more commonly mentioned.

• When asked specifically to rank mobile homes against other types of vehicles, motorists tended to rank mobile homes as the most hazardous, most impeding, and most likely to cause problems in general. Ranking nearly as high on the list were trucks, campers, farm vehicles, and cars pulling trailers.

• Motorists perceive mobile homes to be about twice as troublesome on two-lane highways as on divided highways.

COSTS IMPOSED ON THE MOTORING PUBLIC (SECTION IV)

• Dollar costs to other traffic as measured by imposition of delays, increased fuel consumption, tire wear, etc., were much smaller on multilane than on two-lane highways.

• On two-lane highways, the motoring public often *saves* money by following a wide load because the reduction in operating expenses is greater than the increase in delay costs, using generally accepted value-of-time figures.

• Time delays and increased pollutant emissions were much higher on two-lane highways than on multilane highways.

• Where differences were noted, greater costs, delays, and incremental pollutant emissions were associated with slow moving rather than fast moving wide loads, with 14-wides rather than 12-wides, and with loads accompanied by escort vehicles rather than without.

• The total cost imposed on all traffic on multilane highways is generally less than 2 cents for each mile of travel of a wide load. On two-lane highways the cost is much more variable, is often negative, and seldom exceeds 5 cents for each mile of travel by the wide load.

Costs of Regulations to Shippers and Carriers

• The most notable characteristic of costs to mobile home shippers and carriers brought about by permit and transportation regulations is their variability from trip to trip. The cost of regulations can range from a small fraction of basic line-haul charges to several times the cost of transportation only. However, for interstate shipment of a 12-wide mobile or modular home about 250 miles, the cost of complying with regulations is typically $50 to $100. Compliance costs increase for 14-wides.

• For the most part, the cost brought about by regulations are added to the manufacturer's or carrier's invoice and paid by the shipper; minor costs (up to several dollars), are absorbed by the carrier.

• Permits are required in every state, at least under some conditions, to transport a wide load, and one state's permit is not honored by another. The costs associated with permits can add 10-25% to the basic transportation charges, with the permit acquisition costs often equaling or exceeding the state permit fee.

• Where used, multiple-trip permits are a boon to the state and shipper alike.

• Escort vehicles, where required by regulation, are extremely costly, adding 30-35 cents per mile to the basic transportation charge for each escort vehicle.

• Circuitous routing induced by regulations is extremely variable, but can add appreciably to the transportation costs because the line-haul charges are based on mileage.

• Differences among the states in allowable length, and in the method of specification, have caused the carriers to resort to specially designed tractors to enable interstate moves.

• Regulations pertaining to signing, flagging, and warning lights are extremely variable from state to state. Contrary to common belief, however, these variations have relatively little cost impact.

• Organizations of states, such as AASHTO, WASHO, etc., are attempting to bring about more uniformity among the state regulations.

• Mobile and modular homes are usually treated under the same regulations which apply to other over-sized vehicles, although, because of the high volume of such movements steps have been taken to routinize mobile and modular home movements.

Safety Hazards

• Escorts although presumably employed to make a wide load movement safer, often result in degraded safety. Lack of two-way radio communication, misunderstanding of the function of an escort vehicle, lack of training, and blatantly unsafe practices are all reasons for such degradation.

• Faulty or inadequate tires are a very common problem in the movement of mobile homes and modular homes.

• High winds continue to plague the movement of mobile homes on the highways, despite the concern and awareness of the states and the industry of this problem.

RECOMMENDATIONS IN THE FHWA-HUD REPORT

Conditions Under Which Permits Should be Required

- In general, 12- and 14-wides should move only under permit, as presently required.
- General policies, as much as possible, should replace specific judgments by permit-issuing agencies regarding permissible combinations, size and configuration, routing, and travel times.
- To encourage wide loads to travel on the roads most capable of handling them, the Federal-Aid Highway Act should be amended to allow loads as wide as 12 ft to move on the Interstate System without permits.
- All states should compile a route system suitable for use by oversize homes and publish it in the form of a route map.

Use of Multiple-Trip Permits

- Multiple-trip permits should be issued by the states for frequent and standard movements of coaches of widths up to and including 12 ft.
- Consideration should be given, in those states where 14-wides are allowed, to granting multiple-trip permits for 14-wides on a limited system of routes.
- When the use of multiple-trip permits becomes widespread, Section I-A of pertinent I.C.C. Tariffs should be reviewed to ensure that overdimension charges accurately reflect average costs to carriers.
- Issuance of bulk permits, where applicable, should be superseded by conventional multiple-trip permit operations.
- Published route systems should be disseminated by the states to aid in controlling routing under multiple-trip permit operations.

Permit Reciprocity

- Proposals of standardization such as those of WASHO and others should be reviewed, discussed, and considered as possible models for adoption by other compact groups of states and by AASHTO.
- Permit reciprocity should be a goal of the states in order to better serve the infrequent carrier and to encourage standardization of institutions and regulations among the states.
- Municipalities and counties should universally honor state permits which would include, if necessary, special city and county requirements—thus eliminating city and county permits.

State Permit Fees

- Permit fees should be charged for the right to transport extra-legal loads.
- Permit fees should reflect only incremental costs directly associated with the extra-legal vehicle.
- Six dollars, being sufficient at this time to cover issuance costs of single-trip permits in most states, should be adopted as the permit fee for mobile and modular homes.
- If states can clearly demonstrate other incremental costs brought about specifically by the transportation of mobile and modular homes, those costs should be considered for inclusion in the permit fee.
- The states should charge a fee for multiple-trip permits designed to recover issuance costs plus any other specific incremental costs to the state brought about by wide-load movements on either a one-time or variable basis.

Divisible Loads

- The states should not prohibit oversize divisible loads, which otherwise meet permit requirements, if such loads would remain overwidth even after subdivision.

Length Restrictions

- The states should adopt the maximum length recommendations of AASHTO.
- The states should establish maximum load length limits as well as maximum combination length limits to discourage unusual and possibly unsafe tractor configurations.

14- vs 12-Loads

- Certain restrictions, in addition to those imposed on 12-wides, should be imposed on 14-wide movements. These restrictions should include:
  - Discouraging or prohibiting 14-wide movements on highways with less than 12-ft lane widths.
  - Discouraging 14-wide movements on two-lane highways with 12-ft lane widths if the highways have narrow or poor shoulders, or frequent constrictions of the roadway.
  - Confining 14-wides to the right-hand lane in urban areas or other locations where more than two lanes are available, except under extenuating circumstances.
  - Requiring installation of highly visible and effective warning beacons on the rear of the wide load, because 14-wides tend to move slower than 12-wides.
  - Discouraging 14-wides from using highways with poor sight distance, or else requiring that they employ two-way-radio-equipped front escorts on such highways.

Speed of Wide Load

- Regulated, statewide, maximum speeds of wide loads should be not less than 45 mph on two-lane roads and 50 mph on multilane highways.

Usage of Interstate Highways by Wide Loads

- The states should make every effort to encourage wide-load transportation on divided highways, in preference to two-lane roads.
- The Federal Government should provide relief to the few states with outmoded laws by modifying Title 23, Section 127 of the United States Code relative to usage of the Interstate System by overwidth loads.

Time of Day/Day of Week Restrictions

- Mobile and modular homes should be allowed to move during daylight hours on weekdays, except on major holidays or in congested areas during peak hours.

• Saturday and Sunday movements should be allowed if traffic volumes on such days do not exceed weekday volumes.

• Nighttime movements should be prohibited except in times of national emergency or disaster relief, and even then only after all possibilities of daytime movements have been exhausted.

Special Lighting

• Where special lighting is required, either on an escort vehicle or on a wide load, it should be of high intensity as specified in SAE J-5956 or equivalent.

Use of Escorts

• Escort vehicles should not be used on divided highways.

• Front escorts should be required wherever short sight distances, narrow clearances, etc., dictate the need for motorist and wide-load driver warnings.

• The states should publish route maps showing locations requiring escort vehicles.

• High intensity rear lighting should be specified in lieu of a rear escort.

• All escort vehicles should be required to have two-way radio communications with the wide-load driver.

Additional Research

• A study should be undertaken to establish reasonable axle, braking, and tire requirements for mobile homes.

• A study should be undertaken to determine reasonable size and power characteristics for towing vehicles for 12- and 14-wides.

• A study should be undertaken to investigate the wind effects on the stability of mobile and modular homes.

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