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Night scene showing Brent Spence Bridge between Cincinnati, Ohio, and Covington, Ky., on Interstate 75.

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IN THIS ISSUE

NOTICE

It has been called to our attention that some copies of the February 1966 magazine, "Public Roads, A Journal of Highway Research," were received in a damaged condition and/or were missing pages 249 through 254 and pages 271 through 276. If you were unfortunate enough to receive such a copy, please notify the editor—if possible return the damaged copy—and a replacement will be made.

Errata

Please correct the second listing in the February 1966 issue of this magazine under "IN THIS ISSUE" to read:

Mechanisms of Soil-Lime Stabilization, An Interpretive Review, *by Sidney Diamond and Earl B. Kinter* 260

U.S. DEPARTMENT OF COMMERCE
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BUREAU OF PUBLIC ROADS
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Public Roads

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Traffic Flow Responses to Unannounced Increases in Progression Speeds of Signal Systems

BY THE OFFICE OF RESEARCH AND DEVELOPMENT BUREAU OF PUBLIC ROADS

by[1] **RICHARD D. DESROSIERS, Highway Research Engineer, and CLYDE H. LEIGHTY, Highway Engineer Trainee, Traffic Systems Division**

To determine the effect on vehicular traffic when a change is made in the speed of progression of progressively timed signal systems, the time required for responses to the changes must also be determined. This knowledge will be helpful in designing traffic responsive signal systems. This article is a report on a study made of the time required by drivers to adapt to a change in speed of progression from 27 to 33 m.p.h. and from 33 to 40 m.p.h. on a 1-way urban arterial when the drivers had no knowledge of the change. The authors believe that better adaption could be obtained if information on the changes in the signal system were available to the drivers.

For the three speeds of progression studied, the drivers had neither completely adapted to the change in progression speed from 27 to 33 m.p.h. after a period of 2 months nor to a change from 33 to 40 m.p.h. after a period of approximately 1 month. The authors also believe that large traffic volumes are a limiting factor in the ability of drivers to adapt to a change in progression—choice of speed is restricted by the speed of other vehicles in the traffic stream. This belief was confirmed by the greater adaptation that was made for both changes in progression speed when the volume of traffic was lighter than during the peak rush hours.

Introduction

THE FIRST phase in a continuing study of the time required by drivers to adapt their driving pattern to changes in traffic control signal systems is discussed in this article. These studies are being conducted by the Bureau of Public Roads to gain an insight into the ability of drivers to adapt to changes in speeds of progression and other changes in the signal system, and the resultant effect on vehicular traffic. Determination of the time it takes drivers to adapt to these changes in progression of the timing of signals, and other modifications made or contemplated by traffic engineers, affects the evaluation of any changes. In the first phase, an attempt was made to determine the time required by drivers to adapt to changes in the progression of a coordinated signal system on 13th Street NW., Washington, D.C.—a 1-way urban arterial street—when no information regarding the change had been provided. Any knowledge the drivers had of the change had to be obtained from the experience of driving through the test section. Much of the field data gathered in the first phase of the study are expected to be used during the other phases.

Three speeds of progression were studied: 27 m.p.h., the initial condition; 33 m.p.h.; and 40 m.p.h. Data to establish the existing traffic characteristics for the initial condition of 27 m.p.h. were collected early in February 1964. The progression speed was changed on February 21, 1964 to 33 m.p.h.; data collection was started immediately and continued until the pattern of driver adaptation to the change in speed of progression had been clearly established. The speed of progression was changed April 17, 1964 to 40 m.p.h., and data collection was continued until completion of the first phase of the study, May 23, 1964.

Conclusion

On the basis of data collected in the study reported here, the conclusion has been made that a considerable length of time is required for drivers to adapt to changes in the speed of progression of a progressively timed signal system on an urban arterial street, particularly when the driver has no knowledge of this change. The drivers did not adapt in a day, a week, or even a month. Drivers had not fully adapted to a change in progression speed from 27 to 33 m.p.h. after 2 months nor to a change from 33 to 40 m.p.h. after approximately 1 month. The drivers made a slight adaptation to the change during the peak hour of traffic but seemed to adapt more readily to the changes when traffic was lighter at the off-peak hours.

The authors also recommend that research be undertaken in the future to determine the adaptation time of drivers to changes in the speed of progression of the signal system when the drivers are provided information of the change by signs or other media.

Test Site

Thirteenth Street, an arterial street in Washington, D.C., with a progressively timed signal system was used for the study site. As shown in figure 1, the limits of the study site extended from Park Road to Euclid Street, approximately 2,700 feet. Thirteenth 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 rest of the day. Data reported here were collected only during the morning rush period when all traffic was southbound in each of the 4 lanes. The existing signals were coordinated for 27 m.p.h. speed of progression. An 80-second cycle and a through band for traffic of 55 seconds were in effect.

Total turning movements from the test site constituted 18 percent of the average hourly traffic volume; these turns were made as follows from 13th Street to: Columbia Road, 5.3 percent; Harvard Street, 3.3 percent; Irving Street, 3.0 percent; and other, 6.4 percent. Vehicles turning onto 13th Street within the test site constituted 16.5 percent of the average hourly traffic, but these vehicles did not cause any interference with the study platoon because of the separation by traffic signals.

Study platoon

The term study platoon as used in this article refers to the group of vehicles that entered the test site on a green phase of the signals southbound on 13th Street. As the

[1] This study was made with the cooperation of the District of Columbia Department of Highways and Traffic. Special acknowledgment is made for the assistance of Joseph Rice, Chief of the Traffic Operations Division, and Mike Flanakin, Head of the Research Section, in obtaining a suitable test site and for their continued cooperation throughout the study.

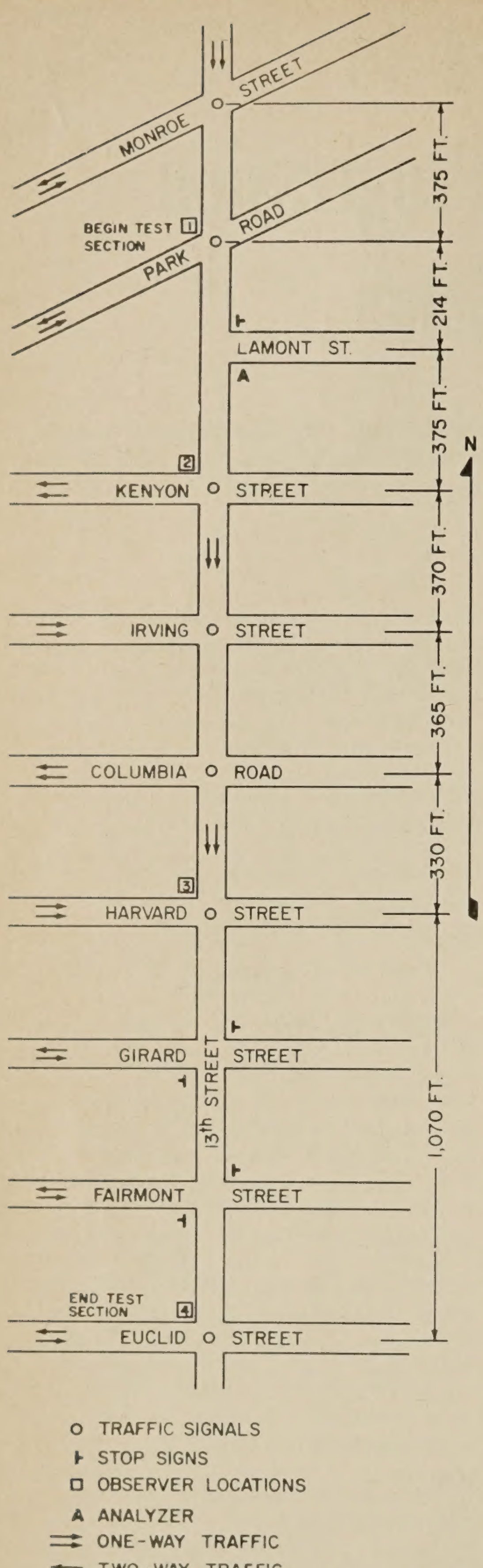

Figure 1.—Test site.

group of vehicles proceeded through the test site, some vehicles turned off or onto 13th Street. Also, others were stopped at signalized intersections within the test site. Thus the study platoon was not a fixed group of vehicles but a flexible group, which reflected the effect of turns and stops on the composition of the group that entered the test site. Traffic during the study period had essentially the same composition: passenger cars, 97+ percent; buses, 1.0 percent; and trucks, 1.0 to 2.0 percent.

Observers were stationed along 13th Street at the intersections with Park Road, Kenyon, Harvard, and Euclid Streets, as shown in figure 1. Each observer had a portable radio and five watches mounted on a clip board; the watches were adjusted so that each observer could start the five simultaneously but stop them individually. The observers recorded the speed, volume, and headway characteristics of the study platoon as it moved through the test site. To obtain usable data, accurate identification of a specific study platoon by each observer was essential. Platoon identification was difficult because different vehicles alternately assumed the lead position. To assist the observer in identifying each study platoon, radio communication from a spotter car in each platoon was used.

The spotter car assumed a position at or near the beginning of the formation of the study platoon at Monroe Street, a street preceding the beginning of the test site. On the amber signal, the radio operator in the spotter car transmitted an alert message to all observers. Then a start signal was given and each observer started his five watches. This start signal coincided with the beginning of the green phase at Monroe Street. As the study platoon moved down the street, the driver of the spotter car maintained a position within the platoon so that he could always see the lead vehicle. As the platoon approached the location of each observer, the radio operator notified him of the color, make, and year of the lead vehicle and the lane in which it was traveling so that each observer could identify the beginning of each study platoon.

As the study platoon passed each observer, he stopped the watches in sequence as the 1st, 10th, 20th, 35th, and the 50th—or last vehicle if less than 50—in the platoon passed. After the passage of time at which each of these vehicles had passed the observer was recorded, the watches were reset at zero for the timing of the next platoon. The traveltime southbound seldom exceeded 2 minutes, but the return trip of a spotter car frequently took from 8 to 10 minutes on parallel streets. Therefore, two spotter cars were used so that it was possible to study a platoon at intervals of approximately 6 minutes.

Travel speed

The recorder in the spotter car recorded the total traveltime through the test site, the time lost for each delay, and the cause of the delay. This method was similar to the floating car technique except for the instruction to the driver to maintain a position near the lead vehicle in the platoon. Thus, a running speed rather than an average speed was obtained because the lead vehicle at the front of the platoon was not stopped within the test site. This technique also was used to collect travel speed data on days when the observers and the traffic analyzer were not used. This permitted periodic observation of the speed trend and required only a few field personnel.

Traffic analyzer

The Bureau of Public Roads traffic analyzer was located just south of the Lamont Street intersection within the test site. Speed, volume, and headway data were collected by individual lanes for all traffic during the study period. By use of a coding system, each vehicle was classified as to whether it came from above Monroe Street or from off Monroe Street, Park Road, or Lamont Street. Data from the analyzer were used for speed, volume, and headway distributions and for comparison with data provided by the observers.

Data Analysis

An analysis of variance was performed to determine statistically the significance of any difference in the data reported by the observers for several volume groupings. Data for speed and headway of the study platoons were analyzed in relation to the positions of the four observers and vehicle position within the platoon. Statistically significant differences were subjected to a simple Fisher (F) test. When no statistically significant differences in variances were obtained, it was concluded that the observed difference in the analysis of variance was the result of a significant difference in means. The 5-percent level of significance was used for all tests. A 5-percent level of significance means that even without significant statistical differences, an actual difference as large as that obtained could occur by chance alone 5 times in 100. Only significant variables are discussed in this article. A regression analysis was performed on the speed data obtained from the spotter vehicle. More information on the regression analysis is presented later.

Traffic Characteristics for 27 M.P.H. Progression Speed

The daily traffic volume on the test site during 1963 on Tuesdays, Wednesdays, and Thursdays was fairly constant according to traffic counts made by the District of Columbia Department of Highways and Traffic. The mean daily volume of traffic was approximately 26,700 vehicles and never varied more than 5 or 6 percent. Also, very little variation occurred between weeks or month; this variation being ±5 percent of the mean reflected by the daily variation. The mean of the peak hour volume was 3,465 vehicles and the fluctuation was ±5 percent of the peak hourly volume. On the basis of past volume trends, it was determined that a representative sample of normal traffic could be obtained by collecting data on any Tuesday, Wednesday, or Thursday. Data on traffic volume collected in early February 1964 are reported in figure 2. Volume is shown for each 12-minute period from 7:18 to 9:30 a.m. The peak 12-minute volume of 710 vehicles occurred during the period from 8:06 to 8:18 a.m. The traffic volumes recorded in February 1964 were comparable to those reported for 1963.

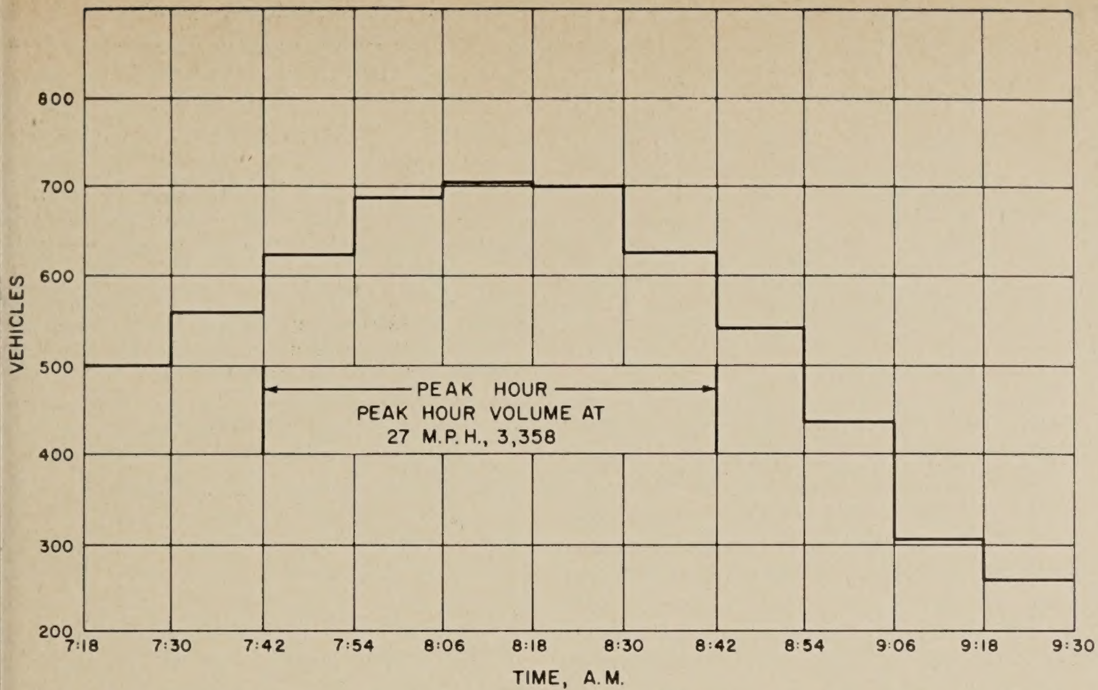

Figure 2.—Average traffic volume for all lanes for 12-minute periods for 27 m.p.h. speed of progression.

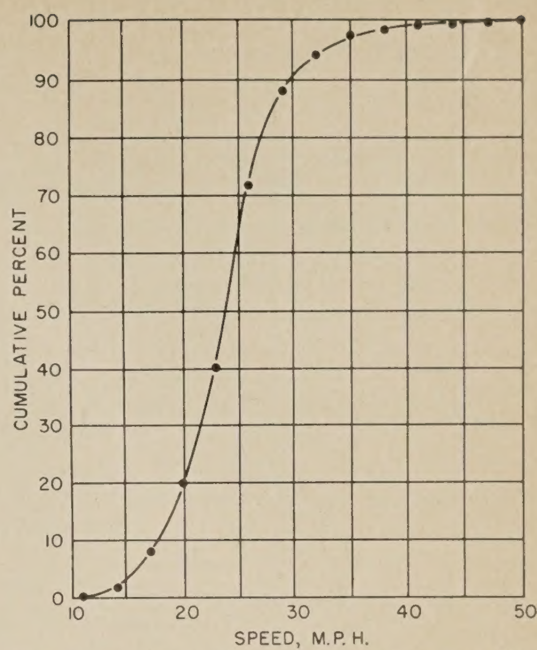

Figure 4.—Distribution of spot speeds for all lanes at 27 m.p.h. speed of progression.

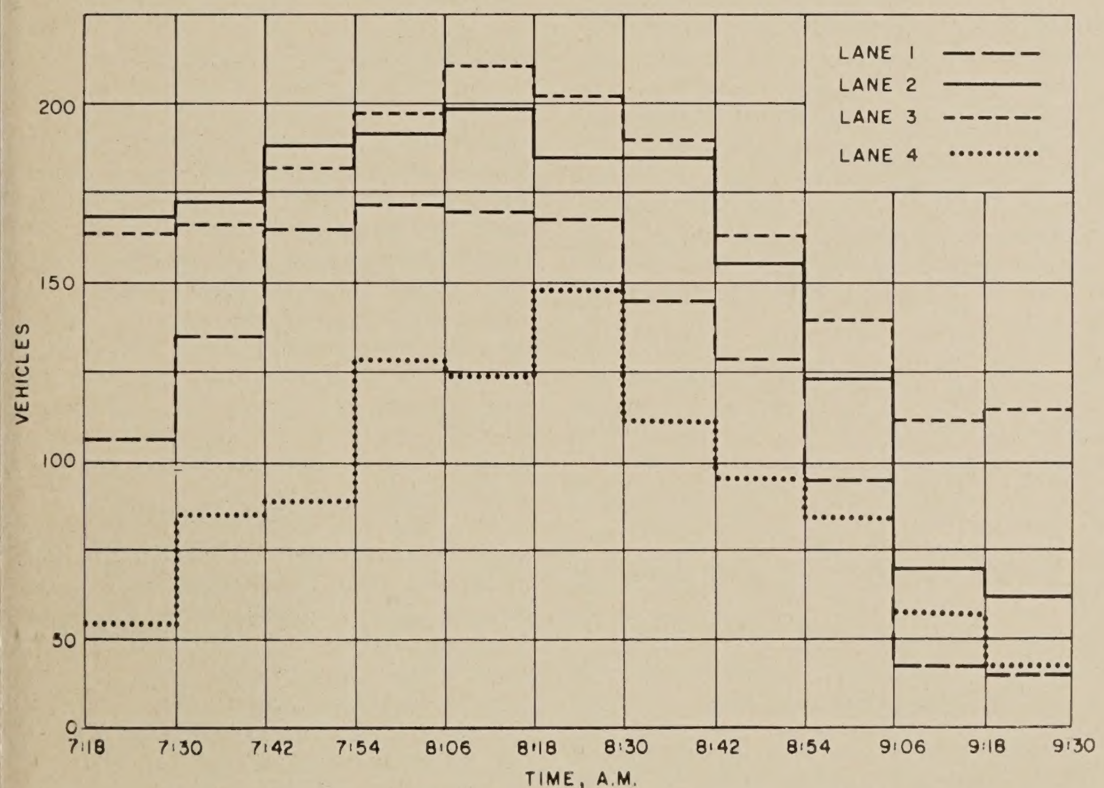

Figure 3.—Average traffic volume per lane by time increment for 27 m.p.h. speed of progression.

The traffic volume by lane is reported in figure 3. Each of the center lanes carried considerably more vehicles, in all time periods, than the two curb lanes. Traffic in the right curb lane was especially low for all time periods studied. Even in the peak hour this lane carried only about one-half to two-thirds the traffic volume carried by the center lanes. Drivers in the right curb lane are restricted by turning vehicles and buses; and, generally, drivers not wishing to turn avoid this lane. This reasoning is confirmed by the large percentage of through traffic in relation to turning traffic noted in the study reported here.

Speed

The distribution of spot speeds obtained with the traffic analyzer, which was placed midway between the signalized intersections of Park Road and Kenyon Street, is shown in figure 4. The speeds of all vehicles observed during the period from 7:30 to 9:30 a.m. for a typical study day are included. The mean speed was 23.9 m.p.h. with a standard deviation of 5 m.p.h. With this mean and standard deviation, 67 percent of all vehicles can be expected to travel at speeds within the range from 18.9 to 28.9 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. The distribution of speeds by lane is shown in table 1. The speed in lane 1—the far left lane when travel is southbound—was significantly lower statistically than in the other three lanes, in which speeds were nearly identical. The differences in mean speed, 85th percentile speed, and standard deviation for the different lanes were small.

Headways

Times recorded for the passing of the 1st, 10th, 20th, 35th, and 50th vehicles were used to compute the average time headway per vehicle per lane for each of the several groups of vehicles by the following formula: Headway is defined as the time between successive vehicles.

$$H=\frac{TL}{N-1}$$

Where,

H= Average headway in seconds per vehicle per lane for the group of vehicles being considered.
T= Passage time for the group in seconds.
L= All four traffic lanes.
N= Number of vehicles in group (10 or 15).

Headway was computed in this manner for groups of vehicles of: 1 through 10, 11 through 20, 21 through 35, and 36 through 50. As no significant differences in headway were observed between these groups, the data were combined for further analyses. This does not mean that no differences occurred: it does mean that if differences existed they could not be detected by this technique. Figure 5 shows the average time headway in seconds per vehicle for the time of day for the platoons studied during the 27 m.p.h. speed of progression. The range of average headways was from 2.5 to 4.0 seconds. The headway for the mean peak hour platoon was 2.7 seconds. The

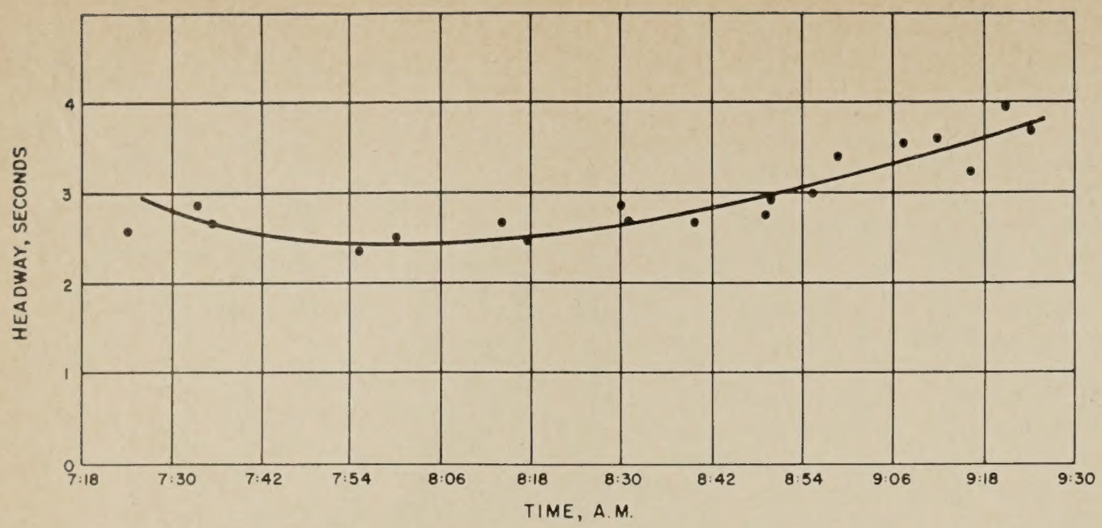

Figure 5.—Average time headways related to time of day for platoons during 27 m.p.h. speed of progression.

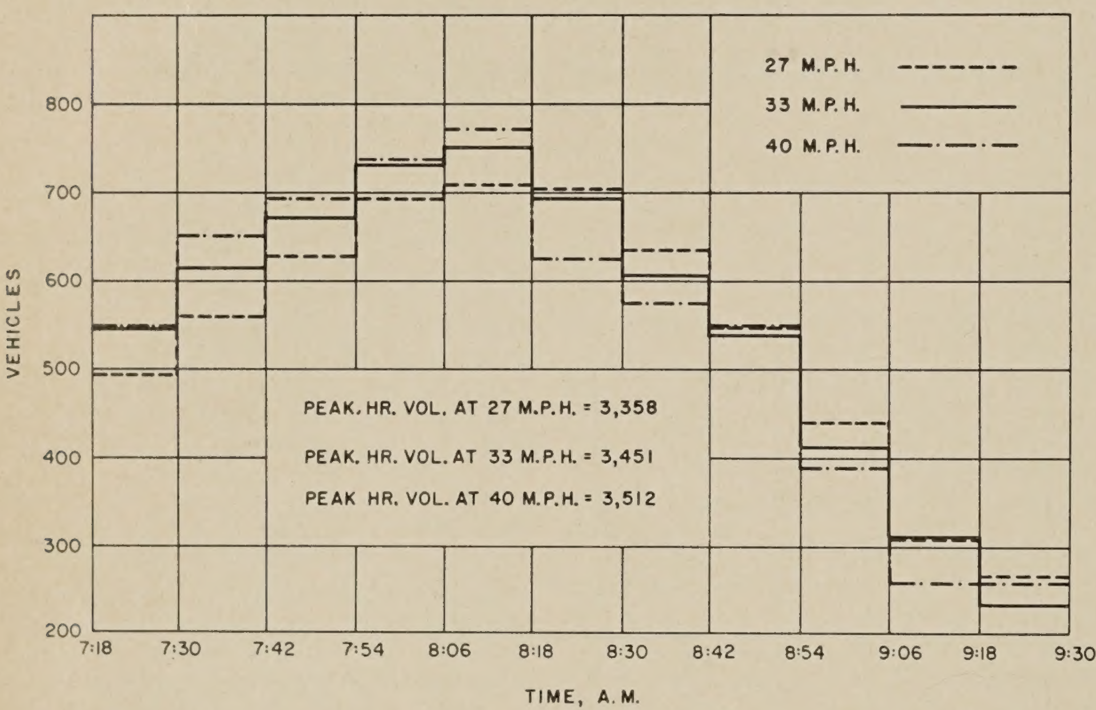

Figure 6.—Average traffic volume for all lanes by time increment for three speeds of progression.

headway for the mean off-peak hour platoon was 3.5 seconds.

Effect of Increase in Speed of Progression

Traffic volume conditions for typical days at each speed of progression are shown in figure 6. The peak hour volumes of traffic increased slightly, being 3,358 at 27 m.p.h., 3,451 at 33 m.p.h., and 3,512 at 40 m.p.h. It was not possible to establish whether the increase that accompanied the change in speed was a true increase or a chance occurrence because the increases were within 5 percent of the historical daily mean. It seems that as the speed of progression was increased, a higher volume per 12-minute period occurred until the peak hour volume was attained; but when the peak hour volume was reached the trend was reversed and traffic volume per 12-minute period was less.

Speed Distribution

The distribution of spot speeds for all vehicles passing the traffic analyzer during the study period the last study day for each speed of progression is shown in figure 7. The mean spot speed increased from 23.9 m.p.h. to 26.5 m.p.h. and then to 27.9 m.p.h. respectively for the 33 m.p.h. and 40 m.p.h. progression speeds. Also, the variance was essentially unchanged when the speed increased from that of the original condition. The 85th percentile speed increased from 28.4 m.p.h. to 31.3 m.p.h., when the speed of progression was increased from 27 to 33 m.p.h. but little change occurred when the speed of progression was increased to 40 m.p.h.

The mean speeds, standard deviations, and 85th percentile speeds for each lane are listed in table 2. Lane 2 had the largest increase in speed (4.6 m.p.h.) and lane 4 had the least

Table 1.—Speed characteristics analysis

Lane	Mean speed	Standard deviation	85th percentile speed
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

Table 2.—Mean, standard deviation, and 85th percentile spot speeds by lane for each speed of progression

Speed of progression, m.p.h.	Mean, $\overline{X}$	Standard deviation, S_x	85th percentile
Lane 1:			
27	23.0	4.74	27.5
33	26.3	4.35	30.8
40	26.7	5.01	29.8
Lane 2:			
27	24.6	5.25	29.0
33	27.5	3.24	32.5
40	29.2	5.39	32.7
Lane 3:			
27	24.0	5.01	28.2
33	26.0	4.53	30.5
40	27.0	5.40	31.0
Lane 4:			
27	24.5	5.67	29.3
33	26.1	5.49	31.5
40	26.5	5.30	30.5

(2.0 m.p.h.). In lane 1—where speed was significantly slower at the 27 m.p.h. speed of progression than in the other lanes—no lag in speed was noted at 33 m.p.h. and 40 m.p.h. speeds of progression. There was no significant change in the standard deviation. The 85th percentile speed also increased with the increase in progression speed. Most of the increase in mean and 85th percentile speed can be accounted for by the increase from 27 m.p.h. to 33 m.p.h., with little additional increase noted when the progression speed was increased to 40 m.p.h.

The mean and 85th percentile speeds may mask the true magnitude of the adaptation of drivers when traffic volumes are smaller because a large proportion of the observations were recorded in the peak hour when the driver's choice of speed was limited by traffic volume considerations,this is shown in figure 8. For each of the speeds of progression, the spot speed decreased as the volume increased. Of greater importance, however, is the apparent converging of the curves as the volume increased, which indicates that greater adaptation was being made at the smaller traffic volumes.

Speed of Lead Vehicle

Any adaptation to change in speed of progression should be reflected by the lead vehicle in the platoon as this vehicle is free of interference from vehicles in front of it. However, if the speed of the lead vehicle is to be used as an indicator of driver adaptation, this speed must be established as representative of the entire platoon. In table 3 the running speed of the lead vehicle is compared

(Continued on p. 13.)

Variability in an Asphalt Concrete Mix

BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS

Reported [1] by EDWARD R. OGLIO and JOSEPH A. ZENEWITZ, Chemists, Materials Division

Introduction

THE CONSTRUCTION of quality highways and the procedures to assure achievement of quality have always been primary concerns of those involved in the many phases of planning, designing, and building highways. In recent years highway programs of increased magnitude to accommodate larger traffic volumes, faster speeds, and heavier wheel loads have demanded increasingly higher levels of quality in highway construction and improved control and acceptance procedures to assure attainment of such levels.

The dictionary gives more than 15 definitions for the word quality. However, a definition that perhaps applies best to highway construction describes quality as the degree to which a product satisfies a consumer. In the highway industry a product could be the finished highway, any or all of its structural components, and any of the constituent materials used in construction of the finished product or of its components. A consumer in this context would be a State highway department or other government department, a contractor, a subcontractor, or even a private individual.

Findings Summarized

As the study discussed in this article covered but one type of asphalt mixture produced at one plant for a single construction project, no general conclusions can be drawn from the data at this time. Such conclusions should await acquisition of results from similar studies contemplated under the nationwide Bureau of Public Roads Quality Control Program. Pending acquisition of these additional data, the significant results obtained are summarized as follows:

- Inherent process variability was the major factor contributing to variation in mixture composition, as determined by extraction and gradation tests. When variability is expressed as variance, approximately 60 percent of the variation in asphalt content and 85 to 98 percent of the variations in gradation were attributable to the plant process. Variation attributable to the sampling and test procedures accounted for the remainder of variation in composition.

The research reported in this article was conducted as part of the first phase in a broad program being undertaken by the Bureau of Public Roads to develop control and acceptance procedures, based on statistical quality control techniques, to all aspects of highway materials and construction. As the program is now constituted, the first phase calls for determination of two basic statistical parameters—the average and the standard deviation—for the materials and structural elements now being used in good highway construction.

In the work reported here, averages and variations in temperature, asphalt content, and aggregate gradation were determined in an asphalt concrete wearing course mix produced for a construction job. A statistical analysis was made to show the effect of test method, sampling procedure, and material (batch-to-batch) variation on the overall variations obtained.

- The sampling and testing procedures used were minor factors in the variations observed in mix composition; they accounted for substantially less than half of the variation for each item of composition.
- Deviations of the test averages from the design values were the major cause of the deviation of individual test results from the permissible limits (tolerances).
- The feasibility of conducting studies of this type without appreciable interference with the normal course of plant production was confirmed.

The Concept of Quality

Two aspects (*1*)[2] are involved in the concept of quality: (1) quality of design and (2) quality of conformance. Quality of design is usually incorporated in plans, specifications, special provisions, or other formal documents, any or all of which describe the item wanted or produced. It is the levels of quality of products that are intended to perform the same basic function. For example, a box camera and a 35-mm. camera serve the same basic function. However, they differ substantially as to the levels of design incorporated in each. Similarly, highways are designed at different levels of quality depending on the expected traffic, climate, and other considerations. Obviously a highway or pavement whose function is to bear high-density, high-speed, heavy wheel load traffic is designed at a higher level and requires better materials and material control than one intended to serve low-density, low-speed, and lighter wheel load traffic.

Quality of conformance, however, refers to the fidelity or degree to which a product conforms to its design. A high degree of conformance to the design elements means a high degree of assurance that the designed quality has been attained. A 35-mm. camera that does not take pictures differs as to quality of conformance from one that does, to use an extreme example. Usually, a variation will exist in the ability of individuals using 35-mm. cameras that had been made to the same design and specifications or even in individual cameras from the same production line. Such variation is a manifestation of the fact that variation is a universal phenomenon whether products, processes, measurements, or materials are concerned. The better the control of such variations, the closer the individual items will conform to the design quality level under which they were produced. In production, allowance is made for variation by permitting design tolerances in the specifications under which the items are produced.

Although present knowledge and capabilities permit attainment of almost unlimited levels of quality in both design and conformance, the limiting factor of cost must always be considered. The higher these levels, the higher will be the cost of achieving them. However, there are levels at which the costs of quality achievement are in balance with the value for the consumer or, at least, in balance with what he needs and with what he can pay. In the highway field these levels should be the desired goals.

Bureau of Public Roads Program

Different methods have been used to achieve quality goals. Those based on statistical concepts have been widely and successfully used in industry. Such methods are generally referred to as quality control methods when used by producers and as acceptance plans when used by purchasers or consumers. However, except for some notable exceptions such as construction of the Garden State Parkway in New Jersey, the Illinois toll road, and the

[1] Presented at the annual meeting of the Association of Asphalt Paving Technologists, Philadelphia, Pa., Feb. 15–17, 1965.

[2] Italic numbers in parentheses indicate the references listed on page 11.

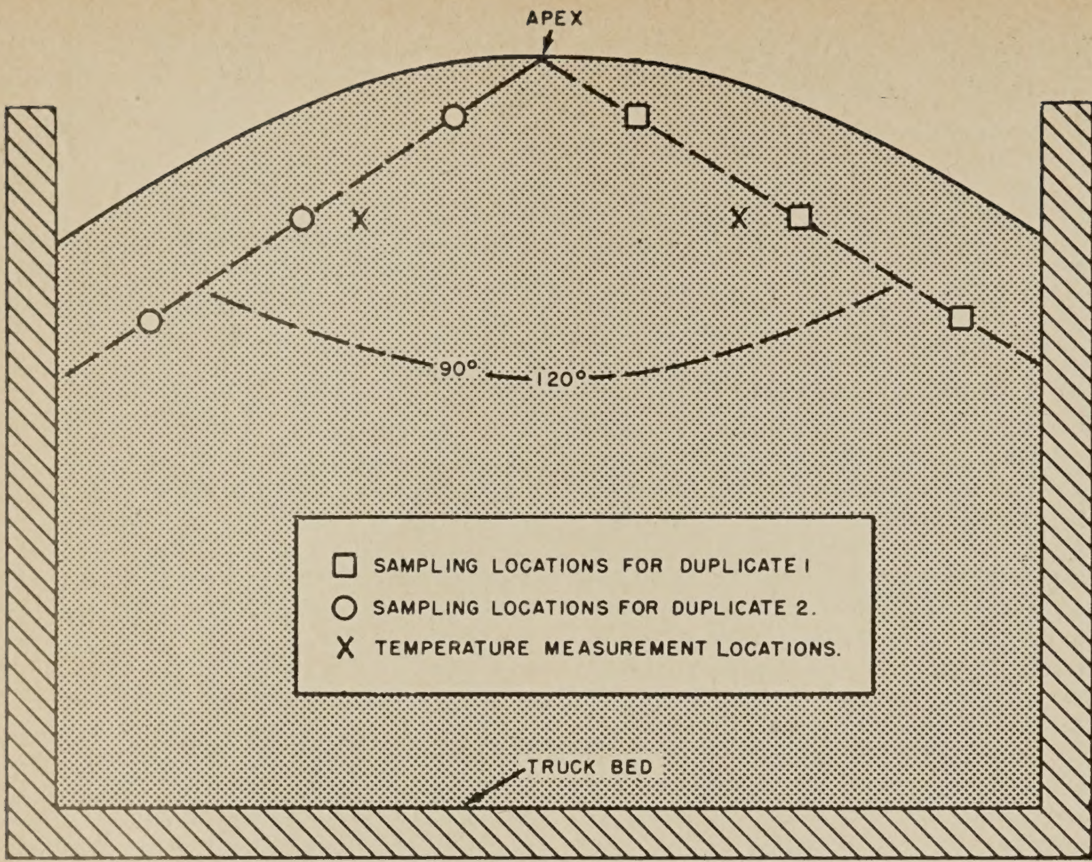

Figure 1.—Schematic of sampling locations.

AASHO Test Road, quality control procedures have not been used to the fullest by the highway industry.

Accordingly, the Bureau of Public Roads has undertaken a broad program aimed at applying statistical techniques to the development of improved procedures for control and acceptance in all phases of highway construction. Basically the objective of the program is to develop procedures that will assure, with a known degree of confidence, production and acceptance of the materials and structural elements of highways at the levels of quality required by modern traffic conditions and economic considerations. Attainment of this objective, in three more or less consecutive phases, is being sought through coordinated efforts with the States and other segments of the highway industry. These efforts are explained in the following paragraphs.

- The first phase is aimed toward determination of the basic statistical parameters associated with the significant requirements and characteristics specified or designed for highway materials and structural elements through studies of a broad spectrum of current good highway design and construction. The basic parameters required for the overall program, as now constituted are the average and the variability of the measurable characteristics and requirements.
- The second phase includes development of guidelines, based on statistical concepts, for preparing highway specifications; together with development of sampling and acceptance plans for evaluating conformance to the specifications at known levels of confidence.
- The third phase includes development of acceptable levels of quality and uniformity (tolerances) that will provide an optimum balance between construction, performance, and maintenance, and overall cost.

Purpose of Study

The study discussed in this article was undertaken primarily to obtain some of the data required to determine the statistical

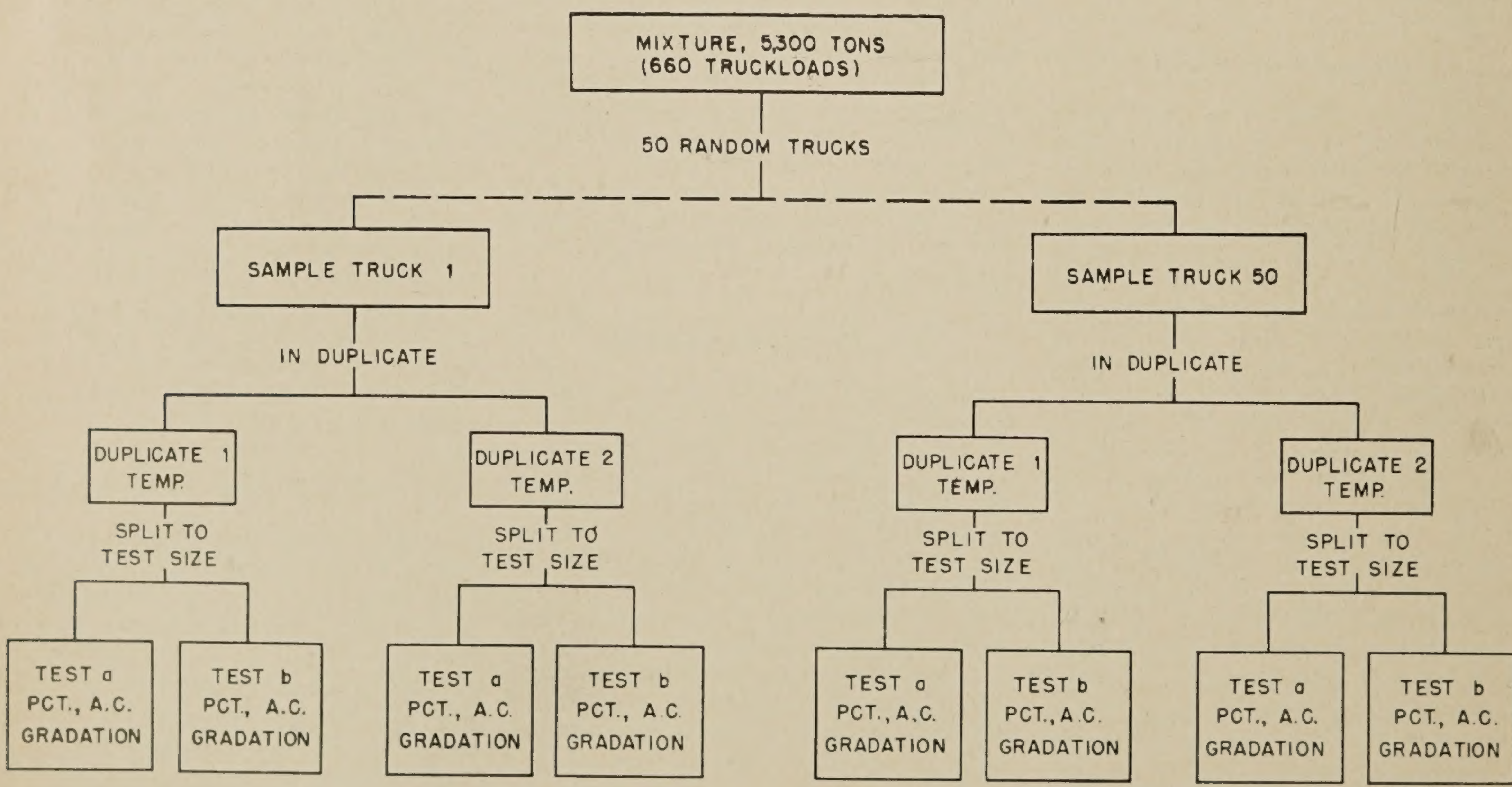

Figure 2.—Sampling plan.

Table 1.—Summary of extraction test results

Test property	Mix design (JMF)	Number of tests	Test results				
			Average	Standard deviation	Percent of tests—		
					Within JMF	Below JMF	Above JMF
Mix temperature ° F	305 ±20	100	305.5	[1] 18.0	70.0	[1] 18.0	[1] 12.0
Asphalt content percent	6.0± 0.3	200	5.955	0.120	100.0	0.0	0.0
Gradation, aggregate passing sieve:							
½-inch percent	100	200	100.0	--------	100.0	0.0	0.0
⅜-inch do	93 ± 7	200	97.5	1.72	100.0	0.0	--------
No. 4 do	63 ± 7	200	62.0	4.18	94.0	[2] 4.5	[2] 1.5
No. 10 do	42 ± 4	200	38.9	2.13	74.5	[3] 25.5	0.0
No. 20 do	------------	200	26.4	2.05	--------	--------	--------
No. 40 do	18 ± 4	200	18.3	1.69	100.0	0.0	0.0
No. 80 do	7 ± 4	200	9.5	1.46	89.5	0.0	[4] 10.5
No. 200 do	4 ± 2	200	5.59	1.16	77.5	0.0	[4] 22.5

[1] Ascribed mainly to changes in plant operation made to compensate for changes in atmospheric temperatures.
[2] Ascribed mainly to high variability.
[3] Ascribed mainly to average lying below design value.
[4] Ascribed mainly to average lying above design value caused at least in part by dry sieving of hot bin aggregates during plant control.

Table 2.—Summary of combined hot bin gradations test results

Aggregate passing sieve, percent	Mix design (JMF)	Test results [1]—	
		Average	Standard deviation
½-inch	100	100	-------
⅜-inch	93±7	98.8	0.15
No. 4	63±7	65.2	2.14
No. 10	42±4	41.7	1.41
No. 40	18±4	16.9	1.13
No. 80	7±4	7.04	1.32
No. 200	4±2	3.75	1.11

[1] Ten tests were made for each size of aggregate.

parameters under phase 1 of this quality control program. Secondarily, the study was made to evaluate some of the factors contributing to variability in the characteristics studied as a guide for future efforts to improve uniformity and control.

The work discussed in this article concerned: (1) Determinations of the averages and the variations in temperature, asphalt content, and aggregate gradation in an asphalt concrete wearing course mixture produced by one plant for a normal job; and (2) an evaluation of the effects of inherent process variability, sampling procedure, and test method (measurement process) on the variations obtained.

Methods and Materials

The job selected for this study was a resurfacing of an existing pavement requiring an estimated 7,700 tons of asphalt concrete for the wearing course. However, for practical reasons, only the last 5,300 tons of production were sampled to obtain the data reported for this study. The mixture consisted of a coarse aggregate of crushed trap rock, river sand, and screenings combined with an 85–100 penetration grade asphalt cement for a job mix formula (JMF) of:

Aggregate, sieve size	*Percent*
½-in.	100
⅜-in.	93±7
No. 4	63±7
No. 10	42±4
No. 40	18±4
No. 80	7±4
No. 200	4±2
Asphalt cement	
Mix basis	6±0.3

Plant and Production

The mix was produced in 2⅔-ton batches in a batch plant that had a 3-ton capacity, twin-shaft pugmill mixer. Heated aggregates were stored in three hot bins that discharged directly into the weigh-hopper. The proportions of hot bin aggregates and asphalt flowing into the mixer were manually controlled. The mixing cycle used for the total production was a 10-second dry mixing of the aggregates followed by 30 seconds of wet mixing. A temperature of 305° F. ±20° F. was specified as mixture temperature. However, the job ran into late November, and increases in mixture temperature were ordered on days when atmospheric temperatures dropped below 50° F. Normal plant control practices were used by plant and inspection personnel throughout the entire production. These practices included, among others, day-to-day control of aggregate gradation through daily hot bin gradation tests made by the inspector, who performed his control activities independently of the study.

In making the hot bin gradation tests, samples were taken from the aggregate stream directly under each bin and dry sieved manually. The sieve sizes used were as follows: (1) Coarse bin: ½-in., ⅜-in., and No. 4; (2) medium bin: ⅜-in., No. 4, and No. 10; and (3) fine bin: No. 4, No. 10, No. 40, No. 80, and No. 200. The combined hot bins gradation was obtained by calculations from the gradation test results and the respective bin proportions of 8, 40, and 52.

Sampling

The mixture selected for the study totaled 5,300 tons and was transported in 660 truckloads. Samples were taken from 50 randomly selected trucks. To ensure randomization a table of random numbers was used in selecting the individual trucks to be sampled. Duplicate samples were taken from each truck. A duplicate sample consisted of a composite of three scoops of mixture, each scoop containing approximately 3 pounds. These scoops of mixture were taken from the pile in the truck at a depth of approximately 1 foot and at three levels along an imaginary straight line from the apex to the bottom. Duplicate samples were taken from different lateral locations in the pile, 90 degrees to 120 degrees apart as measured from the apex. A schematic representation of this procedure is shown in figure 1. One temperature measurement was made at each duplicate sample location (fig. 1). Each duplicate sample was split by a sample splitter a sufficient number of times to provide two samples of approximately 1,200 grams each for extraction and gradation tests.

A schematic representation of the sampling plan is shown in figure 2. Use of this plan permits an evaluation through an analysis of variance of the effects of inherent process variability, sampling, and method of test on total variability.

Test Methods

Asphalt content was determined by ASTM Method D 2172–63T Method A, using benzene as the solvent (*2*). No correction was made for moisture content because spot checks had indicated that moisture was negligible. AASHO Designation: T 30–55 (*3*) was used for sieve analysis of the extracted aggregates. Temperatures were measured at approximately 8-inch depths at the two temperature test sites in the mixture pile, as shown in figure 1. These measurements were made with calibrated dial thermometers immediately after the last batch of mix had been dumped into the truck.

Analysis of Variance

The analysis of variance to evaluate the factors contributing to variability was based on the following relation:

$$(\sigma')^2 = (\sigma_a)^2 + (\sigma_s)^2 + (\sigma_t)^2$$

Where:

$(\sigma')^2$ = Overall variance.
$(\sigma_a)^2$ = Inherent process variance.
$(\sigma_s)^2$ = Sampling variance.
$(\sigma_t)^2$ = Variance caused by test method.

Details of the method used to compute the variance (*4*) are given at the end of this article.

Results

A summary of the extraction test results showing averages, standard deviations, and percentages within or outside the ranges permitted by the job mix formula for each measured property is given in table 1. Similar results for the combined hot bin gradations are given in table 2. These tests were made

Table 3.—Extraction test results

Sample: Number	Sample: Duplicate	Sample: Test	Mix temperature	Aggregate passing sieve [1]— 3/8-in.	No. 4	No. 10	No. 20	No. 40	No. 80	No. 200	A.C. mix basis
			°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
1	D_1	a	304	98.7	63.4	38.8	24.7	14.9	6.4	3.51	[2] 5.75
	D_1	b		97.8	62.9	38.2	24.1	14.8	6.5	3.53	[2] 5.69
	D_2	a	303	98.0	65.2	38.9	24.2	14.8	6.5	3.64	[2] 5.76
	D_2	b		98.5	63.1	38.4	24.1	14.8	6.3	3.52	[2] 5.74
2	D_1	a	308	98.8	60.8	38.2	25.1	16.0	7.7	4.48	[2] 5.73
	D_1	b		98.3	61.4	38.7	25.3	16.1	7.7	4.53	[2] 5.71
	D_2	a	303	98.7	62.7	39.2	25.7	16.4	8.0	4.81	[2] 5.69
	D_2	b		98.2	62.6	39.8	25.8	16.5	8.0	4.79	[2] 5.71
3	D_1	a	308	98.6	60.8	39.2	27.2	17.3	6.3	3.53	[2] 5.83
	D_1	b		99.0	60.7	39.7	27.7	17.8	6.5	3.57	[2] 5.94
	D_2	a	303	98.7	61.8	39.8	27.2	17.5	6.5	3.48	[2] 5.81
	D_2	b		98.1	60.1	39.7	27.2	17.6	6.6	3.57	[2] 5.78
4	D_1	a	278	97.6	67.7	39.6	27.8	18.6	7.7	4.47	[2] 5.69
	D_1	b		97.9	60.9	39.2	27.8	18.4	7.7	4.51	[2] 5.70
	D_2	a	277	97.5	61.9	39.5	27.8	18.6	7.7	4.49	[2] 5.93
	D_2	b		96.8	60.7	38.8	27.6	18.3	7.7	4.48	[2] 5.84
5	D_1	a	307	97.7	63.4	40.2	27.2	18.5	10.0	6.47	[2] 5.61
	D_1	b		96.8	64.5	40.1	27.4	18.7	10.0	6.55	[2] 5.63
	D_2	a	303	96.9	61.9	39.1	26.9	18.2	9.6	6.18	[2] 5.69
	D_2	b		96.6	62.1	39.2	26.9	18.2	9.6	6.10	[2] 5.70
6	D_1	a	292	93.8	57.5	39.6	26.4	17.6	8.4	5.02	[2] 5.68
	D_1	b		95.0	58.2	39.9	26.3	17.4	8.3	4.90	[2] 5.67
	D_2	a	301	95.2	58.3	40.1	26.5	17.6	8.4	4.95	[2] 5.76
	D_2	b		95.3	58.7	39.7	26.4	17.6	8.4	5.02	[2] 5.70
7	D_1	a	302	95.7	61.6	40.6	26.3	16.9	7.6	4.25	[2] 5.92
	D_1	b		95.4	60.5	40.0	26.5	17.1	7.8	4.35	[2] 5.88
	D_2	a	303	94.4	62.1	40.9	26.8	17.1	7.7	4.30	[2] 5.87
	D_2	b		95.7	57.6	39.2	25.8	16.6	7.4	4.09	[2] 5.77
8	D_1	a	298	96.5	63.2	40.1	28.1	18.5	7.6	4.03	[2] 5.77
	D_1	b		97.0	63.4	41.1	28.5	18.7	7.8	4.19	[2] 5.75
	D_2	a	298	98.1	68.2	43.8	29.7	19.4	8.0	4.32	[2] 5.91
	D_2	b		97.5	63.9	41.1	28.5	18.7	7.8	4.17	[2] 5.78
9	D_1	a	312	97.8	51.2	35.3	25.6	17.7	8.2	4.31	[2] 5.57
	D_1	b		96.8	52.7	35.6	25.8	18.1	8.5	4.55	[2] 5.65
	D_2	a	311	96.0	50.5	34.7	25.2	17.7	8.2	4.39	[2] 5.52
	D_2	b		97.6	53.6	35.9	25.6	17.7	8.2	4.36	[2] 5.63
10	D_1	a	272	92.5	56.4	39.7	26.8	18.2	8.6	4.90	[2] 5.57
	D_1	b		92.7	56.4	40.6	27.2	18.2	8.6	4.79	[2] 5.62
	D_2	a	270	93.1	60.3	42.2	27.9	18.6	8.6	4.81	[2] 5.67
	D_2	b		93.1	58.3	41.0	27.3	18.3	8.6	4.82	[2] 5.57
11	D_1	a	280	92.0	57.6	40.3	27.5	18.6	9.1	4.97	[2] 5.63
	D_1	b		94.4	58.7	40.7	27.6	18.7	9.0	5.04	[2] 5.84
	D_2	a	281	92.3	52.6	37.5	26.0	17.7	8.8	5.00	[2] 5.66
	D_2	b		95.1	58.5	40.3	27.2	18.3	8.8	4.76	[2] 5.79
12	D_1	a	300	94.4	60.8	37.3	23.1	16.4	9.8	5.64	[2] 5.80
	D_1	b		92.0	59.2	36.6	22.9	16.1	9.5	5.31	[2] 5.76
	D_2	a	301	93.3	60.9	37.0	22.9	16.3	9.8	5.63	[2] 5.76
	D_2	b		94.9	59.9	36.9	23.0	16.2	9.6	5.43	[2] 5.74
13	D_1	a	294	97.9	64.8	39.6	25.3	17.4	9.2	5.64	[2] 5.73
	D_1	b		98.1	63.2	38.9	25.2	17.3	9.1	5.58	[2] 5.53
	D_2	a	293	98.1	65.3	40.0	25.6	17.5	9.2	5.60	[2] 5.84
	D_2	b		98.1	62.2	38.8	25.3	17.4	9.3	5.68	[2] 5.63
14	D_1	a	284	97.5	64.5	40.6	27.1	18.7	9.6	5.79	[2] 6.06
	D_1	b		97.4	64.7	41.1	27.2	18.7	9.5	5.66	[2] 6.08
	D_2	a	281	98.2	62.8	39.8	26.5	18.1	9.1	5.47	[2] 5.99
	D_2	b		98.2	62.7	40.0	26.8	18.3	9.2	5.53	[2] 6.01

Sample: Number	Sample: Duplicate	Sample: Test	Mix temperature	Aggregate passing sieve [1]— 3/8-in.	No. 4	No. 10	No. 20	No. 40	No. 80	No. 200	A.C. mix basis
			°F.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
26	D_1	a	312	97.7	58.4	40.3	28.8	19.8	8.6	4.62	5.90
	D_1	b		98.1	60.2	40.9	29.2	20.3	9.0	5.00	5.96
	D_2	a	313	98.5	60.7	41.3	29.4	20.2	8.8	4.73	5.91
	D_2	b		97.6	59.5	40.5	29.1	19.9	8.7	4.69	5.89
27	D_1	a	298	98.8	64.3	42.2	29.7	20.5	10.0	5.78	5.86
	D_1	b		99.2	62.5	41.4	29.1	20.3	10.0	5.81	5.74
	D_2	a	295	98.5	62.9	41.3	29.1	20.1	9.8	5.55	6.04
	D_2	b		98.8	63.4	41.4	29.1	20.0	9.7	5.54	6.04
28	D_1	a	282	95.7	62.3	40.7	29.2	21.9	14.2	9.56	6.17
	D_1	b		95.4	61.8	40.2	29.0	21.8	14.1	9.45	6.21
	D_2	a	279	93.2	58.7	39.1	28.5	21.5	13.8	9.26	6.04
	D_2	b		95.2	59.5	39.2	28.7	21.7	14.1	9.55	6.01
29	D_1	a	312	98.2	61.8	37.6	25.1	17.1	8.7	5.04	5.86
	D_1	b		96.9	61.8	37.8	24.9	17.0	8.8	5.19	5.83
	D_2	a	311	96.0	58.5	36.6	24.6	16.8	8.7	5.07	5.83
	D_2	b		96.9	59.9	36.3	24.6	16.8	8.6	5.01	5.85
30	D_1	a	282	97.9	63.7	40.8	29.1	21.2	12.1	7.00	5.84
	D_1	b		98.0	64.9	41.7	29.5	21.5	12.3	7.25	5.87
	D_2	a	281	98.4	60.4	39.0	28.5	20.8	11.9	7.01	5.67
	D_2	b		97.3	60.0	38.9	28.5	20.9	11.9	7.00	5.69
31	D_1	a	322	96.0	57.3	39.6	25.8	17.7	9.1	4.95	5.86
	D_1	b		96.3	54.7	37.4	25.1	17.4	9.0	4.82	5.79
	D_2	a	321	96.0	53.6	37.1	25.1	17.3	9.0	4.89	5.69
	D_2	b		96.3	54.0	36.9	25.0	17.2	8.9	4.86	5.75
32	D_1	a	322	97.3	60.0	34.7	23.2	16.5	9.4	5.54	5.75
	D_1	b		98.6	62.8	36.2	23.8	16.8	9.6	5.74	5.90
	D_2	a	321	98.7	62.9	35.9	23.8	16.8	9.6	5.71	5.80
	D_2	b		98.9	63.5	37.2	24.3	17.2	9.9	6.02	5.82
33	D_1	a	326	99.5	69.7	38.9	24.3	16.9	9.4	5.53	6.04
	D_1	b		98.7	69.9	38.6	24.4	17.0	9.4	5.58	6.01
	D_2	a	327	98.9	70.1	38.8	24.4	17.1	9.6	5.74	5.90
	D_2	b		98.8	70.3	38.5	24.3	17.1	9.7	5.82	5.87
34	D_1	a	312	99.4	63.7	38.4	26.2	18.5	9.9	5.45	5.95
	D_1	b		98.4	66.4	39.4	26.6	18.8	10.1	5.56	6.04
	D_2	a	313	98.4	67.0	39.4	26.6	18.7	9.9	5.40	6.04
	D_2	b		99.1	63.7	38.1	26.1	18.4	9.8	5.27	5.86
35	D_1	a	330	98.5	67.9	36.9	24.0	16.9	9.4	5.49	5.89
	D_1	b		99.5	69.5	37.4	24.7	17.4	10.0	6.00	5.87
	D_2	a	330	99.2	67.0	36.7	24.3	17.2	9.8	5.89	5.96
	D_2	b		98.9	69.1	36.7	24.4	17.2	9.9	5.94	6.05
36	D_1	a	316	99.2	65.4	39.1	25.5	18.0	10.3	6.24	6.05
	D_1	b		98.3	64.2	38.4	25.4	17.9	10.3	6.17	6.01
	D_2	a	317	97.9	66.2	38.8	25.7	18.2	10.4	6.30	6.06
	D_2	b		99.4	66.0	38.8	27.4	17.9	10.3	6.18	6.01
37	D_1	a	316	98.1	58.9	40.5	26.8	19.0	10.6	5.94	6.05
	D_1	b		98.4	60.4	41.4	27.4	19.3	10.8	6.05	6.14
	D_2	a	318	98.4	59.5	40.6	26.8	18.8	10.6	5.91	6.12
	D_2	b		97.0	60.4	40.8	27.2	19.2	10.8	6.04	6.10
38	D_1	a	310	98.1	58.4	41.2	28.2	20.2	11.8	7.64	5.93
	D_1	b		95.8	57.2	39.8	27.3	19.6	11.4	7.35	5.74
	D_2	a	311	97.8	57.1	40.0	27.9	20.0	11.6	7.36	5.86
	D_2	b		96.7	56.7	39.3	27.3	19.6	11.3	7.25	5.75
39	D_1	a	305	95.2	55.0	39.7	27.9	20.4	11.8	7.28	6.02
	D_1	b		96.8	57.8	41.3	28.6	20.9	12.0	7.40	6.16
	D_2	a	306	98.0	59.7	42.8	29.2	21.3	12.4	7.76	6.02
	D_2	b		97.8	55.7	40.7	28.4	20.6	12.0	7.45	5.93

	D₁	b		97.1	61.0	41.5	29.5	12.0	12.0	7.91	[2] 5.63
	D₂	a	288	97.6	61.1	41.2	29.6	12.2	12.2	8.07	[2] 5.79
	D₂	b		96.7	59.8	40.8	29.3	12.0	12.0	7.90	[2] 5.72
16	D₁	a	291	96.7	57.1	39.2	27.8	19.4	9.5	5.49	[2] 5.83
	D₁	b		96.9	57.1	39.0	27.5	19.2	9.3	5.44	[2] 5.95
	D₂	a	296	98.7	60.3	40.6	28.4	19.8	9.5	5.50	[2] 5.88
	D₂	b		98.1	60.7	40.5	28.3	19.7	9.5	5.50	[2] 5.82
17	D₁	a	287	97.7	60.8	39.1	26.9	19.5	11.3	7.55	[2] 5.76
	D₁	b		98.6	60.5	38.8	26.8	19.4	11.2	7.53	[2] 5.68
	D₂	a	286	98.6	60.6	38.7	26.6	19.2	11.1	7.49	[2] 5.71
	D₂	b		98.4	61.4	38.8	26.6	19.1	11.0	7.42	[2] 5.75
18	D₁	a	277	94.8	58.2	42.1	29.2	20.5	10.2	5.79	[2] 5.83
	D₁	b		96.5	59.5	42.9	29.6	20.7	10.3	5.83	[2] 5.72
	D₂	a	271	96.0	58.6	42.1	29.2	20.6	10.3	5.83	[2] 5.76
	D₂	b		96.8	56.4	41.1	28.9	20.4	10.2	5.77	[2] 5.73
19	D₁	a	266	96.7	60.5	44.9	31.1	21.3	9.9	5.49	6.11
	D₁	b		96.6	58.4	44.1	30.8	21.2	9.9	5.46	6.02
	D₂	a	267	94.8	57.1	43.0	30.4	21.0	9.8	5.52	6.01
	D₂	b		95.1	55.7	42.2	29.9	20.7	9.7	5.45	5.90
20	D₁	a	310	97.9	60.2	37.8	25.9	17.6	8.5	4.97	5.96
	D₁	b		97.8	60.5	37.8	25.7	17.4	8.5	5.01	5.92
	D₂	a	307	97.8	60.5	37.8	25.7	17.3	8.3	4.88	6.05
	D₂	b		97.0	60.3	37.6	25.7	17.3	8.3	4.92	6.01
21	D₁	a	317	94.5	58.3	39.2	27.0	18.9	9.8	5.72	5.76
	D₁	b		94.6	56.5	38.7	26.6	18.5	9.4	5.42	5.84
	D₂	a	316	94.0	56.1	38.4	26.4	18.4	9.3	5.29	5.86
	D₂	b		96.8	57.7	38.9	27.0	18.8	9.7	5.57	5.76
22	D₁	a	272	96.0	61.3	39.6	27.7	19.3	9.4	5.41	6.19
	D₁	b		95.6	58.1	38.7	27.6	19.3	9.7	5.76	6.04
	D₂	a	271	95.8	57.9	38.1	27.2	18.9	9.3	5.41	6.10
	D₂	b		95.5	58.8	38.1	27.0	18.7	9.1	5.22	6.09
23	D₁	a	310	97.9	60.5	34.9	24.0	16.4	8.1	5.04	6.03
	D₁	b		98.2	61.6	34.6	23.6	15.9	7.5	4.20	6.10
	D₂	a	307	98.6	64.0	36.3	24.4	16.5	8.1	4.77	6.12
	D₂	b		97.6	63.1	36.0	24.4	16.5	8.0	4.74	6.16
24	D₁	a	322	98.5	65.1	39.1	27.7	19.3	9.3	5.23	5.89
	D₁	b		98.2	65.2	38.8	27.4	18.9	9.0	5.02	5.80
	D₂	a	321	98.4	68.5	40.5	28.0	19.3	9.2	5.09	5.95
	D₂	b		99.0	67.1	39.5	27.7	19.1	9.1	5.08	5.95
25	D₁	a	320	98.1	62.4	41.7	29.2	19.9	8.9	4.87	5.78
	D₁	b		98.1	60.3	40.4	28.7	19.4	8.5	4.70	5.81
	D₂	a	315	98.2	60.0	39.7	28.5	19.4	8.7	4.85	5.83
	D₂	b		97.9	57.0	39.0	28.2	19.2	8.6	4.76	5.79

	D₁	b		96.4	63.9	27.6	25.1	17.6	9.6	5.57	6.02
	D₂	a	328	98.2	63.4	37.5	25.4	17.9	9.7	5.57	6.03
	D₂	b		97.4	63.4	37.6	27.3	17.9	9.7	5.66	5.97
41	D₁	a	319	98.4	67.1	35.4	23.3	16.1	8.8	5.22	5 95
	D₁	b		99.0	68.3	35.6	23.1	16.0	8.7	4.98	5.95
	D₂	a	320	98.9	68.1	35.6	23.5	16.3	8.9	5.19	6.13
	D₂	b		99.3	67.4	35.5	23.2	16.2	8.8	5.23	6.17
42	D₁	a	325	98.5	65.7	35.7	22.8	15.6	8.4	5.01	6.02
	D₁	b		98.9	67.9	36.0	22.9	15.6	8.5	4.95	6.05
	D₂	a	325	98.2	64.4	35.6	22.6	15.4	8.3	4.93	5.99
	D₂	b		98.1	65.5	35.4	22.6	15.3	8.2	4.93	6.03
43	D₁	a	318	99.0	65.1	35.6	22.6	15.3	8.3	4.78	5.99
	D₁	b		98.9	66.6	36.7	23.2	15.6	8.3	4.79	6.07
	D₂	a	318	99.2	64.8	35.9	22.7	15.4	8.3	4.73	6.10
	D₂	b		99.6	65.9	36.0	22.8	15.5	8.4	5.07	6.04
44	D₁	a	300	99.7	69.3	34.7	22.4	15.5	8.5	4.84	6.00
	D₁	b		98.8	68.1	34.5	22.3	15.4	8.4	4.79	5.96
	D₂	a	300	99.5	71.1	35.2	22.4	15.6	8.5	4.75	6.10
	D₂	b		99.0	67.0	34.3	22.2	15.5	8.5	4.91	5.99
45	D₁	a	324	99.2	63.7	37.8	25.6	18.0	10.1	6.09	5.99
	D₁	b		99.7	63.7	37.7	25.2	17.6	9.9	5.96	5.99
	D₂	a	324	98.3	62.1	36.6	24.7	17.3	9.6	5.74	6.07
	D₂	b		99.2	61.1	36.1	24.5	17.1	9.5	5.74	6.02
46	D₁	a	322	97.9	58.6	38.9	25.6	17.5	9.1	5.03	6.03
	D₁	b		97.5	59.7	39.3	25.9	17.7	9.2	5.08	6.04
	D₂	a	322	97.0	59.7	38.8	25.6	17.5	9.1	5.04	6.11
	D₂	b		97.1	57.1	37.4	25.1	17.3	9.0	5.03	5.94
47	D₁	a	292	99.5	66.4	37.4	25.1	18.0	10.7	7.02	6.03
	D₁	b		99.4	66.2	36.3	24.6	17.7	10.3	6.58	6.00
	D₂	a	292	99.6	67.5	37.2	24.6	17.6	10.2	6.53	6.08
	D₂	b		99.6	68.1	37.2	24.7	17.7	10.3	6.57	6.07
48	D₁	a	332	99.3	63.9	37.0	26.1	19.2	11.8	8.10	5.72
	D₁	b		99.7	67.7	37.8	26.1	19.2	11.8	8.10	5.83
	D₂	a	332	98.8	65.2	37.0	26.0	19.1	11.6	8.04	5.84
	D₂	b		99.8	64.8	36.8	25.8	18.8	11.3	7.73	5.83
49	D₁	a	344	98.9	63.8	40.1	28.2	20.2	11.0	6.48	5.84
	D₁	b		98.7	63.8	39.6	28.0	19.9	10.8	6.25	5.81
	D₂	a	345	98.8	67.3	43.9	29.7	20.8	11.3	6.63	6.04
	D₂	b		97.6	65.7	42.8	29.1	20.5	11.2	6.56	5.91
50	D₁	a	334	99.4	69.3	40.1	27.1	19.1	10.0	5.60	[2] 5.79
	D₁	b		99.3	71.3	41.7	27.9	19.7	10.3	5.87	[2] 5.71
	D₂	a	335	99.1	68.0	39.4	26.9	19.0	9.9	5.49	[2] 5.74
	D₂	b		99.2	72.8	42.5	28.0	19.6	10.3	5.80	[2] 5.80

[1] For all samples, 100 percent of the aggregate passed the ½-inch sieve.
[2] Change in plant target value (JMF) for asphalt content ordered by project engineer on days these samples were taken. Therefore, a correction, 0.20, was added to these prior to statistical treatment.

Table 4.—Analysis of variance-extraction test results

Test property	Number of tests	Variance—				Standard deviation
		Process	Sampling	Testing	Total	
Mix temperature ° F	100	341.4	[2] 1.9	--------	343.3	18.0
Asphalt content [1] percent	200	0.00864 [3] 0.093	0.00234 [3] 0.048	0.00339 [3] 0.058	.01438	0.120
Gradation, percent passing sieve:						
⅜-inch percent	200	2.507 [3] 1.567	0.0185 [3] 0.136	0.4277 [3] 0.654	2.9527	1.718
No. 4 do	200	14.863 [3] 3.855	0.6245 [3] 0.790	1.9428 [3] 1.394	17.4305	4.175
No. 10 do	200	3.7528 [3] 1.937	0.3544 [3] 0.595	0.4115 [3] 0.641	4.5186	2.126
No. 20 do	200	4.0376 [3] 2.008	0.0566 [3] 0.238	0.0877 [3] 0.296	4.1819	2.045
No. 40 do	200	2.7892 [3] 1.670	0.0216 [3] 0.147	0.0411 [3] 0.203	2.8519	1.689
No. 80 do	200	2.1103 [3] 1.453	0.0101 [3] 0.100	0.0199 [3] 0.141	2.1402	1.463
No. 200 do	200	1.3193 [3] 1.149	0.0026 [3] 0.051	0.0172 [3] 0.131	1.3390	1.157

[1] Percent of mix.
[2] Sampling and testing.
[3] Square root for preceding result of analysis of variance.

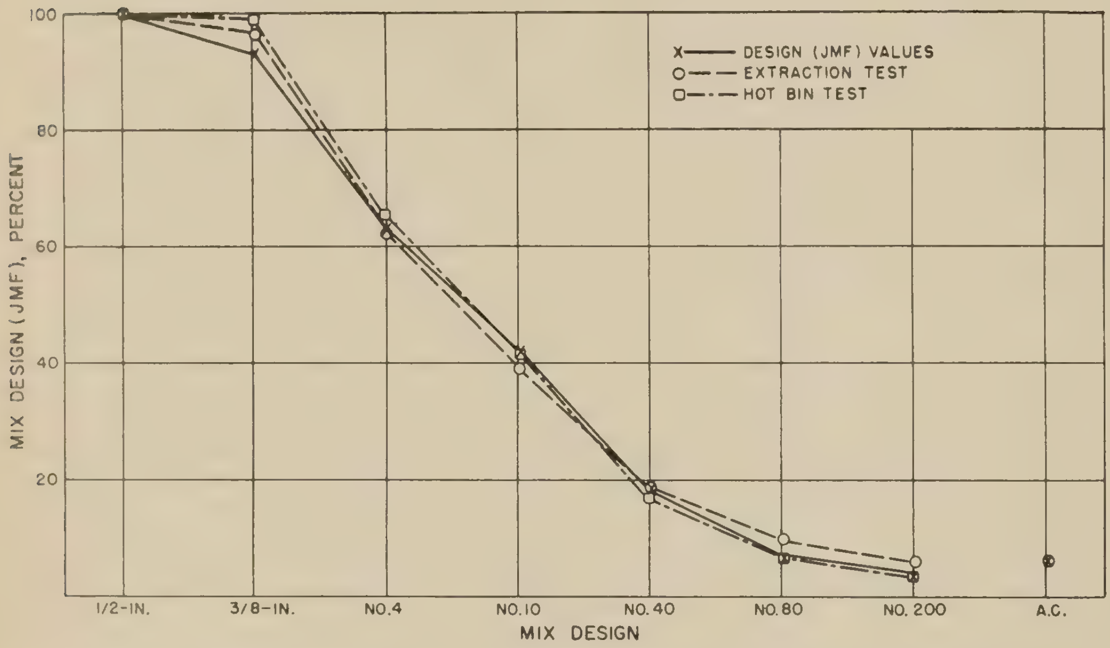

Figure 3.—Averages of test results and their relation to mix design (JMF) values.

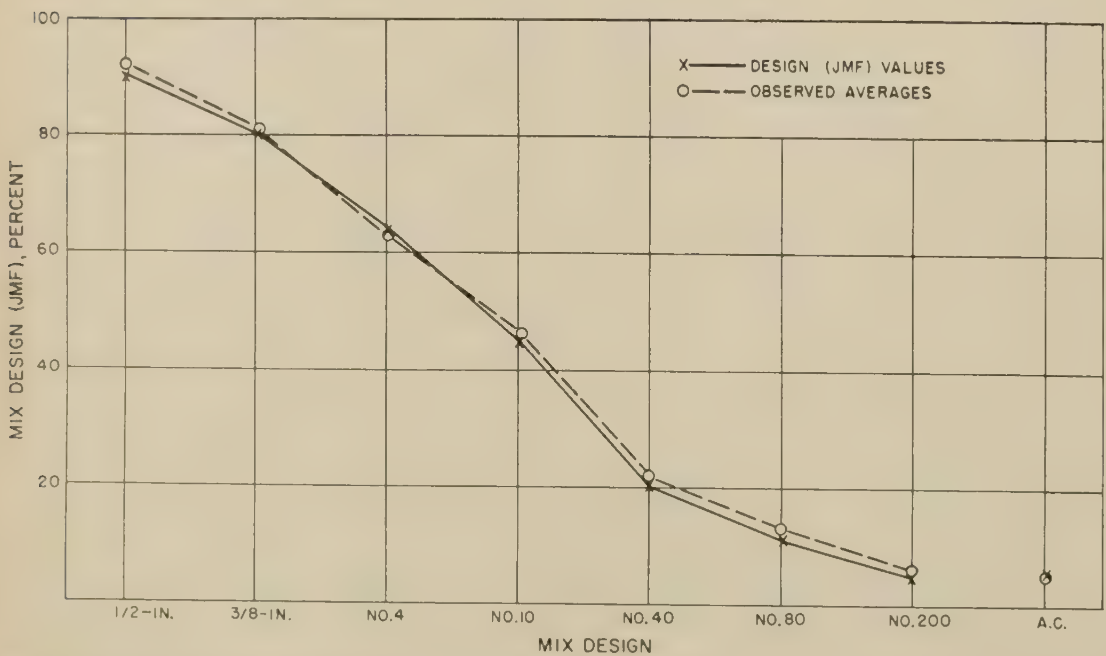

Figure 4.—Averages of extraction test results from AASHO Road Test and their relation to design (JMF) values.

by the plant inspector during normal plant control work on the sampling days covered by the study reported here. Although not shown in the table, all of these test results were within the ranges permitted by the job mix formula. A complete tabulation of the individual extraction test results is given in table 3.

The results of the analysis of variance are given in table 4. Total variance and its calculated components attributed to the plant process, sampling procedure, and test method are shown.

The percentages of all extraction test results for each test property lying within given ranges of their respective averages compared to theoretical percentages for the Normal Curve (*5*) are given in table 5. The close agreement of the observed percentages with the theoretical percentages indicated that the data were essentially normal and, therefore amenable to statistical treatment.

Plots of cumulative frequencies on normal probability paper also indicated that the data were essentially normal in distribution, except for the percentage of aggregate passing th No. 200 sieve. The data for this sieve siz showed some deviation from a normal distri bution—starting at the 87th percentile However, this moderate deviation was no considered sufficient to invalidate the statis tical treatment.

Averages

Data for comparing the averages of th extraction and hot bin test results with th mix design for each element of the job mi formula are shown by curves in figure 3. Th extraction test averages conformed closely t the design for each item. In the extractio test results, the averages for aggregate passin the ½-inch, No. 4, and No. 40 sieves, and th asphalt content were within 1 percentag point of their respective design values. Th largest departure from design, was the 4 percentage obtained for aggregate passing th ⅜-inch sieve. Also shown in figure 3, are th averages obtained in the hot bin gradatio control tests. These averages, although base on only 10 test results, had generally goo agreement with the mix design. Compare with the extraction test results, the hot b averages were somewhat larger for the larg sieve sizes (No. 20 and larger) and lower f the smaller sieve sizes (No. 40 and less). Su differences were not unexpected because of th differences in handling and the test metho used for the aggregates. The aggregat obtained in the extraction tests had be subjected to pugmill mixing and centrifugin whereas the hot bin aggregates had not be subjected to either of these influences. Fu thermore, the extracted aggregates we sieved wet and the hot bin aggregates we sieved dry in accordance with the norm control practice used in the constructi project.

The mix design and the correspondi averages obtained by extraction tests f surface course mixtures used in the AASH Road Test (*6*) are shown in figure 4. A co parison of figures 3 and 4 shows that, f

ble 5.—Observed percentages and theoretical percentages of test results within given ranges

Range, $\bar{X} \pm t \times S.D.$	Theoretical percentage within range	Observed percentages within range for data for—							
		Aggregate passing sieve sizes—							Asphalt content
		⅜-in	No. 4	No. 10	No. 20	No. 40	No. 80	No. 200	
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
$\bar{X} \pm 0.675 \times S.D.$	50.0	52.5	51.0	49.5	49.5	52.5	55.0	59.5	45.5
$\bar{X} \pm 1.0 \times S.D.$	68.3	74.5	68.5	67.0	64.5	65.5	71.5	75.5	66.5
$\bar{X} \pm 1.5 \times S.D.$	86.6	91.0	89.5	85.5	84.0	75.5	86.5	85.0	85.5
$\bar{X} \pm 2.0 \times S.D.$	95.5	94.5	96.5	95.0	98.5	96.0	94.5	96.0	96.5
$\bar{X} \pm 2.5 \times S.D.$	98.7	96.5	98.5	99.5	100.0	100.0	98.0	98.0	99.0
$\bar{X} \pm 3.0 \times S.D.$	99.7	99.0	100.0	100.0	100.0	100.0	98.5	98.0	100.0

rages obtained in extraction tests, the rall conformance to design for the mix pro- tion studied was comparable to that ained in the AASHO test. Because of sent tendencies to suspect the accuracy of extraction test for the determination of halt content of mixtures, the close agree- nt, shown in table 1 and figure 3, between determined average 5.955 percent and the ign or target percentage of 6.0 percent is of erest. This close agreement is believed to e been the result of close adherence to the raction test method (*2*) combined with urate plant scales and proportioning, good npling technique, and favorable asphalt- regate interfacial conditions.

riation in individual results

The standard deviations shown in tables 1 l 2 indicate the variations in individual ults obtained for each property by mix raction tests and by hot bin gradation ts, respectively. A comparison of these iations by the statistical F test at the 5- cent level showed no significant difference variability between the two sets of results ept for the ⅜-inch and the No. 4 sieves. riation, expressed in percentages of indi- ual results within and outside design ge, is shown in the last three columns of ble 1. These percentages might be con- ered another indication of the quality of nformance to the design, for each item own. For three of the eight items specified mix composition—percentage of aggregate ssing the No. 10, No. 80, and No. 200 ves—10 percent or more of the results ex- eded the design limits. These departures m 100 percent conformance are explained the footnotes to the table. From the aver- s and the standard deviations for these ms, the deviations seem to have been the ult primarily of the use of aggregate that ted too close to either the upper or lower its of the ranges set in the job mix formula. The large percentage, 30 percent, of mix nperatures outside the permissible limits s caused, at least in part, by the intentional anges in plant operating temperatures to compensate for those day-to-day fluctuations in atmospheric temperatures that seemed to affect compaction.

Table 6.—Comparison of variations—standard deviation

Source of data	Study for this article	AASHO (Ref. 6)	WASHO (Ref. 7)
Number of tests	200	96	72
Asphalt content percent	0.120	0.18	0.40
Gradation, aggregate passing sieve:			
⅜-inch ... percent	1.72	3.17	----
No. 4 ... do	4.18	4.06	4.36
No. 10 ... do	2.13	2.99	2.81
No. 20 ... do	2.05	1.68	----
No. 40 ... do	1.69	2.06	1.69
No. 80 ... do	1.46	1.07	----
No. 200 ... do	1.16	1.16	0.69

Many previous investigators have reported variation in asphalt concrete composition. The variation results from two such investigations—the AASHO Road Test (*6*) and the earlier WASHO Road Test (*7*)—and the results from the study reported here are indicated by the standard deviations shown in table 6. Evaluations of these results by Bartlett's Test (*8*) showed that, except for aggregate passing the No. 4 and No. 40 sieves, the differences in variability between the data sources were statistically significant. Thus the observed variations in asphalt content and in aggregate passing the ⅜-inch, No. 4, No. 10, and No. 40 sieves were equal to or less than those that were obtained in the AASHO and WASHO tests.

Causes of variation

The results of the analyses of variance are summarized in table 4, giving overall or total variance and the components of variance for each item. Although variance is the basic statistical measure of variability (*8*), its computation involves an arithmetic squares of the original units. It is therefore customary to take the square root of a variance in order to obtain results in units on the same scale as the original. The results thus obtained are standard deviations. These are shown in the table just below the entry for each variance component. The square root of total variance is given separately under standard deviation. These results show that inherent process variation was greater than variation attributed to sampling or testing. As variances are additive quantities, it is apparent that for each item process variance was greater than variance from sampling procedure and test method combined.

The relatively large effect of process variability on overall variation indicates that future efforts to improve the uniformity of the plant's product should logically begin with the plant process. Although it is recognized that process variability as determined in the study reported here included several factors, the problem of identifying the significant causative ones may not be as formidable as may seem at first. For instance, helpful clues to improvement might be furnished by the plant's personnel who probably know from experience which phases—aggregate source, stockpile uniformity, cold bin loading, hot bin screens, etc.—of the plant process are likely to be suspect. However, lacking such prior information, a modest test program covering a few phases of the plant's process might be all that is necessary to locate the real cause of undesirable product variation so that specific corrective action might be suggested.

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(*5*) *ASTM Manual on Quality Control of Materials*, by ASTM Committee E–11 on Quality Control of Materials, Jan. 1951, p. 25.

(*6*) *The AASHO Road Test—Report 2, Materials and Construction*, HRB Special Report 61B, 1962.

(*7*) *The WASHO Road Test—Part 1: Design, Construction, and Testing Procedures*, HRB Special Report 18, 1954.

(*8*) *Statistical Methods for Chemists*, by W. J. Youden, 1951.

Method of Computing Analysis of Variance

To compute the variances proceed as follows:

Step 1.—Construct form similar to the sample worksheet, figure 5, with spaces in the left column equal to the number of units to be sampled. Assign an identification number to each unit sampled.

Step 2.—Identify the duplicate samples taken from each unit as D_1 and D_2. Identify the two portions obtained by splitting each duplicate sample as a and b. Each unit is now represented by 4 portions D_1a; D_1b; D_2a; D_2b.

Step 3.—List the values obtained from measurement or testing in columns (1) and (2) in the spaces provided for the 4 portions representing the unit identified by the number in the left column.

Step 4.—In column (3) list the difference between columns (1) and (2) for both the D_1 and D_2 duplicate samples.

Step 5.—In column (4) list the sums of columns (1) and (2) for both the D_1 and D_2 duplicate samples.

Step 6.—In column (5) list the differences between the D_1 and D_2 duplicate samples of each unit that appear in column (4).

Step 7.—In column (6) list the sums of the D_1 and D_2 duplicate samples of each unit that appear in column (4).

Step 8.—Total all the numbers that appear in columns (1) and (2). Then total the numbers in columns (4) and (6). If no error has been made, all totals will be the same. Enter totals in blocks A for each column in row (7) Totals.

Step 9.—Square each number in column (3) and total these squares. Enter this total in block B in column (3) in row (8) Sums of Squares. Repeat for columns (5) and (6) and enter sums in blocks C and D.

Step 10.—Record n, the number of sampled units appearing in the left column in row (9).

Step 11.—Compute $\frac{A^2}{4n} = CF$ (correction factor) and enter in row (10).

Step 12.—Compute unit sum of squares $\frac{D}{4} - CF = V_1$. Enter result in row (11).

Step 13.—Compute duplicate sample sum of squares $\frac{C}{4} = V_2$ and enter result in row (12).

Sample number	Duplicate number	Column (1) a	Column (2) b	Column (3) (1) - (2)	Column (4) (1) + (2)	Column (5) $(4D_1)-(4D_2)$ Duplicate difference	Column (6 $(4D_1)+(4D_2$ Duplicate sum
1	D_1						
	D_2						
2	D_1						
	D_2						
3	D_1						
	D_2						
50	D_1						
	D_2						
(7) Totals			A		A		
(8) Sums of squares				B		C	

(9)	n	Analysis of Variance			
		Source d.f.	Sum of squares	Mean squares	Varianc compone
(10)	$CF = \frac{A^2}{4n}$	Samples n-1=	$V_1=$	$MS_1=$	$\sigma_a^2=$
(11)	$V_1 = \frac{D}{4} - CF$	Duplicates n=	$V_2=$	$MS_2=$	$\sigma_s^2=$
(12)	$V_2 = \frac{C}{4}$	Portions 2n=	$V_3=$	$MS_3=$	$\sigma_t^2=$
(13)	$V_3 = \frac{B}{2}$				$\sigma' =$

Figure 5.—Suggested worksheet for computing analysis of variance.

Step 14.—Compute sum of squares for test portions $\frac{B}{2} = V_3$ and enter result in row (13).

Step 15.—Fill in analysis of variance table using value of n from row (9); V_1 from row (11); V_2 from row (12); and V_3 from row (13).

Step 16.—Compute mean squares (MS) by dividing sum of squares (SS) by degrees of freedom (d.f.).

Step 17.—Compute variance component

$\sigma_t^2 = MS_3$

$\sigma_s^2 = \frac{MS_2 - MS_3}{2}$

$\sigma_a^2 = \frac{MS_1 - MS_2}{4}$

Record these values in lower right corne worksheet. If any value is negative, rec as zero.

Step 18.—Compute overall sigma (σ'):

$\sigma' = \sqrt{\sigma_a^2 + \sigma_s^2 + \sigma_t^2}$

Traffic Flow Responses to Unannounced Increases in Progression Speeds of Signal Systems

(Continued from p. 4.)

that of the 10th, 20th, and 35th vehicles the platoon for each speed of progression. e maximum difference between any two these vehicles for each speed of progression s 1 m.p.h. As this difference is small, the nning speed of the lead vehicle was conered representative of the running speed all vehicles in the platoon.

ect of lapse of time

One method of evaluating drivers adaptan to a change in the speed of progression to analyze the daily increases in running ed through the test site after the change s been made. If adaptation is occurring, rend should be identifiable by a regression alysis. First, second, and third degree rves were fitted to the data for two traffic w conditions: 2,000 and 3,300 vehicles per ur. It was determined that a straight line st fit both sets of data but additional tistical tests indicated that the slope of lines was not statistically significant from o. Figure 9 is a scatter diagram for 2,000 hicles per hour. At a flow of 2,000 vehicles r hour evidence is strong that adaptation s being made despite the lack of statistical nificance. The evidence justifies additional idy with this technique as it may be posle that better experimental control of the riables plus an increase in sample size ght permit the establishment of a statistilly significant trendline. For the larger ffic flow of 3,300 vehicles per hour no aptation to the increase in the speed of ogression was evident. This seems to conm that the volume of traffic provides the iting factor in the speed selected by the iver.

adways

No significant difference in time headways s detected when the speed of progression s increased. This probably is the result of e large time variation between platoons and ssibly the inability of the observer techque to detect small changes in average time adways. Headway data from the traffic alyzer will be analyzed later and it is sumed that this data will show a difference the headway distribution for the different eeds of progression.

able 3.—Average running speed of vehicle by position in platoon [1]

Speed of progression, m.p.h.	Vehicle position in platoon			
	1st	10th	20th	35th
27	27.0	27.3	27.3	26.4
33	29.5	29.2	28.6	28.5
40	29.1	29.5	30.0	29.5

[1] This is the average of the running speeds between observers 1 and 2, 2 and 3, and 3 and 4.

Vehicle Stops

If the traffic signals are set at a certain speed of progression, and to the extent that drivers do not adapt to this speed, an increased number of vehicles will be stopped on the artery within the effective limits of the signal progression. An investigation of this extra stopping was not an objective of the study reported here, but the data do provide some insight into the relative magnitude of the number of stops attributable to the three speeds of progression investigated.

The number of stops made in the test site was estimated by using the volume counts made by the observers to compute the loss in platoon volume through the test site. This loss was adjusted for: (1) the number of vehicles overtaken by the platoon, (2) the expected number of turning vehicles, and (3) the number of vehicle stops that were attributable to emergency vehicles, police cars and tow trucks, and passenger pickups. The net adjusted loss was assumed to represent vehicles stopped for lack of driver adaptation to the effective speed of progression. Although additional factors might have accounted for minor changes in platoon size, it is assumed that any major change reflects the lack of adaptation to the change in the speed of progression. In other words, drivers who do not increase their speed relative to an increased progression speed in the signal system will be delayed by stops more frequently than those who do.

The percentage of vehicles stopped at each speed of progression is shown in figure 10 as a function of the hourly volume. Up to a flow

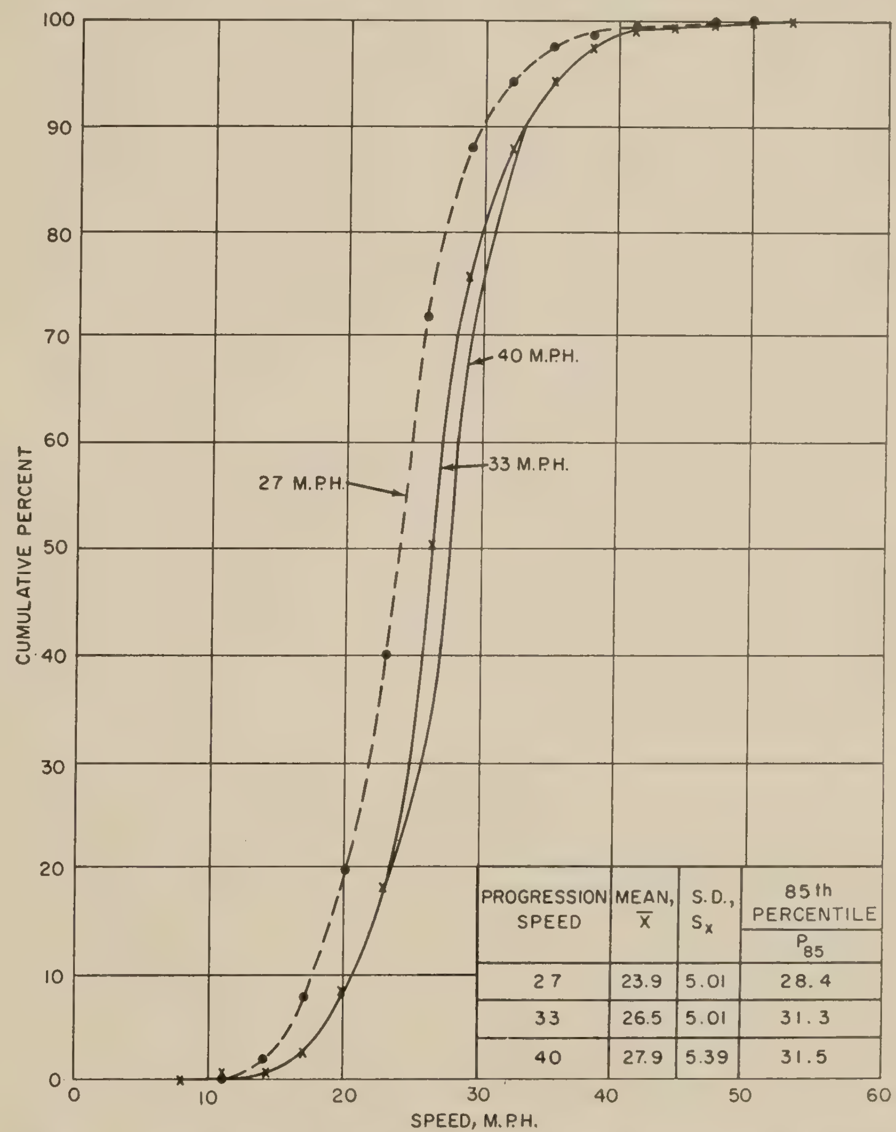


Figure 7.—Distribution of spot speeds for all lanes for three speeds of progression.

of 2,000 vehicles per hour, little difference occurred in the percentage of stops at any of the three progression speeds. At a flow of 2,500 vehicles per hour, the stopping percentage was negligible for the 27 m.p.h. speed of progression, but the percentages increased to 16 and 28 percent respectively for the 33 m.p.h. and 40 m.p.h. speeds of progression. When the flow of traffic was more than 2,500 vehicles per hour, the percentage of stopping increased for all speeds of progression. This large percentage of vehicles stopped is not alarming as the stopping was hardly noticeable on the street. On the average, the effect of the 40 m.p.h. speed of progression was to stop half of the vehicles, once each, within a test section of 3,000 feet. Stops were distributed uniformly at the six signalized intersections within the test site and had little adverse effect on the individual driver.

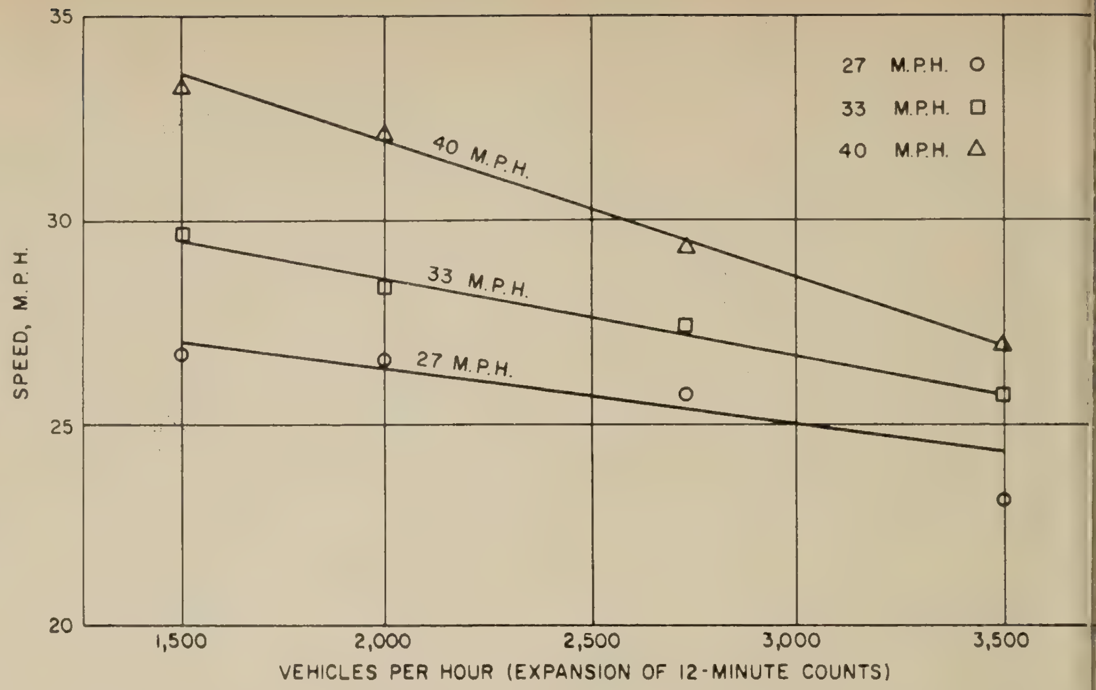


Figure 8.—Spot speed related to traffic volume for three speeds of progression.

Economic Considerations

Data collected were insufficient to permit a comprehensive analysis of the economic factors but they do provide some insight into the relative costs and benefits for the three progressions of speed studied. Data were obtained on the running speed and the number of vehicles stopped within the test site. Except for stops, no data were obtained for speed changes, which were not considered in the analysis. As the test site essentially was free of vertical and horizontal curvature, it was assumed that the test site was level and tangent. And, as more than 98 percent of the traffic was passenger vehicles, it was assumed that all the traffic was passenger cars.

The 2.2-hour period selected for analysis was the actual length of time (7:18 to 9:30 a.m.) that data were collected for each speed of progression. In this time period, 6,070 vehicles were observed. Results of the analysis are presented in table 4. As the speed of progression was increased from 27 m.p.h. to 33 m.p.h. and then to 40 m.p.h., the total operating costs also increased.

As expected, the running time of the vehicles decreased with an increase in the speed of progression. Less expected, however, was the effect of stopped time on the total traveltime. When the speed of progression was increased from 27 to 33 m.p.h. a net decrease in traveltime of approximately 2.3 hours was obtained but a further increase in the speed of progression to 40 m.p.h. actually caused a net increase in traveltime of approximately 2.3 hours.

In the analysis no dollar value was assigned to time savings as they were considered a benefit rather than a cost item. Increase in the speed of progression from 27 to 33 m.p.h. was a benefit in time saved of approximately 2.3 hours for the analysis period, but this benefit was realized at the expense of an increased operating cost of approximately $12. Final decision concerning the optimum speed of progression could be made only after considering all engineering, nonmarketable economic items, and administrative considerations.

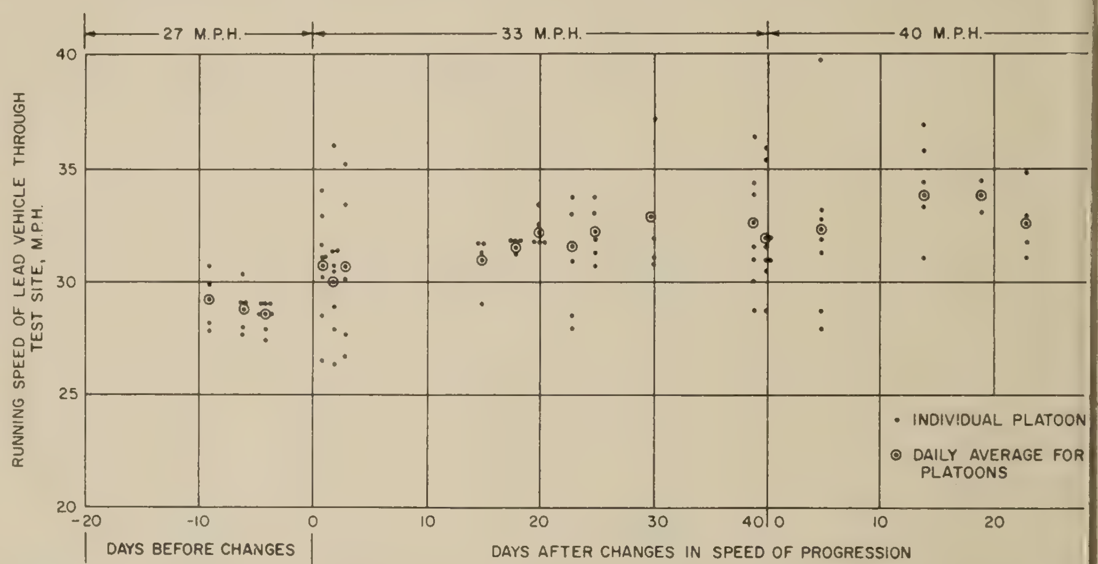


Figure 9.—Scatter for speed of lead vehicle related to days after change in progress speed for time period 8:45 to 9:30 a.m. when traffic volume was approximately 2, vehicles per hour, expansion of 12-minute counts.

Evaluation of Study Techniques

Prior to conducting the study, the authors were unable to determine whether speed or headway data would be more indicative of driver adaptation to a change in the speed of progression. Further, it was not known which of the techniques available would be best suited for a study of this type. Therefore, three techniques were utilized for collecting data: the Public Roads traffic analyzer, observers stationed along the roadway, and a modified version of the floating car speed and delay study. Jointly, these techniques provided a variety of speed and headway information that could be analyzed to determine which technique and parameter were the best indicators of driver adaptation.

Traffic analyzer

The traffic analyzer, as used in the study, provided spot speed, volume, and headway information by lanes for each test condition. With this technique, data were collected at

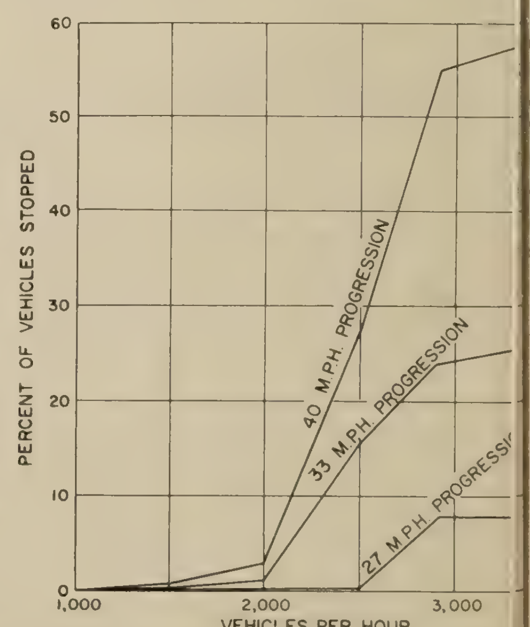
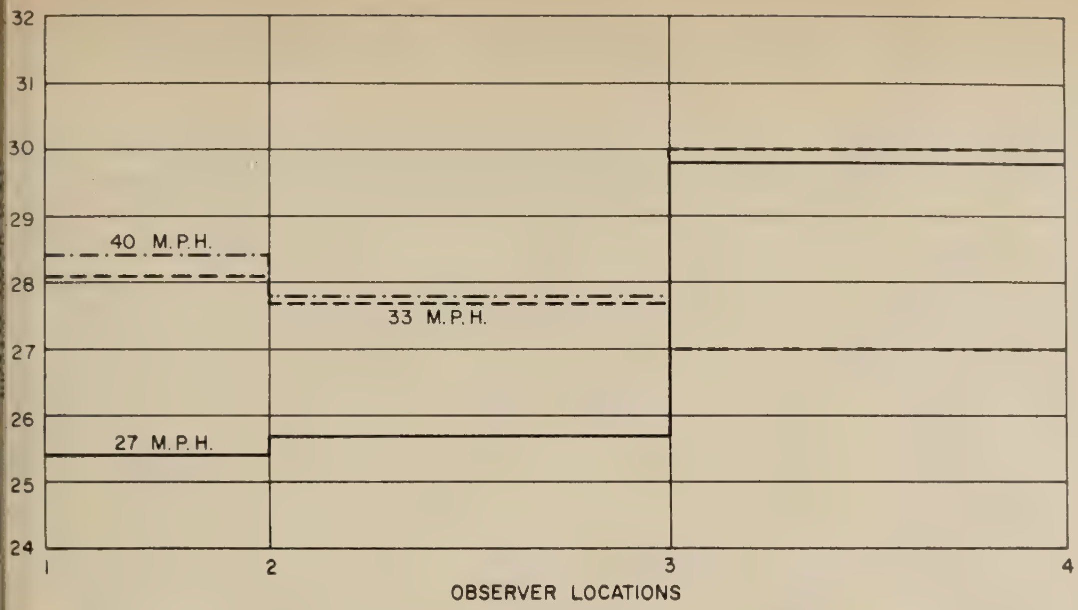


Figure 10.—Percent of vehicles stoppe each speed of progression as a funct of volume.



gure 11.—Average running speed of lead vehicle between observer locations for three speeds of progression.

Table 4.—Analysis for economy [1]

Item of cost	Speed of progression—		
	27	33	40
	M.p.h.	*M.p.h.*	*M.p.h.*
Running cost at uniform speed on level tangents	$111.09	$109.49	$109.59
Excess cost of stops [2]	2.30	10.16	21.94
Cost of idling engine of stationary vehicle	.72	3.20	6.54
TOTAL COST	$114.11	$126.19	$138.07
Running time through test site ------- hours	114.944	107.389	105.222
Excess consumed per speed change ---- hours	.630	2.789	5.698
Time consumed while stopped hours	.917	4.056	7.892
TOTAL TIME --- do	116.491	114.234	118.812

[1] The figures were provided from studies reported in Motor Vehicle Running Costs for Highway Economy Studies, by Robley Winfrey, Nov. 1963.
[2] Excess cost above continuing at initial speed.

ly one point along the street and may not e representative of the total test site. Evience that this may be so is shown in figure 11. he analyzer was located south of Lamont treet, which was in the test site between bservers one and two. For the 27 and 33 .p.h. speeds of progression, different spot eeds would have been observed had the analyzer been located between observers three and four. This deficiency can be overcome in the future by placing the analyzer at several locations within the test site and using an average of the spot speeds as representative of speeds on the entire test site.

Speed and delay vehicle

The modified version of the floating car speed and delay technique permitted running speed information to be collected over the distance of the test site. This had the effect of averaging the differences in running speed over short subsections of the site, which had different traffic-related characteristics. No headway data were obtained with this technique.

Observers

The running speed of the vehicle through the entire test site was obtained by calculating the elapsed time between observers at the ends of the test site. However, a marked car in the stream of traffic was required to permit identification of the lead vehicle. The headway information obtained did not show any differences in average headway for the three speeds of progression tested. This lack of differences was attributed to the large variability in average platoon headways and inaccuracies in recording the time headways by this technique.

Vehicle stoppage

There was some indication that adaptation patterns can be obtained by analyzing the stopping characteristics for vehicles at one or more intersections along the street. Lack of adaptation would be indicated by an increase in the number of vehicles stopping immediately after the change in progression speed. Driver adaptation, if present, would be indicated by a gradual decrease with time in the number of vehicles stopping.

Preferred technique

The authors determined that the floating car technique and analyzing the stopping characteristics of cars seem to be the best methods of measuring driver adaptation to changes in the speed of progression of a coordinated signal system. Each of these techniques can be used by one person and the expense will be relatively small. However, the floating car method was preferred because detection of the drivers adaptation seems to be more certain. Others planning to use this method should be certain that the sample size studied is large enough to permit detection of significant differences at the level of confidence selected, if, in fact, differences do exist. Acceptable results may also be obtained by recording traffic analyzer data at more than one location within the test site.

Limitations of the Study

The study reported here was somewhat limited by several factors. Although the speed limit was officially changed for the successive speeds of progression, it was not posted. Many drivers undoubtedly believed the speed limit to be that prevailing throughout much of the city—25 m.p.h. This belief probably affected the willingness of some drivers to increase their speeds in relation to the changes in progression speed. No knowledge by the drivers of the changes made in the speed of progression also was a limiting factor. The physical characteristics of the test site, such as the heavily signalized section from Kenyon Street to Harvard Street, accompanied by relatively frequent turning movements of the traffic, could have placed considerable restriction on speed increases, particularly at the 40 m.p.h. speed of progression.

Estimated Travel by Motor Vehicles in 1964

BY THE OFFICE OF PLANNING
BUREAU OF PUBLIC ROADS

By THEODORE S. DICKERSON, JR., Highwa
Engineer, Current Planning Divisio

Motor-vehicle travel in the United States in 1964 totaled 841.9 billion vehicle-miles, an increase of 5.1 percent over the travel in 1963. The travel data were compiled by the Bureau of Public Roads from information supplied by the State highway departments and toll authorities. Total travel for 1965, based on information for the first 10 months of the year, is estimated at 880 billion vehicle-miles, a 4.5-percent increase over 1964.

The proportions of travel by road system and by vehicle type changed very little from 1963 to 1964. Of the 1964 travel, 37.6 percent was on main rural roads comprising 14 percent of the Nation's total of 3.6 million miles of roads and streets. Some 48.0 percent of the travel was on urban streets, which also comprise 14 percent of the total mileage. Travel on local rural roads was only 14.4 percent, although these roads are 72 percent of the total mileage.

Passenger cars represented 84 percent of the vehicles registered and accounted for 82 percent of the travel in 1964; trucks and truck combinations accounted for 16 percent of the vehicles and 18 percent of the travel; similar figures for buses were less than 1 percent.

Average vehicle performance in 1964 differed very little from that reported for 1963.

Table 1.—Estimated motor-vehicle travel in the United States and related data for calend year 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 road	Local rural road	Total rural	Urban	Total			Total	Average per vehicle	
	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]	246, 850	94, 853	341, 703	345, 432	687, 135	72, 970	9, 417	47, 924	657	14. 34
Buses:										
Commercial	908	181	1, 089	1, 803	2, 892	82. 3	35, 140	619	7, 521	4. 67
School and nonrevenue	674	743	1, 417	307	1, 724	223. 1	7, 727	241	1, 080	7. 15
ALL BUSES	1, 582	924	2, 506	2, 110	4, 616	305. 4	15, 115	860	2, 816	5. 37
All passenger vehicles	248, 432	95, 777	344, 209	347, 542	691, 751	73, 276	9, 440	48, 784	666	14. 18
Trucks and combinations	68, 180	25, 416	93, 596	56, 562	150, 158	14, 019	10, 711	19, 117	1, 364	7. 85
All motor vehicles	316, 612	121, 193	437, 805	404, 104	841, 909	87, 295	9, 644	67, 901	778	12. 40

[1] For the 50 States and District of Columbia, includes minor revisions to previously released 1964 figures.
[2] Includes taxicabs; also 985,445 motorcycles, which are estimated to account for 0.4 percent of the total travel.

The average motor vehicle traveled 9,644 miles in 1964, almost half of it in cities, and consumed 778 gallons of fuel at a rate of 12.40 miles per gallon, as compared with 1963 figures of 9,590 miles, 772 gallons, and 12.42 miles per gallon, respectively. The average passenger car traveled 9,417 miles and consumed 657 gallons of fuel at a rate of 14.34 miles per gallon, in 1964; comparable 1963 figures were 9,378 miles, 652 gallons, and 14.. miles per gallon.

The travel and related information for 19 are shown on table 1 by road system a vehicle type. Such data have been report in PUBLIC ROADS, A JOURNAL OF HIGHW RESEARCH for a number of years, the lat for 1963 appeared in vol. 33, No. 7, Ap 1965, pp. 148–150.

NEW PUBLICATIONS

Two new publications have been issued recently by the Office of Planning, Bureau of Public Roads, U.S. Department of Commerce. Both are for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. The price for each is $1.00. A brief discussion of each of the new publications is presented in the following paragraphs.

Traffic Assignment and Distribution for Small Urban Areas

The *Traffic Assignment and Distribution for Small Urban Areas* manual explains and illustrates the theory and use of a system of analytical procedures and computer programs for assigning and distributing trips to transportation systems with the IBM 1620 (60 K) electronic computer. The procedures described are designed to process a basic set of trip cards. They allow the computation of surveyed trip length frequency, distribution of trips between zones by the gravity model formula or Fratar method, and assignment of trip interchanges to an existing transportation network. The procedures also accommodate estimates of future trip production and trip attraction and provide for assigning the trip distribution to a proposed transportation network.

The battery of computer programs was developed by several State highway departments and the Bureau of Public Roads and is generally applicable to urban areas having populations up to 150,000 persons.

Calibrating and Testing a Gravity Model for Any Size Urban Area

The volume on *Calibrating and Testing a Gravity Model for Any Size Urban Area* is a revision of the manual of the same title pu lished in July 1963. In this new edition, t model calibration discussions have been vised to bring them in line with current pr tice. Also, the program descriptions ha been completely rewritten to correspond the most current computer programs. T manual documents in detail the process trip distribution utilizing the gravity moc The computer programs that are described the text are, with the exception of two ripheral IBM 1401/1410 programs, desigr for use on the high speed binary IBM 70 7094 computer.

A companion publication, *The Traffic signment Manual,* was published by the I reau of Public Roads in June 1964. Toget these manuals document two of the be steps necessary for transportation analy and forecasting.

U.S. GOVERNMENT PRINTING OFFICE:1966

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.

NNUAL REPORTS

nnual 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 (1962). 15 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 Laws, Regulations, and Other Material Relating to Highways (1960). $1.00.

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.

ighway Research and Development Studies, Using Federal-Aid Research and Planning Funds (1964). $1.00.

PUBLICATIONS—Continued

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

Highway Statistics (published annually since 1945):
1956, $1.00. 1957, $1.25. 1958, $1.00. 1959, $1.00. 1960, $1.25. 1962, $1.00. (Other years out of print.)

Highway Statistics, Summary to 1955. $1.00.

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

Specifications for Aerial Surveys and Mapping by Photogrammetric Methods for Highways (1958): a reference guide outline. 75 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. $1.00.

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.

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