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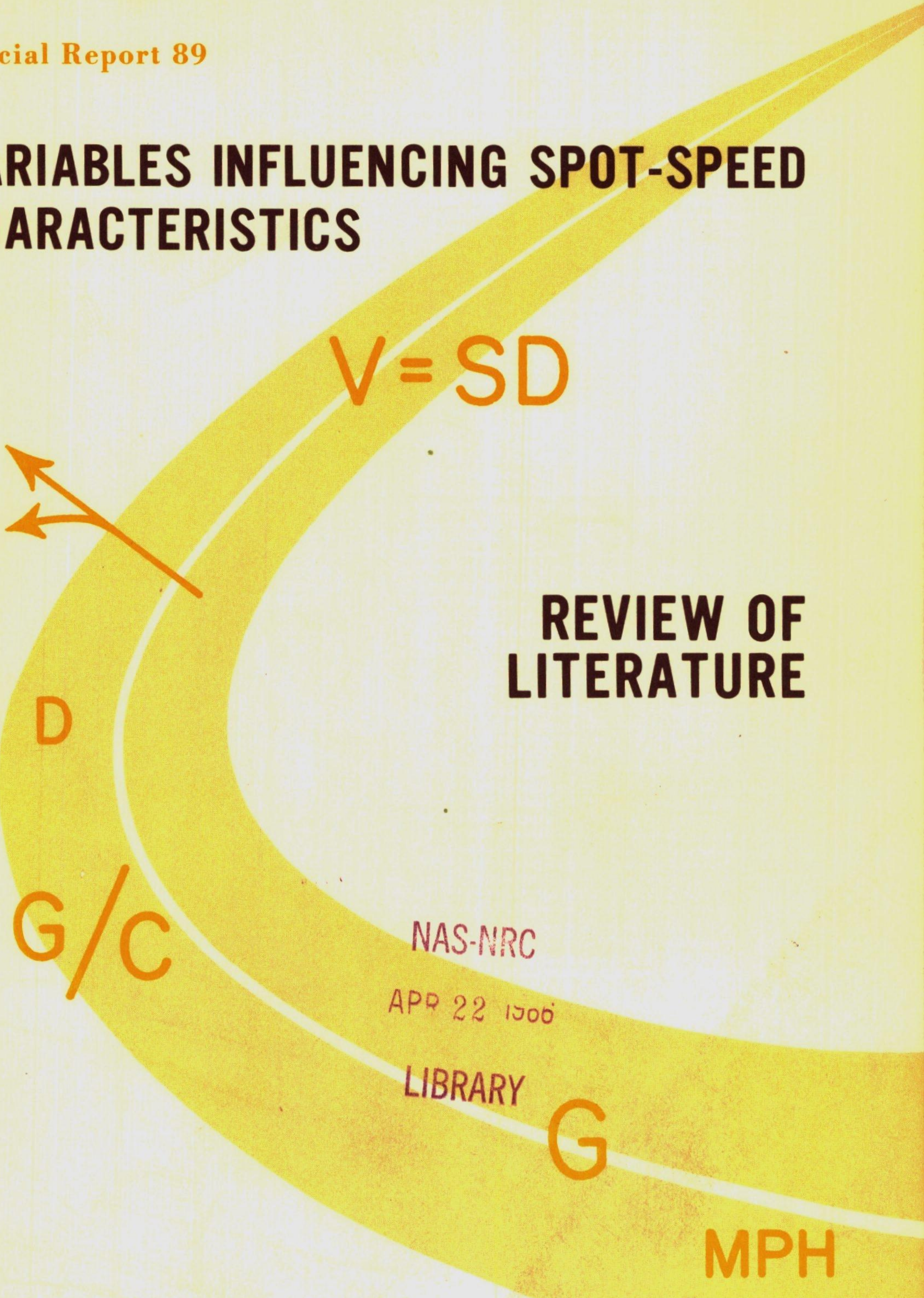
Special Report 89

VARIABLES INFLUENCING SPOT-SPEED CHARACTERISTICS



REVIEW OF LITERATURE

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VARIABLES INFLUENCING SPOT-SPEED CHARACTERISTICS

REVIEW OF LITERATURE

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Department of Civil Engineering, University of Illinois

SUBJECT CLASSIFICATION
53 Traffic Control and Operations
54 Traffic Flow
55 Traffic Measurements

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Foreword

Proper planning, design, and operation of highway systems must take vehicular speed characteristics into account. Sound engineering decisions depend upon broad knowledge of such characteristics. This literature review will be of special use and interest not only to highway department personnel engaged in planning, design, and operations, but to urban and rural traffic engineers and enforcement personnel as well.

The review is divided into five basic groups: driver, vehicle, roadway, traffic and environment. A total of some 160 articles is included; each article makes a significant contribution.

The articles seem to indicate that of the driver variables, trip distance has the most significant influence on spot speed. Type and age of vehicle are also predominant in their effect on spot speeds.

In the area of roadway characteristics, those of classification, curvature, gradient, number of lanes, and surface type tend to be of significant influence. Traffic density and vehicle volume dominate the traffic variables and the important environmental factors are usually time and weather insofar as spot speeds are concerned.

This review was prepared by Dr. Joseph C. Oppenlander under the auspices of the Engineering Experiment Station of the University of Illinois and with the cooperation and financial assistance of the Division of Highways, State of Illinois, and U.S. Bureau of Public Roads. Publication of this report was aided in part by a financial grant from the Eno Foundation for Highway Traffic Control, Inc.

Contents

VARIABLES INFLUENCING SPOT-SPEED CHARACTERISTICS

REVIEW OF LITERATURE

Synopsis

Numerous quantitative and qualitative analyses, appraisals, and discussions of vehicular speeds have appeared in the literature of highway and traffic engineering to provide a better understanding of vehicular-speed characteristics. In the planning, design, and operation of a highway transportation system, a knowledge of such characteristics is imperative if sound engineering decisions are to be realized. This comprehensive review of the literature is confined to those articles on vehicular-speed characteristics that appear to be a definite contribution to the disciplines of highway and traffic engineering.

In summarizing driver variables, trip distance has the most significant influence on spot-speed characteristics, whereas passengers in the car and the sex of the driver are of less importance. From the discontinuities evident in the literature on driver characteristics, it is reasonable to assume that driver variables influence vehicular speeds to different degrees in various parts of the country. Vehicle type (passenger car, single-unit truck, combination truck, or bus) and vehicle age appear to have predominant effects on spot speeds of highway motor vehicles. A further subdivision by gross weight is feasible in evaluating spot-speed characteristics of single-unit and combination trucks.

In a recapitulation of roadway characteristics, vehicular spot speeds are most significantly influenced by functional classification, curvature, gradient, length of grade, number of lanes, and surface type. Other elements are geographic location, sight distance, lane position, lateral clearance, and frequency of intersections. Vehicle volume and traffic density exert pronounced influences on spot-speed characteristics. Percentage of commercial vehicles, passing maneuvers, opposing traffic, and access control and also important variables in evaluation of traffic-stream characteristics. Environmental variables such as time and weather are to be considered in evaluation of spot-speed characteristics.

Introduction

SPOT speeds of motor-vehicle traffic are affected by an exceedingly large number of conditions or variables present at the instant when the speed of an individual vehicle is observed at a particular roadway location. The literature, however, contains results of studies on spot-speed characteristics for only a few conditions — no doubt, predicated on a priori considerations of traffic-stream characteristics.

Discussion of these variables and their effects on distributions of spot speeds is categorized into the following five groups: driver, vehicle, roadway, traffic, and environment. Many of these research investigations consider only the relationship of spot-speed statistics with one selected independent variable, all other elements being maintained or assumed constant throughout the experiment. The results thus derived are valid for only the constant level of conditions classed in the above-mentioned groups. Several investigators report experimental findings and statistical summaries on multivariate analyses of two or more traffic-stream restrictions. These reports are reviewed under the appropriate categories, with proper cross-references made in those cases where the individual variables studied fall into two or more classes.

The Driver

The subject of road-user influence on spot-speed characteristics assumes a minor role in the research activities of highway and traffic engineers. The absence of literature in this specialized field is probably due to psychologists' lack of interest and to engineers' deficiency in understanding psychology.

In discussing studies on driver behavior and vehicle performance, Holmes stated that:

> Today, however, few drivers attempt to attain the potential speed of which their vehicles are capable, and in many cases very probably do not even know what the top speeds are. Few drive over our more modern roads at the speeds the surfaces permit. Their driving performance must, therefore, be largely dependent on their inherent personal characteristics. (50)

Apparently the individual motorist can focus his attention on only one thing at a time, but he can oscillate his attention very rapidly among several stimuli. Thus, a driver traveling in heavy traffic tends to realize that he is unable to observe all the events occurring around him and, as a result, may slow down, change position, or trust others to observe him and to compensate for his mistakes. (144) To generalize driver influence on speed statistics, the average individual driving performance has been determined based on such variables as sex, age, driving experience, and occupation, etc.

Sex of the driver has often been considered in analyzing spot-speed characteristics. In general, it has been concluded that women drivers travel at about the same or at a slightly lower average speed than male operators. (22, 51, 65) In a study of vehicular speeds on two-lane rural highways, Lawshe reported in 1940:

> Of the 608 speed records that were obtained, 505 of the drivers were men and 103 were women. These men had a mean speed of 45.5 mph ± 0.40 as compared to a mean of 42.5 mph ± 0.77 for the women. This difference of 3 mph is statistically significant since the critical ratio is 3.45. (66)

On the other hand, studies of vehicle speeds on rural highways in Connecticut and Rhode Island indicated a non-significant difference between spot speeds of men and women drivers. (24, 142) In 1940 a slight difference was observed in the driving practices of men and women in California. Normann stated that:

> The average speed of the vehicles driven by men was practically the same as the average speed of the vehicles driven by women. In the daytime, however, 9.1 percent of the men exceeded the prima facie speed limit of 55 miles per hour compared with 7.5 percent of the women. At night, 8.2 percent of the men and 2.8 percent of the women exceeded 55 miles per hour. (93)

It has further been demonstrated that more men than women drive at dangerously high speeds (23) and that divorced men and women and single women drive faster than married men and women. (93)

In addition to sex, age of the driver has often been considered in the evaluation of driver influence on spot-speed characteristics. Little difference in speed characteristics of various age groups was discovered in investigating passenger-car operation in California. An article published in 1944 concluded that on two-lane, rural highways:

> ...the men, those in the age group from 25 to 30, traveled at the highest average speed in the daytime and also at night. A higher percentage of this group than of any other group exceeded the speed limit.
>
> Speeds of drivers younger than 25 decreased with a decrease in age and speeds of drivers older than 30 decreased with an increase in age, with the exception that at night men over 60 traveled at approximately the same speed as the average driver. Most drivers traveled more slowly at night than in the daytime. The men over 60 traveled faster at night than in the daytime.
>
> The youngest group of women drove faster in the daytime than any other age group but not appreciably faster than the women between the ages of 20 and 30. Fourteen percent of women under 25 years of age exceeded the speed limit in the daytime. All women speeding at night were between 40 and 50 years old. (93)

As a rule, persons under the age range of 40 to 49 years drive somewhat faster than those over this age group. (21, 22, 47, 51) However, as indicated in other studies, very young and very old drivers operated their vehicles at speeds less than the average drivers. (3, 15) On rural highways in New York, Lefeve observed in 1950-1951 a continuing decrease in average speed as age of the driver increased, even when the age of car and the annual mileage were the same for all age groups. (69) From observations of traffic on Iowa highways, youthful male drivers seemed to travel too fast at late hours of the night for their experience and for visibility conditions. (65)

The literature contains only two references to the variable of race in studying motor-vehicle speeds. In South Carolina, Negro drivers with passengers, in contrast to white drivers, were observed operating their vehicles from 3 to 7 mph faster than when traveling alone. (22, 23) In Connecticut in 1939, it was noted that foreign-born male drivers had a slightly lower average speed than native-born drivers. (21)

Driver residence has been classified into two categories for analyzing spot-speed data: rural or urban groups and in-state or out-of-state residents. In 1940, Lawshe reported a mean speed of 39.9 mph ± 0.97 for drivers with rural route addresses and a mean speed of 45.5 mph ± 0.53 for drivers with street addresses, the speed data being representative of travel on two-lane, rural highways. This difference of 5.6 mph was concluded to be statistically significant with a critical ratio of 5.00. (66) Normann also observed in the same year higher speeds of travel for drivers living in urban areas than for those having rural residences. (93) However, in Connecticut in 1939, no difference in the average speeds of these two residence groups was noted. (21)

The subject of in-state or out-of-state drivers has been evaluated in several research reports. It has generally been concluded that out-of-state cars are driven at higher rates of speed than in-state cars. (24, 26, 51, 142) From the California study of driver characteristics, Normann stated that:

> In the daytime, out-of-state men who were uninfluenced by other traffic traveled 2.3 miles per hour faster than California men. Out-of-state women who were uninfluenced by other traffic traveled 1.9 miles per hour slower than the California women. (93)

The study of drivers in Connecticut provided somewhat different results:

> ...out-of-state men drove faster than Connecticut men...,
> out-of-state women drove faster than Connecticut women, the average difference being 3.1 miles per hour for men and 3.2 miles per hour for women. (21)

Lawshe observed a significant difference with a critical ratio of 4.94 in the mean speed of 43.6 mph ± 0.43 for in-state residents and in the mean speed of 47.5 mph ± 0.66 for vehicles bearing out-of-state license plates. However, he concluded that in-state or out-of-state residence itself is not a factor and that those observed more than 25 miles from home could be combined with the out-of-state group. (66)

Several authors reported trip distance as one of the most important factors affecting driving speeds. In general, persons traveling long distances have newer cars than local travelers and drive faster, their speeds increasing with trip length. (22, 23, 24, 47, 51, 142) The following remarks are from the report on the 1940 study of driver characteristics in California:

> There is not a significant difference between speeds of out-of-state drivers and California drivers for corresponding travel distances. The fact that the out-of-state drivers were traveling farther on the day of the study than the California drivers, therefore, accounts for their higher average speed rather than any greater tendency on the part of out-of-state drivers to disregard local speed regulations.

In citing actual figures from this report, Normann presented the following comparisons:

> In the daytime, men going over 400 miles traveled 7.6 miles per hour faster than the men going less than 20 miles. The corresponding value for women in the daytime is 6.1 and for men at night is 6.5 miles per hour. ...These speed differences were, however, not due entirely to the travel distance because the average age of the vehicles driven on the long trips was considerably lower than the average age of the vehicles driven on the short trips.
>
> ...Regardless of the age of the vehicle, the average speed increases with an increase in travel distance. The newer the vehicle, however, the greater is the relative increase in speed. The rate of speed increase is much greater for the shorter travel distances, especially those below 75 miles, than for the travel distances. (93)

On the other hand, in 1939 De Silva observed a positive, linear relationship between average speed and trip distance up to 100 miles: $S = 39 + 0.045\ L$, where S = speed in miles per hour and L = trip length in miles. (21) Another publication indicates that beyond a trip length of 100 miles this relationship is curvilinear, with the average speed increasing at a decreasing rate to an asymptote of about 47 mph. (47) De Silva further concluded that drivers who had traveled short distances were driving at lower speeds than drivers who had traveled long distances, and that drivers who still had long distances to go were traveling much faster than drivers who were near their destination. As recorded in 1940 by Lawshe in Ohio, those drivers having rural route addresses and those residing within 25 miles of the place of speed observation drove more slowly, respectively, than did those with street addresses and those who resided more than 25 miles away. (66)

Non-owners generally drive faster than those who own the vehicle they are operating. (51) This is particularly true of younger drivers. (21) From speed data and driver information collected in California, it has been determined that men not owning the vehicles they were driving traveled slightly faster than men owning the vehicles that they were driving, whereas the opposite was true for women drivers. (93)

With passengers in the motor vehicle the driver tends to reduce speed. Lone drivers travel at higher speeds than drivers with passengers. (21, 24, 51, 142) According to one study, Connecticut drivers tended to travel slightly faster alone or with passengers that were of no relation than with passengers related to them. (21) The same conclusion was reached in the Ohio study, where the mean speed of lone drivers was 46.4 mph ± 0.64 and the mean speed of vehicles with one or more passengers was 44.3 mph ± 0.43, a significant difference of 2.1 mph with a critical ratio of 2.73. (66) In California, however, according to Normann:

> Car occupancy had no effect on the speed at which the men traveled. Women traveling alone went 2 miles per hour faster than the average woman and women with more than 5 passengers went 4.6 miles per hour slower than the average woman. (93)

In only one investigation (which was of Negro motorists in South Carolina) did the average speed ot drivers with passengers exceed the average speed of drivers traveling alone. (22, 23)

Two publications considered the influence of driver occupation on spot-speed characteristics. Results of the 1939 Connecticut study of driver characteristics indicated that:

> Chauffeurs were the fastest drivers and truck drivers in private cars were the slowest. The speed of salesmen was about the same as the speed of the average driver. ... The various occupational groups among women drivers had no marked differences in averages speeds. (21)

Concerning occupation, the findings of the 1940 California driver-characteristics study were considerably different from those in the Connecticut study. Salesmen and those in professions drove at higher speeds than the average driver, but not at higher average speeds than any other group of drivers of newer vehicles on trips of corresponding lengths. This highest-speed group of men drivers traveled approximately 2.5 mph faster during the day and 3.5 mph faster at night than the average driver. Of women driving during the day, students had the highest average speed exceeding the average for all women drivers by 2.3 mph, and 22 percent traveled faster than the speed limit. Business women were recorded as the highest-speed drivers at night, driving on the average 2.5 mph faster than the highest-speed men drivers and 5.9 mph faster than the average women drivers. (93)

Both men and women drivers traveled at approximately the same average speed whether the trip purpose was business or pleasure. (21) However, a larger percentage of drivers on business trips exceeded the speed limit. (93) The literature generally indicates that the length of driving experience for men has no effect on vehicular speed; however, the average speed of women drivers increases as the number of years of driving experience increases. (21, 93)

On the average, drivers with higher annual mileages drive at higher speeds than those with lower annual mileages. The influence of annual travel on spot-speed statistics is more pronounced for men traveling during the day than for men traveling at night, or for women. (69, 93)

Another attempt to measure driver behavior has been the correlation of speed with traffic accidents and violations. In the Connecticut study of 1939, De Silva found: "Drivers who traveled faster than 50 miles per hour had been involved in more accidents, traffic violations, and speeding violations than drivers who traveled between 35 and 45 miles per hour." (21) Several other investigations into driver characteristics in relation to vehicular speed have noted the same behavior. (3, 15, 67, 142)

In a recent factor study of driver attitudes, Goldstein and Mosel demonstrated that women drivers apparently have good attitudes toward speed and violate few speed laws.

The attitude of men drivers toward speed was not significantly correlated with any of the measured variables. (39) In the Ohio study, a significant correlation was observed between the driver's opinion of a maximum safe speed and the actual speed at which he was traveling. Lawshe further concluded that 21 percent of the variation in driving speed can be attributed to the variation in drivers' attitudes. (66)

In 1938, Allgaier reported the influence of several miscellaneous driver variables on spot-speed characteristics. The results are briefly summarized as follows:

1. Driver reaction time — As reaction time increased from 0.29 to 0.66 sec, the actual speed of travel increased from 46.0 to 47.2 mph. Above 0.66 sec the speed of the drivers decreased with increases in their reaction time.
2. Muscular coordination — Persons who scored high on this test drove at an average speed which was 4.4 mph faster than that driven by those who scored low.
3. Vision — Drivers with good vision drove at higher speeds than those with poor vision.
4. Distance judgment — Drivers in the average range of distance judgment had an average speed of 47.5 mph, whereas drivers with good and poor distance judgment had an average speed of 46.4 mph.
5. Blood pressure — Persons with high blood pressure drive slower than those with normal or low blood pressure.
6. Excitability — No definite relationship was observed between speed and driver excitability.
7. Driving skill — Drivers who steer better tended to drive faster.

In summarizing driver variables, trip distance has the most significant influence on spot-speed characteristics, whereas passengers in the car and the sex of the driver alter driving speeds to a lesser extent. From the discontinuities evident in the literature on driver characteristics, it is reasonable to assume that driver variables influence vehicular speeds to different degrees in various parts of the country.

The Vehicle

The influence of the motor vehicle on spot-speed characteristics has been limited to consideration of several variables — normally, features of the automobile or commerical vehicle that were readily observable or easily measured. Most articles on this subject have been written by highway and traffic engineers; automotive engineers apparently devote little time and attention to the performance of vehicles and their respective characteristics under actual travel conditions.

Because the maximum speeds of American cars are higher than motorists desire, Holmes concluded that the vehicle may be eliminated as an element influencing speeds, and that driving speeds are due to the characteristics, personal traits, and limitations of the driver. (51) However, several vehicle characteristics that definitely modify spot speeds are discussed in the literature.

Speed maneuverability, safety, and service are fundamental considerations in passenger-vehicle design; load capacity, type and value of load, and safety dictate the design of freight vehicles. (100) Performance characteristics generally classify highway motor vehicles as passenger cars, single-unit trucks, combination trucks, and buses. Thus, motor vehicles can be grouped according to type because passenger cars and light trucks are designed to operate at relatively high speeds, and heavy trucks are built for maximum operational economy at much lower speeds. (100) This fact is well illustrated in the literature, where reported field studies showed that the average speeds of buses were consistently higher than the average speeds of passenger cars, with trucks traveling noticeably slower. The widest speed ranges were associated with passenger cars, whereas a greater consistency of speed selection was evidenced by trucks and buses. (25, 26, 40, 48, 72, 76, 95, 112, 145) Average speeds of commercial vehicles decrease from light single-unit trucks, to medium trucks, to heavy combination trucks, to heavy single-unit trucks. (24, 26, 33, 37, 74, 105)

Another variable analyzed in studying the effect of vehicle characteristics on speed statistics is the price of passenger cars. There appears to be a slight tendency for drivers of high-priced cars to travel faster than drivers of low-priced cars. (47) In the study of driver behavior in Connecticut in 1939, De Silva states: "Low-priced vehicles as a group averaged 43.9 miles per hour, medium-priced vehicles, 44.7 miles per hour, and the high-priced vehicles, 45.9 miles per hour." (21)

The weight of motor vehicles, both passenger and commerical, has been correlated with their speeds of operation. On the average, heavier passenger cars are driven faster than lighter models (66, 74), although in an investigation conducted in 1950-1951, no significant difference was observed in the average spot speeds for passenger cars of different weights. (69) From the 1960 truck weight-speed study on Indiana highways, it was observed that single-unit trucks with a gross weight of less than 5,000 lb had the highest average speed, 53.3 mph, for all groups of commercial vehicles; combination trucks ranked second with an average speed of 50.3 mph; and the lowest average speed, 48.6 mph, was observed for single-unit trucks with a gross weight of 5,000 lb. Within both the single-unit truck and the combination truck classifications, average spot speeds generally decreased with an increase in the gross weight of the commercial vehicle. (106)

The average road speeds of trucks in freight service on rural highways were observed to decrease sharply as the gross weight of gasoline-powered commerical trucks in the lowest range of engine size and power increased. However, this decrease in speed was less pronounced as the engine horsepower and gross vehicle weight increased. These conclusions were developed by the Bureau of Public Roads from data collected in 1957-1958 on travel characteristics of trucks operating in free-flowing traffic on rural, line-haul service. (60, 61)

The gross weight of a commerical vehicle largely determines the speed on grades.

The sustained speed over the entire length of grade, "grade ability," is reduced by increases in gross vehicle weight and gradient. This speed reduction becomes more critical for heavier trucks as the length of grade increases. Saal concluded in a study made in 1938 that for trucks to maintain reasonable speeds on grades:

1. Grades must be reduced to 3 percent or less, or
2. Engine power must be more than doubled, or
3. Gross vehicle weights must be reduced excessively, or
4. Some combination of the three must be used. (115, 116)

Both the average speed and the horsepower of the automobile have continually increased over the years. (126) In studying the relationship between speed and automobile horsepower, Schmidt determined in 1953 that:

> The highest powered vehicles, while driven more frequently in the high speed ranges, are not driven at any greater maximum speeds than the lower-powered cars, except perhaps for those under 100 horsepower.
>
> As the percentage of higher-powered vehicles on the highway increases, the average speed of traffic may be slightly increased.
>
> The vehicles with from 100 to 130 horsepower appear to be driven as fast as any vehicles of any horsepower.
>
> Inasmuch as vehicles of 100 to 130 horsepower are generally capable of maximum speeds in the range of 85 to 100 miles per hour, it would appear that the critical factor in determining highway speeds is still the driver and not the vehicle. (117)

On the other hand, in England the average spot speeds of high-horsepower passenger cars were approximately 5 mph greater than for low-horsepower automobiles. (37) Furthermore, an increase in the power of the truck motor results in less speed reduction for a particular gross vehicle weight on a given grade. (115, 116)

The maximum speed of motor vehicles is another variable of spot-speed characteristics. Driving speeds have roughly paralleled the maximum speeds of motor vehicles. (47) However, one author concluded that maximum operating speeds are limited by the stopping distance, which depends on the coefficient of friction between the tires and the pavement surface (a roadway characteristic), or on a comfortable rate of deceleration (a driver characteristic). (45)

A number of research investigations on highway travel characteristics have evaluated the influence of vehicle age on spot-speed statistics. The results show a higher average speed for newer models than for older vehicles. (21, 22, 23, 37, 47, 51, 69) Normann concluded from the speed data collected in California: "For a given travel distance, the average vehicle speed decreases as the vehicle age increases, the rate being slightly greater for the older vehicles." (93) This correlation between spot speed and vehicle age was evaluated in the Ohio study by Lawshe as having a correlation coefficient of -0.48 ± 0.04; i.e., newer cars were driven faster than older ones. (66) This is because new cars go faster, ride more comfortably, travel more smoothly and quietly, handle better, and are generally in better mechanical condition. (21, 23)

One exception to this finding was reported in 1953 by Lauer in a study of driver characteristics in Iowa, where in both rural and urban areas older cars were driven by older persons, yet in the country older cars were driven faster than newer models. (65) De Silva noted that out-of-state operators drove both new and old vehicles at higher speeds than did Connecticut drivers, thus indicating that character of the trip as well as age of the vehicle had an effect on speed. (21) Similarly, Normann stated that average speed is a function of both travel distance and vehicle age. (93) A multiple correlation of average speed with driver age, vehicle age, and annual mileage permitted Lefeve to explain 12 percent of the total variation in vehicular speeds. (69)

Vehicle type (passenger car, single-unit truck, combination truck, or bus) and vehicle age appear to have predominant effects on spot speeds of highway motor vehicles. A further subdivision of single-unit trucks and combination trucks by gross weight is feasible in evaluating spot-speed characteristics.

The Roadway

Actual speeds adopted by motor-vehicle operators are greatly affected by various aspects of the roadway. Different rates of travel result from the driver's attempt to evaluate roadway conditions to select a safe speed. Numerous engineering surveys have been conducted to evaluate quantitatively the influences of roadway features on spot-speed characteristics.

For this review, roadway characteristics were classified as the physical elements of the traveled way of the highway transportation system. Regardless of the traffic and environmental conditions, these roadway variables remain constant as a result of the design, construction, and maintenance of the particular highway facility.

Several authors have evaluated vehicular-speed patterns by geographic location. The average speeds on main, rural highways in the central and western regions of the United States have been consistently 4 to 7 mph higher than in the eastern region. (25, 72, 112, 145) In 1950 Raff concluded in his analysis of speeds on rural highways: "Not only are there differences between one region and another, but even within a single region there is considerable variation from one station to another." (112) This variation has been confirmed by other investigations. (25, 92, 97, 145) However, in 1956 a survey of traffic speeds in Canada indicated that, under similar roadway conditions, there was little difference between motor-vehicle speeds on main, rural highways in Ontario and the United States. (26)

On rural highways and urban expressways, drivers can operate their motor vehicles at safe speeds predicated on the geometric design elements of those roadways, whereas vehicular speeds on major streets are regulated by recurring peak traffic volumes, traffic control devices, intersections, and other physical and psychological retarding forces peculiar to the urban environment. (1) Thus, the functional classification of highway facilities with similar characteristics is a variable influencing spot-speed characteristics. On rural highways in New York, speeds of all vehicles progressively increased from primary-feeder to intercity to interstate-and-interregional highway systems. (25) These speed differences by highway type remained consistent throughout the range from low to high traffic volumes. (98) Field observations in 1959 further indicated higher vehicular speeds on toll roads than on free routes for typical traffic volumes. (13, 14)

As the transition from rural to urban travel is made, average spot speeds become lower. (18, 40, 92, 97) In extending the influence of highway functional classification on vehicular speeds to urban roadways, May reported the following ranges of average speeds on various urban arterials in Detroit and Lansing, Michigan: freeways — 40 to 60 mph; unsignalized arterials — 32 to 40 mph; signalized arterials in intermediate areas — 22 to 32 mph; and signalized arterials in downtown areas — less than 22 mph. (77) Speeds are consistently higher on one-way streets than on two-way streets. (28)

From a theoretical consideration of the laws of circular motion, the maximum speed on a horizontal curve is given by the following equations: $S = \sqrt{15\,R\,(e + f)}$ and $S = \sqrt{85{,}900\,(e + f)/D}$, where S = speed in miles per hour, R = radius of curvature in feet, e = rate of roadway superelevation, f = coefficient of side friction, and D = degree of curve. (2, 76) Because the laws of mechanics govern the maximum speed at which a vehicle may transcribe a curved path without flying off at a tangent, horizontal alignment is the principal roadway feature related to spot-speed characteristics.

The findings of numerous investigations on traffic-stream characteristics conclude that vehicular speeds are lower on horizontal curves than on tangent alignments, with the average spot speed approaching the calculated design speed as the degree of curvature increases. (2, 40, 69, 92, 97, 118, 125) In addition, the average spot speed on a low-design speed curve is near the design speed, and the average spot speed on a high-design speed curve is substantially below the design speed, approaching the average speed observed on tangent sections. (2)

Concerning driver performance on horizontal curves of two-lane rural highways, the U.S. Bureau of Public Roads analyzed speed data collected during 1951-1953 in five states for vehicle operation on horizontal curves ranging in curvature from 3 to 29 deg and in sight distance from 200 to 655 ft. A highly significant linear relationship was observed between spot speed and degree of curve. For average operating speeds, the linear regression analysis produced the equation, $S = 46.26 - 0.746\ D$, where S = average spot speed in miles per hour and D = degree of curve, with an adjusted standard error of 3.15 mph and an adjusted correlation coefficient of 0.819. (132, 133) This theoretical equation depicts a curved relationship between speed and horizontal curvature, whereas the actual performance of drivers is a linear relation. A similar linearity on rural roadways was noted in studies of the influence of horizontal and vertical alignment on vehicular speeds in England. As a result, the following multiple linear expression was developed: $\Delta S = 1.22\ D + 1.37\ G$, where ΔS = reduction in average speed in miles per hour, D = average curvature in degrees per 100 ft, and G = average gradient in percent. (37)

From an investigation of the economics of highway alignment in 1937-1938, McCullough correlated average spot speeds with horizontal curvature measured in degrees of total central angle per mile. The average speed on these rural highways in Oregon was found to decrease at a decreasing rate with an increase in the total central angle per mile. (82) In a study of maximum-safe and comfortable speeds (defined as critical speeds) observed on horizontal curves in Illinois, Baldwin empirically developed a third-degree polynomial equation in 1934: $V_C^3 = 466\ R\ (e + 0.2)$, where V_C = critical speed in miles per hour, R = radius of curve in feet, and e = rate of superelevation. This formula was applicable to circular curves that were not spiraled and had an average surface smoothness. However, higher critical speeds were recorded on horizontal curves with spiraled transition sections than on ordinary circular curves. (7)

In A Policy on Geometric Design of Rural Highways published by AASHO, the plot of average running speed versus minimum radii for curves at intersections was curvilinear, with the speed increasing at a decreasing rate as the degree of curvature became less. (2) Taragin supplemented the findings on speed-curvature relations by considering the combined influence of curvature and sight distance on spot-speed characteristics. The results of this multiple curvilinear regression analysis were represented by average-speed contours with an adjusted standard error of 3.09 mph on a graph with curvature as the ordinate, and minimum sight distance as the abscissa. Appraising the influence of curvature and sight distance under comparable conditions, Taragin stated that curvature caused nearly three times as great a change in speed as did sight distance. (132, 133)

Superelevation, another element of horizontal alignment, has been investigated in measuring the influence of roadway characteristics on vehicular speeds. Studies on the Pennsylvania Turnpike in 1940 indicated that highway motor vehicles were operated at faster speeds on highly superelevated curves than on flat curves. Because the average person possesses an inherent sense of balance, this phenomenon was explained as the driver's desire to keep his body vertical by equating the angle of roll to the angle of superelevation. (127) However, in 1954 Taragin reported that for vehicular operation on two-lane, rural highways:

> The amount of superelevation on the curves studied had no effect on vehicle speeds. For this reason the utilized coefficient of side friction on the same degree of curvature is smaller when the superelevation is high than when it is low. ...
>
> Superelevation, as normally used in terms of feet of rise per foot of pavement width, without regard to the sharpness of the curve, bears no relation to the percentage of vehicles exceeding the "safe" speed based on curvature, superelevation, and coefficient of side friction. A close correlation exists, however, between unit superelevation and the percentage of vehicles exceeding the computed safe speed based on

> curvature and superelevation; the "unit superelevation" being the feet of rise per foot of width per degree of curvature. The analysis indicates that few vehicles exceed a safe speed on horizontal curves designed with a unit superelevation or more than 0.005 foot per foot of width per degree of curvature. (132, 133)

The following quotation from Traffic Engineering briefly summarizes the extent to which vehicular speeds are modified by side friction, the remaining element of horizontal alignment:

> Curvature does not result in speed reduction until the cornering ratio required to offset centrifugal force approaches 0.16 of the weight of the vehicle. Since the road user generally attempts to keep the required cornering ratio at or below 0.16, with a given superelevation, any increase in curvature (decrease of radius) which tends to raise this cornering ratio above 0.16 will instead result in lowered speed. (76)

The influence of horizontal alignment on spot-speed characteristics was summarized in the report of driver performance on horizontal curves by Taragin:

> Drivers of free-moving passenger cars do not change their speeds appreciably after entering a horizontal curve. Any adjustment in speed that is made because of curvature or limited sight distance is made on the approach to the curve. ...
>
> Vehicle speeds are considerably lower on horizontal curves than on vertical curves with the same minimum sight distance. (132, 133)

The entire discussion on horizontal alignment has been applicable only to rural roadways and can probably be extended to include at-grade expressways and freeways located in urban areas. However, the horizontal alignment of major streets assumes an insignificant role in affecting the operation and speed of traffic. (1)

The vertical alignment of a roadway has a marked influence on vehicular speeds, which is more pronounced on trucks than on passenger cars. (2) Average spot speeds on downgrades, compared to travel on level tangent sections, are increased on gradients up to 5 percent for trucks and 3 percent for buses and passenger cars. The speeds are reduced on downgrades in excess of these limits and on upgrades for all vehicle types. (92, 97) The effect of grades on vehicular speeds is greater for low than for high traffic volumes. Although the resultant speeds on grades may be less for high volumes than for free-flow conditions, the greater portion of this reduction can be attributed to traffic volume. (113) Whereas cars are not affected to a great degree by normal grades, slow trucks speeds on two- or three-lane highways restrict all vehicles. On this subject Normann expressed the opinion that

> Grades have a somewhat different effect on operating speeds than curves, but the primary reason that they reduce operating speeds is because they generally cause certain restrictions in the sight distance. The fact that trucks travel at slower speeds on grades than on a level has a tendency to increase the number of passings required by a vehicle trying to maintain a certain speed, but if the sight distance was not also reduced by the existence of the grade, the reduced speed of the truck would have only a slight effect on the operating speeds of the other vehicles. (98)

Several extensive investigations on the upgrade speeds of trucks have been reported in the literature. These speeds were determined by the hill-climbing ability

TABLE 1

SPEED REDUCTIONS PER 1000-FT LENGTH OF GRADE FOR HEAVILY LOADED TRUCK

% Grade	Speed Loss (mph)	Crawl Speed (mph)
2	2.0	23
3	5.0	17.5
4	9.5	12
5	15.5	9
6	23.0	7
7	33.5	6

of the commercial vehicle. (159) With the effect of gross vehicle weight previously discussed, the speed on a given grade was reduced almost linearly with an increase in the length of the grade until the crawl speed was reached. The truck then continued up the grade at this minimum speed. (46, 47, 115, 116, 118, 134) Typical values of these speed reductions are given in Table 1, with respective crawl speeds. (158) It was readily apparent that the speed decreased at an increasing rate for steeper grades and/or for heavier gross weights of the vehicle. (46, 47, 115, 116)

The approach speed of the truck at the bottom of the ascent may alter the speed of operation on a grade. If the approach speed is relatively high, the speed at the top of the grade will be greater than that resulting from a lower approach speed. The effect of momentum, which is directly proportional to the square of the velocity, aids the vehicle in negotiating the grade. However, the influence of approach speed diminishes as the length of grade and/or the gradient increases. (134)

Downgrade speeds of trucks were largely controlled by the sight distance and the driver's mental attitude, and they approximated the speed characteristics of passenger cars. (159) From this study conducted in 1949-1950, Willey concludes further:

> Traffic congestion on narrow 2-lane roads was an important cause of reduced truck speeds on downhill grades.
>
> Results of this study gave no indication of any correlation between downhill truck speeds and either gross vehicle weight or pounds per brake horsepower ratios.
>
> There was no indication of any correlation between downhill truck speeds and percentages of downgrade. (157)

Concerning the influence of vertical curves at changes in vertical alignment, drivers reduce their speed as they approach crest vertical curves. The amount of speed reduction appears to increase at an increasing rate with a decrease in the sight-distance. (68)

It may be concluded that the speeds of commercial vehicles on a grade are dependent on gradient, length of grade, gross vehicle weight, approach speed, and power of the truck.

Sight distance has been discussed in considering horizontal and vertical alignment. Regression analyses reported by Taragin in 1954 have established hyperbolic relationships between speeds on two-lane rural highways and minimum sight distances on horizontal curves. These equations are $S = 56.8 - 75.4/(M + 1)$ for inside lanes and $S = 55.6 - 80.2/(M + 1)$ for outside lanes, with adjusted standard errors of 4.55 and 4.14 mph and adjusted correlation coefficients of 0.613 and 0.623, respectively; where S = average spot speed in miles per hour and M = minimum sight distance in hundreds of feet. The author asserted, however, that the change in speed was largely attributed to curvature rather than to sight distance. (132, 133) Observations of traffic-stream characteristics also indicated that vehicular speeds decrease as the percentage of sight distance less than the passing sight distance increases, as measured over the total length of two-lane highways in rural areas. Because restricted sight distances limit the opportunities for passing maneuvers, the actual operating speed is determined by the combined influence of the traffic volume and the percentage of the total roadway length with sight distances insufficient to permit passing. (46, 98, 118)

Several cross-section elements of the roadway have been considered in evaluations of spot-speed characteristics. Speed-trend surveys have indicated that roadways with more than four lanes have operational characteristics similar to four-lane facilities. (113) There is a general tendency for four-lane highways, on which passing is not restricted by opposing traffic, to have higher average speeds than two- and three-lane highways; this discrepancy is more pronounced for divided roadways. (25, 92, 97, 105) However, in 1959 a survey of the characteristics of passenger-car travel showed little difference between overall speeds on two-lane roads and four-lane highways. One exception was noted: in large cities on main urban routes outside of the downtown areas overall speeds on the four-lane facilities were approximately 25 percent greater than on the two-lane routes. (13, 14) Observed speeds on three-lane facilities are only slightly higher than on those with two lanes. (92, 97, 113) A comprehensive speed survey in Canada in 1956 indicated that:

> ...the highest mean speeds occur on 2-lane highways and the lowest means on 3-lane highways. The difference in speeds on 2- and 4-lane facilities is quite small and may be due entirely to chance. (26)

It appears that the number of lanes produces different speed statistics for highways having four lanes or less.

Another variable of the cross-section was the influence of lane position on vehicular speeds. On two-lane rural highways the average speeds on horizontal curves are higher on the inside lane than on the outside lane for equal minimum sight distances. (132, 133) Average speeds of in-bound traffic are consistently 2 to 4 mph faster than those for out-bound traffic on roadway approaches to urban areas. This phenomenon is probably due to drivers traveling at high speeds in rural areas, losing their sense of speed and not slowing down on the approach to a community until the actual environment of the urban center impedes their progress. (21)

The distribution of spot-speeds by lane position on three-lane highways has been observed. The average speeds in the two outside lanes show the normal linear decrease with an increase in volume, whereas the average speed in the center lane is faster and does not change with variation in traffic volume. (46, 92, 97) The analysis of spot speeds on multilane freeways showed a general reduction in average speed as the lane position progressed from the medium to the middle to the shoulder lanes. The marked reduction in speed noted in the curb lane was largely attributed to commercial vehicles in this lane, to the speed-change maneuvers performed by ingress and egress traffic in the outside lane, and to hazards of merging and diverging traffic anticipated by through traffic in the right lane. (29, 31, 40, 58, 59, 73, 78, 80, 81, 86, 119, 149, 154)

The findings of speed-lane width studies are somewhat inconsistent. Regarding the influence of lane width on spot-speed characteristics, Taragin reported:

> For the sections included in this study on which vehicle speeds were typical of modern two-lane highways, pavemend width apparently had no consistent effect on the average speeds of either the free-moving vehicles or those meeting oncoming traffic. ...
>
> Perhaps the most important consideration is that drivers did not travel more slowly on the narrower than on the wider surfaces. (135, 136)

Other writers have made similar inferences in regard to the functional relationship between spot speed and lane width. (10, 33, 76, 119) However, a speed survey in New York during 1950-1951 revealed that the average spot speeds of cars and trucks increased 0.3 and 0.2 mph, respectively, for each additional foot of pavement over

20 ft. (148) Average spot speeds of traffic on streets in London decreased as a straight-line function with increasing traffic flow, although this reduction occurred at higher volume levels as the street width increased: above traffic volumes of a particular level depending on the roadway width, average speed decreased linearly with increasing flow, but was substantially constant below that level. This speed-volume-lane width relationship was generalized by the expression: $S = 31 - (V + 430)/(3W - 18)$ or 24 mph, whichever is less, where S = average spot speeds in miles per hour, V = traffic volume in vehicles per hour, and W = total pavement width in feet. This equation is valid for $W \geq 20$ ft and $S > 10$ mph. (36, 152)

The majority of research findings on speed information, analyzed according to different types and widths of shoulders, indicated that vehicular speeds were not significantly influenced by shoulder width and shoulder type. (40, 114, 119, 130, 131, 139) Studies in Ohio and West Virginia noted a slight increase in average spot speeds as shoulders became wider. (114) The generally accepted hypothesis from an article by Taragin and Eckhardt states: "The speed of moving vehicles is not substantially affected by the width of shoulder, providing the shoulder is more than 4 ft in width." (139)

Little study has been made of the effect of curbs on traffic operations. The presence of mountable curbs in the roadway cross-section does not materially modify vehicular speeds. Barrier curbs tend to reduce average spot speeds by 2 to 3 mph, unless an increase in lane width is made to compensate for these curbs. (76)

A median is provided in the cross-section of the roadway primarily to separate opposing traffic streams. As evidenced from many traffic surveys, average speeds were higher on divided roadways than on undivided facilities in both urban and rural areas. (77, 92, 97, 143) Speed data collected in 1950 on six different types of medians in New York showed that average speeds were not influenced by median type. (8)

The roadway variable of lateral clearance apparently has a definite effect on vehicular speeds as well as on lateral placement of vehicles. Taragin presented the following findings obtained in 1953 in a study of driver behavior as affected by objects on roadway shoulders:

> There is only a slight tendency for passenger car drivers to reduce their speeds when traveling in the lane adjacent to the unoccupied shoulder. On an average, the reduction in speed was less than 1 mile per hour. ...
>
> The average passenger car driver traveling in the lane adjacent to the occupied shoulder reduced his speed an average of 3 miles per hour on two-lane pavements 16 and 20 feet wide, and an average of 1 mile per hour on pavements 22 and 26 feet wide. There was a somewhat greater tendency under these conditions for the drivers to reduce their speeds with a barricade on the shoulder than with a truck or passenger car parked on the shoulder. ...
>
> Truck drivers, regardless of the lane in which they were traveling, were influenced by the shoulder condition even less than passenger car drivers.
>
> The average passenger car driver, meeting another vehicle traveling in the opposite direction at the same place on the highway as the object was located on the shoulder, reduced his speed 2.3 miles per hour if in the lane adjacent to the occupied shoulder, and 1.5 miles per hour if in the other lane. ...
>
> On the four-lane highway there was no consistant tendency for drivers in either lane under any of the study conditions to change their speeds with respect to those under normal conditions. (128, 129)

Studies have discerned a general reduction in vehicular speeds when vehicles parked on roadway shoulders restricted lateral clearances. Except as indicated in the previous quotation, the type of object producing the restricted lateral clearance, its location on the shoulder, and the pavement width made little difference on spot-speed characteristics. (99, 119) Results of speed observations at narrow bridges are somewhat conflicting. Several surveys noted a reduction in speed as the bridge was approached. (76, 111) It was also reported that the restricted lateral clearance of a narrow bridge had no influence on vehicular speeds. (33)

Spot speeds tend to increase as the road surface progresses from low to high types. (113) In Connecticut, average speeds on concrete highways exceeded those on macadem pavements by 3 to 4 mph. (142) In 1938 in Iowa, the speeds on gravel surfaces averaged about 9.5 mph lower than on concrete roads, (88), whereas in another appraisal, speeds decreased 5 mph on unsurfaced roads compared to gravel roads. 90) However, different road surfaces within a comparable type, such as portland cement concrete and bituminous concrete, have similar spot-speed characteristics. (55, 148)

A research project designed to evaluate quantitatively the effect of commercial roadside development, classified here as a roadway variable, on traffic operations was completed in 1960 in North Carolina. Although speeds were determined by the moving-vehicle technique, the average travel speed, no doubt, closely approximated the average spot speed. The average speed of the traffic stream was functionally related to traffic volume by the equations: $S = 44.67 - 0.02\,V$ for developed sections, and $S = 47.67 - 0.02\,V$ for undeveloped sections, where S = average speed in miles per hour and V = traffic volume in vehicles per 15 min. The reduction in speed occasioned by roadside development was constant and independent of traffic volume. (52)

Although little quantitative information is published in the literature, spot speeds on urban roadways tend to decrease with an increase in the number of friction points passed per unit of distance. These points of friction include intersections, at-grade railroad crossings, and hospital or school zones. (57, 76, 77) Speed reductions have also been observed at special pedestrian crossings. (71) In 1959 average overall speeds on roadways with fewer than 2 crossroads per mile were observed to decrease with an increase in the frequency of driveways from less than 10 to 10 - 20 to more than 20 driveways per mile. When the number of crossroads exceeded two per mile, average speeds increased slightly with an increase in the frequency of driveways from less than 10 to 10-20 per mile, but these speed values dropped abruptly for a frequency of more than 20 driveways per mile. (13, 14)

In summary, functional classification, curvature, gradient, length of grade, number of lanes, and surface type are roadway characteristics influencing vehicular spot speeds most; whereas geographic location, sight distance, lane position, lateral clearance, and frequency of intersections are other elements of interest.

The Traffic

Vehicular speeds are controlled to various degrees by traffic streams and operational techniques and devices designed to regulate traffic flows. Considerable attention has been devoted to this subject of highway research.

In the theoretical approach to the mathematical derivation of motor-vehicle movement expressed in quantitative terms, the basic elements of traffic flow are volume, speed and density. The fundamental relationship among these three variables is established by $V = SD$, where V = average volume in vehicles per hour, S = average speed in miles per hour, and D = average density in vehicles per mile. (42, 43) Although this expression is dimensionally valid, it appears that in reality the dependent variable is speed and the independent variables are volume and density.

Thus, the functional relation between spot speed and vehicular volume is an important consideration in the evaluation of traffic-stream characteristics: a vehicle must have unlimited opportunity to overtake and pass on two- or three-lane highways or to change lanes and pass on multilane roadways if the driver is to maintain his desired speed. Investigations conducted on an extensive scale have shown that the speed-volume relationship for a given type of roadway facility in a specific traffic area was represented by a straight-line function with a negative slope when all other modifying variables were identical. As the volume on a given roadway increased, the average speed decreased approximately linearly until the traffic volume had reached the possible capacity of the particular facility under the prevailing roadway and traffic conditions. (10, 12, 17, 31, 37, 38, 40, 46, 57, 80, 81, 92, 94, 96, 97, 98, 118, 146, 151) This linear relation between average speed and traffic volume was also depicted in an investigation of traffic congestion in Melbourne, Australia. In 1956 the following equations were reported: $S = 44.5 - 1.03\ V_1$ for a suburban highway section, and $S = 44.9 - 1.27\ V_2$ for an urban highway location, where S = mean speed in miles per hour, V_1 = volume in hundreds of vehicles per hour for both directions of travel on a two-lane road, and V_2 = volume in hundreds of vehicles per hour for one direction of travel on a four-lane road. The coefficients of correlation were, respectively, -0.91 and -0.90. (35)

The variation in spot-speed data, as well as the mean, decreases with an increase in traffic volume. As the traffic flow becomes greater, the increasing difficulty of passing, the increasing need to pass, and the tendency of faster vehicles to follow slower ones, even on multilane highways, reduce the measures of central tendency and variability of vehicular speeds. (46, 98, 102) Regarding the existence of passing opportunities for traffic on two-lane roadways, the Highway Capacity Manual states that:

> The total number of passings required for all drivers to maintain their desired speed increases as the square of the traffic volume. Actually, however, the total number of passings that occur increases with an increase in the total traffic volume up to 1300 vehicles per hour and decreases rapidly. To maintain free speed, the number of passings each driver would make increases directly as the traffic volume increases. Actually, however, the number of passings made by the average driver increases as the density increases up to 800 vehicles per hour, remains about the same between 800 and 1200 vehicles per hour, and thereafter decreases with a further increase in the traffic density. (46)

On two- or three-lane facilities passing opportunity is dependent on the opposing-traffic volume, whereas on multilane highways the traffic volume in one direction controls the opportunity to change lanes and pass in that direction. Thus, spot speeds are reduced as the opportunities for lane change and passing are limited by the increasing volume of traffic, with faster vehicles slowed to the speeds of slower drivers.

At traffic densities greater than the critical density, both volume and speed are reduced, respectively, below the possible capacity and the optimum speed. This relationship is depicted on the graphical diagram of average speed versus hourly volume as a parabolic curve which begins at the point of possible capacity, decreases at a decreasing rate with a reduction in traffic volume, and ends at the origin representing no traffic flow. (31, 42, 43, 44, 46, 53, 96, 104, 118, 146, 151) As a result, there is a maximum volume and, except at the point of possible capacity, two possible speeds exist at the same volume. The higher speed on the straight-line portion of the graph results when the traffic density is below the critical value, and the lower speed on the curved section of the plot denotes the rate of traffic movement if the critical density is exceeded. (43)

In 1943 Normann reported the equation for average two-lane rural highways with small percentages of commerical traffic: $S = 43 - 0.009\ V$, where S = average speed in miles per hour and V = volume in vehicles per hour. This expression became $S = 48.5 - 0.009\ V$ for high-speed highways and $S = 43 - 0.012\ V$ for average highways with 17 percent or more trucks in the traffic stream. (98) In a recent study by Bunte, linear regression analysis of vehicular speed and volume data produced similar findings to those developed by Normann. The following equations represent travel conditions on two-lane rural highways having little truck traffic and on the same average roadways having 15- to 25-percent commercial vehicles, respectively: $P_{50} = 52.8 - 0.00939\ V$ and $P_{50} = 54.5 - 0.0127\ V$, where P_{50} = 50th-th percentile speed in miles per hour and V = volume in vehicles per hour. (10) Other references in the literature indicated similar uniformities between the intercept and/or the slope of the speed-volume relationship with changes in other influencing travel variables, such as vehicle type (37, 40), functional classification (46, 92, 97, 98), grade (86), sight distance (113), number of lanes (76, 92, 97), lane position (80, 81, 86), roadside development (52), opposing traffic (40), speed limit (46, 96, 98), etc. Therefore, a range of possible average spot speeds exists within these two boundary curves, with the actual value predicated on the traffic volume, the traffic density, and the various driver, vehicle, roadway, traffic, and environmental characteristics of a highway or street location at the time of the spot-speed survey.

When the negative straight-line relationship between spot speed and traffic density ($S = a - bD$) is combined with the basic traffic-flow equation ($V = SD$), the resulting expression relating speed to volume is a parabola ($aS - S^2 = bV$), where S, D, and V are average speed, density, and volume, respectively, and a and b are constants. Several investigations on highway operating characteristics, particularly on freeways, have reported a parabolic relationship between speed and volume. The curvature and drop in speed were very slight until the sharp down-break that occurred just before the possible capacity was reached. As the origin of the parabola was the point defined by the optimum speed and the possible capacity, the speed-volume relation for densities exceeding the critical value was identical to the parabolic relationship discussed previously. (29, 31, 41, 42, 44, 53, 58, 73, 86, 96, 104, 146, 154)

Research work by the Chicago Area Transportation Study led to the theoretical development of a series of speed-volume curves for travel on signalized urban arterials. Based on vehicle arrival rates generated by the Poisson distribution, the average speed on a particular roadway facility remained relatively constant as the volume to capacity ratio increased to 60 percent for signalized streets and 80 percent for rural and urban freeways. The speed of each curve then decreased linearly as this ratio increased beyond the respective limits. The negative slope of these lines increased with increasing values of the best attainable legal speeds, for which the various speed-volume curves were developed. (11) Although these speed-volume relationships were predicated on a theoretical analysis of traffic flow with realistic arrival rates, B.D. Greenshields demonstrated in 1934 that free speeds existed up to a volume to capacity ratio of 30 to 35 percent. Beyond this point, the average speed decreased in a linear or slightly curvilinear fashion with an increase in traffic volume. (41, 42) These field investigations seem to confirm the validity of the theoretical approach in describing the characteristics of traffic flow.

The rate of traffic movement is functionally related to the density of the traffic as discussed previously in the theoretical consideration of vehicular flow on roadways. From data collected in a study of traffic flow in Ohio, Greenshields found a linear relationship with a negative slope between average speed and average density, and the maximum volume or possible capacity of a particular highway facility occurred at the mean density, or critical density, located at the midpoint of the curve. The average spot speed at the critical density, defined as the optimum speed, was located halfway between the maximum average speed, which corresponded to minimum density, and the point of no traffic flow, which represented maximum density. (41, 42, 43) This linear correlation between speed and density was verified in 1956 by field studies of traffic flow on the Merritt Parkway. (53, 104) If the negative linear expression relating spot speed and vehicle volume ($S = a - bV$) is substituted in the general traffic-flow equation ($V = S\ D$), the derived functional relationship between speed and density becomes the following non-linear equation: $S = a/\ (b\ D + 1)$, where S, V, and D are, respectively, average speed, volume, and density and a and b are constants. The graphical representation of this expression is nearly a straight line. This leads to the fairly valid assumption that speed varies with density in a negative linear manner. However, in 1961, curvilinear relationships were reported between average speed and average density, with speed decreasing at a decreasing rate for increasing values of density. (104, 146)

The longitudinal distribution of vehicles in the traffic stream affects the driver's selection of speed. (76) Headway, measured in some unit of time, is the time interval between the passage of successive vehicles going by a fixed point on the roadway. Headway is, therefore, a direct measure of and inversely proportional to volume. Several field observations have considered the influence of time spacings between vehicles on spot speeds. These studies concluded that as the headway decreased there was little or no difference in the spot speeds of successive vehicles until the time spacing was reduced to some critical value falling within the range of 3 to 9 sec. With headways decreasing below this critical value, the average speed of the following vehicle began to decrease rapidly and approach the speed of the vehicle ahead. (29, 46, 94) From traffic data collected at a temporary bridge on the Merritt Parkway in Connecticut in 1956, a headway of 4 sec was determined to be the critical time-spacing value. Below a time spacing of 4 sec, the rear vehicle was usually traveling slower than the one in front, while at headways above 4 sec the rear vehicle was often the faster. (104)

The longitudinal arrangement of traffic is also measured as the gap or distance interval between successive vehicles. Gap, recorded in some unit of length, is an inverse measure of traffic density. Studies dealing with highway capacity have measured the influence of gaps on vehicular speeds. The findings indicated that average spot speeds were little affected until the distance spacing was reduced to some critical value. This critical gap length was not constant, but varied with the speed of operation. Normann stated: "...the average driver starts to be influenced by the speed of the preceding vehicle at a fairly constant time spacing or at a distance spacing that varies with his speed." (94) In regard to the longitudinal distribution of vehicles, from the analysis of traffic data collected on a six-lane freeway in 1950 Forbes concluded: "...drivers are not necessarily affected by the car ahead at a given time spacing, and that a nine-second figure previously reported for two-lane highways probably resulted from the restriction of passing opportunities." This article also implies that drivers tend to maintain a fixed, minimum gap length rather than a minimum headway. (29) The relative number of commercial vehicles in the traffic stream is another traffic variable. The presence of trucks within the range of 0 to 45 percent, apparently has no influence on the average spot speeds of free-flowing vehicles. (17, 41) As the vehicle volume increases, the effect of increasing percentages of commercial vehicles on spot-speed characteristics becomes more pronounced. (92, 97) When the increasing volume limits the opportunities for passing, average speeds decrease linearly with an increase in the percentage of commercial vehicles. The negative slope of this line becomes greater for conditions of heavier traffic movement. (10, 57) As mentioned previously, the negative slope of the speed-volume relationship increases with greater proportions of commercial vehicles in the traffic stream.

Drivers cannot maintain their desired speeds unless the faster-moving vehicles can change lanes and pass the slower-moving vehicles. Therefore, passing maneuvers necessitate speed changes and alter spot-speed characteristics. The influence of the passing maneuver on vehicular speeds has been reported by Prisk as the result of an extensive investigation of passing practices on rural highways during 1938-1940:

1. The average passing driver wants to travel approximately 10 mph faster than the vehicle he passes and about 6 mph faster than the average speed of all traffic.
2. The passing vehicle, on the average, slows down before passing to within 5 mph of the speed of the vehicle to be passed.
3. The normal or desired speeds of the passed and passing vehicles are approximately the same as their average speeds during the passing.
4. There is no appreciable change in the speed of the passed vehicle during the passing.
5. The average maximum speed attained by the passing vehicle during the maneuver is 3 to 4 mph above its normal driving speed and about 10 mph higher than the average for all traffic on the highway. (109)

A comparison of passing practices over the years shows little change. Normann gave the following data for studies conducted in 1938 and 1957, respectively: average speeds of passed vehicles, 35 and 39 mph; average speeds of passing vehicles, 45 and 52 mph; and average speeds of free-moving vehicles, 41 and 45 mph. (96) In 1943 Taragin reported that average speeds of the passing vehicles on two-lane highways ranged from 45 to 52 mph, whereas speeds of the passed vehicles averaged between 32 and 37 mph. (138) The information given by these three authors is very similar in regard to the effect of passing maneuvers on spot-speed statistics. A study of motor-vehicle operation on freeways showed a reduction in the speed of the vehicle when it was between the passing vehicle and another vehicle parked on a bridge shoulder. (119)

Several field investigations of driver characteristics on rural highways indicated approximately the same average speeds whether or not drivers met opposing traffic. (93, 135, 136) However, Normann's study on highway capacity in 1934-1935 depicted a definite influence of opposing traffic on vehicular speeds. A regression of the average spot speed with traffic volumes in the same and opposing directions produced the following multiple linear equation with a multiple correlation coefficient of -0.877: $S = 44.92 - 0.01044\ V_s - 0.00719\ V_o$, where S = average speed in one direction in miles, V_s = traffic volume in one direction in vehicles per hour, and V_o = opposing traffic volume in vehicles per hour. Solutions to this expression are valid only for traffic flow on two-lane rural highways with a density equal to or less than the critical value. This equation is represented on the speed-volume plot as a series of parallel lines, one for each level of opposing traffic volume, with a negative slope and the intercept decreasing as the opposing traffic volume increases. (94) Another study showed that passenger cars reduced their average speeds about 1 to 2 mph when meeting other passenger cars and 3 to 5 mph when meeting commercial vehicles, as compared to operation under free-flowing conditions. Average speeds of truck drivers were approximately 0 to 3 mph and 0 to 4 mph below free-moving speeds when the opposing vehicles were, respectively, passenger cars and other commercial vehicles. (138) In addition, the range of spot speeds of vehicles impeded by opposing traffic appears to be reduced. (40)

Various types of traffic-control techniques and devices are employed to regulate the rate of vehicular movement. The control of access to roadways is usually a prerequisite in the design of modern freeways and expressways. An analysis of spot-speed characteristics was performed in 1954 for various types of access control (full, partial, and none) under different degrees of urbanization (urban, suburban, and rural). In rural areas the degree of access control apparently had little influence on spot speeds, whereas in suburban and urban districts the average speeds increased with greater control of access. Average speeds of traffic on roadways having full-controlled access were not appreciably affected by the degree of urbanization, whereas the speeds on facilities with partial and no control of access increased as the environment changed from urban to suburban to rural. This study reported that average speeds on full-controlled-access highways in rural, suburban, and urban areas were, respectively, 2.5, 10.3, and 20.9 mph higher than corresponding speed values for travel on uncontrolled-access roadways. (79) Frequent access points or frequent at-grade intersections tend to produce a traffic stream carrying a high proportion of slow-speed vehicles. (98) Claffey concluded from an investigation of the characteristics of passenger-car travel in 1959: "The greatest difference in average overall operating speed observed was between the 60.1 mph average on rural 4-lane divided controlled-access routes and the 48-50 mph average on 2- and 4-lane rural routes without control of access." (13, 14)

Vehicular speeds are apparently influenced by the presence, type, frequency, and timing of traffic signals. In Connecticut the average speed on a four-lane divided highway with at-grade intersections was about 49 mph before the installation of traffic signals. After a progressive signal system was installed on this rural facility in 1951, the average spot speed dropped to approximately 45 mph, with vehicles traveling in platoons instead of at random spacing. (49) Although pretimed traffic-control signals cause a reduction in speeds in urban and rural areas, (49, 63) flashing beacons apparently have no significant effect in reducing speeds of vehicles approaching intersections. (153) In regard to the frequency of signals, a statistical investigation of speed and volume characteristics on urban streets in Chicago produced a negative linear relationship between average speed and the number of traffic signals per mile. (57) Another study indicated that average speeds on a major street were increased by changing the signal timing from a simultaneous to a progressive system. (12) The effects that traffic-control signals may have on vehicular speeds can be widely varied between different roadway facilities and types of signal systems. (151)

The influence of traffic signs on spot-speed characteristics is evidently predicated on the type of sign—regulatory, warning, and guide. At the intersection of a minor road with a major highway, on the minor road a "stop" sign reduced approach speeds more than either a "slow" or no sign. This decrease in approach speed became more pronounced with increasing traffic volumes on the major roadway. (123) A "speed zone ahead" sign was observed to produce no significant changes in speed at the location of this sign. (108) A traffic study in Oregon in 1955 revealed that, with or without edge stripes on the pavement, the regulatory sign, "no traveling on paved shoulders," had no influence on spot-speed statistics. (130, 131) The "speed limit" sign, a regulatory device, is reviewed in later paragraphs dealing with speed zones.

"Slow" signs warning motor-vehicle operators are not very effective in reducing vehicular speeds. (54, 123) As the result of a study of traffic patterns at a narrow bridge, Quimby stated in 1947:

> ...the type of warning sign had little effect in controlling the basic desire of the driver to maintain a constant speed. Rather, it would seem that the bridge itself performs the function of the warning sign in that the attention of the driver is focused on the entrance and not on the warning message of the particular sign series. (111)

Many highway agencies have adopted the policy of posting "advisory speed" signs at the entrance to horizontal curves. A summary of before-and-after studies to determine the effect of "safe speed" signs on curves has been presented by Moyer and Berry: "In general, the studies indicate that speed signs result in reduction in speeds on the sharp curves requiring low speeds, but on flatter curves with speeds above 40 mph the changes are not so great in the before and after studies." (89)

In 1954 similar results were reported in a California study where the "advisory speed" signs served to reduce vehicular speeds only for those horizontal curves which required an appreciably slower speed and which contained an element of surprise for the drivers. (147) In Rhode Island, posting of "safe speed" signs on various roadways had no effect on the speeds at which drivers traveled. (24) Sign size and its location on the roadway seem to have little influence on spot speeds. (66)

The purposes of pavement markings are to supplement other traffic-control devices and to convey warning or information to vehicle drivers without diverting their attention from the roadway. The comparison of vehicular speeds on two-lane pavements with and without centerline markings indicated that higher speeds existed on pavements with centerlines. This difference in average spot speeds was approximately 4 mph. (137) Nighttime speeds are further augmented when centerline markings are reflectorized. (123) The influence of "no-passing zone" markings and the effect of two different types of these markings on spot-speed characteristics were evaluated in 1949 by Prisk:

> Average operating speeds 500 feet in advance of the no-passing zones compared were almost identical, and were slightly over 52 miles per hour for vehicles proceeding toward the zone. At a point 300 feet within each of the zones the general average speed level was lower by 2 to 3 miles per hour, and the greater decreases occurred with foreign drivers on the Missouri type marking and with Missouri drivers on the national standard marking. The difference between Missouri and the foreign drivers' reaction to the zone, measured in terms of that speed change, was larger at the Missouri zone, probably because Missouri drivers were better acquainted with the conventional barrier-line location than foreign drivers were with the center-of-the-lane position used throughout Missouri. (110)

The placement of pavement-edge markings near the outside edge of fully paved shoulders has been shown to have no marked effect on spot speeds of the traffic on the two-lane rural highways studied in 1955. However, these reports revealed that the average spot speed was reduced 3 mph when pavement-edge markings were applied near the inside edge of partially paved shoulders. (130, 131) After the installation of pavement-edge markings on rural highways in Connecticut, average spot speeds in the daytime and nighttime increased, respectively, 4.1 and 6.5 mph. In addition, the excess of day-over-night average speeds was reduced from 4.1 to 1.7 mph after the delineation of pavement edges. (160) A research study conducted at three hazardous rural locations on Indiana highways in 1958 demonstrated that the delineation of friction points by roadside reflectors, pavement-edge lines, signs, and channelizing islands did not alter speed patterns during daytime or nighttime travel. (107) Pavement markings, roadside delineators, and combinations of delineators and markings had no effective influence on speeds in the daytime and in the nighttime under conditions of full, partial, and no highway lighting. This finding was reported in 1960 for traffic operations on the Connecticut Turnpike. (140, 141) A study of the merits of painting speed-limit numerals on the pavement at the beginning of speed zones showed no effect on spot-speed statistics. (108)

Traffic engineers establish speed zones with posted speed limits to regulate the rate of traffic movement on various roadway facilities. The benefits accruing from properly determined and properly posted speed limits are generally summarized as permitting the concentration of enforcement on violators of safety, reducing maximum speeds, decreasing the range in speeds and the number of passing maneuvers, and informing people of the actual speeds being traveled within the speed zone. (18) The controlling effect of speed limits on the speed-volume relationship has been described by Normann. Average speeds at very low traffic volumes are governed by speed limits. The speed values influenced by speed limits are less than the average speeds controlled by traffic densities at corresponding volume levels. With increased volumes, average speeds decrease in a linear manner with a slope that is less than that of the normal speed-volume relation. At specific traffic volumes, depending on the actual speed limit, the speed-limit line intersects the speed-volume line. This critical volume increases with a reduction in the speed limit. At higher volumes beyond this point of intersection, average speeds are influenced by traffic volumes rather than speed limits. (96, 98, 118)

The results of many studies on the influence of speed regulations on spot-speed characteristics appear in the literature; however, little consistency exists in the findings. Speed regulations in urban areas seem to have no significant effect on the speeds adopted. From speed observations of local and through traffic in Champaign, Illinois, on major streets with no posted speed limits and with posted speed limits of 20, 25, 30, 35, and 40 mph, Wiley, Matyas, and Henberger concluded in 1949:

1. Traffic consistently ignores posted speed limits and even the absence of speed limit signs, and runs at speeds which the drivers consider reasonable, convenient, and safe under existing conditions.
2. Drivers do not operate by the speedometer but by the conditions they meet.
3. The general public gives little attention to what speed limits are posted. (156)

Similar results were observed in Nashville, Tennessee, by Deen: "Posted speed limits in Nashville have little, if any, significant effect on traffic speeds, regardless of whether the posted limit is set at even multiples of 5 mph or not." (20) Elmberg and Michael also conlcuded from traffic surveys in several Indiana cities during 1958-1959: "...drivers, in general, do not drive according to posted speed limit signs. Most of them select a speed which they consider proper, reasonable, and safe for conditions prevalent, regardless of regulations." (27) Other publications advance the same conclusion. (6, 18, 70, 103, 124)

However, several research investigations have indicated that average spot speeds were reduced when reasonable speed limits were posted on urban roadways previously not speed zoned. (9, 16, 34, 64, 91) A statistical analysis of urban traffic data collected in Chicago produced a positive, linear relation between average speed and posted speed limit. (57) Raising speed limits on urban roadways apparently has no significant influence on spot-speed characteristics. (9, 18, 34, 56, 155) From a study of raising urban speed limits, Avery stated in 1960: "The tendency is for any speed change to be small and to bear no relationship to the change in the limit. There appears to be little or no relation between the amount of the limit raise and any changes in actual speeds." (4) In addition, the lowering speed limits in urban areas of St. Paul, Minnesota, had little effect on vehicle speeds, and a slight tendency to increase was noted for the mean and 85th-percentile speeds. (155)

Conflicting evidence also exists in appraising rural speed zoning. Mohr concluded from studies in Wisconsin: "...when speed limits on rural highways are reasonably lowered through properly applied speed zoning, there is generally a substantial reduction in the average and 85th-percentile speeds of all motor vehicles." (85)

This same conclusion has been observed in other investigations of speed zoning in rural and intermediate areas. (17, 32, 40, 95) Several traffic research reports reveal that erecting speed limits on rural highways produced no significant changes in spot-speed distributions. (32, 33, 70, 124) From data collected in a comprehensive before-and-after survey of traffic speeds on Illinois highways, reductions in vehicular speeds were observed where new speed zones were established and where existing speed limits were lowered, whereas no changes were apparent in the spot-speed characteristics where existing speed limits were raised. (62) In summary, drivers apparently respond favorably to speed limits that seem reasonable, proper, and safe for existing travel conditions and disregard speed limits that appear unreasonably high or low.

The modification of vehicular speeds occasioned by enforcement activities has been the subject of several research projects. These findings generally implied that on rural highways increasing enforcement caused no significant decrease in average spot speeds, the proportion of drivers exceeding the legal limit did not decrease after the application of enforcement, and an increase in the level of enforcement produced a statistically significant decrease in the variance of the spot-speed distributions. (56, 84, 120, 121) As the degree of enforcement was increased, a study in Nebraska indicated that fewer vehicles traveled at exceedingly high speeds. (56) Recent publications on freeway operations note that average speeds recorded on freeways with no or lightly-enforced speed limits were higher than those values indicative of freeways with well-enforced speed limits. (31, 96)

Although the literature contains many articles on the relation of speed to various types of traffic accidents, little information is available on the influence of accidents on vehicular speeds. It is postulated that reductions in traffic speeds depend mainly on the severity of the accident, the traffic volume in relation to the roadway capacity at the time of the accident, and the time required to remove the disabled vehicles. (151)

Vehicle volume and traffic density exert pronounced influences on spot-speed characteristics. Percentage of commercial vehicles, passing maneuvers, opposing traffic, and access control are also important variables that should be considered in evaluation of traffic-stream characteristics.

The Environment

The operation of motor vehicles on highways is subject to various influencing conditions that are cyclic or random in occurrence. These variables are independent of the driver, vehicle, roadway, and traffic elements previously discussed and are presented under the general classification of environment. Little attention has been devoted to research on environmental variables because they are difficult to control and to express in terms of quantitative measures.

Variations in vehicular speed have been analyzed according to the various time cycles of year, season, month, day, and hour. Since 1942 the average speeds on main rural highways have continued to increase each year. The rate of this yearly increase in average spot speeds was approximately 1.0 mph per year. (5, 31, 48, 96, 112) Other measurements of vehicle speeds during different seasons of the year have indicated that average speeds are highest in the fall and winter, intermediate in the spring, and lowest in the summer. (112, 142) A study of the variability of fixed-point speed measurements in Wisconsin, reported in 1959, showed statistically significant differences between monthly mean spot speeds; that is, vehicular speeds were not the same for different months of the year. (122)

Conflicting statements appear in the literature in regard to daily fluctuations in spot speeds. The previously mentioned investigation in Wisconsin disclosed that real and significant differences existed in speed characteristics between the various days of the week. On the other hand, several speed surveys evidenced no significant variation in vehicular speeds for different days of the week. (15, 17) In 1957 no difference existed in mean speeds at similar volumes between weekday and weekend drivers on an expressway in Detroit, Michigan. (73) Other authors reported that only on Sunday do spot speeds differ materially from the operational pattern of the remainder of the week; Sunday speeds were lower than those observed on other days. (23, 83)

The influence of the hour of the day on speed patterns is likewise subject to disagreement. Several research studies found no significant differences in spot speeds during different hours of the day. (15, 17, 78, 80, 149, 156) Other investigators of traffic-stream characteristics reported a reduction in average speeds as the day progressed from early morning hours to later evening hours. (24, 142) There is evidence to suggest a definite hourly variation in vehicular speeds, with a significant difference in average spot speeds between the hours of the day. (83, 122)

Observation of vehicular speeds for day and night travel measures the influence of light conditions on the rate at which motor vehicles are operated. As many articles on highway travel characteristics indicate, average spot speeds in the daytime are about 1 mph higher in urban areas and 2 to 8 mph higher in rural areas, depending on the particular roadway facility, than the corresponding speed values during the nighttime. (20, 23, 33, 40, 46, 73, 75, 83, 92, 97, 107, 111, 142, 150, 160) However, several speed-characteristic studies did not show significant differences between average daytime and nighttime speeds. (80, 135, 136, 140, 141, 149) Some reports indicate that trucks and buses operate at higher average speeds during the night than during the day. (107, 138, 144) In 1939 an investigation of driver behavior under night travel conditions demonstrated that average night speeds with or without highway illumination were lower than average day speeds, and that average speeds were slightly less with highway lighting than with no fixed illumination. (75, 150) A recent appraisal of the value of highway illumination on traffic operations showed no significant differences with respect to average vehicle speeds for various conditions of illumination and delineation on the Connecticut Turnpike. Variations in daytime speeds were as great as or greater than those between day and night speeds. (140, 141)

Weather conditions have a tendency to modify vehicular speeds because of the reduction in visibility and the impairment of surface conditions. The general effect of inclement weather is to lower spot speeds, with the amount of reduction depending on the severity of the weather. (33, 40, 73, 74, 151) Tilden has described the influence of weather on the rate of highway travel: "The effect of weather on speed ranged from stopping altogether during bad snowstorms to driving at high speeds on clear, crisp winter mornings when the road was free from snow or ice." (142) However, unfavorable surface conditions appear to produce greater speed reductions than low visibility. (23, 76) Reductions in average spot speed attributed to weather conditions ranged from 7 to 23 percent for poor visibility, 4 to 38 percent for unfavorable road surface, and 10 to 24 percent for both impaired visibility and road surface. (142) Other traffic reports present evidence of reduced speeds on snowy or icy pavements. (30, 33) The exact influence of wet pavements on spot-speed characteristics is not definitely defined in the literature, with indications of both a reduction (74, 123) and no significant difference (75, 123, 125, 150) in vehicular speeds on wet as compared to dry pavements.

As evidenced in a research report of 1959, presence of pneumatic road tubes on the pavement produced a significant bias in observed speeds, with the measured value consistently lower than the true spot speed. This systematic error became more pronounced with increasing speeds. Tube spacing, tube color, and legal speed limits were observed to affect the magnitude of error. It was concluded that systematic error resulting from the placement of road tubes on the highway can not be compensated for by means of corrective constants. (19)

Environmental variables of time and weather present important considerations for the actual evaluation of spot-speed characteristics.

Although many research studies have been conducted to assess the influences of various travel conditions on vehicular speeds, few investigators have applied the techniques of statistical inference in the evaluation of their experimental findings.

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Subject Index

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