VOL. 34, NO. 6

FEBRUARY 1967

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

West Potomac Park in Lincoln Memorial area, Washington, D.C., and interchange for Arlington Memorial Bridge.

PUBLISHED
BIMONTHLY
BY THE BUREAU
OF PUBLIC ROADS,
U.S. DEPARTMENT
OF COMMERCE,
WASHINGTON

IN THIS ISSUE

Gap Utilization, A Warrant for Traffic Signal Control, *by R. D. Desrosiers* 121

Vehicle Speed Estimation From Visual Stimuli, *by Santo Salvatore* 128

Travel by Motor Vehicles in 1963, 1964, and 1965, *by Alexander French and T. S. Dickerson, Jr* . . . 132

New Publications 127

ERRATA

In the article *State Highway Patrol Functions and Financing,* in the December 1966 issue of Public Roads, *A Journal of Highway Research,* volume 34, No. 5, on page 111, column 1, the following statement was inadvertently included. "The increased mileage of divided highways is followed by increased traffic accidents and fatalities each year." The following statement is more accurate. "Traffic accidents continue to increase despite the increase in mileage of divided highways. Accident rates on divided highways are much lower than those on undivided highways."

U.S. DEPARTMENT OF COMMERCE
JOHN T. CONNOR, Secretary

BUREAU OF PUBLIC ROADS
REX M WHITTON, Administrator

Public Road

A JOURNAL OF HIGHWAY RESEARC

Vol. 34, No. 6 *February 196*

Published Bimonthly

Muriel P. Worth, ***Editor***

THE BUREAU OF PUBLIC ROAD

WASHINGTON OFFICE
1717 H St. NW., Washington, D.C. 20235

REGIONAL OFFICES

No. 1. 4 Normanskill Blvd., Delmar, N.Y. 120
Connecticut, Maine, Massachusetts, New Ham shire, New Jersey, New York, Rhode Islan Vermont, and Puerto Rico.

No. 2. 1610 Oak Hill Avenue, Hagerstown, M 21740.
Delaware, District of Columbia, Maryland, Oh Pennsylvania, Virginia, and West Virginia.

No. 3. 1720 Peachtree Rd. NW., Atlanta, Ga. 3032
Alabama, Florida, Georgia, Mississippi, Nor Carolina, South Carolina, and Tennessee.

No. 4. 18209 Dixie Highway, Homewood, Ill. 604
Illinois, Indiana, Kentucky, Michigan, and W consin.

No. 5. Civic Center Station, Kansas City, M 64106.
Iowa, Kansas, Minnesota, Missouri, Nebrask North Dakota, and South Dakota.

No. 6. 819 Taylor St., Fort Worth, Tex. 76102.
Arkansas, Louisiana, Oklahoma, and Texas.

No. 7. 450 Golden Gate Avenue, Box 36096, S Francisco, Calif. 94102.
Arizona, California, Hawaii, and Nevada.

No. 8. 412 Mohawk Bldg., 222 SW. Morrison Stre Portland, Oreg. 97204.
Idaho, Montana, Oregon, and Washington.

No. 9. Denver Federal Center, Bldg. 40, Denv Colo. 80225.
Colorado, New Mexico, Utah, and Wyoming.

No. 10. Post Office Box 1648, Juneau, Alaska 998
Alaska.

Eastern Federal Highway Projects Office— Region 15.
1000 N. Glebe Rd., Arlington, Va., 22201.

No. 19. Apartado Q, San Jose, Costa Rica.
Inter-American Highway: Costa Rica, Guatema Nicaragua, and Panama.

Public Roads, A Journal of Highway Research, is sold by the Su intendent of Documents, Government Printing Office, Washing D.C. 20402, at $1.50 per year (50 cents additional for foreign mail or 25 cents per single copy. Subscriptions are available for 1-, 2 3-year periods. Free distribution is limited to public officials a ally engaged in planning or constructing highways and to instruc of highway engineering. There are no vacancies in the free li present.

Use of funds for printing this publication has been approved by Director of the Bureau of the Budget, March 16, 1966.

Gap Utilization,
A Warrant for Traffic Signal Control

Y THE OFFICE OF
ESEARCH AND DEVELOPMENT
UREAU OF PUBLIC ROADS

Reported by [1] RICHARD D. DESROSIERS,
Highway Research Engineer,
Traffic Systems Division

Results of the research reported in this article show that a warrant for traffic signal control is feasible based on the relation of the gap availability in the traffic on major streets to the lag or gap acceptance characteristics of the driver on minor streets. Properly operated traffic signals for allocating time and space to the different movements at intersections and other street and highway locations are undoubtedly necessary, but traffic signals are not the answer to all traffic problems at intersections. The volume of traffic in itself does not determine the need for signals; distribution and utilization of available gaps in traffic flow on main streets by vehicles or pedestrians on minor streets should be of critical consideration. The methodology developed in the research reported in this article can be applied to any unsignalized intersection. To use the methodology accurately, however, it is necessary that the traffic engineer obtain data on the variations in the distribution of available gaps and characteristics of gap acceptance at the individual intersections studied.

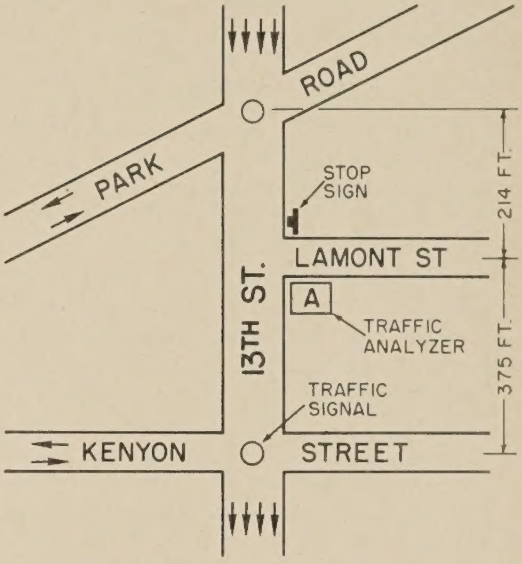


Figure 1.—Test site.

Introduction

A HIGHWAY traffic signal is a means of allocating time and space to the different ovements necessary at intersections and ther street and highway locations. Properly cated and operated, traffic signals can rve several purposes:[2]

- They provide for orderly movement of affic. Where proper physical layouts and ontrol measures are used they can increase e traffic-handling capacity of the interction.
- They reduce the frequency of certain ypes of accidents.
- Under conditions of favorable spacing, hey can be coordinated to provide for ontinuous or nearly continuous movement of raffic at a definite speed along a given oute.
- They can be used to interrupt heavy raffic at intervals to permit other traffic, edestrian or vehicular, to cross.
- They represent a considerable economy, s compared to manual control, at interections where the need for some definite eans of assigning right-of-way first to one ovement and then to another is indicated y the volumes of vehicular and pedestrian raffic or by the occurrence of accidents.

The necessity for and the usefulness of raffic signals is unquestionable. However, any laymen and some engineers believe hat traffic signals are the answer to all traffic problems at intersections. This belief has caused public and private pressures on the practicing traffic engineer or agency with the responsibility for the traffic engineering function.

The existing warrants for traffic signal control are presented in the manual on uniform traffic control devices, page 185. The manual also includes as desirable information the number and distribution of gaps in vehicular traffic on the main street when traffic from the minor street finds it possible to use the intersection safely. This point is very important and should receive additional study. It is reasonable to assume that no traffic signal should be installed if all traffic on the minor street can be accommodated without conflict by existing gaps in the traffic on the major street. This is the basis for the major premise for the study reported here; namely, that the volume of traffic in itself may not be critical but the distribution and utilization of available gaps on the main street by vehicles from the minor street may be.

The purpose of the research was to determine whether a warrant for traffic signal control could be established by using the relation between the availability of gaps in the traffic stream on the major street and the lag and/or gap acceptance by the driver on the minor street. Definition of the following terms is necessary for an understanding of the procedures and results of the research reported in this article.

Gap.—A gap is the elapsed time between arrival of successive vehicles on the main street at a specified reference point in the intersection area.

Lag.—A lag is that part of a current gap remaining when a vehicle on the minor street arrives; in other words, the elapsed time at an intersection between arrival at the intersection of a vehicle on the minor street and arrival of the next vehicle on the main street.

Gap or lag acceptance.—A gap or lag is either accepted or not accepted by the driver of the vehicle on the minor street. A lag is accepted if the vehicle on the minor street crosses the intersection or enters the main street before arrival of the next vehicle on the main street. A gap is accepted if the vehicle on the minor street crosses or enters between two vehicles on the main street.

Gap utilization.—Gap utilization refers to the probability that the length of an available gap in the traffic on the main street is the same as the gap length acceptable to the driver of the vehicle on the minor street. That is, the gap is both available and acceptable, and the result is a gap in the traffic on the main street being used by a vehicle on the minor street.

To accomplish the objective of the study, information had to be obtained on gap distribution in a traffic stream and the characteristics of the driving population as to gap acceptance and to relate this information by use of acceptable statistical probability techniques. The general procedure used is described in the following paragraphs. Gap distribution (availability) information was obtained by collection of field data on 13th Street NW., Washington, D.C. Driver characteristics on gap acceptance were obtained from a survey of the existing literature.

The probability of the availability or the acceptance of a gap of any given size was

---

[1] Past Presidents Award Paper presented at the 36th nnual meeting of the Institute of Traffic Engineers, Cininnati, Ohio, Oct. 11, 1966.

[2] *Manual on Uniform Traffic Control Devices for Streets nd Highways*, by the National Joint Committee on Uniform raffic Control Devices; published by U.S. Department of ommerce, Bureau of Public Roads, Washington, D.C., 961, p. 155.

determined by using the probability distributions developed for gap availability and acceptance. The probability of a gap of a given length being *both* available and accepted was computed by taking the product of the two individual probabilities. By summing the product probabilities for all turning movements and considering all gap lengths, the percentage of total gaps on the main street that would be expected to be utilized by vehicles from the minor street in 1 hour were established. This percentage was converted into an expected number of gaps utilized, which is the same as the number of vehicles that can be accommodated on the minor street when the intersection has no traffic signal control.

Conclusions

The results of the research reported here show that a warrant for traffic signal control is feasible based on data on the availability of gaps in the traffic stream on the major street and the gap acceptance characteristics of the drivers on the minor street. The methodology developed in the study reported here can be applied to any intersection that does not have a traffic signal.

Gap availability and acceptance by the driver vary in relation to geometrics, sight obstructions, type of entering maneuver, traffic volume, speed of the vehicles on the main street, and sequence of gap formation during periods of heavy traffic. The extent of importance of this variation on the resultant number of gaps available or accepted is unknown. Therefore, the methodology requires that the user obtain data on the distribution of available gaps and the drivers characteristics on gap acceptance at each intersection studied. Future research should include an examination of the extent and importance of all parameters on the resultant answers; that is, the number of gaps utilized. Relations between the variables could be presented in a graphic form similar to the one used in the *Highway Capacity Manual, 1965*, Highway Research Board Special Report 87. Presentation in this manner would permit the practicing traffic engineer to enter inventory data in the manual and thus establish the expected number of gaps utilized. Such simplicity of application would encourage more use of vehicular gap characteristics when traffic signal requirements are being considered. Hopefully, the installation of unneeded traffic signals would thereby be reduced.

Test Site and Equipment

Thirteenth Street, an arterial street in Washington, D.C., with a progressively timed signal system was used as the study site, which is shown in figure 1, to obtain the gap availability information required. This street is a 4-lane arterial on which traffic is 1-way southbound from 7 to 9:30 a.m.; 1-way northbound from 4 to 6:30 p.m. and 2-way for the remainder of the day. Data used in the study were collected only during the morning rush period when all traffic was southbound in each of the 4 lanes. Traffic during the study period had essentially the same composition at all times data were collected: passenger cars, 97 percent; buses, 1 percent; and trucks, 2 percent. The traffic signals were coordinated for a 27 m.p.h. speed of progression. An 80-second cycle and a through band for traffic of approximately 55 seconds were in effect.

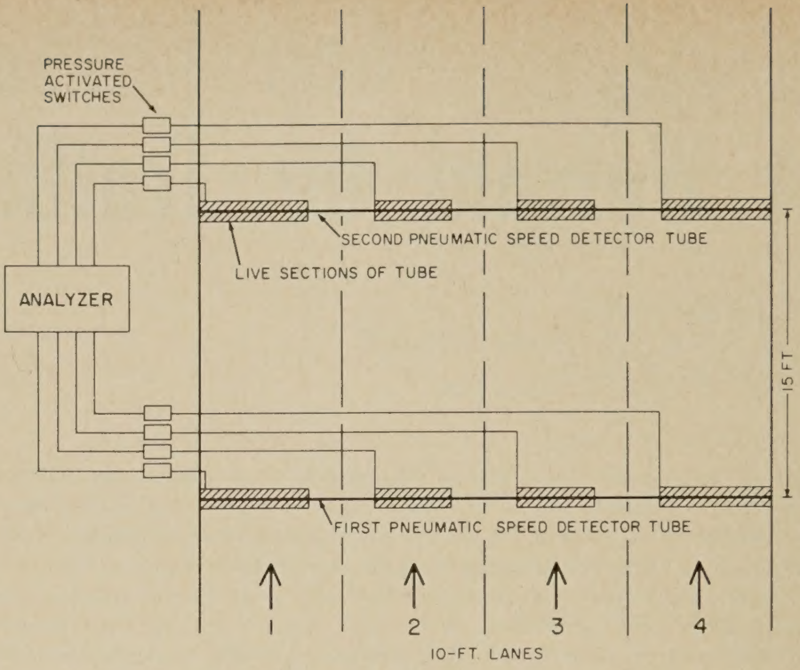


Figure 2.—Layout of speed detection equipment.

Speed, volume, and headway information were obtained with the Bureau of Public Roads traffic analyzer. The traffic analyzer is a mobile unit containing an assembly of equipment that provides traffic information by an automatic digital recording of speed, time headway, volume, and lateral placement data at a single point on a street or highway. All capabilities of the analyzer, except for recording lateral placement, were used. The equipment consists essentially of four adding machine recorders that have specially designed solenoids mounted over the keys, a digital timer to register the time of day for each recording, and a speed timing device. Speed is detected by use of two pneumatic pressure tubes that form a speed trap. The sequence of operation is initiated when a vehicle actuates the first speed detector tube. This electrical contact starts the speed timer and activates the placement detector for that location. When the front wheels of the vehicle pass over the second tube of the speed detector, the reading in units of one-hundredths of a second is recorded, the reading of the timer in ten-thousandths of an hour is transferred to the recorder, and a control signal activates the adding machine, which prints these data.

A typical layout of the speed detectors is shown in figure 2. Two pneumatic tubes were spaced 15 feet apart. Speed by lane was obtained by alternating live and dead areas—areas of detection and nondetection, respectively—along the pneumatic tubes. A dead area of 5 feet, 2½ feet on either side of the lane line, was provided between adjacent lanes. The live area was extensive enough for positive detection of all vehicles in the lane, but small enough to eliminate fa actuations by vehicles traveling in adjac lanes. Detection was obtained and sign were transmitted to the analyzer by press actuated switches attached to each live ar

A section of a typical 14-column printi tape output is shown in figure 3. Time day in ten-thousandths of an hour was corded in columns 1 through 4. Columns through 10, in which lateral placement d are recorded, were not used in the study ported here. The time in one-hundredths a second required for the vehicle to trave the trap distance was recorded in columns and 12. Column 13 was used to show whet the vehicle originated above Monroe Stre off Monroe Street, off Park Road, or Lamont Street. The last column was used

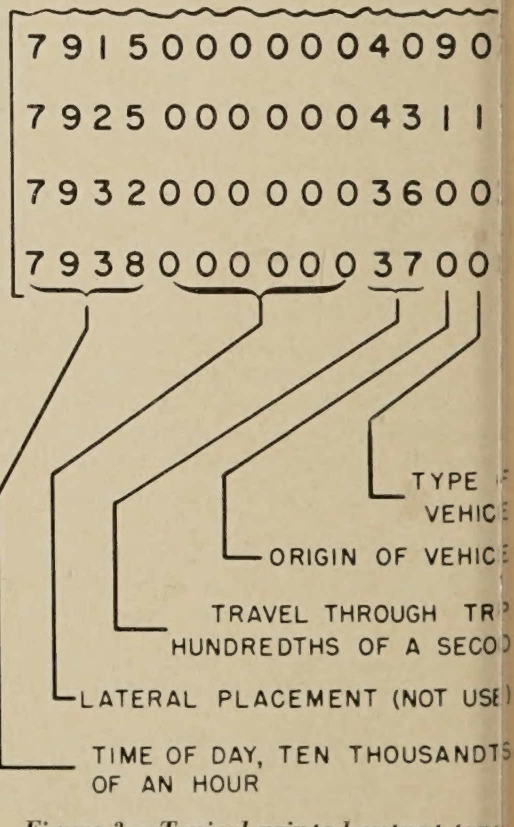


Figure 3.—Typical printed output tap

ode vehicle type. Coding of vehicle origin nd type was performed manually; an operator as stationed at each recorder to observe and lassify each vehicle and to depress the key r the appropriate code light. An explana-ion of the coding in columns 13 and 14 is iven in table 1.

Analysis

The analysis of distribution of gaps in a raffic stream cannot be separated from olume and speed characteristics because dis-ance between vehicles decreases with an icrease in volume and increases with an icrease in speed. This interrelation pre-ludes the analysis of any of the three items ithout discussing the characteristics of the emaining two as a base or background ondition.

raffic volume

Traffic volume during the study period is eported in figure 4. Volume is shown for ach 12-minute period from 7:18 to 9:30 a.m. he peak 12-minute volume of 710 vehicles ccurred during the period from 8:06 to 8:18 .m. The traffic volume by lane is reported n figure 5. Each of the center lanes carried onsiderably more vehicles, in all time pe-iods, than the two-curb lanes. Traffic in he right-curb lane was especially low for all ime periods studied. Even in the peak hour his lane carried only about one-half to two-hirds the traffic volume carried by the center anes.

Table 1.—Traffic analyzer coding

Code:	
	COLUMN 13
0	Vehicle on 13th St. north of Park Rd.
1	First vehicle clearing green period on 13th St.
2	Vehicle entering 13th St. from Lamont St.
3	Vehicle entering from Park Rd., eastbound.
4	Vehicle entering from Park Rd., westbound (left turn).
9	First vehicle clearing green period on Park Rd.
	COLUMN 14
Code:	
0	Passenger car.
1	Pickup or panel truck, single tires on rear.
2	Single-unit truck, dual tires on rear.
3	Single-unit truck, tandem axle, dual tires on rear.
4	3-axle truck tractor semitrailer, dual tires on rear.
5	4- or 5-axle truck tractor semitrailer, dual tires on rear.
7	Towing vehicle or passenger car with trailer.
8	Motorcycle or scooter.
9	Bus (commercial).

Table 2.—Speed data by lane

Lane	Speed		
	Mean	Standard deviation	85th percentile
	M.p.h.	*M.p.h.*	*M.p.h.*
1	23.0	4.74	27.5
2	24.6	5.25	29.0
3	24.0	5.01	28.2
4	24.5	5.67	29.3

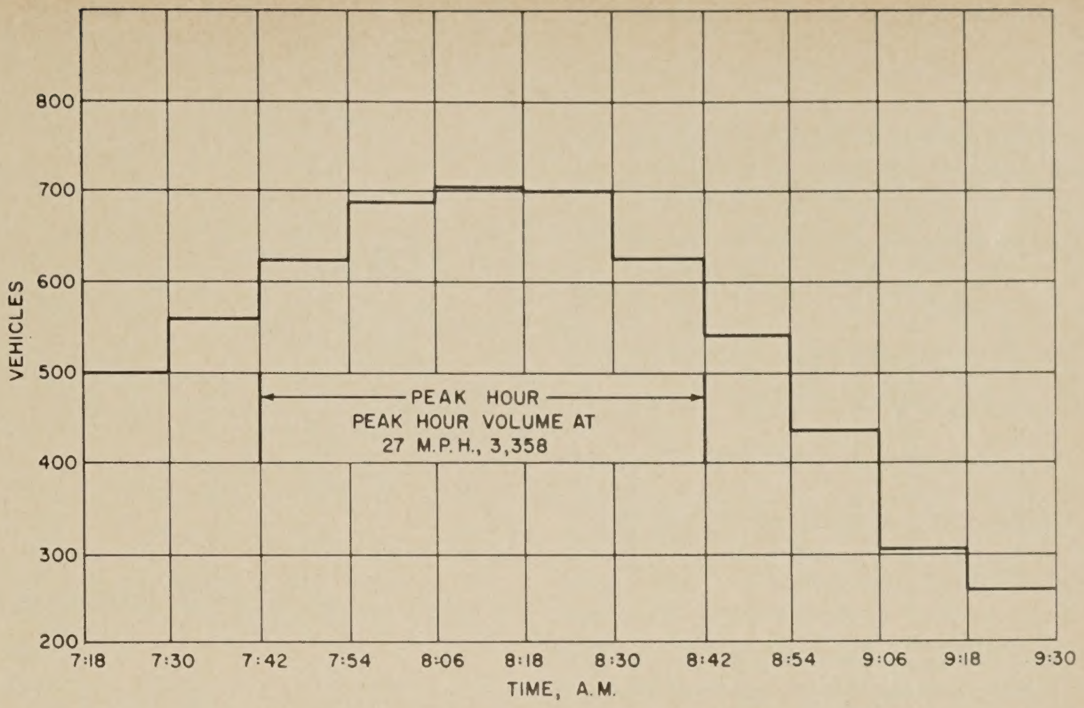


Figure 4.—Average number of vehicles by 12-minute periods, all 4 lanes.

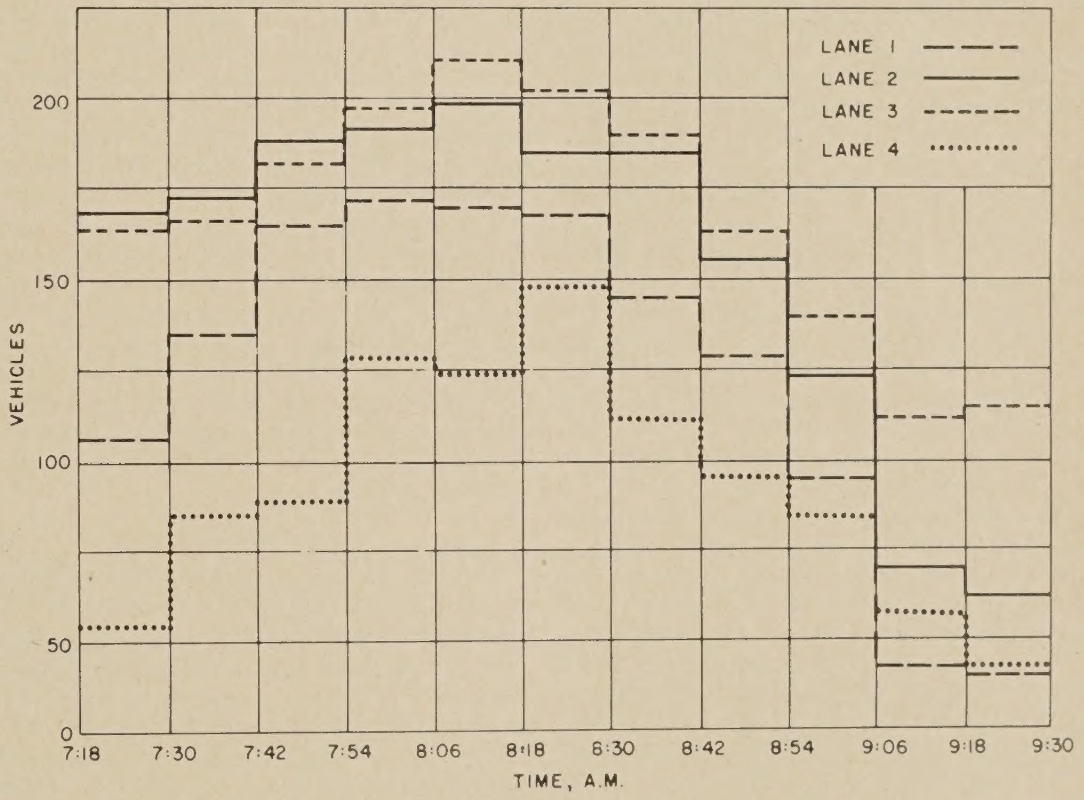


Figure 5.—Average number of vehicles per lane by 12-minute periods, southbound.

Vehicle Speed

The distribution of spot speeds is shown in figure 6. The speeds of all vehicles during the period from 7:30 to 9:30 a.m. are included. The mean speed was 23.9 m.p.h. and the standard deviation was 5 m.p.h.; at this mean speed and standard deviation, 67 percent of all vehicles can be expected to travel at speeds from 18.9 to 29.9 m.p.h. and 95 percent can be expected to travel at speeds from 13.9 to 33.9 m.p.h. The 85th percentile speed, a speed often used by traffic engineers to establish speed limits, was 28.4 m.p.h. Speed characteristics by lane are shown in table 2. The speed in lane 1—the far left lane when travel is southbound—was significantly slower (5-percent level) than in the other 3 lanes, where speeds were nearly identical. The differences in mean speed, 85th percentile speed, and standard deviation for the different lanes were small.

Gap Availability

The distribution of all gaps observed during the study period is presented in figure 7. The majority of the gaps (83.5 percent) was in the range of 0.5 to 1.5 seconds, 6.5 percent of the gaps were in the range of 1.5 to 2.5 seconds, and headway for only 10 percent of the gaps was more than 2.5 seconds. From these figures, it can be concluded, and rightfully so, that few acceptable gaps would

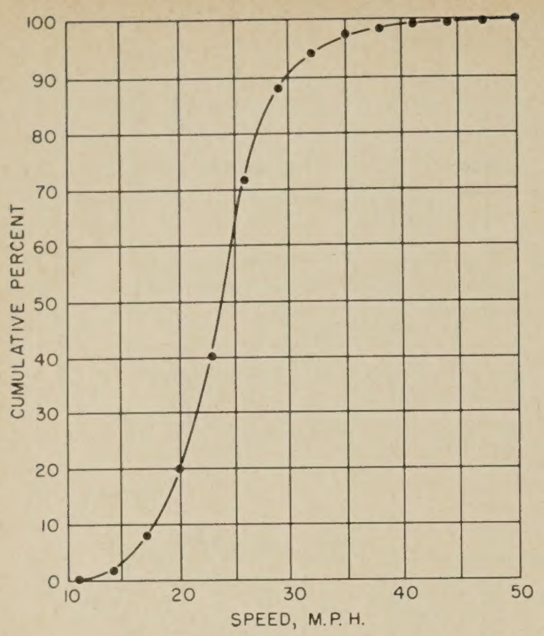


Figure 6.—Cumulative distribution of spot speeds on 13th Street, midway between Park Road and Kenyon Street.

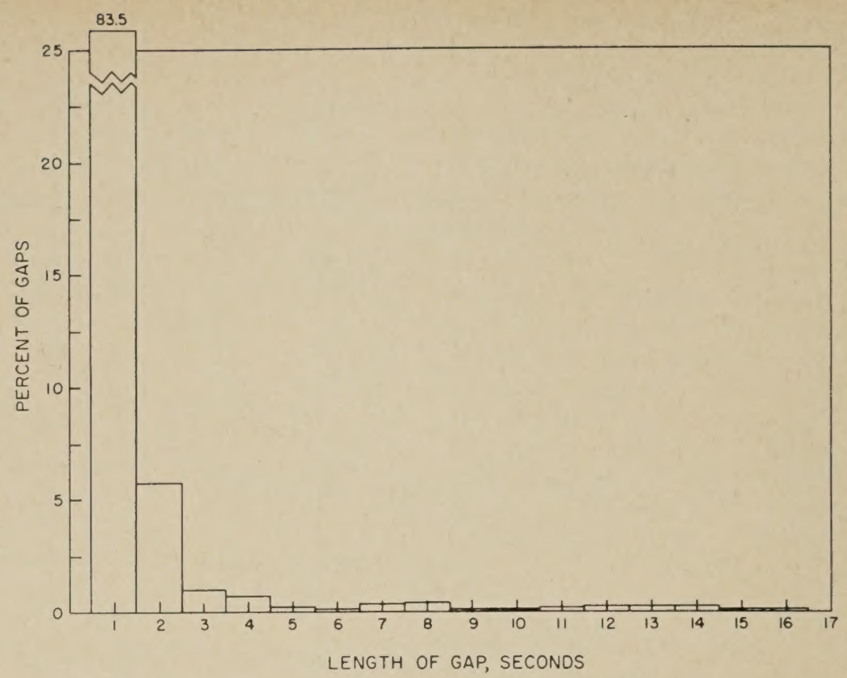


Figure 7.—Percentage of available gaps as a function of gap size.

be available to drivers of vehicles on the minor street trying to enter the traffic stream on the main street. If the distribution of gaps is considered at different vehicle flow rates, however, a somewhat different opinion may be formed. The cumulative gap distribution for five flow rates is shown in figure 8. The shape of the curves and the increased steepness as flow rate increased was not unexpected. The magnitude of these differences, however, is worthy of note. At a flow rate of 1,000 to 1,050 vehicles per hour per lane, 84 percent of the gaps were 0.5 second or less in length, 90 percent 1.0 second or less, and 96 percent 2 seconds or less. For a flow rate of 300 to 350 vehicles per hour per lane, distribution of gap length would be 40 percent, 6 percent and 80 percent, respectively.

The platooning effect of vehicles has often been mentioned in the literature but few data have been presented to determine the magnitude of this effect. A comparison of the gap distribution for vehicles within and between platoons is presented in figure 9 for five flow rates. For purposes of the study described here, vehicles between platoons are defined as those vehicles that entered the main street while traffic on the main street was stopped at a traffic signal (minor movement phase) and vehicles that entered the main street from uncontrolled minor streets between groups of vehicles. For the vehicles within platoons, a curve was drawn for each of the five flow rates. Because of the overlap in the data points for certain flow rates, only two curves are shown for the vehicles between platoons. One curve represents flow rates for 300 to 500 vehicles per hour per lane and the other represents flow rates for 650 to 1, 050 vehicles per hour per lane.

The separation between gap distributions for vehicles with and between platoons is a measure of platooning effect. Even at the largest rate of flow, 45 percent of the gaps between platoons would exceed 2 seconds. Thus, the presence of a traffic signal would cause two distinctly different gap distributions to occur at a downstream uncontrolled intersection. The within platoon distribution would have a large concentration of very short gaps, and the between platoon distribution would have long gaps. Platooning provides more gaps acceptable to drivers from the minor street; the absence of platooning provides fewer acceptable gaps because vehicle gaps are more uniformly distributed. The development of a gap utilization warrant for traffic signal control, which is discussed subsequently, was based on knowledge of the effect of platooning. However, note that the distributions referred to will vary in relation to cycle length, split, distance to the nearest upstream traffic signal, and possibly geometric conditions; but, the basic relation should remain unchanged.

Gap Acceptance

Data on gap acceptance were not collected in the research because satisfactory information could be obtained from a composite of the findings reported in the available literature. The results of five of the more significant research projects are shown in figure 10. The differences between the reported results are not fully understood, but some evidence exists that gap and/or lag acceptance distributions would vary with geometrics, sight obstructions, type of entering maneuver, volume, speed of the vehicles on the main street, and sequence of gap formation during periods of heavy traffic. The researchers on the five projects studied intersections that differed substantially in these characteristics. Despite these differences, the results are reasonably consistent.

A composite of the results of these five projects is shown in figure 11. This composite is essentially an approximate average of the results reported for the five projects; however, no gap of less than 2 seconds long was considered acceptable. Raff reported acceptance of gaps less than 2 seconds but did not report conditions under which these acceptances occurred. This composite curve of gap acceptance is used in conjunction with the gap availability distribution curve as example of the application of the methodolo developed in the research for this report.

Traffic Signal Warrant Methodolo

As with conventional traffic signal warran each approach on the minor street must analyzed separately to determine which one critical. Gap utilization logic was develop for both approaches on the minor street the intersection shown in figure 12. T intersection is the crossing of a 4-lane, 1-w urban arterial and a 2-lane, 2-way stre The equations developed subsequently restricted to this geometric configuration b the general methodology could be used develop equations for any other geomet conditions.

Gap utilization on east approach

For gap utilization by vehicles on the ea approach three probabilities were considere (1) The probability of a gap being utiliz by a vehicle crossing the main street, (2) t probability of a gap being utilized by a vehic turning left, and (3) the probability of vehicle crossing from the west approa interfering with a vehicle turning left fro the east approach. The latter must be su tracted from the sum of the other two obtain the net percentage of gaps utilize This can be represented algebraically as:

$$P(U_t)=P(E_T)+P(E_L)-P(W_I) \qquad ($$

Where,

$P(U_t)$ = The probability that a gap size t seconds will be utilized.

$P(E_T)$ = The probability that a gap size t will be utilized by a vehic crossing the main street.

$P(E_L)$ = The probability that a gap size t will be utilized by a vehic turning left.

$P(W_I)$ = The probability that a vehic crossing from the west approac will interfere with a vehicle turnir left.

The probability of gap utilization by the ossing vehicle can be determined by the uation:

$$P(E_T)=T_E[P(x)][P(y/x)] \qquad (2)$$

here,

T_E= The percentage of the vehicles from the east approach that are through vehicles, expressed as a decimal.
$P(x)$= The probability of a gap of size t being available in the traffic stream on the main street.
$P(y/x)$= The probability of a gap of size t being accepted by the driver of a vehicle on the minor street.

Assuming that turning maneuvers can be rformed in 2 lanes and some number of ch maneuvers will be executed if gaps are ailable in the 2 lanes nearest the turning hicles even if main street vehicles are present in the 2 farthest lanes, the probability of a gap being utilized by a vehicle turning left can be determined from the equation:

$$P(E_L)=L_E[P(V)][P(y/v)] \qquad (3)$$

Where,

L_E= The percentage of minor street traffic turning left, expressed as a decimal.
$P(V)$= The probability of a gap of size t being available in lanes 1 and 2 combined.
$P(y/v)$= The probability of a gap of size t in lanes 1 and 2 being accepted by a vehicle from the minor street that is turning left.

The probability that a crossing vehicle from the west approach will interfere with a vehicle turning left can be obtained from the equation:

$$P(W_I)=(T_W[P(x)][P(y/x)])(L_E[P(V)][y/v]) \qquad (4)$$

Where,

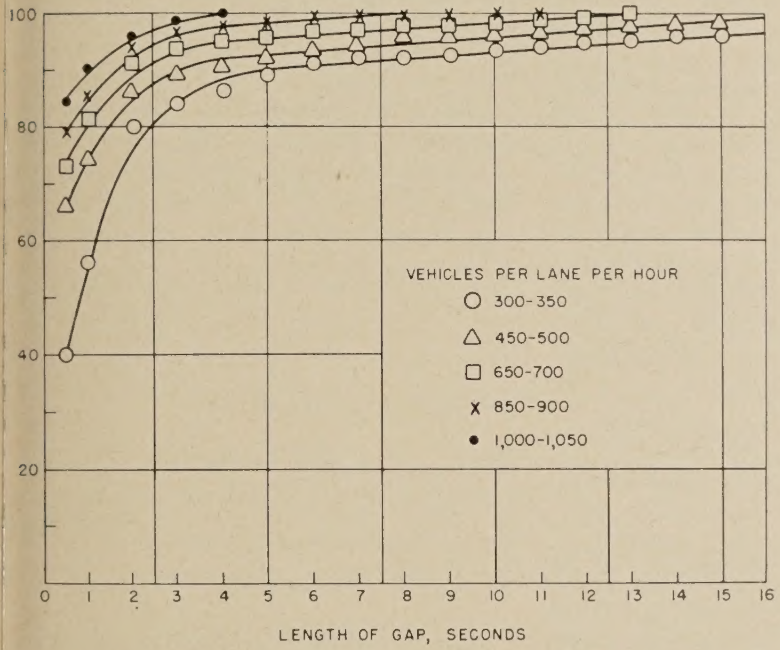
T_W= The percentage of through vehicles from the west approach of the minor street, expressed as a decimal.

Substitutions in equation (1) yield the percentage of gaps of size t that would be utilized:

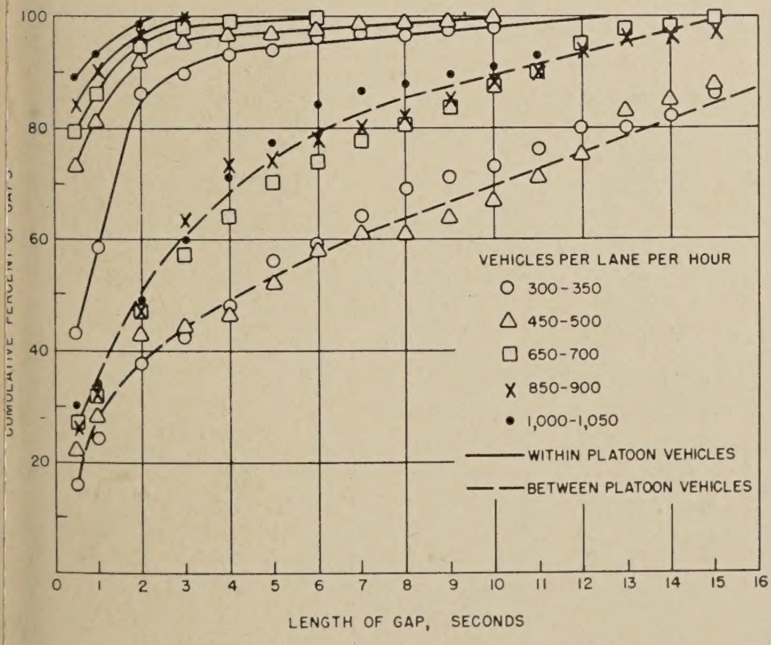
$$P(U_t)=T_E[P(x)][P(y/x)]+L_E[P(v)][P(y/v)] - (T_W[P(x)][P(y/x)])(L_E[P(v)][P(y/v)]) \qquad (5)$$

Gap utilization on west approach

The gap utilization by vehicles from the west approach also involves three probabilities: (1) The probability of a gap being utilized by a vehicle crossing the main street, (2) the probability of a gap being utilized by a vehicle turning right, and (3) the probability of a



igure 8.—Cumulative percentage of gaps for within and between platoons as a function of flow rate, all 4 lanes.



igure 9.—Cumulative distribution of gaps for within and between platoons as a function of flow rate, all 4 lanes.

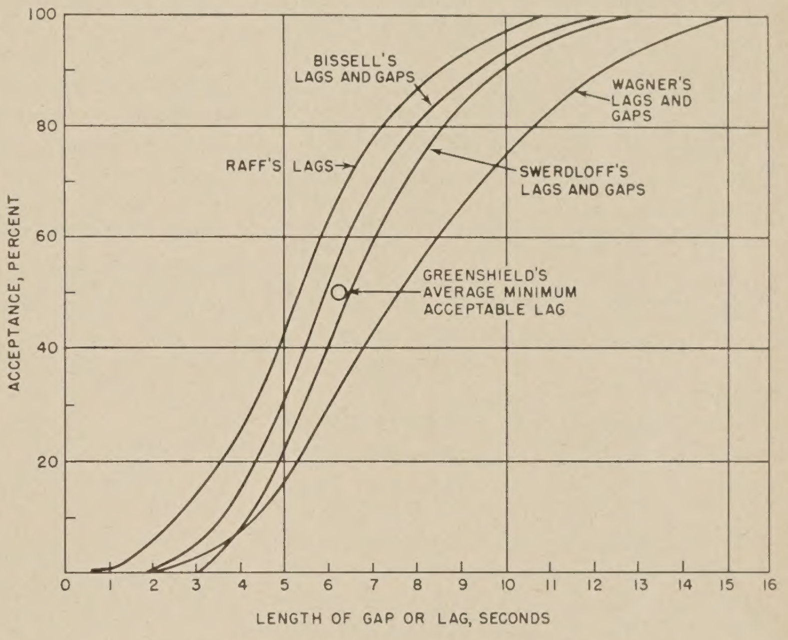


Figure 10.—Gap acceptance distributions obtained from the literature.

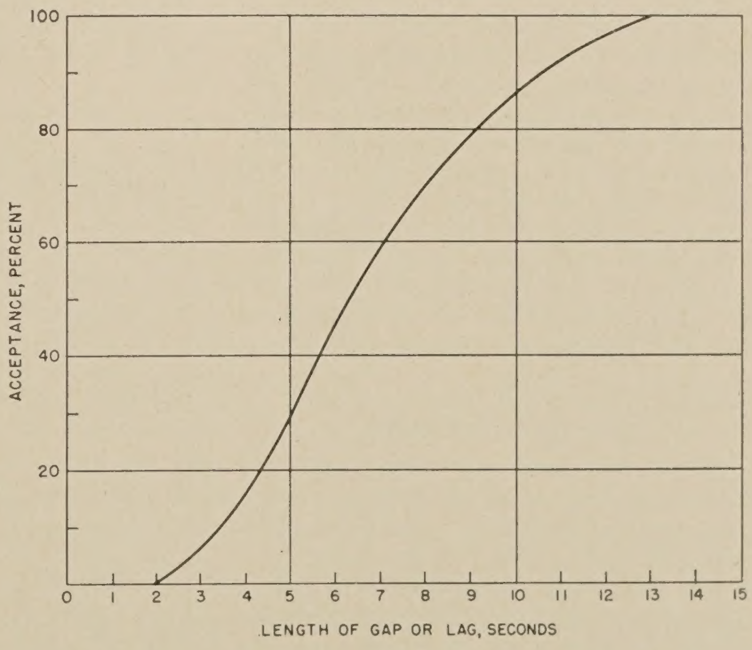


Figure 11.—Gap acceptance distribution used for the study reported in this article.

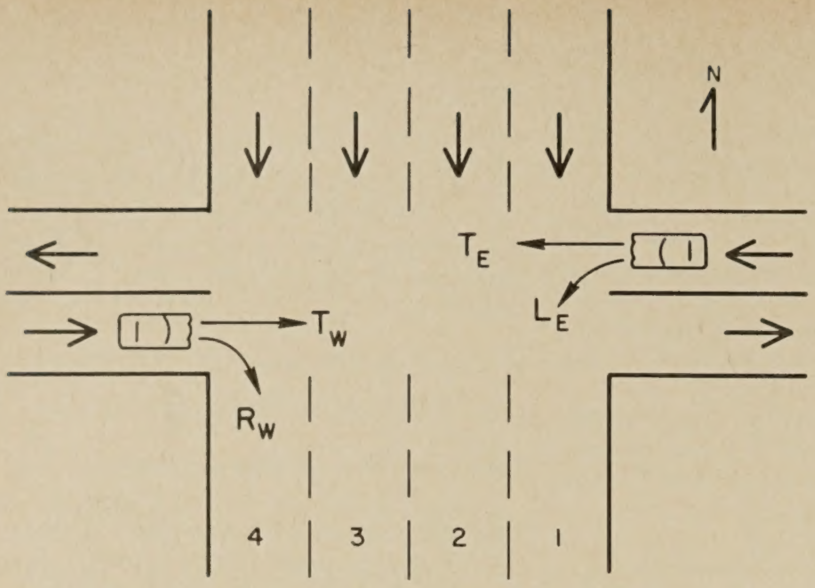


Figure 12.—Intersection schematic for sample problem calculations.

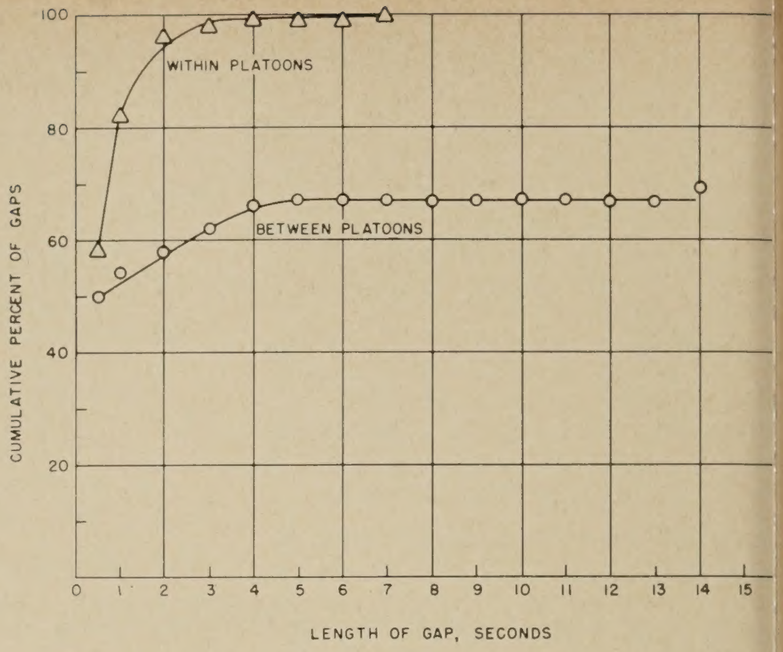


Figure 13.—Cumulative distribution of gaps for within a between platoons as a function of flow rate, lanes 1 and

vehicle turning left from the east approach interfering with a vehicle crossing from the west approach. By using the same techniques as for the east approach the resultant equation for the percentage of gap utilized by vehicles from the west approach is:

$$P(U_t) = T_W[P(x)][P(y/x)] + R_W[P(W)][P(y/w)] - (T_W[P(x)][P(y/x)])\,(L_E[P(v)][P(y/v)]) \quad (6)$$

Where,

R_W = The percent of traffic that is turning right from the minor street expressed as a decimal.

$P(W)$ = The probability of a gap of size t being available in lanes 3 and 4 combined.

$P(y/w)$ = The probability of a gap of size t in lanes 3 and 4 being accepted by a vehicle that is turning right from the minor street.

The equations developed for the east and west approaches yield the probable percentage of gaps of size t that would be utilized. By summing all values of t, the probable percentage of all gaps utilized can be obtained. This can be converted to an expected number of gaps by taking the product of the probable percentage utilized and the total number of gaps available in the main stream. The latter is an estimate of the number of vehicles that could be accommodated on the side street when the intersection has no traffic signal control.

Sample Calculation

A clearer understanding of the application of the technique may be obtained from a sample calculation. The objective of the calculation is to determine the number of vehicles that can be accommodated in 1 hour on the east approach of the intersection shown in figure 12 when no traffic signal control is present; that is, to determine the number of gaps on the main street that would be expected to be utilized by vehicles on the east approach. Calculations are based on the assumptions that 10 percent of the vehicles on each approach will turn and that traffic volume on the main street is 1,025 vehicles per lane per hour. In practice the information in the two assumptions can be obtained by field study or possibly from existing data on file in the public agency having responsibility for the traffic function. The equation for gap utilization by vehicles on the east approach is:

$$P(U) = T_E[P(x)][P(y/x)] + L_E[P(v)][P(y/v)] - (T_W[P(x)][P(y/x)])\,L_E[P(v)][P(y/v)]) \quad (7)$$

For ease of application, format of table 3 has been established for calculation of the sum of the product terms $[P(x)][P(y/x)]$ and $[P(v)]$ $[P(y/v)]$. The sums of the product terms have been calculated separately for the gaps within and between platoons. This permits conversion from probability of utilization to expected number of gaps utilized by vehicles from the minor street, which will beco clearer as the solving of the sample problem continued. The detailed calculations of th terms are included in a subsequent paragrap The probability of utilization of gaps wit platoons is determined by:

$$P(U)_W = T_E[P(x)_W][P(y/x)] + L_E[P(v)_W][P(y/$$
$$= (T_W[P(x)_W][P(y/x)](L_E[P(v)_W]\ [P(y/v)])$$

solved as:

$$P(U)_W = 0.9(0.002) + 0.1(0.019) - (0.9)(0.1)(0.002)(0.01$$
$$= 0.0018 + 0.0019 - (0)$$
$$= 0.0037,\ \text{rounded to } 0.004.$$

The probability of utilization of gaps tween platoons is obtained from the same equ tion (8) except that $P(X)_B$ and $P(V)_B$ substituted for $P(X)_W$ and $P(V)_W$, resp tively, so that

Table 3.—Product terms for use in sample problem

Gap length t	Available gaps		Acceptance of a gap of size t $P(y/v)$	[1] $[P(v)_W]$ $[P(y/v)]$	[2] $[P(v)_B]$ $[P(y/v)]$	Available gaps		Acceptance of gap of size t $P(y/x)$	[3] $[P(x)_W]$ $[P(y/x)]$	[4] $[P(x)_B]$ $[P(y/x)]$
	Within $P(v)_W$	Between $P(v)_B$				Within $P(x)_W$	Between $P(X)_B$			
Seconds										
0-0.9	0.58	0.50	0	0	0	0.90	0.30	0	0	0
1.0-1.9	0.24	0.04	0	0	0	0.06	0.14	0	0	0
2.0-2.9	0.14	0.04	0.05	0.007	0.002	0.04	0.12	0.05	0.002	0.006
3.0-3.9	0.02	0.04	0.13	0.003	0.005	------	0.10	0.13	--------	0.013
4.0-4.9	0.01	0.04	0.23	0.002	0.007	------	0.10	0.23	--------	0.023
5.0-5.9	0	0.01	0.37	0	0.004	------	0.06	0.37	--------	0.022
6.0-6.9	0	0	0.52	0	0	------	0.05	0.52	--------	0.026
7.0-7.9	0.01	0	0.65	0.007	0	------	0.01	0.65	--------	0.007
8.0-8.9	------	0	0.75	0	0	------	0.00	0.75	--------	0
9.0-9.9	------	0	0.83	--------	0	------	0.02	0.83	--------	0.017
10.0-10.9	------	0	0.91	--------	0	------	0.02	0.91	--------	0.018
11.0-11.9	------	0	0.97	--------	0	------	0.02	0.97	--------	0.019
12.0-12.9	------	0	1.00	--------	0	------	0.03	1.00	--------	0.010
13.0-13.9	------	0	1.00	--------	0.010	------	0.01	1.00	--------	0.010
14.0-14.9	------	0.02	1.00	--------	0.020	------	0.01	1.00	--------	0.010
15.0 and longer	------	0.30	1.00	--------	0.300	------	0.01	1.00	--------	0.010

[1] Total is 0.019. [2] Total is 0.348. [3] Total is 0.002. [4] Total is 0.191.

$$\begin{aligned} P(U)_B &= 0.9(0.191)+0.1(0.348) \\ &\qquad -(0.9)(0.1)(0.191)(0.348) \\ &= 0.1719+0.0348-0.0126 \\ &= 0.2141, \text{ rounded to } 0.214. \end{aligned}$$

The probability of utilization of gaps within and between platoons determined, the probable number of gaps utilized by vehicles on the minor street can be obtained from the product of the appropriate probability and volume. For example, the probable number of gaps within platoons that would be utilized is the product of the within platoon probability of utilization and the within platoon volume. Similarly, the probable number of gaps between platoons that would be utilized is the product of the between platoon probability of utilization and the platoon volume. The total number of gaps on the main street that would be expected to be utilized by vehicles on the east approach is obtained by summing the corresponding within and between platoon gaps. The probable number of gaps within platoons utilized by vehicles on the minor street is:

$$\begin{aligned} N_W &= P(U)_W(V_W) \\ &= (0.004)(3{,}484) = 14 \qquad (9) \end{aligned}$$

The probable number of gaps between platoons utilized by vehicles on the minor street is:

$$\begin{aligned} N_B &= P(U)_B(V_B) \\ &= (0.214)(615) = 132 \qquad (10) \end{aligned}$$

Then, the total number of gaps expected to be utilized by vehicles on the east approach would be:

$$\begin{aligned} N &= N_W + N_B \\ &= 14+132 = 146 \qquad (11) \end{aligned}$$

Thus 146 is analogous to the number of vehicles that can be accommodated in 1 hour on the subject approach when the intersection has no traffic signal control. This does not mean that 146 vehicles from the minor street could be accommodated at *any* intersection where traffic volume is 1,025 vehicles per hour per lane (4 lanes). The number accommodated at *this* intersection is large because of the platooning effect caused by an upstream traffic signal. In the development of this analysis, it has been assumed that (1) vehicles are continuously present on the minor street and (2) no allowance has been made for multiple acceptances of a gap. The former is the same concept employed in determining the capacity of an intersection. The results of the latter may be an actual accommodation of a slightly larger number of vehicles on the minor street than would be expected from the methodology developed in the research discussed here.

Determination of Sum of Product Terms for Sample Problem

Table 2 has been structured to simplify the calculations for the sample problem. A listing of the terms that appear in the table and their sources are: $P(x)_W$, figure 9; $P(x)_B$, figure 9; $P(y/x)$, figure 11; $P(v)_W$, figure 13; $P(v)_B$, figure 13; and $P(y/v)$, figure 11.

BIBLIOGRAPHY

Starting Delay Time and Time Spacing of Vehicles Entering Signalized Intersections, by R. M. Bartle, V. Skoro, and D. L. Gerlough, HRB Bulletin 112, Effects of Traffic Control on Street Capacity, 1956, pp. 33–41.

Traffic Gap Acceptance From a Stop Sign, by H. H. Bissell, Master's Thesis, University of California, Berkeley, May 1960 (processed).

Distribution of Acceptance Gaps for Crossing and Turning Manoeuveres, by W. R. Blunden, C. M. Clissold, and R. B. Fisher, Australian Road Research Board Proceedings, vol. 1, part 1, 1962, pp. 188–205.

Statistical Theory and Methodology in Science and Engineering, by K. A. Brownlee, New York: John Wiley & Sons, Inc., 1960.

Road Traffic Headway Distributions, by D. C. Buckley, Australian Road Research Board Proceedings, vol. 1, part 1, 1962, pp. 153–187.

Effect of Control Devices on Traffic Operations, Interim Report, by Cather De Leuw & Co. Engineers, NCHRP Report 11, 1964.

Traffic Performance at Urban Street Intersections, by E. L. Ericksen, Traffic Quarterly, vol. 1, No. 3, July 1947, pp. 254–267.

Pressurized Versus Normal Headways at a Signalized Intersection, by J. R. Fiske, Student Thesis, Yale University, Bureau of Highway Traffic, 1957 (processed).

Effect of Size of Gaps in Line on Acceptance of the Lag at a Stop Sign, by C. Y. Gagnon, Master's Thesis, Northwestern University, June 1962 (processed).

Traffic Performance at Urban Intersections, by Bruce D. Greenshields, Donald Schapiro, and Elroy L. Ericksen, Yale Bureau of Highway Traffic, Technical Report No. 1, 1947.

Traffic Engineering, by T. M. Matson, W. S. Smith, and F. W. Hurd, New York: McGraw-Hill, Inc., 1955.

Space-Time Relationships at "Stop" Intersections, by Morton S. Raff, Institute of Traffic Engineers Proceedings, 1949, pp. 42–49.

Lag and Gap Acceptance at Stop Controlled Intersections, by Per Solberg and J. C. Oppenlander, Highway Research Record 118, Statistical and Mathematical Aspects of Traffic, Jan. 1965, pp. 48–67.

A Study of Gap Acceptance at a Stop Sign Location, by Carl N. Swerdloff, Master's Thesis, Northwestern University, June 1962 (processed).

A Traffic Analyzer: Its Development and Application, by A. Taragin and R. C. Hopkins, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 31, No. 5, Dec. 1960, pp. 120–124.

An Evaluation of Fundamental Driver Decisions and Reactions at an Intersection, by F. A. Wagner, Highway Research Record 118, Statistical and Mathematical Aspects of Traffic, Jan. 1965, pp. 68–84.

Average Vehicle Headways at Signalized Intersections, by Bruno R. Wildermuth, Traffic Engineering, vol. 33, No. 2, Nov. 1962, pp. 14–16.

NEW PUBLICATIONS

Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds

The 1966 issue of *Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds* is now for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, for $1. The studies listed are those approved in the Office of Research and Development, Bureau of Public Roads, for fiscal year 1967 and calendar year 1966 as of July 1, 1966.

The information has been grouped by 8 major technical goals of the National Program and 27 projects, that contribute data toward solutions of the major goal. The eight major technical goals are: Definition of Underlying Requirements for Highway Transport; Analytic Definition of Complex Traffic Movements; Analysis of Essential Components of Highway Transport; Development of Methods for Reliable Forecasting of Demand for Highway Transport; Development of Methods for Increased Capacity, Control, and Safety in Traffic Movement; Development of Techniques for More Precise Structural Design and Incorporation of New Materials and Structural Concepts; Development and Application of New Technology to Location, Design, Construction, and Maintenance Processes; and staff, administrative contract, or HPR projects of major local, regional or national importance. Data are also presented on the objective of each study, the conducting agency, and the funding for each study.

This publication also contains information on active projects in the American Association of State Highway Officials National Cooperative Highway Research Program (NCHRP). These projects are financed from a pool of funds consisting of 5 percent of the 1½-percent Federal-aid funds of the participating State highway departments, sponsored by AASHO and administered by the Highway Research Board of the National Academy of Sciences.

Figure 1.—Foveal view of visual field.

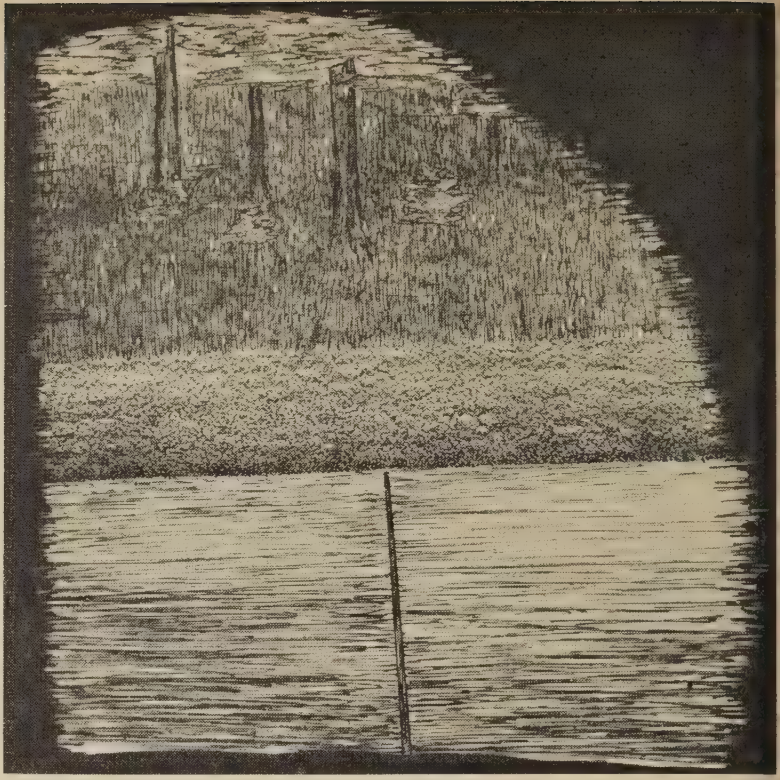


Figure 2.—Peripheral view of visual field.

Vehicle Speed Estimation from Visual Stimul

BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

Reported by SANTO SALVATOR
Research Psycholog
Traffic Systems Divisio

Accurate estimation of vehicle speed is necessary for precise psychomotor coordination and anticipation of future response needs. Vehicle control is dependent on information perceived from the complex and changing stimuli of the surrounding environment. The test reported in this article was aimed at determining how the vehicle operator obtained speed estimates from visual stimuli in the field. Response to both foveal and peripheral visual stimulation was recorded to determine which mode of visual stimulation allowed the driver the best information for estimating the speed of the vehicle. The author reports that speed was most accurately estimated through peripheral stimulation. It was also concluded that increased acceleration reduces the accuracy of speed estimation and that deceleration is more effectively sensed than acceleration.

Introduction

FOR THE STUDY reported in this article an apparatus was constructed and experimental procedure developed to test how the vehicle operator obtains speed information from the visual field. In the driving task the driver must process information for directional control or heading, longitudinal control or distance to significant objects, lateral position, and vehicle speed. As driving becomes less and less dependent on muscular strength and more and more a task of exercising control in response to a complex and continuously changing environment, the importance of split-second judgment and psychomotor skill is paramount. The importance of accurately estimating vehicle speed cannot be underestimated because the amount of force exerted by the driver to control the vehicle is dependent on his perception of speed. But more important is the fact that accurate estimation of vehicle speed is required for the driver to achieve smoothness of the psychomotor response. Anticipation of future psychomotor response needs leads to precise psychomotor coordination and short reaction time.

The following list contains definitions for some terms used in this article:

Fovea centralis.—The fovea centralis is a depression at the back of the retina of the eye, the point where the vision is most acute, corresponding to approximately the central 2° of the visual field. In this article the fovea centralis is referred to as fovea.

Interocular distance.—Interocular distance is the horizontal distance between the centers of the pupils of the two eyes when they are in the normal position for distance vision.

Iris diaphragm.—The iris diaphragm is a mechanical device in a camera composed of thin metal leaves arranged and shaped to provide a circular opening that can b varied in size.

Kinesthetic.—Kinesthetic pertains to th sense that yields knowledge of the movemen of the body or of its several members.

Parafovea.—The parafovea is the area of the retina surrounding the fovea, approx mately the central 4° of the visual fiel excluding the area of the fovea.

Periphery.—Periphery refers to the ou ward bounds of something, such as visio as distinguished from its center.

Psychomotor.—Psychomotor refers to th precise coordination of a sensory or ideation process and a motor activity, such as aimin at a target.

Tactual.—Tactual refers to the sense touch.

Conclusions

From the experiments to determine ho the vehicle operator obtains speed informatio from visual stimuli in the field, the auth made several conclusions:

- Speed estimation is more accurate in th periphery than in the fovea.
- The effect of increased acceleration in creases all absolute and relative error th reducing the sensitivity of the visual mod
- Absolute error is directly proportional speed and relative error is inversely propo tional to speed for the central stimulatio only when the influence of acceleration minimized.

- Under the condition of the experiment, eceleration is more effectively sensed than eceleration.
- Processes underlying speed estimation e far from perfectly understood and the ithor believes a program of research in this ea would be fruitful. The dimensions that ed to be studied are: exposure time; aveled field structure classified as to width road or proximity to roadside objects, road arkings, and type of pavement; area of tinal stimulation; and speed.

Background

Despite the significance of the operator's bility to estimate speed and the processes nderlying it, studies in this area are limited. laboratory experiments, Poulton (*1*)[1] has eated tracking as an analog to the driving sk and has differentiated between course ticipation and speed anticipation. Speed ticipation refers to vehicle control based on e perception of stimulus movement; course ticipation refers to vehicle control based the perception of course stimulus. Gen- ally laboratory studies use small moving rgets usually within the limits of the para- vea. But Gordon in his study has shown at the angular speed is minimal in the fovea ntralis and maximum in the periphery for ree dimensional movement (*2*).

Field studies of absolute speed estimation ave been sparse; most have dealt with speed tainment. In studying speed attainment, hr and Lauer (*3*) recorded underestimation low speeds and overestimation at high- eeds. Barch (*4*), studying speed adapta- on, determined that adaptation did not cur for exposure times of up to 8 minutes d that underestimates were made for celeration. Hakkinen (*5*) compared esti- ates made by subjects viewing films of the riving situation and estimates made by assengers in an actual traffic situation. hough the split-half reliability for each chnique is high, the correlation between chniques was not significantly different om zero.

Basis for Study

In the actual driving situation the rapidity obtaining a speed estimate is critical. The ehicle operator can make a speed estimate rough a foveal or a peripheral view, as own in figures 1 and 2, respectively. But, e value of the estimate decreases as the time quired to make it increases, if the two stimates are of a given accuracy and relia- ility. One purpose of the research discussed ere was to test the hypothesis that speed stimates are more accurate based on periph- ral stimulation than foveal stimulation nder the condition of equal exposure time. he theoretical discussion of whether the peed of moving objects is perceived directly r by relating perceived spatial displacement perceived duration was considered. The nswer depends partially on the locus of retinal timulation used in obtaining speed informa- ion. In the peripheral view angular speed eems relatively fast and movement is obvious so that recognition of movement of the vehicle through the environment is apprehended directly. In the foveal view movement seems slower so that speed may have to be computed by estimating the distance traversed and the time elasped; this computation procedure is time consuming.

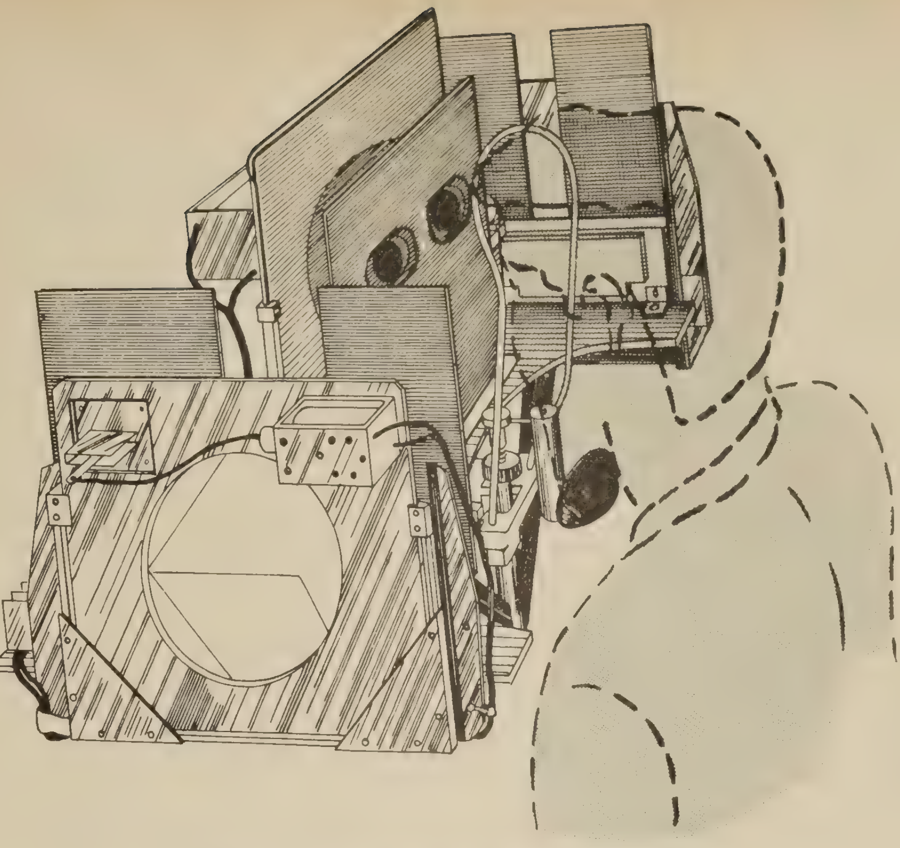


Figure 3.—Test subject and test apparatus.

Two hypotheses were tested in the experiment reported here: (1) estimates of speed based on peripheral stimulation are higher than estimates of speed based on foveal stimulation; (2) estimates of speed based on peripheral stimulation are more accurate than estimates of speed based on foveal stimulation.

Test Apparatus

Experimental apparatus for the speed estimation study was basically two camera iris diaphragms mounted on a base. The purpose of the apparatus was to control the relevant segment of the visual field and time for observation. The distance between iris centers, corresponding to the interocular distance, was adjusted to accommodate individual sight variation. With the eyes of the test subject 2 inches from the iris, the foveal opening could be adjusted in a range from 1° to 30°. The peripheral field was controlled by two slats placed in a groove that ran parallel to the optical axis at a distance of 5 inches on either side of the subject's eye. The rear slat was positioned so that it subtended an angle of 90° at the subject's eye. The forward slat was adjustable so that the amount of the peripheral field available for observation could be varied. The testing apparatus, shown in figures 3 and 4, was constructed with the cooperation of the Engineering Systems Division of the Bureau of Public Roads.

The duration of visibility of the field was controlled by three, 4½-inch diameter shutters. The two shutters were placed on either side of the slats and the third in front of the two irises. An electronic timer controlled the voltage to the solenoids that operated the opening and closing of the shutters. The electronic timer ranged from one-fourth to 64 seconds in the geometric series of nine steps. The subject's head was placed in position by a chin rest attached to the diaphragm base. The base was held in approximate position by a boom held in tension between the floor and the roof of the car and was leveled by two turnbuckles attached to the base from the vehicle visor rods.

Test Subjects

Four subjects were chosen at random from a list of volunteers. The three females and one male in the sample ranged in age from 18 to 37; the mean age was 25 years. Uncorrected vision was tested by a technician on the Bausch and Lomb Ortho-rater; foveal visual acuity was 20/29 or better and the peripheral field was 80° or more on both sides. None of the test subjects wore glasses and all had from 2 to 20 years of driving experience, or a mean of 8½ years.

Test Site

The test site was a 5-mile stretch of unopened Interstate 64 a few miles east of Richmond, Va. Although this concrete highway is a 4-lane divided freeway, only the two westbound lanes, each 12 feet wide, were used in the test. Lane and edge striping had not been painted yet so the highway was classified as a semistructured environment. Maximum slope and horizontal curvature were 3 percent and 2° respectively. The longitudinal central

---

[1] Numbers in parentheses indicate references, which are sted on p. 131.

joint and the transverse construction joints which were spaced 61.5 feet apart, were filled with approximately 1 inch of conventional black asphalt joint-filler. The right shoulder width was constructed of 10 feet of asphalt paving and 10 feet of earth fill. During the experiment, the vehicle was centered in the right lane. Estimates were never made when nontest vehicles were in the testing area.

Experimental Design

The research was carried out as a two-factor design, as shown in figure 5. Factor 2, mode of observation or manner of visual stimulation, was tested for 25° centrally and 25° peripherally. Factor 2, vehicle speed, was tested for 20-, 40-, and 60-m.p.h. speeds. This basic design was used at 1 m.p.h./sec. acceleration and was repeated at 5 m.p.h./sec. acceleration because it was assumed that acceleration would affect the estimates. Four subjects made speed estimates for the 6 experimental conditions, 5 times each, for a total of 120 estimates at each rate of acceleration.

Two sets of experiments were made. In the first set of experiments a 1 m.p.h./sec. acceleration-deceleration was used to attain the desired actual speed; in the second a 5 m.p.h./sec. acceleration-deceleration was used. Visual exposure time for both experiments was a constant 1 second and a masking noise was piped into the subjects' ears by a headset to eliminate auditory cues. Windows were closed to eliminate wind cues. In set 1, the time between visual exposure to the field was held constant to eliminate the influence of time on estimates. In set 2, visual exposure was made when the actual test speed had been reached. Subjects were instructed to count aloud between visual exposures as a distraction from nonvisual cues of speed. The order of the experimental conditions was semirandom.

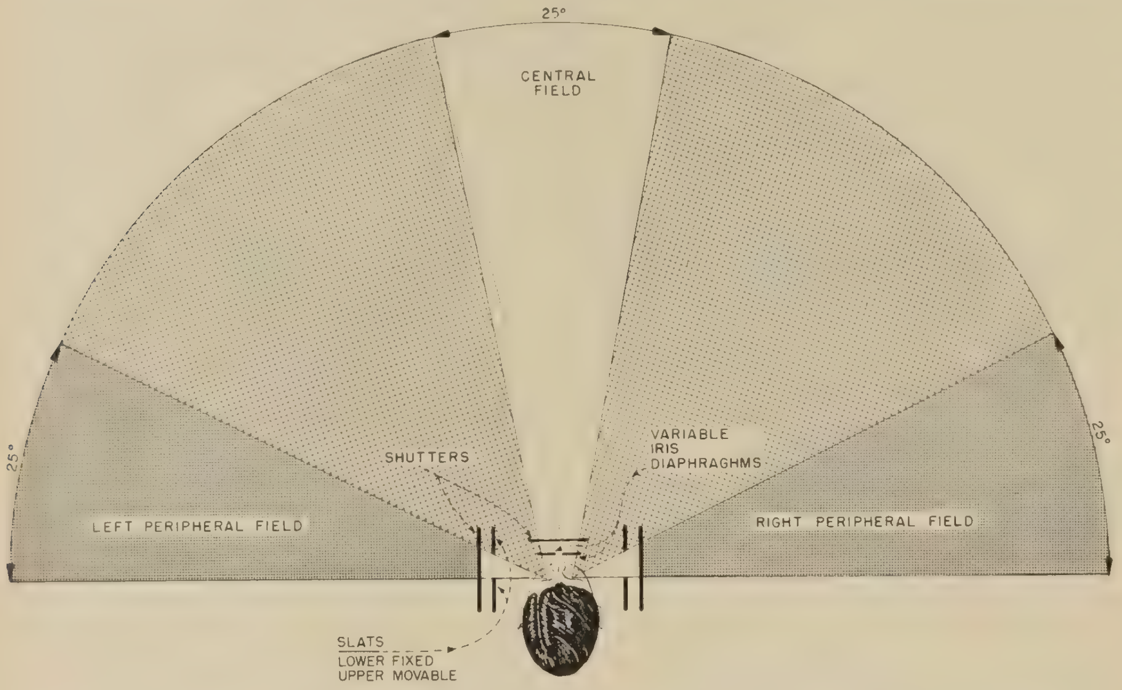


Figure 4.—The foveal and peripheral visual field as seen through the test apparatus.

Instructions

Test subjects were given the following instructions: The purpose of this experiment is to find out how people estimate speed. Your job in the experiment will be to give verbal estimates of the speed that you think the car is traveling. Give your estimates to the nearest 5 m.p.h., for example, 25, 30, 35 m.p.h., and so on. Your view of the road will be blocked by the apparatus for most of the time that you are in the experiment. Every 45 seconds either the front or side shutters will open for a short time. You will not know ahead of time whether your view will be forward or to the side so be ready to observe in either direction. The best way to accomplish this is to stare straight ahead in what we call the stare mode. Try it. Staring straight ahead you should also be able to see the sides without moving your eyes, as you did in the eye test. A tap on the shoulder from me will indicate that either the front or side shutters will open for a short time and that you should be ready to observe. As soon as the shutter(s) close(s) give your estimate of the speed that you think the car was traveling while the shutter(s) was open. Give your estimate of the speed as soon as the shutter(s) closes. Speed estimates that are delayed cannot be used. If you are not sure of the speed, guess. Do not hesitate. The sequence of events will be: dark phase for 45 seconds; tap on shoulder, be ready to observe; opening of side or front shutter, observe; closing of shutters, report estimated speed to the nearest 5 m.p.h., repetition.

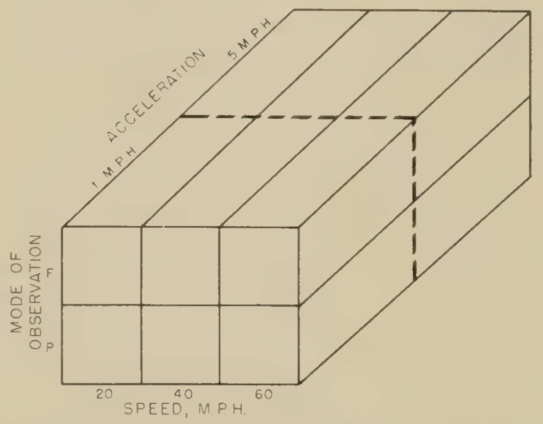


Figure 5.—Experimental design showing the factors of analyses of variance.

Analyses of Variance

Two analyses of variance were made: one for each of the two levels of acceleration. The analyses showed that vehicle speed was extremely significant regardless of the mode of observation or level of acceleration. The mode of observation at the 1 m.p.h./sec. acceleration was significant beyond 0.001—results such as those obtained would occur by chance less than one in a thousand—but, the mode of observation at 5 m.p.h./sec. acceleration was not so significant statistically as it was less than 0.05. Such statistical results show that an interaction was present between acceleration and mode of observation; this interaction is discussed in a subsequent paragraph. However, the lack of interaction between speed and mode of observation at the 1 m.p.h./sec. level of acceleration strengthens the belief that the effectiveness of the perceptual technique is independent of speed when acceleration effects are minimized.

The relation of estimated speed to actual speed for an acceleration of 1 m.p.h./sec. is shown in figure 6. The parameter is the mode of observation. The broken line indicates the ideal speed. Estimates made by the subjects from peripheral stimulation were statistically significantly faster than the estimates they made from foveal stimulation. Thus, hypothesis 1 was confirmed; the foveal estimates were underestimates at all three speeds. The subject estimated that he was moving slower than he actually was. The peripheral speed estimates were slightly less than the actual speed at the 20 and 60 m.p.h. speeds and slightly more at 40 m.p.h. Thus, hypothesis 2, that peripheral stimulation is more conducive to accurate estimates than central stimulation was confirmed. At the 5 m.p.h./sec. acceleration test, subjects shifted their estimates to slower speeds for both peripheral and foveal modes of observation, as shown in figure 7. The peripheral estimates were faster than the foveal estimates at all speeds, but the difference between the two was smaller and not statistically significant.

At the 1 m.p.h./sec. acceleration the complete lack of overlap of both the absolute and the relative errors for the foveal and peripheral stimulation shows the gain in accuracy of speed estimates under the condition of peripheral stimulation. Furthermore, absolute error directly proportional to the speed, and relative error inversely proportional to the speed holds true only for foveal stimulation. For peripheral stimulation no obvious trend in relation of errors

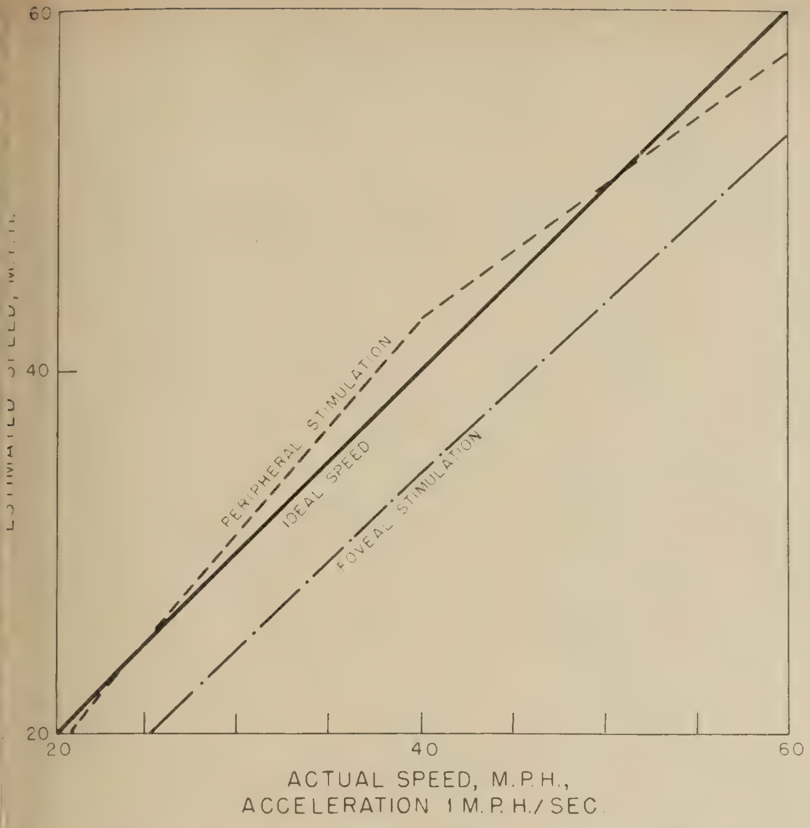


Figure 6.—Estimated speed as a function of actual speed, 1 m.p.h./sec. acceleration.

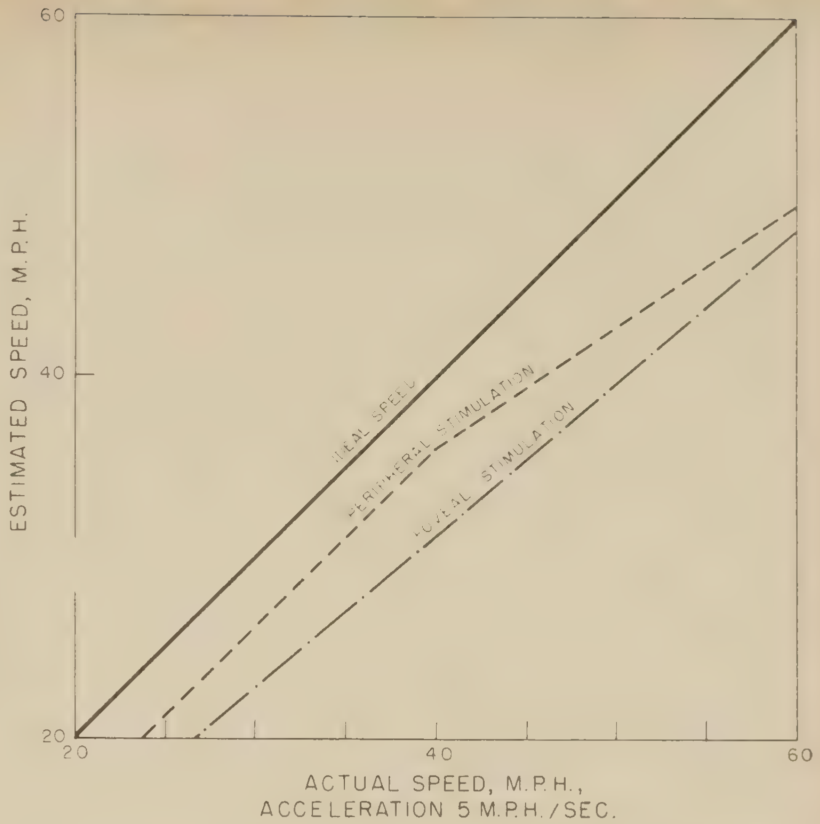


Figure 7.—Estimated speed as a function of actual speed, 5 m.p.h./sec. acceleration.

to speed was noted, and the relative error is best described by a straight line parallel to the ordinate. The general effect of acceleration was an increase in both the absolute and relative errors at each speed for both modes of stimulation. The interaction between acceleration and mode of observation was marked and has the effect of making peripheral and foveal curves look alike. Thus, acceleration tends to cancel out the better sensitivity to the peripheral stimulation. Some difference between peripheral and foveal stimulation was maintained, but for the most part the acceleration cue tended to overpower the visual sensitivity. The net effect was to increase the absolute error making it seem that under the conditions of this experiment, deceleration was more effectively sensed than acceleration.

The possible cues to speed are manifold. The movement of the visual field on the retina, auditory cues of engine and road noise, kinesthetic and tactual cues of acceleration, wind speed, and gas pedal displacement can all play a part when vehicle speed is being estimated. An overall impression incorporating stimulation from the different sources and senses may provide the basis for the best estimation of speed. For the purpose of the study reported here, however, it was assumed that the visual sense was the primary source of speed information and that movement of the visual field is directly proportional to vehicle speed through the environment. It was also assumed that most information necessary to the driving task is obtained visually and, because switching from one sense to another is detrimental to performance under time limitations, it also seemed advantageous to obtain velocity information visually. The discovery of the order and relative weighting of the cues that enter into speed judgments were considered scientifically interesting.

A cursory examination of the relation of the visual field to its external counterpart shows that, for any particular objective speed, the visual field has diverse values of motion depending on the mode of observation. Motion is least in the fovea along the direction of motion. The question arises as to where in the field the observer should concentrate to obtain speed information. The experiment reported here proves that a more accurate assessment of speed information is obtained from peripheral visual stimulation than from foveal visual stimulation. The immediate explanation for this result seems to be that angular speed is much faster in the periphery than in the fovea. For example, at a vehicle speed of 60 m.p.h. and 25° of available visual stimulation, the corresponding maximum angular speed is 1,080° per second peripherally and 81° per second foveally. For the 1-second time constant used, which is generous, the observer was able to respond better to peripheral stimulation. Angular speed in both the foveal and peripheral field is directly proportional to vehicle speed but as the angular speed was faster in the peripheral visual field by more than one order of magnitude, this speed could be scaled more easily. A more stringent test of the relation of the visual field to its external counterpart would be to reduce available observation time toward zero. Such an experiment is planned in which updated equipment will be used.

For the foveal mode of observation at the 1 m.p.h./sec. acceleration, the absolute error was directly proportional to vehicle speed and the relative error was inversely proportional to vehicle speed. Both errors were practically parallel to the ordinate when the stimulation was peripheral. As Hakkinen (*6*) reported a high degree of reliability within the methods of observation when the observer was in motion and the camera in the position of the observer and a zero correlation between modes of observation, the author has assumed that the process underlying the estimates was altered by substitution of foveal for peripheral stimulation. The author also believes that an experienced driver can use this experience in judging speed when he is restricted to foveal mode of observation but that this ability to compensate probably would be eliminated as observation time is reduced toward zero.

REFERENCES

(*1*) *Perceptual Anticipation in Tracking*, by E. C. Poulton (processed), available from the Armed Services Technical Information Agency, Arlington Va., ATI 127 135, Aug. 1950.

(*2*) *Static and Dynamic Fields in Vehicular Guidance*, by D. A. Gordon and R. M. Michaels, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 34, No. 3, part II, Aug. 1966, pp. 57–61.

(*3*) *Judgment of Speed on the Highway and on the Auto Trainer*, by V. W. Suhr, A. R. Lauer, and E. Allgaier, Traffic Safety, A National Safety Council Publication, vol. 53, No. 6, Dec. 1958, pp. 27–31.

(*4*) *Judgments of Speed on the Open Highway*, by A. M. Barch, Journal of Applied Psychology, vol. 42, No. 6, 1958, pp. 362–366.

(*5*) *Estimation of Distance and Velocity Judgments in Traffic Situations*, by Sauli Hakkinen, Reports From the Institute of Occupational Health, Helsinki, Finland, No. 3, May 1963.

Travel by Motor Vehicles in 1963, 1964, and 1965

BY THE OFFICE OF PLANNING
BUREAU OF PUBLIC ROADS

By ALEXANDER FRENCH, Chief Planning Services Branc
and THEODORE S. DICKERSON, JR,
Highway Engineer, Current Planning Divisi

Introduction

Motor-vehicle travel during 1965 in the United States has been estimated at 887.6 billion vehicle-miles, an increase of 4.9 percent from 1964. Based on preliminary data, 1966 motor-vehicle travel has been estimated at 932 billion vehicle-miles, a 5-percent increase from 1965. These Public Roads estimates are based on information supplied by State highway departments and toll authorities. Recently, a more accurate interpretation of these data has become possible by use of information collected in 1963 by the Bureau of the Census, and by the State highway departments in cooperation with Public Roads. Accordingly, motor-vehicle travel for 1963 and 1964 has been reestimated as described in the article.

Definitions

Vehicle-miles.—Vehicle-miles refers to the amount of travel by one motor-vehicle traveling 1 mile and includes travel on all highways and streets in the United States.

Registered weight groups.—Registered weight groups are the weights used as a basis for vehicle licensing, separated into intervals according to State registration weight practices.

Trailer combinations.—A trailer combination is a truck or truck tractor pulling one or more trailers and/or a semitrailer.

Motor-fuel consumption.—Motor-fuel consumption is the total consumption of motor fuel by highway vehicles for the year, obtained from State records.

Motor-fuel consumption rate.—Motor-fuel consumption rate is the average rate of motor fuel usage in miles per gallon (m.p.g.).

1965 Travel

The travel by road system and vehicle type changed little from 1964 to 1965, as shown in table 1. In 1965, travel on main rural roads was 37.8 percent of the total vehicle-miles of travel; main rural roads are 14 percent of the Nation's 3.7 million miles of roads and streets. The 1965 travel on urban streets was 47.8 percent of the total travel, urban streets are 14 percent of the total mileage of roads and streets. But only 14.4 percent of the travel in 1965 was on local rural roads although these roads are 72 percent of the total mileage of roads and streets.

Passenger cars in 1965 were 84 percent of the vehicles registered and accounted for 80 percent of the travel. Single-unit trucks accounted for 15 percent of the vehicles registered and 16 percent of the travel; trailer combinations accounted for less than 1 percent of the vehicles registered but 4 percent of the travel. Buses accounted for less than 1 percent of the vehicles registered and the total travel.

Motor-vehicle performance

Average vehicle performance estimates for 1965 were only slightly different than the corresponding estimates for 1964. The average motor-vehicle travel in 1965 was 9,674 miles, almost half of it in cities; and average motor-fuel consumption was 775 gallons at a rate of 12.48 m.p.g. In 1964, the estimated average motor-vehicle travel was 9,698 miles; and average motor-fuel consumption was 778 gallons at the rate of 12.47 m.p.g. Averages for passenger cars in 1965 and 1964 were, respectively: 9,255 and 9,286 miles of travel and 649 and 652 gallons of motor-fuel consumed at a rate of 14.27 and 14.25 m.p.g.

Basis for Estimates

For the first time, it has been possible to provide separate estimates for single-unit trucks and trailer combinations The yearly travel average for trailer combinations, 41,292 miles, is four times the average travel of single-unit trucks. These separate estimates were developed from information obtained in cooperation with the State highway departments from the 1963 special trucking characteristics study (*1*)[1] and from data in the *1963 Census of Transportation*. Both the special study and the Census (*1, 2*) were discussed at the 44th annual meeting of the Highway Research Board.

Adjustment of 1963 Travel Estimates

Based on Census data (*3*), adjusted to reflect travel of government-owned vehicles, the vehicle-miles of 1963 truck travel have been reestimated at 9.65 percent more than previously published by Public Roads in table VM–1. In the reestimate, a computer data file, based on responses for 100,845 individual trucks, was obtained from the Bureau of the Census. Information in the file had been obtained from questionnaires mailed to a probability sample selected from motor-vehicle registration files in each State. The sample was stratified for each State by registered weight groups. Census information identifying the type of vehicle was translated to correspond to descriptions used for truck weight trends, which are based on axle arrangements of single-unit trucks and each type of trailer combination. As expected from such a complex questionnaire, apparently inconsistent information was recorded by some respondents. More than 96 percent of the original records were successfully edited and recoded. A comparison then could made of the two sets of data. The avera vehicle-miles traveled each year was comput for each vehicle type and weight group bas only on the questionnaire containing a sponse to the question on annual travel. Th average was expanded to the correspondi number of trucks of each vehicle type a registered weight group in each State in 196

Government-owned vehicles

The adjustment of Census data for gover ment-owned vehicles was necessary so th travel by all vehicles would be reflected as is in the trend data prepared by Pub Roads. Trend data are based primarily continuous traffic counts at 2,500 permane locations and periodic machine and manu traffic counts made by State highway partments. Most counts are made at t roadside, usually on a 6- to 48-hour sampli basis, and all passing vehicles are counte In the adjustment, single-unit trucks a trailer combinations owned by all levels government were estimated to have account for, respectively, 5.6 percent of the tot travel by single-unit trucks and 0.5 percent travel by trailer combinations.

From evaluation of the new informati (*2, 3*), it was concluded that the estimate vehicle-miles of travel for single-unit truc reported during the past few years was lo Evidently, estimates based on roadside cour did not fully reflect the substantial increa in the number of pickup trucks with camp bodies used for recreation. At the same ti underestimates of urban travel were ma because full consideration was not given the increase in urban travel caused by t introduction of small vans, the increased u of walk-in delivery trucks, and the mo extensive use of single-unit trucks in expan ing metropolitan areas. Therefore, the 19 vehicle-miles of travel for single-unit truc and trailer combinations reported in t article are new estimates based on the 19 Census data (*2, 3*), adjusted to include es mated travel by government-owned truc and trailer combinations.

The new estimate for vehicle-miles of tra by single-unit trucks in 1963 was 13.35 p cent more than had been estimated fr Public Roads trend figures; but for trail combinations the new estimate was 3.62 p cent less than vehicle-miles previously es mated by Public Roads. When the go

---

[1] References indicated by italic numbers in parentheses listed at the end of this article.

Table 1.—Estimated motor-vehicle travel in the United States and related data for calendar year 1965 and revised data for 1963 and 1964[1]

Vehicle type	Motor-vehicle travel					Number of vehicles registered	Average travel per vehicle	Motor-fuel consumption		Average travel per gallon of fuel consumed
	Main rural roads	Local rural roads	Total rural	Urban	Total			Total	Average per vehicle	
1965										
	Million vehicle-miles	*Million vehicle-miles*	*Million vehicle-miles*	*Million vehicle-miles*	*Million vehicle-miles*	*Thousands*	*Miles*	*Million gallons*	*Gallons*	*Miles/gallon*
Passenger cars [2]	254, 975	97, 662	352, 637	356, 663	709, 300	76, 643	9, 255	49, 723	649	14. 27
Buses:										
Commercial	922	184	1, 106	1, 815	2, 921	85. 0	34, 365	628	7, 388	4. 65
School and nonrevenue	687	758	1, 445	318	1, 763	229. 3	7, 689	247	1, 077	7. 14
ALL BUSES	1, 609	942	2, 551	2, 133	4, 684	314. 3	14, 903	875	2, 784	5. 35
All passenger vehicles	256, 584	98, 604	355, 188	358, 796	713, 984	76, 957	9, 278	50, 598	657	14. 11
Cargo vehicles:										
Single-unit trucks	56, 832	28, 378	85, 210	55, 949	141, 159	14, 008	10, 077	13, 848	989	10. 19
Trailer combinations	21, 994	1, 395	23, 389	9, 108	32, 497	787	41, 292	6, 658	8, 460	4. 88
TOTAL	78, 826	29, 773	108, 599	65, 057	173, 656	14, 795	11, 737	20, 506	1, 386	8. 47
ALL MOTOR VEHICLES	335, 410	128, 377	463, 787	423, 853	887, 640	91, 752	9, 674	71, 104	775	12. 48
1964 Revised										
Passenger cars [2]	243, 429	93, 539	336, 968	340, 645	677, 613	72, 969	9, 286	47, 567	652	14. 25
Buses:										
Commercial	908	181	1, 089	1, 803	2, 892	82. 3	35, 140	622	7, 558	4. 65
School and nonrevenue	674	743	1, 417	307	1, 724	223. 1	7, 727	242	1, 085	7. 12
ALL BUSES	1, 582	924	2, 506	2, 110	4, 616	305. 4	15, 115	864	2, 829	5. 34
All passenger vehicles	245, 011	94, 463	339, 474	342, 755	682, 229	73, 274	9, 311	48, 431	661	14. 09
Cargo vehicles:										
Single-unit trucks	52, 929	27, 112	80, 041	53, 670	133, 711	13, 275	10, 072	13, 199	994	10. 13
Trailer combinations	20, 592	1, 307	21, 899	8, 661	30, 560	738	41, 409	6, 271	8, 497	4. 87
TOTAL	73, 521	28, 419	101, 940	62, 331	164, 271	14, 013	11, 723	19, 470	1, 389	8. 43
ALL MOTOR VEHICLES	318, 532	122, 882	441, 414	405, 086	846, 500	87, 287	9, 698	67, 901	778	12. 47
1963 Revised										
Passenger cars [2]	231, 298	89, 080	320, 378	324, 993	645, 371	69, 842	9, 240	45, 246	648	14. 26
Buses:										
Commercial	877	170	1, 047	1, 794	2, 841	82. 2	34, 562	606	7, 372	4. 69
School and nonrevenue	642	708	1, 350	292	1, 642	215. 7	7, 612	232	1, 076	7. 08
ALL BUSES	1, 519	878	2, 397	2, 086	4, 483	297. 9	15, 049	838	2, 813	5. 35
All passenger vehicles	232, 817	89, 958	322, 775	327, 079	649, 854	70, 140	9, 265	46, 084	657	14. 10
Cargo vehicles:										
Single-unit trucks	50, 043	25, 981	76, 024	49, 729	125, 753	12, 654	9, 938	12, 348	976	10. 18
Trailer combinations	19, 900	1, 302	21, 202	8, 614	29, 816	706	42, 232	6, 084	8, 618	4. 90
TOTAL	69, 943	27, 283	97, 226	58, 343	155, 569	13, 360	11, 644	18, 432	1, 380	8. 44
ALL MOTOR VEHICLES	302, 760	117, 241	420, 001	385, 422	805, 423	83, 500	9, 646	64, 516	773	12. 48

[1] For the 50 States and District of Columbia, 1963 data have een adjusted, based in part on the 1963 Census of Transpor- ation Truck Inventory and Use Survey, to provide data parately for single-unit trucks and trailer combinations.

[2] Includes taxicabs and motorcycles: 786,318 in 1963, 984,763 in 1964, and 1,381,956 in 1965, estimated to account for less than 1 percent of all travel: 1963, 0.5 percent; 1964, 0.6 percent; 1965, 0.7 percent, respectively.

greement in the two sets of data for travel y trailer combinations was noted, an investi- ation was made for each State of the dif- erences by individual types of combinations. his was possible because most operators of ailer combinations keep fairly complete ecords. It was hypothesized that an under- stimate of travel was more apt to be made or vehicles used infrequently, but, this was ot confirmed by a check of other data (*6*). lthough proportionally more responses were ade by operators of the larger vehicles, hen responses were made by operators of naller vehicles reliable information was iven on annual mileage

Motor-Fuel Consumption

Truck motor-fuel consumption estimates or 1963 reported here were based on detailed alculations of motor-fuel consumption rates or gasoline and diesel powered trucks classified by average operating gross weights for 10 types of trucks. These data were combined (table 1) for estimates of motor-fuel consumption for single-unit trucks and trailer combinations. These calculations were based on the 1963 truck weight study reports—an annual State report submitted to Public Roads—and separate estimates of the average registered gross weight of gasoline and diesel powered trucks for each type (*2*). Operating gross weights for gasoline and diesel powered trucks were computed by adjusting the average operating gross weight by the ratio between average registered gross weights of diesel to gasoline powered trucks. In the *Supplementary Report of the Highway Cost Allocation Study* (*4*), figure 12 relates average operating gross weights and type of motor-fuel. The vehicle-miles of travel by truck type were divided by the miles-per-gallon usage rate to obtain the gallons of motor fuel used by all trucks in 1963.

Passenger car fuel consumption

An adjustment also was made in the 1963 estimate for passenger car motor-fuel consumption. The previously published rate of 14.37 m.p.g. has been revised to 14.26 m.p.g. The revised estimate was based on independent analysis of available data and the previously used trend data was not considered. In the reevaluation, annual automobile sales since 1957 were analyzed to identify significant shifts in the proportion of small, medium, and large cars. Also considered was the proportion of cars equipped with automatic transmissions, optional higher powered engines, and power accessories, which affect motor-fuel consumption rates. Data for these rates were taken from an article by Nathan Lieder (*5*) and industry reports. The estimates of motor-fuel consumption by vehicle type were compared and adjusted so the total equaled the total highway use of motor fuel. The 1964 and 1965 motor-fuel consumption for passenger cars was calculated by a similar procedure in which the new 1963 estimate of travel data was used as the base.

Motor-vehicle fuel consumption, 1964 and 1965

Calculations of 1964 and 1965 estimates of motor-fuel consumption were based on data for travel by vehicle type, truck sales by fuel and truck type, and registrations by vehicle type. A sharp increase in the use of heavy (5 or more axles) trailer combinations was noted. The increased average operating gross weights for these heavier combinations ordinarily would reduce the miles per gallon rate; however, the 1964–65 increase in sales of more efficient diesel powered truck tractors tended to offset this expected reduction for trailer combinations. In contrast, the 1964 single-unit truck motor-fuel consumption rate increased from 10.13 m.p.g. in 1963 to 10.19.

In 1965, travel and sales of 4-tired trucks exceeded that for 1964. According to the 1965 truck weight study reports their travel was up 8 percent while sales increased more than 15 percent, according to industry data. The 1965 increase in miles per gallon by single-unit trucks has been attributed primarily to the increase in vehicle-miles of travel by single-unit, 4-tired trucks. The miles per gallon for other single-unit trucks was much lower. The changes discussed and other changes in truck usage were studied to refine the 1964 and 1965 estimates of motor-vehicle fuel consumption for trucks and trailer combinations (table 1).

REFERENCES

(*1*) *Highway Ton-Miles*, by Alexander French, Highway Research Record 82, Freight Transportation, 1965, pp. 77–93.

(*2*) *New Trucking Data from 1963 Census of Transportation*, by Donald E. Church, Highway Research Record 82, Freight Transportation, 1965, pp. 38–53.

(*3*) *1963 Census of Transportation: Vol. II, Truck Inventory and Use Survey*, by U.S. Bureau of the Census, 1966.

(*4*) *Supplementary Report of the Highway Cost Allocation Study*, House Doc. 124, 89th Cong., 1st sess., 1965, p. 305.

(*5*) *Passenger Car Fuel-Consumption Rates*, by Nathan Lieder, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 32, No. 5, Dec. 1962, pp. 113–120.

(*6*) *Motor-Vehicle-Use Studies in Six States*, by Thurley A. Bostick, Roy T. Messer, and Clarence A. Steele, PUBLIC ROADS, A JOURNAL OF HIGHWAY RESEARCH, vol. 33, No. 12, Dec. 1954, pp. 99–126.

U.S. GOVERNMENT PRINTING OFFICE: 1967

PUBLICATIONS
of the Bureau of Public Roads

A list of the more important articles in Public Roads *and title eets for volumes 24–33 are available upon request addressed to ureau of Public Roads, Washington, D.C. 20235.*

The following publications are sold by the Superintendent of ocuments, Government Printing Office, Washington, D.C. 20402. ders should be sent direct to the Superintendent of Documents. epayment is required.

NUAL REPORTS

nual Reports of the Bureau of Public Roads:
1960, 35 cents. 1963, 35 cents. 1964, 35 cents. 1965, 40 cents. (Other years are now out of print.)

EPORTS TO CONGRESS

ederal Role in Highway Safety, House Document No. 93 (1959). 60 cents.

ighway Cost Allocation Study:
Final Report, Parts I–V, House Document No. 54 (1961). 70 cents.
Supplementary Report, House Document No. 124 (1965). $1.00.

aximum Desirable Dimensions and Weights of Vehicles Operated on the Federal-Aid Systems, House Document No. 354 (1964). 45 cents.

he 1965 Interstate System Cost Estimate, House Document No. 42 (1965). 20 cents.

UBLICATIONS

Quarter Century of Financing Municipal Highways, 1937–61, $1.00.

ccidents on Main Rural Highways—Related to Speed, Driver, and Vehicle (1964). 35 cents.

ggregate Gradation for Highways: Simplification, Standardization, and Uniform Application, and A New Graphical Evaluation Chart (1962). 25 cents.

merica's Lifelines—Federal Aid for Highways (1966). 20 cents.

alibrating and Testing a Gravity Model for Any Size Urban Area (1965). $1.00.

apacity Charts for the Hydraulic Design of Highway Culverts (Hydraulic Engineering Circular, No. 10) (1965). 65 cents.

lassification of Motor Vehicles, 1956–57 (1960). 75 cents.

esign Charts for Open-Channel Flow (1961). 70 cents.

esign of Roadside Drainage Channels (1965). 40 cents.

ederal-Aid Highway Map (40 x 63 inches) (1965). $1.50.

ederal Laws, Regulations, and Other Material Relating to Highways (1966). $1.50.

reeways to Urban Development, A new concept for joint development (1966). 15 cents.

ighway Bond Financing . . . An Analysis, 1950–62. 35 cents.

ighway Finance 1921–62 (a statistical review by the Office of Planning, Highway Statistics Division) (1964). 15 cents.

ighway Planning Map Manual (1963). $1.00.

ighway Planning Technical Reports—Creating, Organizing, and Reporting Highway Needs Studies (1964). 15 cents.

PUBLICATIONS—Continued

Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds (May 1965). 75 cents.

Highway Research and Development Studies, Using Federal-Aid Research and Planning Funds (1966). $1.00.

Highway Statistics (published annually since 1945):
1956, $1.00. 1958, $1.00. 1959, $1.00. 1960, $1.25. 1964, $1.00. (Other years out of print.)

Highway Transportation Criteria in Zoning Law *and* Police Power and Planning Controls for Arterial Streets (1960). 35 cents.

Highways to Beauty (1966). 20 cents.

Highways and Economic and Social Changes (1964). $1.25.

Increasing the Traffic-Carrying Capability of Urban Arterial Streets: The Wisconsin Avenue Study (1962). Out of print. Appendix, 70 cents.

Interstate System Route Log and Finder List (1963). 10 cents.

Labor Compliance Manual for Direct Federal and Federal-Aid Construction, 2d ed. (1965). $1.75.

Landslide Investigations (1961). 30 cents.

Manual for Highway Severance Damage Studies (1961). $1.00.

Manual on Uniform Traffic Control Devices for Streets and Highways (1961). $2.00.
Part V—Traffic Controls for Highway Construction and Maintenance Operations (1963). 25 cents.

Opportunities for Young Engineers in the Bureau of Public Roads (1965). 30 cents.

Reinforced Concrete Bridge Members (1966). 35 cents.

Reinforced Concrete Pipe Culverts—Criteria for Structural Design and Installation (1963). 30 cents.

Road-User and Property Taxes on Selected Motor Vehicles (1964). 45 cents.

Selected Bibliography on Highway Finance (1951). 60 cents.

Standard Plans for Highway Bridges (1962):
Vol. I—Concrete Superstructures. $1.00.
Vol. II—Structural Steel Superstructures. $1.00.
Vol. III—Timber Bridges. $1.00.
Vol. IV—Typical Continuous Bridges. $1.00.
Vol. V—Typical Pedestrian Bridges. $1.75.

Standard Traffic Control Signs Chart (as defined in the Manual on Uniform Traffic Control Devices for Streets and Highways) 22 x 34, 20 cents—100 for $15.00. 11 x 17, 10 cents—100 for $5.00.

The Identification of Rock Types (revised edition, 1960). 20 cents.

The Role of Economic Studies in Urban Transportation Planning (1965). 45 cents.

Traffic Assignment and Distribution for Small Urban Areas (1965). $1.00.

Traffic Assignment Manual (1964). $1.50.

Traffic Safety Services, Directory of National Organizations (1963). 15 cents.

Transition Curves for Highways (1940). $1.75.

UNITED STATES
GOVERNMENT PRINTING OFFICE
DIVISION OF PUBLIC DOCUMENTS
WASHINGTON, D.C. 20402

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
U.S. GOVERNMENT PRINTING OFFICE

If you do not desire to continue to receive this publication, please CHECK HERE ☐; tear off this label and return it to the above address. Your name will then be removed promptly from the appropriate mailing list.