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Public Roads

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FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS

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Interchange between Interstate Highway 485 (entering from left) and Interstate Highway 75 in Atlanta, Ga. A part of the Atlanta business district is visible in the background.

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Use of funds for printing this publication has been a proved by the Director of the Bureau of the Budge March 16, 1966.

Comparison of Day and Night Gap-Acceptance Probabilities

Reported by [1] NICHOLAS G. TSONGOS, Highway Research Engineer, and
SIDNEY WEINER, Mathematician,
Traffic Systems Division

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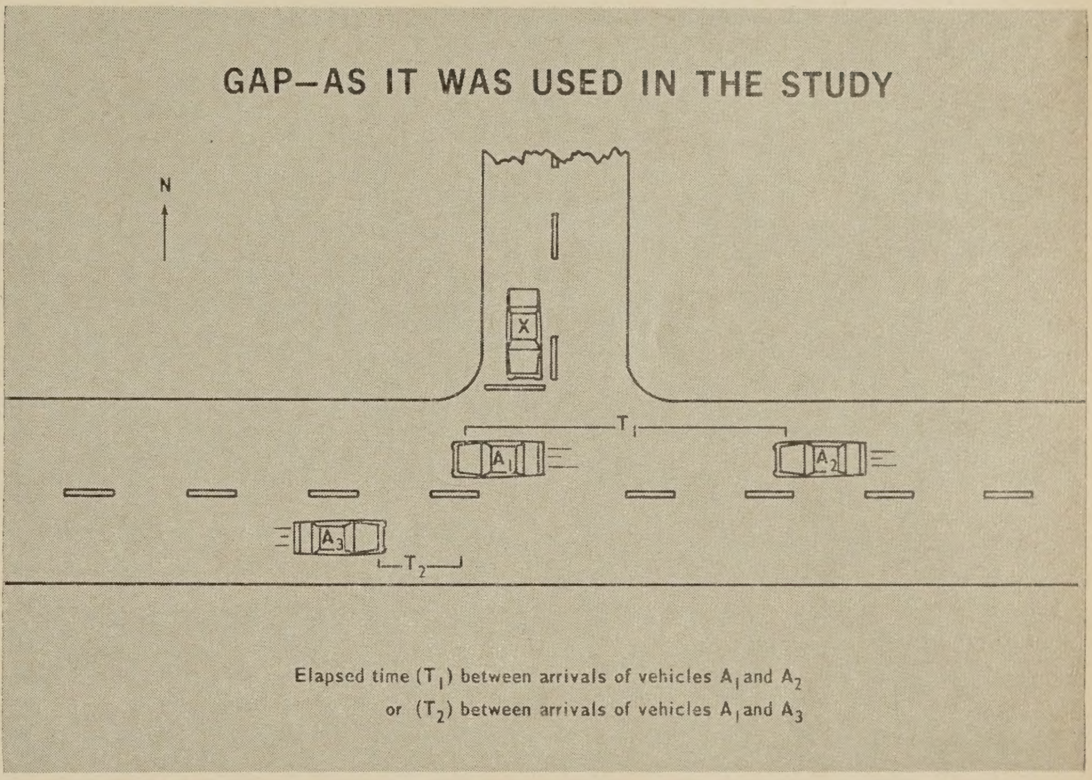

Vehicle X on the side, or minor, street will use a gap, T_1, T_2, *or* $T_{etc.}$, *to enter the traffic stream on the main street. If it uses an oncoming gap to enter the main-street traffic, the gap is accepted. If it waits at the intersection as the gap passes by, the gap is rejected.*

Of the many factors that influence the ability of the driver to see and perform the driving task at night, one of the most important is the effect of the headlight beams of other vehicles. In the study reported here, the headway distribution and gap-acceptance probabilities between day and night on an isolated, unlighted, suburban intersection were compared, and the driver's behavior as a result of the change in lighting conditions explored. The test for conditional homogeneity, an analytical method, and Raff's method, a purely graphical method, were used to analyze and compare the data obtained. Although no significant difference in the gap-acceptance probabilities were shown by the Raff method, the results obtained by the analytical method indicated that the gap-acceptance probabilities for day and night cannot be considered conditionally homogeneous, particularly for very short and long gaps. For the medium size gaps, the acceptance probabilities did not indicate significant differences.

It was shown in the study that there were no significant differences between day and night in the formation of the available gaps under light traffic-volume conditions; but as the volume increased, there was a higher percentage of longer gaps at night than during the day.

According to the authors, further experimentation will be necessary before it can be decided that the gap acceptance depends on lighting conditions.

Introduction

THE STUDY reported here was a part of a project to explore the effects of headlight glare from opposing vehicles on the ability of drivers to perform nighttime highway visual tasks. Although a considerable number of studies have been concerned with descriptions of traffic flow at intersections, and especially with gap acceptance and rejection, a search of the literature indicates that no material about the behavior of drivers entering a major roadway from a stopped position at night has been published. The presence of opposing vehicle headlights is one of the most important factors that influence and determine the ability of the driver to see and perform in the night driving situation. The purpose of the study was not to examine the headlamp effect itself, but rather, to determine and compare the headway distributions and gap acceptance between day and night, as a result of the change in ambient illumination available to the driver at night.

Gap-Lag Acceptance, Definitions and Assumptions

- *Gap* is the elapsed time between the arrivals of successive main-street vehicles at an intersection. For minor-street vehicles entering the main street and turning right, conflicting with one traffic stream, the gap is formed by main-street vehicles traveling in the same direction. For minor-street vehicles entering the main street and turning left, conflicting with both traffic streams, the successive vehicle can be traveling either in the same direction or in the opposite direction.
- *Lag* is the elapsed time between the arrival of a minor-street vehicle at an intersection and the arrival of the next main-street car at the intersection.
- *Arrival* of a main-street vehicle at the intersection is the time at which the car enters the area bounded by two pneumatic tubes, installed for the study, at the extensions of the minor-street curb lines. *Arrival* of a minor-street vehicle at the intersection is the time

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[1] Presented informally to the Visibility Committee of the Highway Research Board at the 48th annual meeting, Washington, D.C., January 1969.

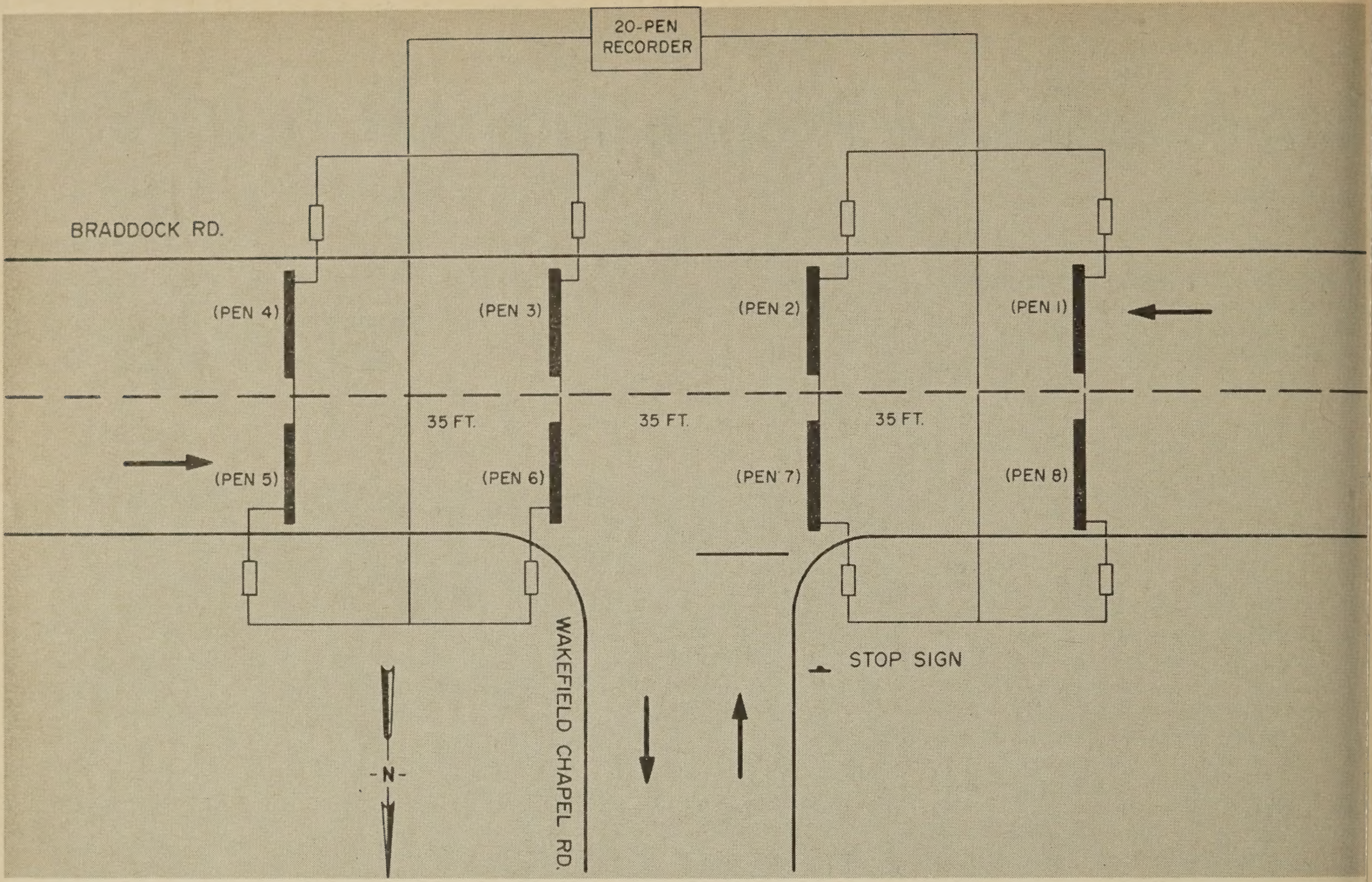

Figure 1.—Layout of detection tubes.

at which the car stops at the stop sign. If a minor-street car under consideration has to stop behind another car waiting to enter the intersection, its arrival is not the time that it stops, but the time that the other car, immediately ahead, enters the intersection.

- A gap is accepted if the minor-street, or side-street, vehicle crosses or enters between two main-street vehicles that form a gap. As a driver can reject any number of gaps but accept only one gap each time that he enters the intersection, the percentage obtained by using all the gaps rejected by each driver would not give a true indication of the proportion of drivers accepting gaps of a certain size, and the conclusions would be inaccurate. To overcome this inaccuracy, the number of rejections must be limited to one for each driver. Accordingly, two assumptions were made in the study: (1) A driver who accepts a given size gap for the same conditions can be expected to accept any gaps of greater length, and (2) a driver who rejects a given size gap can also be expected to reject any gaps of shorter length. (Only six instances in which driver accepted a shorter gap than he previously had rejected were recorded from a total of more than 1,200 gap and lag acceptances, day and night.)
- If the minor-street driver enters the intersection before the next main-street car reaches it, the lag is accepted. If he waits until the main-street car has passed before entering the intersection, the lag is rejected.
- The concept of critical gap–lag was used as it was defined by M. S. Raff (*1*)[2] which is "the number of accepted lags shorter than the critical time lag is equal to the number of rejected lags longer than this specific value." In this article, the data for both gaps and lags have been combined and are referred to as gap–lag data.

Test Site and Collection of Data

The test site selected for the study was an isolated, suburban *T* type intersection of State roads (SR) 620 and 650 in Fairfax County, Va. Braddock Road, SR 620, a major 2-lane road, regularly attains a daily traffic volume of 16,000 vehicles and has an early evening hourly volume of 800–1,000 vehicles. Wakefield Chapel Road, SR 650, a minor 2-lane road regulated by a stop sign, attains a daily traffic volume of 3,000 vehicles and has an early evening hourly volume of 200–300 vehicles. At the site, both roads have unrestricted sight distances.

The traffic volume of the intersection, which is 1.35 miles from the nearest traffic signal, does not approach conditions of congestion, and consequently, the times of arriv
can be considered to be independent.

Speeds of the main-street vehicles we
30–40 m.p.h. A graphic recorder with a cha
speed of 9 in. per min., or 0.15 in. per se
was wired to air switches and recorded i
stantly the passage of each vehicle on Bra
dock Road. The layout of the detection tub
that actuated the air switches is shown
figure 1. These pneumatic tubes were spac
35 feet apart on Braddock Road at the en
of the intersection curve to avoid false act
ations by the turning vehicles.

A dead area of 4 feet—2 feet on either si
of the Braddock Road lane line—was pr
vided between adjacent lanes. The line ar
was wide enough to permit detection of
vehicles in the lane, and small enough to eli
inate false actuations by vehicles traveling
adjacent lanes. As each vehicle was detect
at the various locations on Braddock Roa
the corresponding pen was actuated to mak
characteristic mark on the moving tape. Thr
pens, actuated manually by three pushbutto
were used to record the vehicles enteri
Braddock Road. Whenever a minor-str
vehicle stopped at the stop sign, the mid
pen was moved out of its normal position a
held as long as the vehicle was rejecting t
available gaps. As soon as the vehicle ente
Braddock Road, the middle pushbutton w

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[2] Italic numbers in parentheses refer to the bibliography listed on page 165.

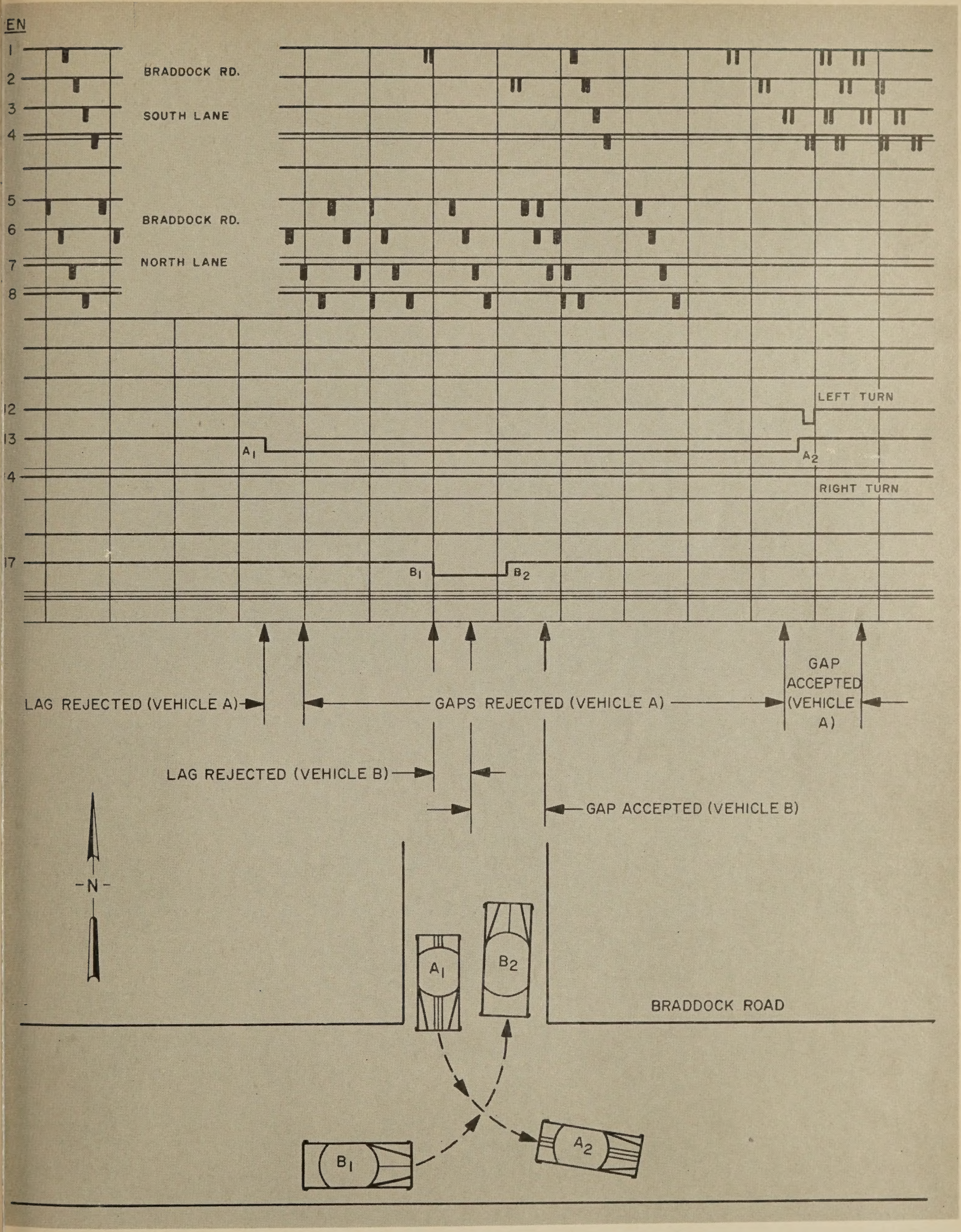

Figure 2.—Data collection, measurements of lags, gaps, and waits.

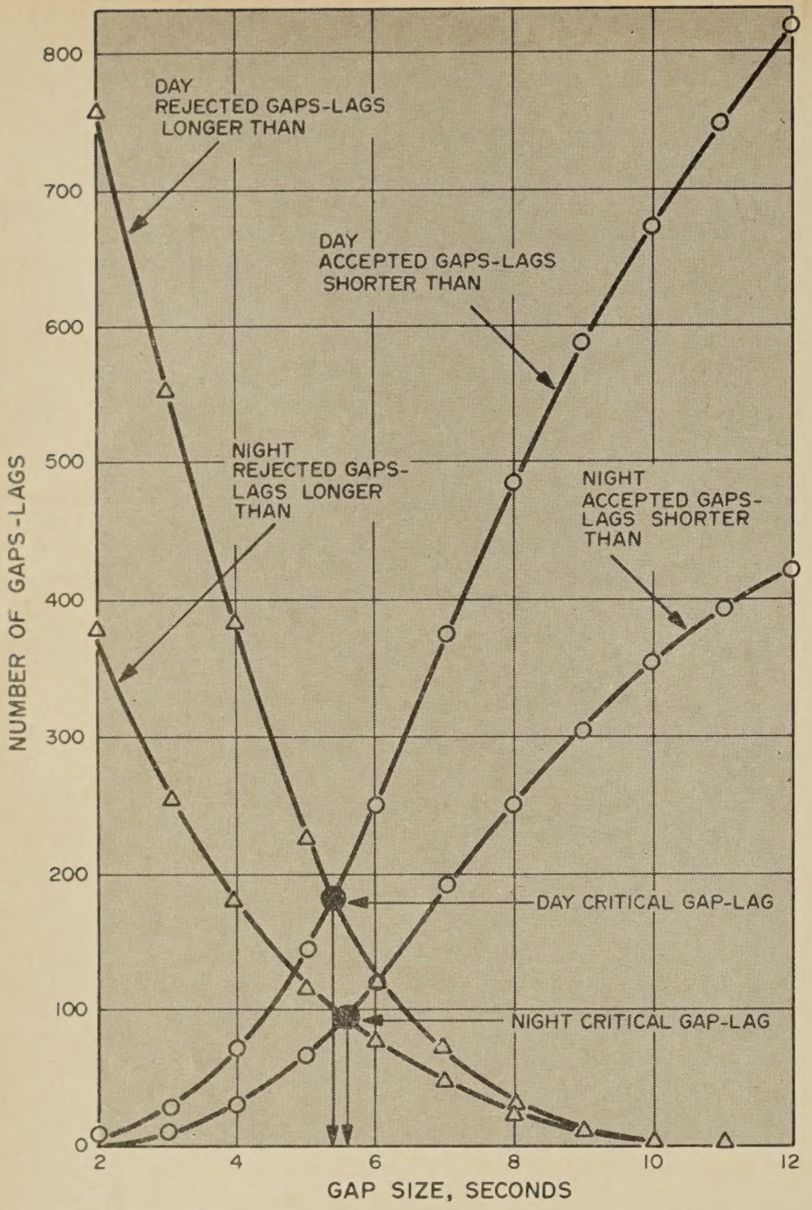

Figure 3.—Distribution of accepted and rejected gaps and lags, all turning movements.

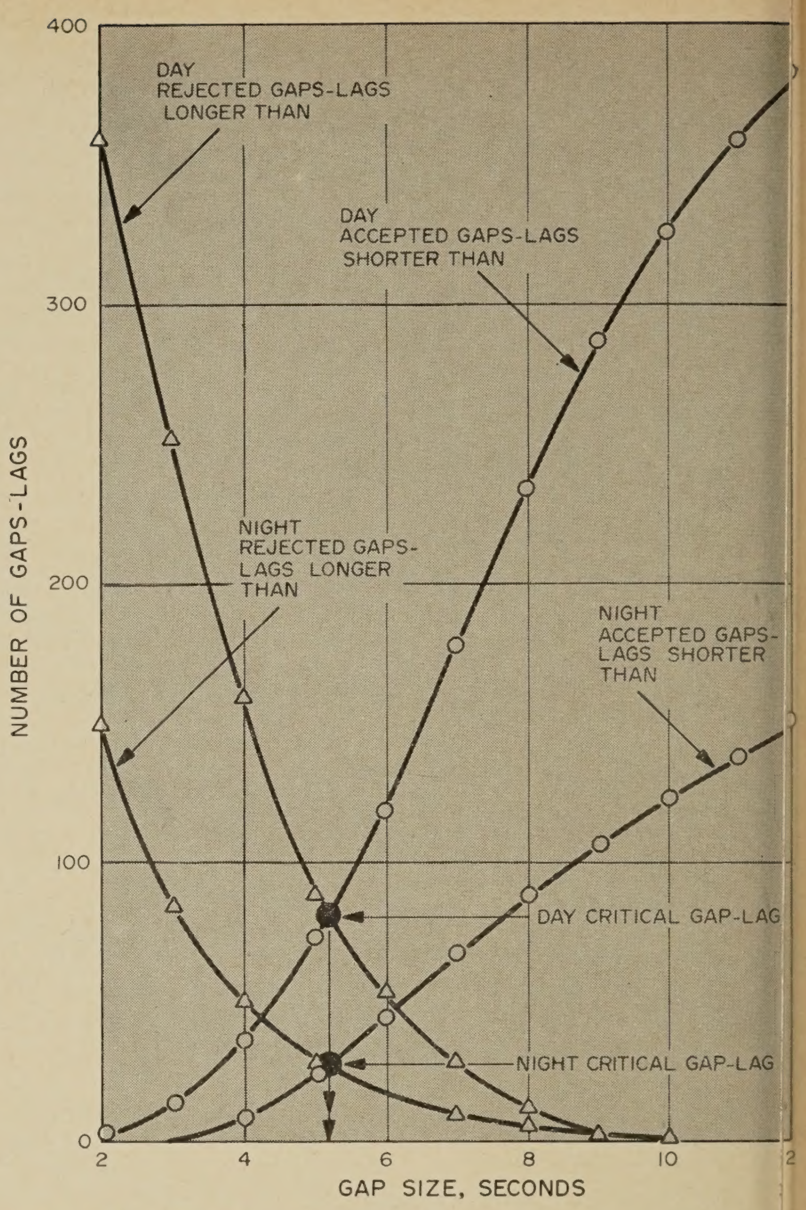

Figure 4.—Distribution of accepted and rejected gaps and lags, conflict with one traffic stream.

released; the pen consequently returned to the normal position, and the appropriate left or right pushbutton was given a quick tap to correspond with the respective left or right maneuver of the vehicle. For main-road vehicles making left turns into Wakefield Chapel Road, the same procedure was followed, except that only one pen showed the time that the vehicle was rejecting the available gaps.

The data collection and recording techniques are shown in figure 2. The role of each pen is indicated on a sample section of the chart, and the intersection drawing illustrates the position of the different vehicles as they are recorded on the chart.

Methodology

Test for conditional homogeneity

In the analysis it was assumed that each driver's decision to accept or reject a gap size is mutually independent and that the probability of accepting a given gap size is constant. Because of the insufficient number of gap observations, the analysis was conducted on the joint set of observations of random gap and lag sizes. It was then further assumed that the driver's probability of accepting a given gap size is equal to that for the same lag size.

The independent random sets of gap–lag acceptances and rejections for daytime and nighttime lead to a series of sampled proportions as follows:

Gap–lag size, seconds:

$$\begin{array}{lccccc} & \underline{1} & \underline{2} & \underline{3} & & \underline{c} \\ \text{Day----} & \hat{P}_{11} & \hat{P}_{12} & \hat{P}_{13} & \ldots & \hat{P}_{1c} \\ \text{Night---} & \hat{P}_{21} & \hat{P}_{22} & \hat{P}_{23} & \ldots & \hat{P}_{2c} \end{array}$$

$$\hat{P}_{1j}=\frac{a_j}{a_j+r_j}$$

and

$$\hat{P}_{2j}=\frac{A_j}{A_j+R_j}$$

Where,

a_j=number of acceptances for the j^{th} gap-lag size in the daytime.

r_j=number of rejections for the j^{th} gap-lag size in the daytime.

A_j=number of acceptances for the j^{th} gap-lag size at night.

R_j=number of rejections for the j^{th} gap-lag size at night.

It is hypothesized that if a given gap size is j then the underlying probabilities of gap acceptance for day and night, P_{1j} and P_{2j}, are the same for all j's—$j=1, 2 \ldots c$. This is the hypothesis of conditional homogeneity of the set of corresponding day and night gap-acceptance probabilities. Thus, if the hypothesis $P_{1j}=P_{2j}$ for all j's is true, it is meant that the day and night samples are conditionally homogeneous as opposed to being strictly homogeneous, which in addition, would be:

$$P_{i1}=P_{i2}= \ldots =P_{ic} \text{ for } i=1, 2$$

In accordance with the procedure and notaion given in reference (*2*), the null hypothesis, H_2, is tested against the alternate hypothesis, H_1, where it is defined (for each $j=1,2,3$ . . c):

$$H_1: P_{1jk} \neq P_{2jk};$$

$$\sum_{k=1}^{2} P_{ijk} = P_{ij.};\ i=1,\ 2$$

$$I_2: P_{1jk} = P_{2jk} = P_{*jk};$$

$$\sum_{k=1}^{2} P_{*jk} = P_{*j1} + P_{*j2} = P_{*j.}$$

Vhere,

$$\sum_{k=1}^{2} P_{.jk} = P_{.j.}$$

The null hypothesis, H_2, states that there is onditional homogeneity, and H_1 states that he day and night samples have different cceptance $k=1$, and rejection, $k=2$, probailities among the gap–lag sizes, j.

This procedure is equivalent to a chiquare procedure, involving a set of 2×2 ontingency tables. However, the computaions here are much less arduous, especially hen use is made of table $2n \log_e n$ given in eference (*3*).

The information component for a null ypothesis of conditional homogeneity, H_2, n which:

$$\frac{P_{ijk}}{P_{ij.}} = \frac{P_{*jk}}{P_{*j.}}$$

or

$$i=1,\ 2;\ j=1,\ 2,\ .\ .\ .\ c;\ k=1,2$$

$$2\hat{I}\ (H_1{:}H_2) = 2 \sum_{i=1}^{2} \sum_{j=1}^{c} \sum_{k=1}^{2} X_{ijk} \log \frac{X_{ijk}}{\frac{X_{ij.}X_{.jk}}{X_{.j.}}}$$

Vhere,

X_{ijk} is the number of observations for the j, k category (see table 1), and where,

=1 represents day, $i=2$ represents night

=1, 2, . . . c represents gap–lag size category

=1 represents accepted category

=2 represents rejected category

Finally the gap marginal total for each ategory is given by the expression:

$$X_{.j.} = X_{1j.} + X_{2j.} = X_{.j1} + X_{.j2}$$

$$= X_{1j1} + X_{2j1} + X_{1j2} + X_{2j2}$$

Table 1.—Test of conditional homogeneity between two samples[1]

	Gap size			
	$j=1$	$j=2$	. . . .	$j=c$
	Seconds	*Seconds*		*Seconds*
Day ($i=1$):				
Accept ($k=1$)	X_{111}	X_{121}	. . . .	X_{1c1}
Reject ($k=2$)	X_{112}	X_{122}	. . . .	X_{1c2}
Night ($i=2$):				
Accept ($k=1$)	X_{211}	X_{221}	. . . .	X_{2c1}
Reject ($k=2$)	X_{212}	X_{222}	. . . .	X_{2c2}
MARGINAL TOTALS				
Day ($X_{1j.}=X_{1j1}+X_{1j2}$)	$X_{11.}$	$X_{12.}$	. . . .	$X_{1c.}$
Night ($X_{2j.}=X_{2j1}+X_{2j2}$)	$X_{21.}$	$X_{22.}$	. . . .	$X_{2c.}$
Accept ($X_{.j1}=X_{1j1}+X_{2j1}$)	$X_{.11}$	$X_{.21}$	. . . .	$X_{.c1}$
Reject ($X_{.j2}=X_{1j2}+X_{2j2}$)	$X_{.12}$	$X_{.22}$	. . . .	$X_{.c2}$
MARGINAL TOTALS				
$X_{.j.}=X_{1j.}+X_{2j.}$ $=X_{.j1}+X_{.j2}$	$X_{.1.}$	$X_{.2.}$	. . . .	$X_{.c.}$
TEST STATISTIC (DISTRIBUTED AS χ^2 WITH c d.f.)				
$2\hat{I}=2\sum_{i=1}^{2}\sum_{j=1}^{c}\sum_{k=1}^{2} X_{ijk} \ln \frac{X_{ijk}}{\frac{X_{ij.}X_{.jk}}{X_{.j.}}}$				

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[1] Sample 1—Gap acceptances and rejections, day. Sample 2—Gap acceptances and rejections, night.

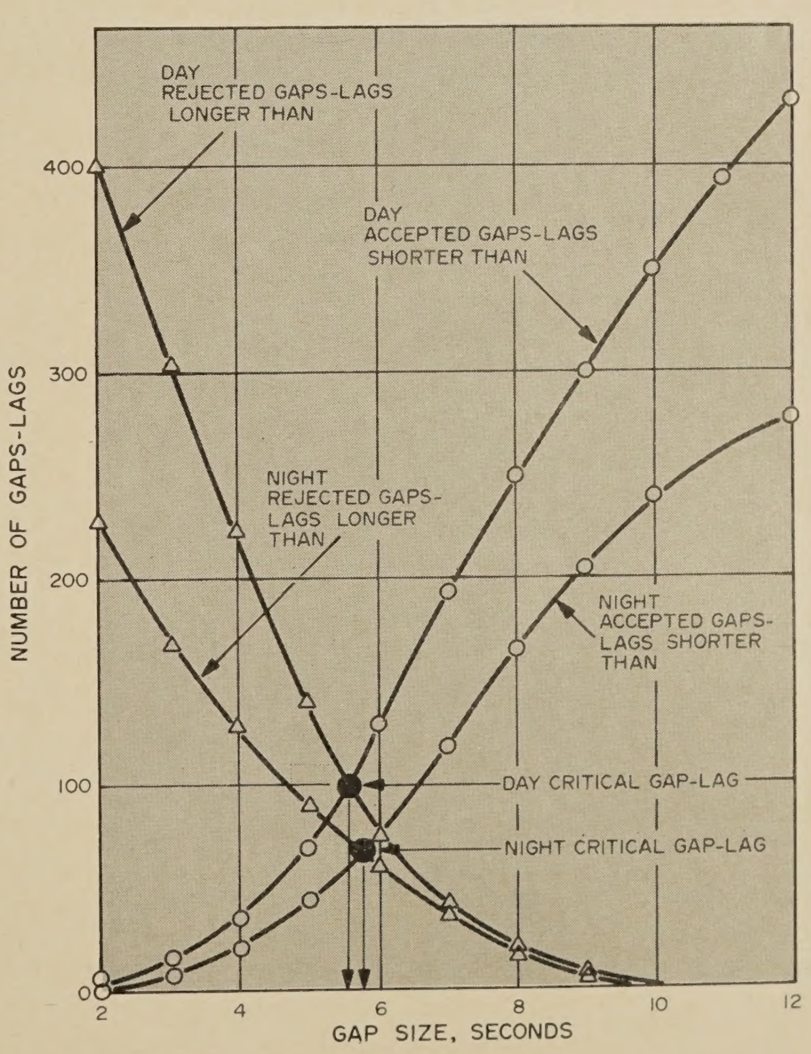

Figure 5.—Distribution of accepted and rejected gaps and lags, conflict with two traffic streams.

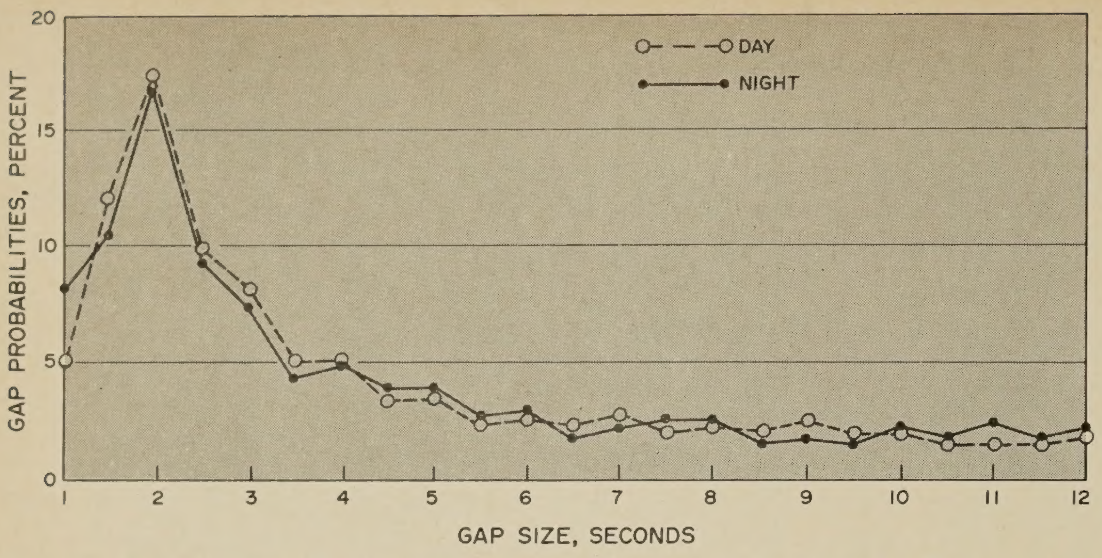

Figure 6.—Gap distribution, Braddock Road, 700–900 vehicles per hour.

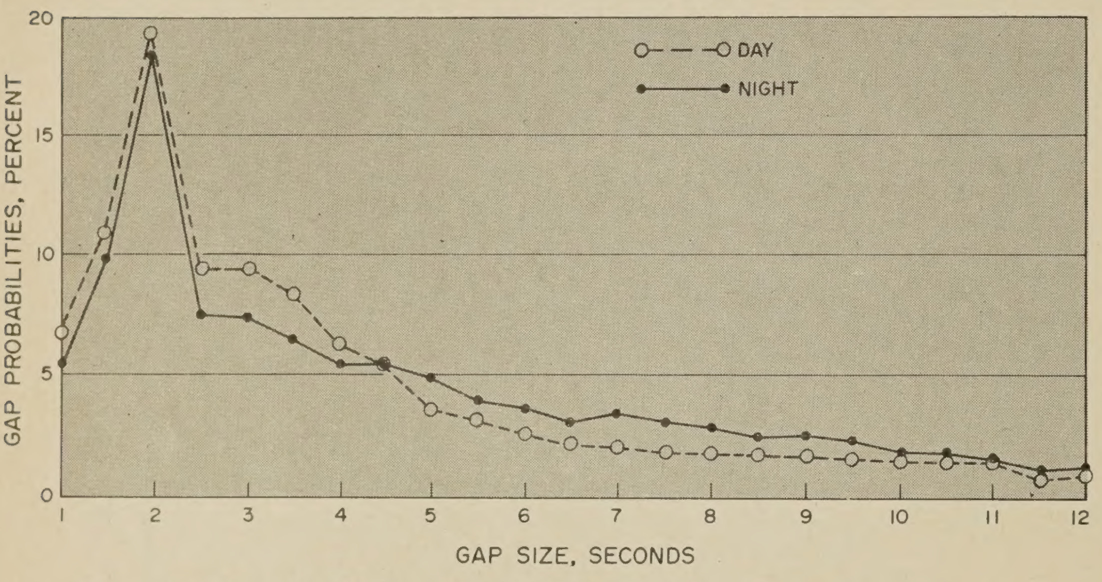

Figure 7.—Gap distribution, Braddock Road, 901–1,100 vehicles per hour.

Using the tables in reference (*3*), the statistic $2\hat{I}$ (H_1:H_2) may be easily calculated by expressing it as:

$$2\hat{I}=2\sum_{i=1}^{2}\sum_{j=1}^{c}\sum_{k=1}^{2}X_{ijk}\ln\frac{X_{ijk}}{(X_{ij.}X_{.jk})/X_{.j.}}$$

$$=\sum_{i}^{2}\sum_{j}^{c}\sum_{k}^{2}2X_{ijk}\ln X_{ijk}+\sum_{j=1}^{c}2X_{.j.}\ln X_{.j.}$$

$$-\sum_{i=1}^{2}\sum_{j=1}^{c}2X_{ij.}\ln X_{ij.}-\sum_{j=1}^{c}\sum_{k=1}^{2}2X_{.jk}\ln X_{.jk}$$

The X_{ijk}'s in this formula are defined in table 1 as the random number of occurrences in the *i*, *j*, *k* category.

As $2n \ln n$ is tabulated in reference (*3*) for all integers from 1 to 10,000, the quantities in table 1 may be used as inputs to the tabulation, that is:

$$\sum_{j=1}^{c}2X_{.j.}\ln X_{.j.}=2X_{.1.}\ln X_{.1.}+2X_{.2.}\ln X_{.2.}$$
$$+\ .\ .\ .\ 2X_{.c.}\ln X_{.c.}$$

The statistic $2\hat{I}$ has the asymptotic distribution with *c* degrees of freedom und the null hypothesis of conditional hom geneity. Accordingly, in the second line table 1, X_{122} represents the occurring numb of rejections during the day for gap size $j=$ and in the third line, X_{221} represents t occurring number of acceptances during t night for gap size $j=2$.

The entry $X_{1j.}$ in the table, under *Margin totals*, represents the total number of accep ances and rejections during the day for g size *j*:

$$\text{Day marginal } X_{1j.}=X_{1j1}+X_{1j2}$$

Similarly under *Marginal totals* are listin for night, accept, and reject:

$$\text{Night marginal } X_{2j.}=X_{2j1}+X_{2j2}$$

$$\text{Accept marginal } X_{.j1}=X_{1j1}+X_{2j1}$$

$$\text{Reject marginal } X_{.j2}=X_{1j2}+X_{2j2}$$

In tables 2, 3, and 4 are summarized t gap–lag acceptance and rejection data fr the different movements of the minor-stre vehicles—all data, conflicts with one tra stream, and conflicts with two traffic strea, respectively. The left turn of the minor-str t vehicle was defined as *conflict with two tra c streams*, and both the right turn of the min - street vehicle and the left turn of the maj - street vehicle were defined as *conflict with e traffic stream.*

Gap and lag size data were compiled i o five groups for each set of data and the hypo - esis of conditional homogeneity was test d according to the procedure shown in e bottom section of table 1.

Table 2.—Analysis of gap-lag acceptance between day and night—all data

	Gap size				
	$j=1$ (2–3)	$j=2$ (4–5)	$j=3$ (6–7)	$j=4$ (8–9)	$j=5$ (10+ ove
Day ($i=1$):	*Seconds*	*Seconds*	*Seconds*	*Seconds*	*Seconds*
Accept ($k=1$)	25	120	233	210	229
Reject ($k=2$)	377	262	98	24	-------
Night ($i=2$):					
Accept ($k=1$)	5	62	124	108	128
Reject ($k=2$)	200	108	53	13	6
MARGINAL TOTALS					
Day ($X_{1j\cdot}$)	402	382	331	234	229
Night ($X_{2j\cdot}$)	205	170	177	121	134
Accept ($X_{\cdot j1}$)	30	182	357	318	357
Reject ($X_{\cdot j2}$)	577	370	151	37	6
Gap marginal total ($X_{\cdot j\cdot}$)	607	552	508	355	363

TEST OF CONDITIONAL HOMOGENEITY

$$2\hat{I}=2\sum_{i=1}^{2}\sum_{j=1}^{5}\sum_{k=1}^{2}X_{ijk}\ln\frac{X_{ijk}\ X_{.j.}}{X_{ij.}\ X_{.jk}}$$

$$=\sum_{i}\sum_{j}\sum_{k}2X_{ijk}\ln X_{ijk}+\sum_{j=1}^{5}2X_{.j.}\ln X_{.j.}-\sum_{i}\sum_{j}2X_{ij.}-\sum_{j}\sum_{k}2X_{.jk}\ln X_{.jk}$$

$$=24{,}642.940+29{,}528.820-26{,}480.349-27{,}673.271=18.140$$

$$\chi^2_5(.05)=11.0$$

Raff's critical-lag comparison method

In addition to the technique just described, he method employed by Raff (*1*) was applied o the original data collected in the study to ompare the daytime and nighttime gap and ags. Raff determined the critical lag by lotting two cumulative distributions on the ame graph, as shown in figures 3, 4, and 5. ne curve describes the accepted number of ags that were shorter than a given time nterval, and the other shows the rejected umber of lags that were longer than this nterval. The value of the critical lag was etermined as the point at which the two urves intersect on the chart.

Results of the Analysis

It was realized that the traffic volume ould affect gap-acceptance probabilities and hat if experimental data were collected under arying traffic volume conditions, the true ifferences between day and night effects ould be obscured. Therefore, to substantially egate the traffic volume effect, all the data ere divided into two groups according to raffic volume. One group was for a lighter

Table 3.—Analysis of gap-lag acceptance between day and night—conflict with one traffic stream

	Gap size				
	$j=1$ (2-3)	$j=2$ (4-5)	$j=3$ (6-7)	$j=4$ (8-9)	$j=5$ (10 + over)
	Seconds	*Seconds*	*Seconds*	*Seconds*	*Seconds*
Day ($i=1$):					
Accept ($k=1$)	9	64	105	110	94
Reject ($k=2$)	201	106	42	12	--------
Night ($i=2$):					
Accept ($k=1$)	--------	26	44	36	44
Reject ($k=2$)	97	37	9	4	2
MARGINAL TOTALS					
Day ($X_{1j.}$)	210	170	147	122	94
Night ($X_{2j.}$)	97	63	53	40	46
Accept ($X_{.j1}$)	9	90	149	146	138
Reject ($X_{.j2}$)	298	143	51	16	2
Gap marginal total ($X_{.j.}$)	307	233	200	162	140

TEST OF CONDITIONAL HOMOGENEITY

$$2\hat{I}=2\sum_{i=1}^{2}\sum_{j=1}^{5}\sum_{k=1}^{2} X_{ijk} \ln \frac{X_{ijk}X_{.j.}}{X_{ij.}X_{.jk}}$$

$$=\sum_{i}\sum_{j}\sum_{k} 2X_{ijk} \ln X_{ijk}+\sum_{j=1}^{5} 2X_{.j.} \ln X_{.j.}-\sum_{i}\sum_{j} 2X_{ij.}-\sum_{j}\sum_{k} 2X_{.jk} \ln X_{.jk}$$

$$=9{,}233.211+11{,}207.837-9{,}963.192-10{,}463.211=20{,}441.048-20{,}426.403$$

$$=14.645 \qquad \chi^2_5(.05)=11.0$$

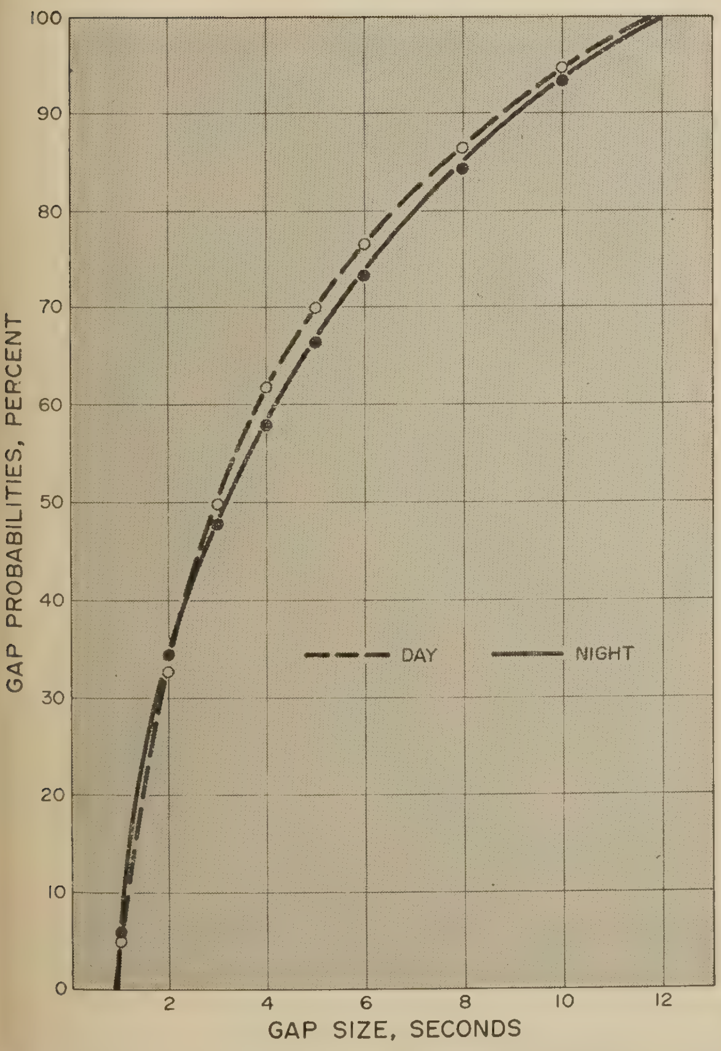

Figure 8.—Cumulative gap distribution, Braddock Road, 700–900 vehicles per hour.

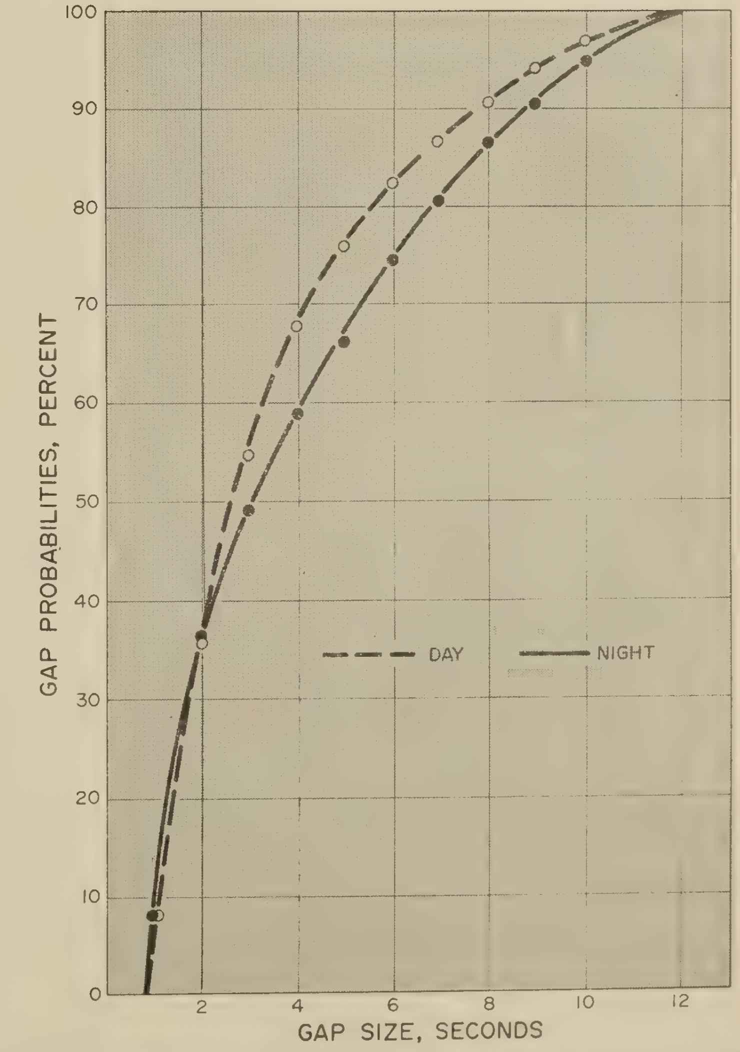

Figure 9.—Cumulative gap distribution, Braddock Road, 901–1,100 vehicles per hour.

Table 4.—Analysis of gap–lag acceptance between day and night—conflict with two traffic streams

	Gap size				
	$j=1$ (2–3)	$j=2$ (4–5)	$j=3$ (6–7)	$j=4$ (8–9)	$j=5$ (10+ over)
Day ($i=1$):	*Seconds*	*Seconds*	*Seconds*	*Seconds*	*Seconds*
Accept ($k=1$)	16	56	128	100	135
Reject ($k=2$)	176	156	56	12	----
Night ($i=2$):					
Accept ($k=1$)	5	36	80	72	84
Reject ($k=2$)	103	71	44	9	4
MARGINAL TOTALS					
Day ($X_{1j.}$)	192	212	184	112	135
Night ($X_{2j.}$)	108	107	124	81	88
Accept ($X_{.j1}$)	21	92	208	172	219
Reject ($X_{.j2}$)	279	227	100	21	4
Gap marginal total ($X_{.j.}$)	300	319	308	193	223

TEST OF CONDITIONAL HOMOGENEITY

$$2\hat{I}=2\sum_{i=1}^{2}\sum_{j=1}^{5}\sum_{k=1}^{2}X_{ijk}\ln\frac{X_{ijk}\;X_{.j.}}{X_{ij.}\;X_{.jk}}$$

$$=\sum_{i}\sum_{j}\sum_{k}2X_{ijk}\ln X_{ijk}+\sum_{j=1}^{5}2X_{.j.}\ln X_{.j.}-\sum_{i}\sum_{j}2X_{ij.}-\sum_{j}\sum_{k}2X_{.jk}\ln X_{.jk}$$

$$=12,212.334+15,073.199-13,297.202-13,976.583=11.748$$

$$\chi^2_5(.05)=11.0$$

Table 5.—Gap availability, Braddock Road—average number of cars per hour for specific traffic volumes [1]

Volume	Day		Night	
	Eastbound	Westbound	Eastbound	Westbound
Vehicles per hr.				
700–900	171	333	103	367
901–1,100	336	328	316	392

[1] Gap size included 1–20 seconds.

Table 6.—Gap distribution percentiles, Braddock Road [1]

Percentile	700–900 vehicles per hr.		901–1,100 vehicles per hr.	
	Day	Night	Day	Night
50	3.0	3.2	2.6	3.1
75	5.8	6.1	4.8	6.2
90	8.8	9.2	8.0	9.2

[1] Gap size included 1–12 seconds.

Table 7.—Gap–lag size, number of acceptances and rejections—all data

	Seconds											Total
	2	3	4	5	6	7	8	9	10	11	12	
Day:												
Accepted	13	12	42	78	104	129	105	105	82	75	72	817
Rejected	205	172	155	107	50	48	18	6	----	----	----	761
Total	218	184	197	185	154	177	123	111	82	75	72	1,578
Night:												
Accepted	----	5	19	43	47	77	57	51	61	42	25	427
Rejected	126	74	62	46	26	27	7	6	6	----	----	380
Total	126	79	81	89	73	104	64	57	67	42	25	807

traffic volume of 700–900 vehicles per hou and the other was for a heavier traffic volun of 901–1,100 vehicles per hour. It is consi ered that each of these groups represente conditions under which gap-acceptance prol abilities should be fairly uniform at night during the day.

In the 700–900 vehicle-per-hour group, reasonable agreement was evident in the da time and nighttime gap distribution (figs. 6 an 8). In the 901–1,100 vehicle-per-hour grou the distribution of the larger gaps was som what higher during the nighttime (figs. 7 a 9). Some numerical values of the gap dist bution in the study intersection are listed tables 5 and 6, and the results of the collect data are shown in tables 7, 8, and 9.

In the analysis of the test of homogenei between day and night gap–lag acceptan distribution, it was found that $2\hat{I}=14.645$ a 11.748, respectively, for the groups *confl with one traffic stream* and *conflict with t traffic streams*. For all the data combin $2\hat{I}=18.140$. The χ^2 value, with $C(r-1)(r-$ $=5$ degrees of freedom and 5 percent level 11.07. Therefore, statistical differences exist in the overall gap–lag acceptance distributi between the day and night environments at t test intersection.

However, a further exploration was ma to detect the size-groups that contributed the rejection of the hypothesis of homog neity. The test was applied to each size-gro separately, and it was found that groups $j=1$ and 5 had $2\hat{I}$ values greater than the value, and that groups $j=2$, 3, and 4 had significant difference that could be detect for a hypothesis of conditional homogenei . The $2\hat{I}$ values for each gap size-group, a the corresponding acceptance or rejection the hypothesis, are shown in table 10.

The corresponding median acceptance- jection times were very close and, for a practical purpose, can be considered to be t same (table 11). For all the data combin the median day acceptance times were .3 seconds lower than those at night, where the rejection times were .15 seconds higher. A comparison of the two movement-grou showed lower acceptance and rejection tim in both day and night gaps and lags for t group *conflict with one traffic stream*. A co parison of the acceptance times between d and night showed that, although the differen is very small, the accepted and rejected tim at night were higher and lower respectiv for both movement groups.

The Raff method, mentioned previous was used to obtain the critical gap and g values. For all the data combined, the criti day gap–lag was 5.4 seconds compared to night value of 5.6 seconds. This same differen 0.2 sec., was evident between the day a night critical gap–lag, even though the val were somewhat higher for the group *conf with two traffic streams*. Aside from the sm differences, the resultant values of the R method depend largely on the manner in wh the curves are plotted on the data poi therefore, this method is a pure visual fitt technique.

Conclusions

The following conclusions, valid only for the intersection under consideration, were inferred from the findings of the reported field investigation:

- There were no significant differences in the formation of gaps between day and night, but it was noticed that, as the volume increased, a higher percentage of long gaps was present at night than during the day.
- Also there were no differences between the median gap-lag acceptance times. The overall median acceptance times for day and night were 7.29 and 7.32 seconds respectively; the overall median rejection times for day and night were 4.01 and 3.86 seconds respectively.
- Night drivers accepted no gap or lag less than 3 seconds and rejected those higher than 10 seconds.
- Day drivers accepted no gap or lag less than 2 seconds and rejected those higher than 9 seconds.
- The overall critical night gap-lag, as defined, was 0.2 seconds higher than the day gap-lag.
- The statistical test used was based on the assumption that successive observations are independent in the probability sense. Because the $2\hat{I}$ values were greater than the χ^2 value, the gap acceptance distribution for day and night could not be considered conditionally homogeneous. However this was found to be true only for the very short and very long gaps—2–3 and 10–12 seconds. In the median size gaps, 4–9 seconds, the distribution of the gap acceptances was the same both during the day and at night.
- Further experimentation and analysis is necessary, especially for the short and long size gaps, before it can be determined that the results of day or night acceptance and rejection are dependent on time.

able 8.—Gap-lag size, number of acceptances and rejections—conflict-with-one-traffic-stream data

	Seconds											Total
	2	3	4	5	6	7	8	9	10	11	12	
Day:												
Accepted	5	4	26	38	44	61	53	57	34	31	29	382
Rejected	109	92	71	35	26	16	10	2	-----	-----	-----	361
Total	114	96	97	73	70	77	63	59	34	31	29	743
Night:												
Accepted	-----	-----	7	19	15	29	17	19	17	14	13	150
Rejected	65	32	24	13	5	4	2	2	2	-----	-----	149
Total	65	32	31	32	20	33	19	21	19		13	299

able 9.—Gap-lag size, number of acceptances and rejections—conflict-with two-traffic-streams data

	Seconds											Total
	2	3	4	5	6	7	8	9	10	11	12	
Day:												
Accepted	8	8	16	40	60	68	52	48	48	44	43	435
Rejected	96	80	84	72	24	32	8	4	-----	-----	-----	400
Total	104	88	100	112	84	100	60	52	48	44	43	835
Night:												
Accepted	-----	5	12	24	32	48	40	32	44	28	12	277
Rejected	61	42	38	33	31	23	5	4	4	-----	-----	241
Total	61	47	50	57	63	71	45	36	48	28	12	518

Table 10.—Test of the hypothesis of homogeneity for each gap-size group separately

Gap-size group	$2\hat{I}$ Values				
	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$
All data	4.629	1.351	0.007	0.021	12.132
Hypothesis [1]	Rejected	Accepted	Accepted	Accepted	Rejected
Conflict with one traffic stream	6.961	0.025	2.922	0.001	4.508
Hypothesis [1]	Rejected	Accepted	Accepted	Accepted	Rejected
Conflict with two traffic streams	1.546	1.786	0.857	0.007	7.552
Hypothesis [1]	Accepted	Accepted	Accepted	Accepted	Rejected

[1] X^2 (.05) for 1 d.f.=3.84.

Table 11.—Median acceptance-rejection times for gaps and lags combined

Gap size-group	Combined gap-lag median time					
	700–900 vehicles per hr.		901–1,100 vehicles per hr.		All data	
	Day	Night	Day	Night	Day	Night
	Seconds	*Seconds*	*Seconds*	*Seconds*	*Seconds*	*Seconds*
Group I—Conflict with one traffic stream:						
Accepted	7.04	7.50	7.35	7.21	7.24	7.30
Rejected	3.63	3.42	3.74	3.20	3.78	3.29
Group II—Conflict with two traffic streams:						
Accepted	7.17	7.47	7.47	7.62	7.33	7.53
Rejected	4.32	4.21	4.29	4.24	4.28	4.23
All movements:						
Accepted	-----	-----	-----	-----	7.29	7.32
Rejected	-----	-----	-----	-----	4.01	3.86

ACKNOWLEDGMENT

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Rapid testing on 6-inch silty-gravel compacted base course. Above left—Plate-bearing test using truck-mounted, hydraulically actuated equipment. Above right—Refraction seismographic test.

Quality Assurance in Highway Construction

BY THE OFFICE OF
RESEARCH AND DEVELOPMEN
BUREAU OF PUBLIC ROADS

Part 2—
Quality Assurance of Embankments and Base Courses

Reported by THURMUL F. McMAHON,
Principal Quality-Assurance Research Engineer,
Materials Division

This is the second part of an interpretative summary of the progress in Public Roads research program for the statistical approach to quality assurance in highway construction. Part 1.—Introduction and Concepts, was presented in the previous issue of PUBLIC ROADS. The remaining parts, to be presented in succeeding issues, are 3.—Quality Assurance of Portland Cement Concrete, 4.—Variations of Bituminous Construction, 5.—Summary of Research for Quality Assurance of Aggregate, and 6.—Control Charts.

Introduction

EMBANKMENTS and base courses, essentially, are structural elements of the highway and are amenable to the same treatment as any other structural element with respect to design, process control, and acceptance. Their function is to provide adequate support to the pavement within the design concepts of load applications.

Density Control

The engineer has learned that proper compaction is essential to the performance properties of soil and rock material. However, the uniformity of support is as important, if not more so, than the absolute magnitude of the support offered; therefore, the control of the compaction process is one of the most important aspects in base and embankment construction.

In the 19th Century, during construction of earth dams, it was discovered that the driving of livestock, particularly sheep, across lifts of soil, as they were placed, improved uniformity of support, increased stability, and decreased permeability of the completed structure. Although many improved methods of compaction and compaction control have evolv over the years from this crude beginnin compaction control is still an item of maj concern to the highway engineer.

The first attempt toward scientific cont of the compaction process resulted from t work of R. R. Proctor (*1*),[1] who develop the moisture-density relations still used compaction specifications and control. He al developed the Proctor Needle to control t uniformity of compaction. Later the overflo volumeter, sand-cone, and rubber-ballo methods were developed to aid in the densi measurement of compacted materials. T newest, and probably the best methods measuring moisture and density of compact materials are those in which nuclear devic are used.

The advent of nuclear equipment not o has provided a faster and better proced

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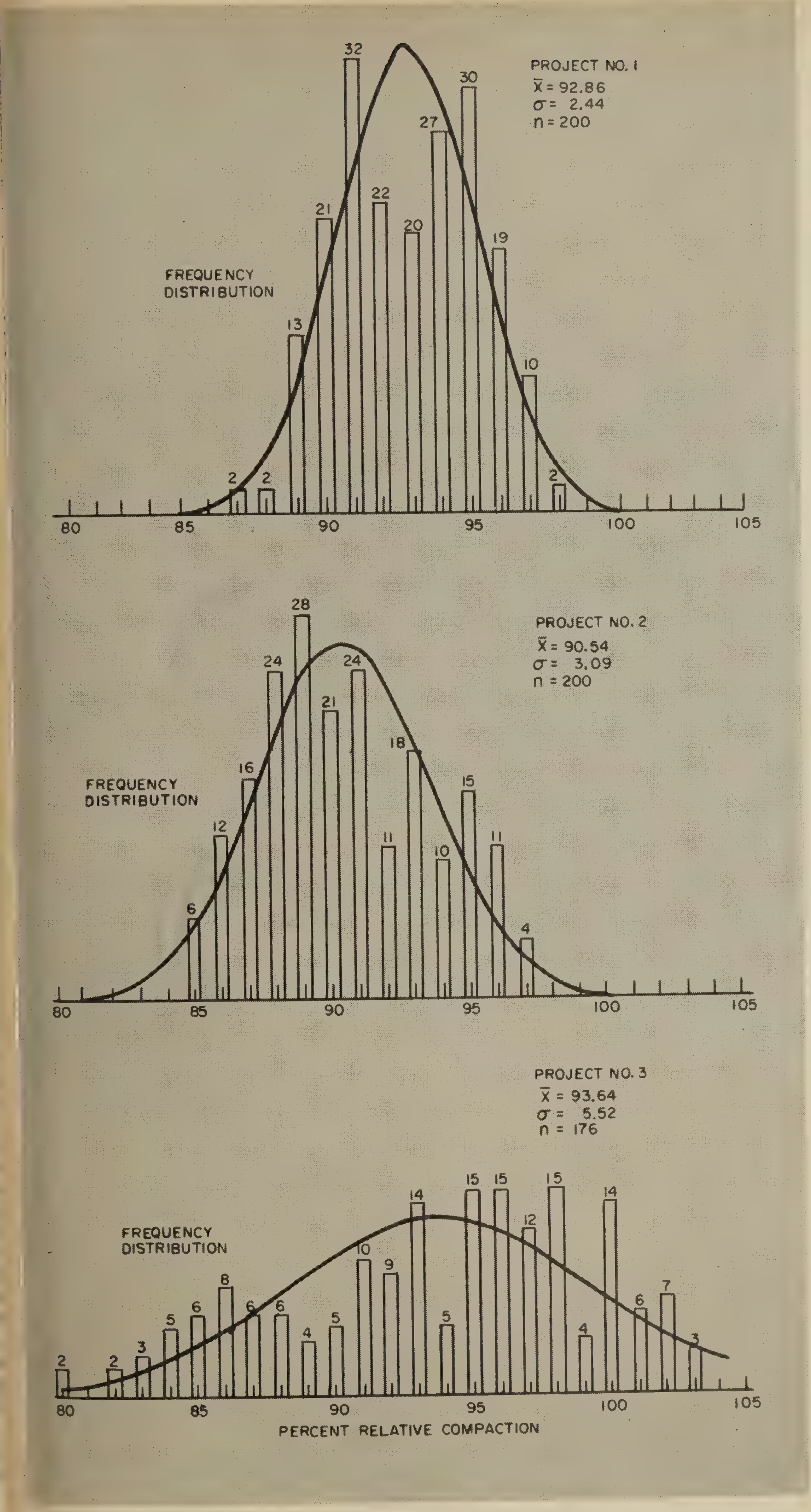
[1] Italic numbers in parentheses identify the referen listed on page 174.



igure 1.—Variation in density of embankments, California road-embankment study.

for measuring compaction but has resulted in a review of the methods and the precisions to be expected. Also, extensive studies are being made to develop better criteria than density for specifying and controlling compaction in the future.

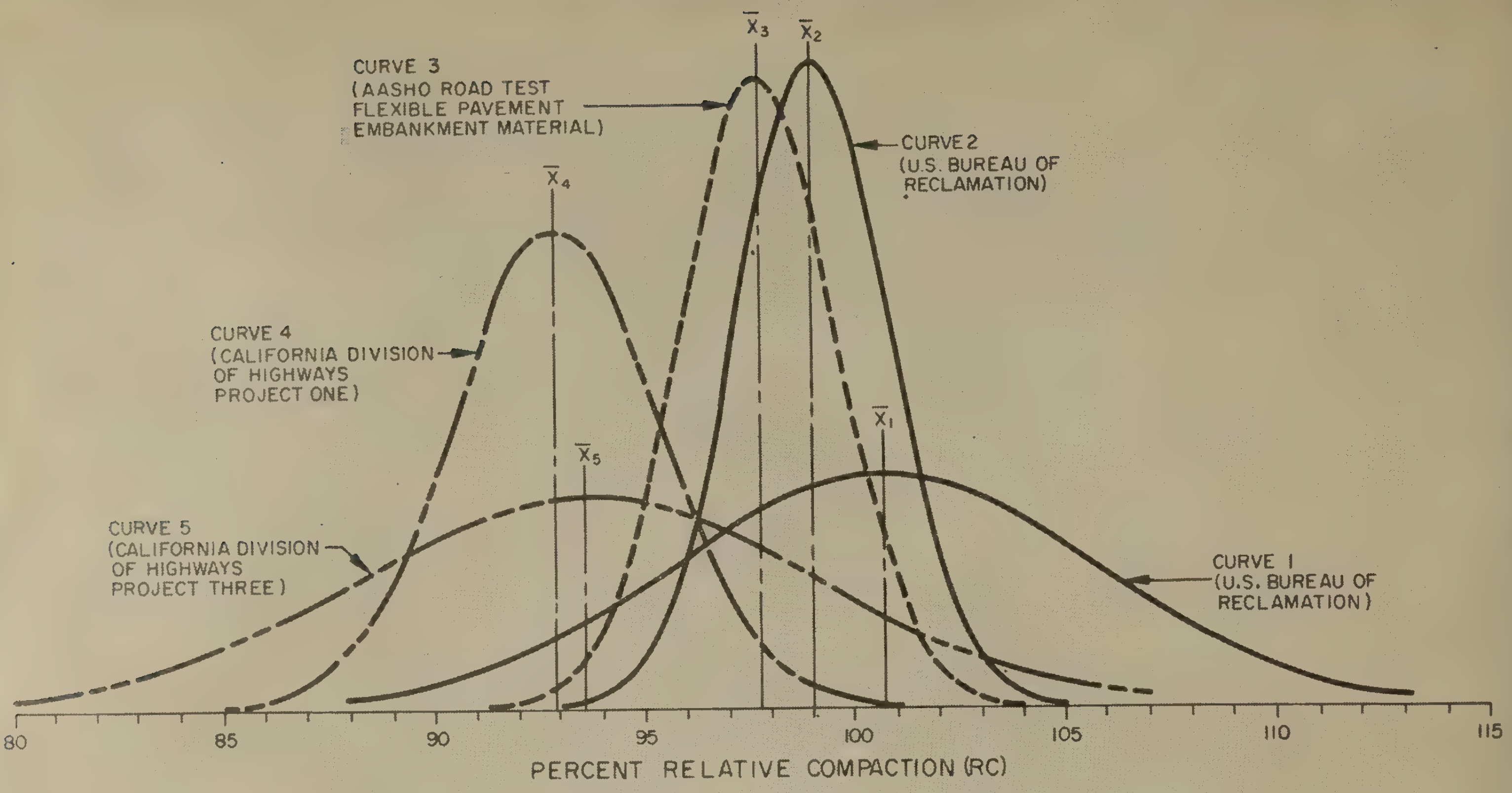
Current practices

It has long been the custom to define desirable compaction as the degree of compaction that is above some lower limit set by engineering judgment and based on experience with various materials and performance requirements. This lower limit is described as percent of a maximum density determined in the laboratory for each type of soil to be encountered on a project.

Although most engineers have recognized that measurements of density are not absolutely reproducible in themselves, and that material variations in any embankment or base may be the rule rather than the exception, the extent of the density-measurement variations seldom has been determined. Because these variations have not been recognized, misunderstanding exists within the engineering profession and between engineers and nontechnical people. Engineers, as well as public agencies, have often been criticized when it was shown in subsequent test results that accepted embankments and base courses failed to meet minimum requirements even though no evidence of unsatisfactory performance existed.

A look at present specifications and compaction-measurement methods emphasizes the misunderstanding that exists. To develop measurement criteria, a series of laboratory compaction tests is run to establish the maximum density and optimum moisture content for each soil or base type. It is common practice to run one series of standard compaction tests for each material although it is fairly common knowledge that if a second series was run on another portion of the same material the results of the two tests might differ by several pounds per cubic foot. Frequently, the field technician uses density values established in the laboratory to determine percent compaction at the construction site by comparing the results of field tests with the laboratory-developed curves. He must make a judgment as to whether the type soil he has tested is the same as that for which a curve has been established. It is often apparent that his decision on which curve to use is based on density comparisons rather than on soil type comparisons. Present day construction methods further contribute to the difficulties of the technician, who seldom will encounter material in the field that is an exact duplicate of the material tested in the laboratory. Excavation and spreading of large quantities of materials nearly always result in mixtures of types or variations of type from spot to spot in the fill.

Not only are the methods of applying the test results difficult to rationalize, but the tests themselves are not reproducible to the extent necessary for exact measurement. Several years were futilely spent in comparing



CURVE NO.	1	2	3	4	5
MINIMUM SPECIFICATION LIMIT, % RC	98	98	95	90	90
COMPACTION TEST METHOD	PROCTOR E-11	PROCTOR E-11	AASHO T-99	CALIF. 216	CALIF. 216
AVERAGE COMPACTION	100.7	99.0	97.7	92.9	93.6
STANDARD DEVIATION	5.0	1.8	1.9	2.4	5.5
APPROXIMATE % LESS THAN MINIMUM SPECIFICATION LIMIT	29.5	28.9	7.8	11.3	25.6

Figure 2.—Normal distribution curves from three organizations.

Table 1.—Percent relative compaction for different test methods

Compacted components	Sand cone			Portable nuclear			Roadlogger		
	Mean	[1] σ_{st}^2	[2] σ_o	Mean	[1] σ_{st}^2	[2] σ_o	Mean	[1] σ_{st}^2	[2] σ_o
Embankments	99.1	3.46	4.46	99.0	2.25	4.55	100.2	2.17	4.44
Bases and subbases	98.7	2.16	2.92	98.1	1.32	2.89	98.0	0.60	2.48

[1] σ_{st}^2 Sampling and testing variance.

[2] σ_o Overall standard deviation.

the results of nuclear measurements to those of conventional measurements. Only recently has it been demonstrated that the nuclear device is capable of producing more precise overall data than can be obtained by conventional methods.

One major factor that influences the variation in conventional-density test results is the common practice of removing the larger particles, greater than 3/4 inch, from the samples tested in the laboratory. The effect of these larger particles on field results is estimated by empirical mathematical equatio and superimposed on the results of the labo- tory tests. Many laboratories realize t fallacy of this practice and are using larg molds in their tests.

Sampling

Selective sampling by the inspector, oft as ordered by the engineer, has played an i- portant part in the failure to recognize t magnitude of the actual variations occurri in embankment and base construction. Wh the inspector has the opportunity to select t test site, he has three alternatives: (1) select an average condition, (2) to select t poorest condition, and (3) to select the b ondition. The general custom in the State or he specific practice of the engineer on the job 1ay well determine the site he selects for test. Regardless of his choice, the results of his tests vill reflect only the condition he is selecting nd not the variability of results or the true verall level of compaction.

Valid measurements of the actual quality of he compaction can be made only if the sample a true representation of the total compacted aterial. It is possible to obtain a represen- ation of the entire mass only when the sam- ling program is so designed that each element the mass has an equal chance of being one of e elements of the sample. Of course, the reater the number of elements sampled, the etter will be the representation.

The Statistical Approach

Although many questions concerning the quired level of compaction and the methods f obtaining it are still unanswered, almost veryone agrees that uniformity of support is e principal requirement of good embankment nd base-course construction. As a result of ecent measurements obtained in research, e need for a change in methods of control as become apparent. Any such change must e directed toward controlling uniformity as ell as degree of compaction.

The use of statistical concepts to establish e requirements of specifications and to aid the analysis of test data provides much of e needed improvement. The specification ther designates a target percent-compaction alue and the allowable variations about this alue or designates a lower limit to be met by given percentage of the construction, when valid statistical analysis of test results is erformed.

A statistically based specification requires at a contractor submit a *lot* of predetermined ze to the buyer for acceptance. Each *lot* is

able 2.—Average, range, and standard deviations of percent compaction of subgrade and subbase projects

Project	Average compaction	Range of compaction	Standard deviation
	Percent	*Percent*	*Percent*
S-1	100.6	84–116	5.3
S-2	96.8	80–110	5.7
S-3	98.2	84–108	4.5
B-1	89.4	82–98	3.3
B-2	91.7	84–100	3.1
B-3	93.6	86–100	2.3

ble 3.—Average differences between sand-cone density tests for replicate tests

Project	Replicates	Average difference between sand-cone density values for replicate tests
	Number	*Lb. per cu. ft.*
S-1	48	3.32
S-2	48	4.95
S-3	49	4.18
B-1	51	4.15
B-2	55	3.35
B-3	50	2.24

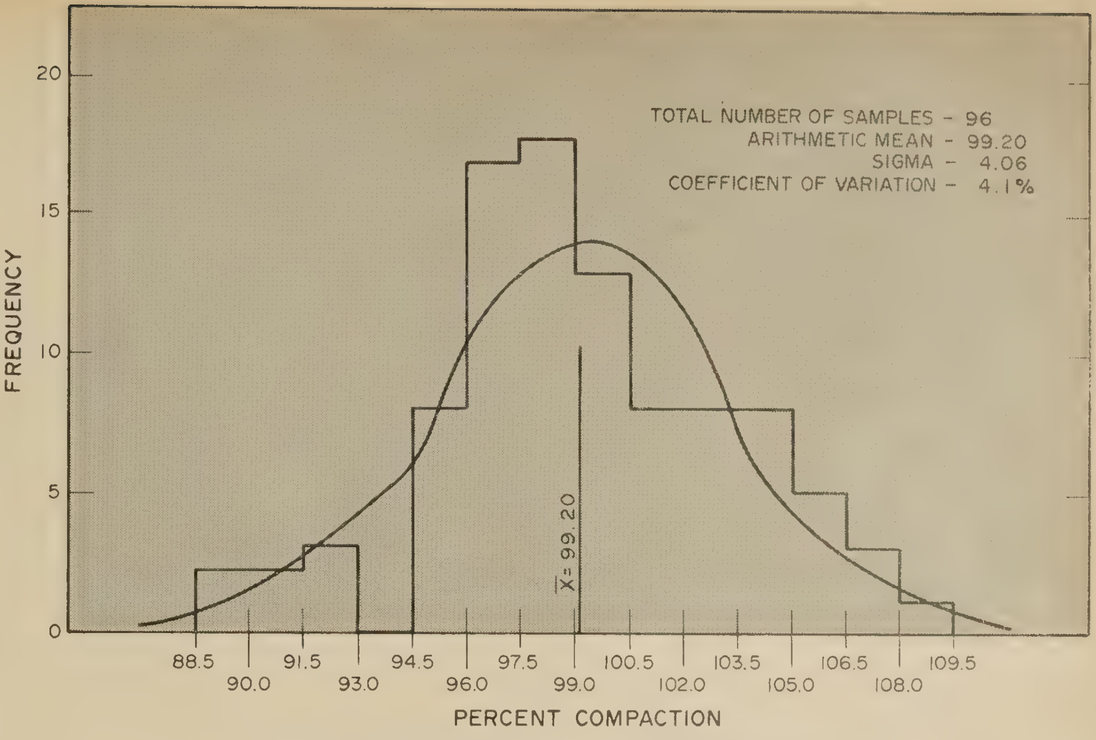


Figure 3.—Soil aggregate base, percent compaction.

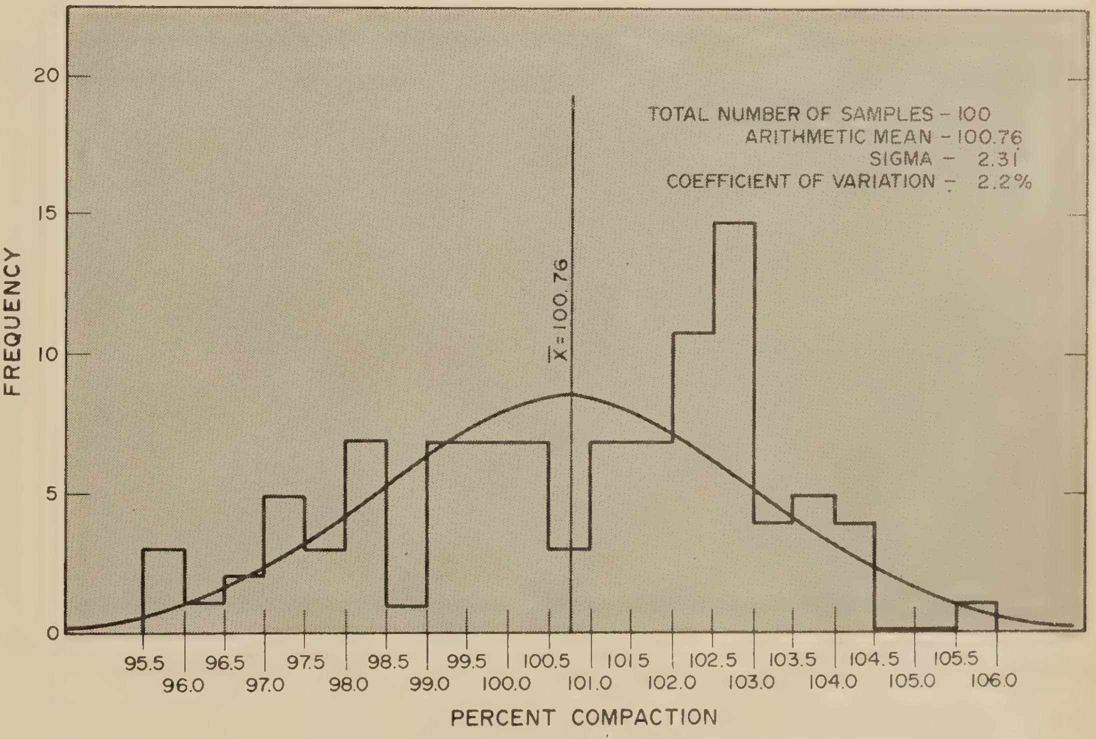


Figure 4.—Selected soil subbase, Class 4, percent compaction.

Table 4.—Maximum dry density and optimum moisture content values for duplicate field samples for Project S-1

Test number	Maximum dry density	Optimum moisture content	Liquid limit	Plasticity index	AASHO classification
	Lb. per cu. ft.	*Percent*			
27 A	118.7	13.7	32.5	13.5	A–6 (8)
27 B	119.3	13.5	36.0	15.2	A–6 (9)
32 A	117.4	14.4	33.9	14.3	A–6 (6)
32 B	115.8	15.4	34.6	13.9	A–6 (8)
34 A	113.5	15.4	41.5	18.4	A–7–6 (11.5)
34 B	110.6	14.3	41.6	16.9	A–7 6 (9)
36 A	123.0	13.4	30.2	12.3	A–6 (7)
36 B	119.7	13.3	31.0	11.9	A–6 (8)
37 A	121.2	12.6	28.1	8.6	A–4
37 B	122.6	11.0	----------	----------	----------
38 A	112.6	17.3	41.3	17.6	A–7–6 (11)
38 B	113.5	15.9	37.6	14.6	A–6 (9)

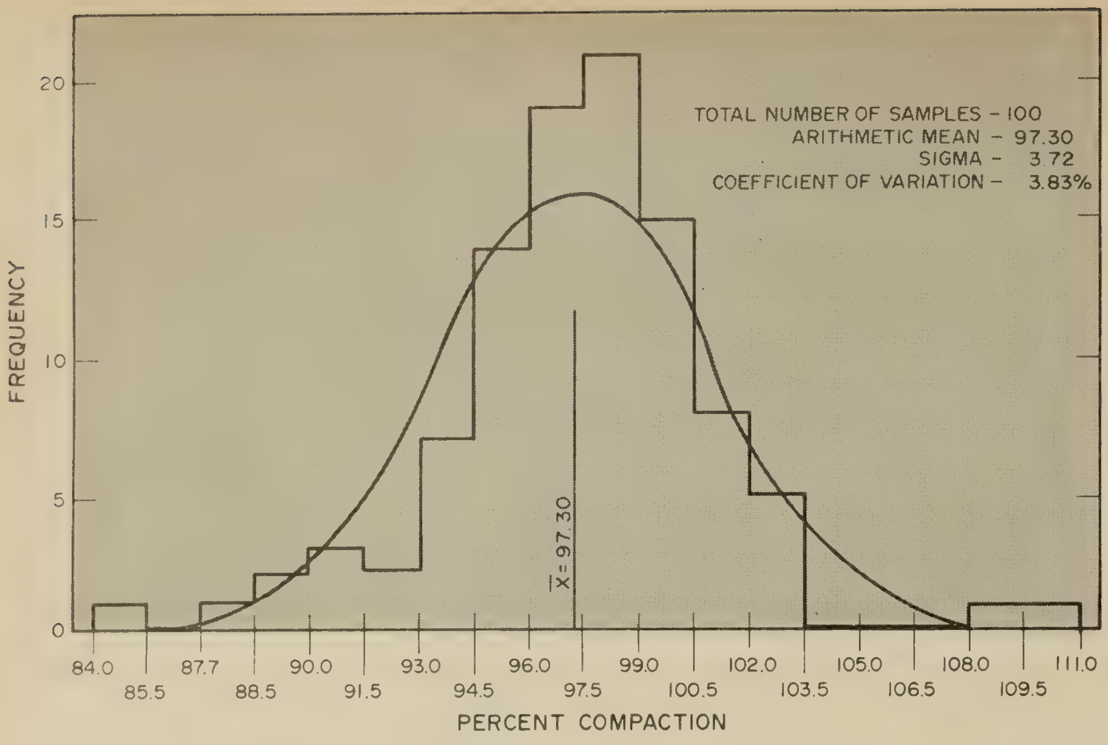


Figure 5.—Embankment, percent compaction.

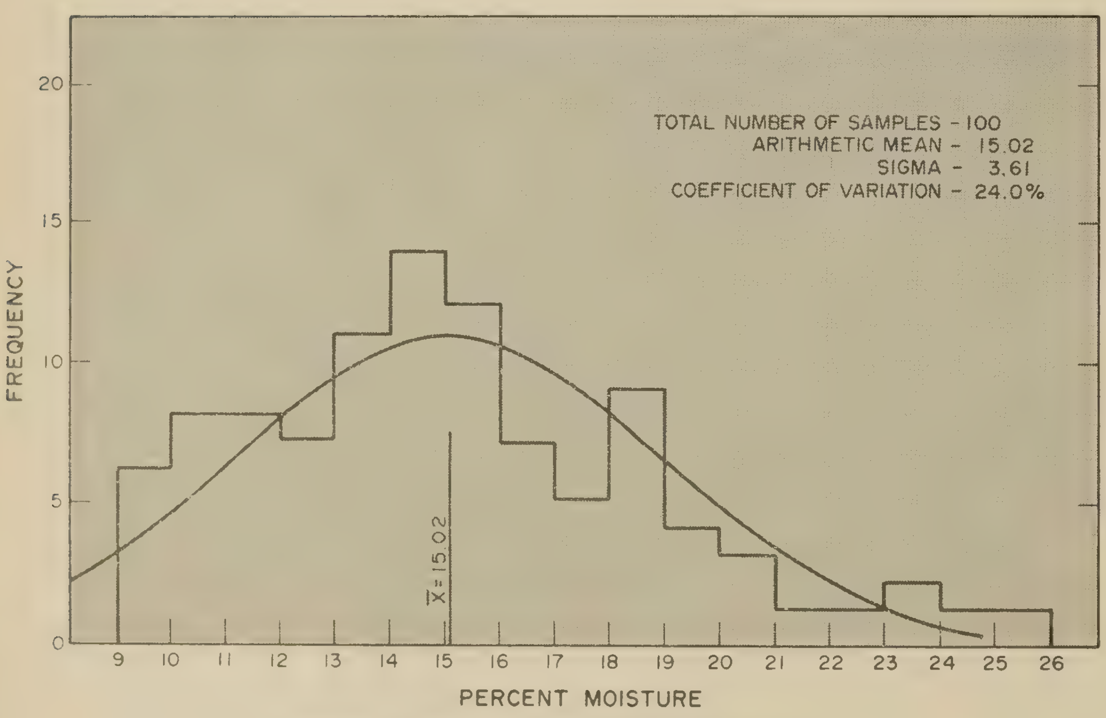


Figure 6.—Embankment, percent moisture.

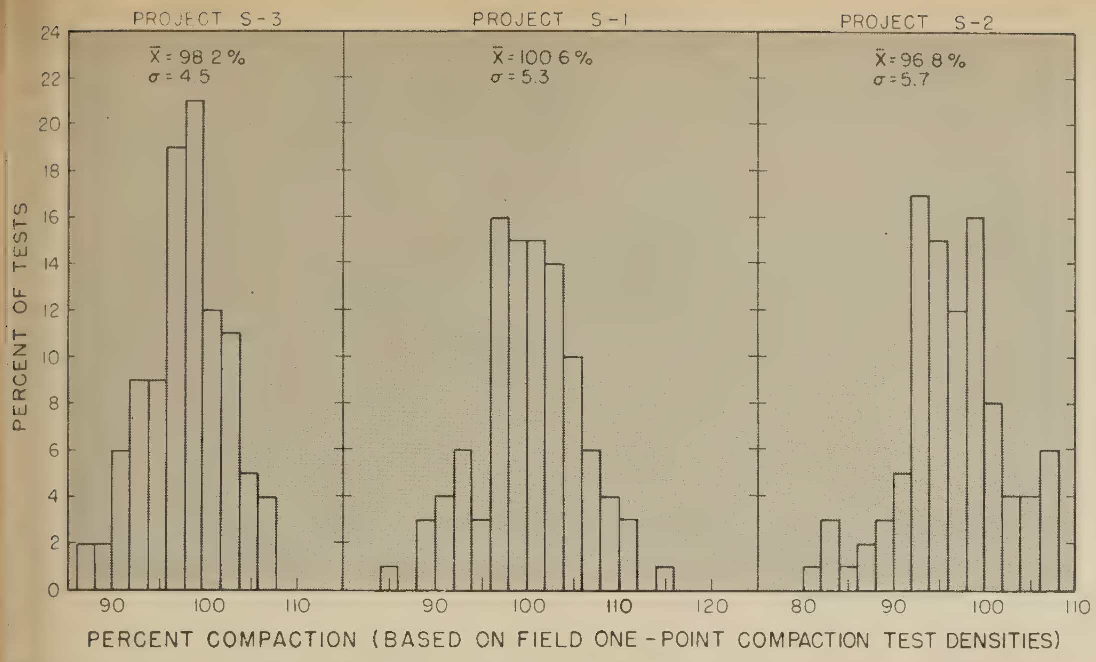
evaluated on the basis of the results of a specified sampling and testing program. This program entails the performance of a specified number of standard tests at random locations on each *lot* submitted. The data analysis procedure to establish compliance and the steps to be taken if noncompliance is indicated are also spelled out.

Several States have developed specifications for embankment or base construction that are great improvements over present methods and are based partly on statistics, even though they are not strictly in accordance with concepts recommended in this series of discussions.

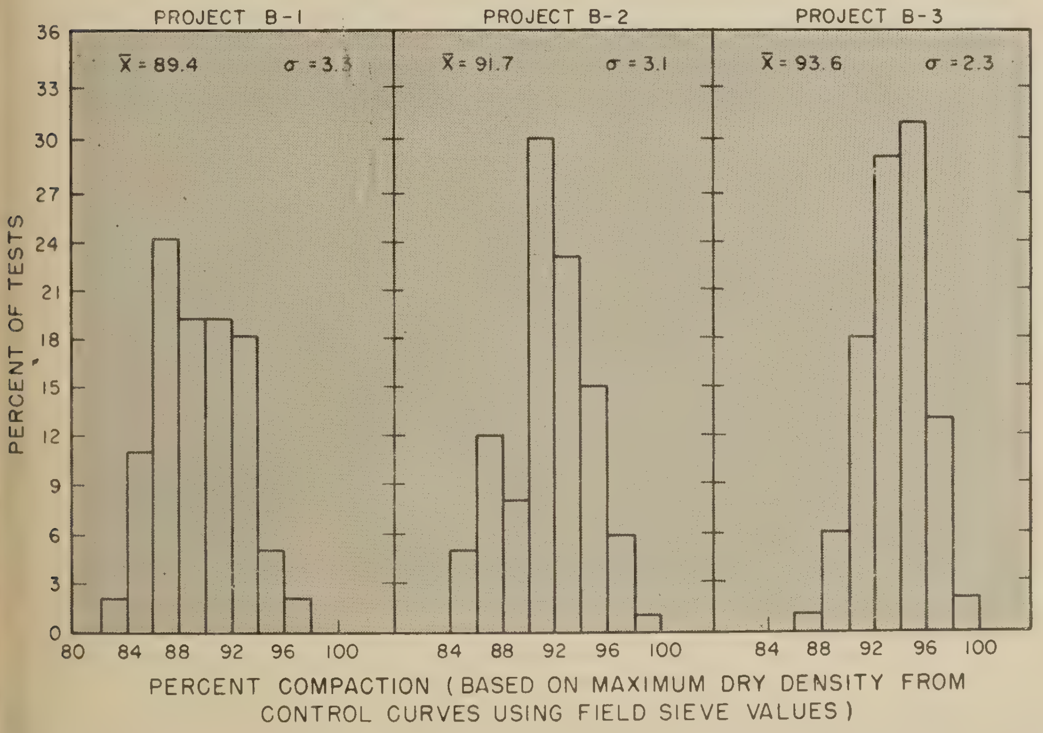
Virginia, for example, is using a control strip technique for control of the compaction of aggregate base. The following special provisions were extracted from a paper (2 presented at the 46th Annual Meeting of th Highway Research Board:

> *"Virginia Department of Highways Special Pr visions For Nuclear Field Density Testing Aggregate Base and Surface Courses*

> *"Section 308 of the 1966 edition of the Ro and Bridge Specifications is amended in th contract to require the construction of densi control strips for the purpose of using the nucle field density testing device. The revisions are follows:*
>
> *"At the beginning of the work the Contract shall build a control strip of the material on approved and stable subgrade for the purpose the Engineer's determining density requireme for the project. This control strip will be at le 400 square yards in area and of the same materi and depth to be used in the remainder of t work. Compaction will be carried out with co- ventional rollers approved by the Engineer un no appreciable increase in density is acco- plished or until in the opinion of the Engin no appreciable increase in density will be - tained by additional rolling. Upon completion the rolling, the density of the strip will be determined by use of a portable nuclear test device.*
>
> *"The compaction of the remainder of the aggregate base course material shall be governed by e density of the control strip. The material shall e tested by sections of approximately 2,800 squ yards each. The mean density of 5 random selected sites from the test section shall be t least 98 percent of the mean density of 10 te taken from the approved control strip. Placi compacting and individual testing may be de in subsections of approximately 280 square ya each. When the mean of the test section is l than 98 percent of the control strip mean e Contractor may be required to rework the en section. Also, each individual test value shall e at least 95 percent of the mean value of the c- trol strip. When an individual test value is l than 95 percent of the control strip mean, e contractor shall be required to rework the a represented by that test.*
>
> *"Each test section shall be tested for thick and any deficiency outside the allowable tolera shall be corrected by scarifying, placing a- tional material, remixing, reshaping and rec- pacting to the specified density.*
>
> *"A new control strip may be requested wh*
>
> *(1) A change in the source of the mate is made, or*
> *(2) a change in the material from the s source is observed, or*
> *(3) ten (10) test sections have been appr without the construction of additi control strips.*
>
> *"Note: The Contractors' attention is dire to the fact that the method for determining den and the requirements for density as describe Section 308.05 have been replaced by the me of determination and requirements for den stated hereinabove."*



igure 7.—Frequency histograms—percent compaction of subgrade materials for three projects.



igure 8.—Frequency histograms—percent compaction of subbase materials for three projects.

eliability of nuclear testing

The Virginia specification is an excellent xample of the more rapid methods that can e used to allow the testing of a more rep-esentative sample of completed work. The ncreased number of test results available for naking a decision assures a higher confidence the decision. The following advantages re claimed by the Virginia Department of lighways:

- Nuclear tests can be made quickly and asily.
- A field control strip provides a practical achievable density.
- The speed of nuclear testing permits determination to be made for each section of material. This procedure provides a sound statistical basis for decisionmaking.

The reliability of nuclear-gage test results is substantiated by tests made in a number of States. For example, the data in table 1 are from two studies in Utah (*3*, *4*). The absolute values of the standard deviations presented in the table have little significance with respect to testing variability because much of the indicated variation is probably caused by actual density variations. However, it is significant that the sampling and testing variance is smaller and that there is no significant difference in the means. The results of the nuclear tests are as good, if not better, than those of the conventional tests; consequently, it can be stated safely that the testing error of nuclear methods is probably no greater than that of conventional methods.

Reported variations in compaction

The variation in density of accepted embankments and bases has been found much greater than had been expected when the Public Roads research program (see part 1 of this article, Feb. 1969 issue) was initiated. Because of this variability, compliance with specifications, as computed by statistical methods, is lower than had been expected. Therefore, designers must judge whether present construction is sufficient for their purposes. If present construction is satisfactory, then specifications should be changed to allow for the existing variation. If better construction is needed, then it is important that specifications and methods be changed to assure better uniformity in embankments and base courses.

Research is showing that overall standard deviation, a measure of variability, is not in itself a true indication of contractor-performance variability. A good contractor may take the same care in constructing two embankments but the variability of test results may be much greater in one than in the other. If the composition of the material itself is more variable, then the results of the compaction process are also going to be more variable.

The variation of density in embankments, with respect to material and process changes, is shown in figures 1 and 2. Figure 1, extracted from a California report (*5*), presents the distributions of the results of density tests on three projects. Project No. 1 was constructed with homogeneous, fine grained soils; Project No. 3 with an extremely heterogeneous soil; and Project No. 2 with a soil of intermediate variability, with respect to the other two. The specification on each of the projects stipulated that the material be compacted to no less than 90 percent relative compaction. It has been shown by many of the research test results obtained after acceptance by normal control procedures, that the construction does not meet specification requirements when the data are analyzed on a statistical basis and the total material is considered.

Figure 2, also from the California report, is presented to show that variability of compaction test results is not unique to the highway industry.

Figures 3 and 4 have been extracted from an Alabama Research Report (*6*) to show indicated variation in density of compacted base and subbase materials. The standard deviations of 4.06 and 2.31 percent are in line with values reported by other States. Figures 5 and 6 are from the same report; the data reported

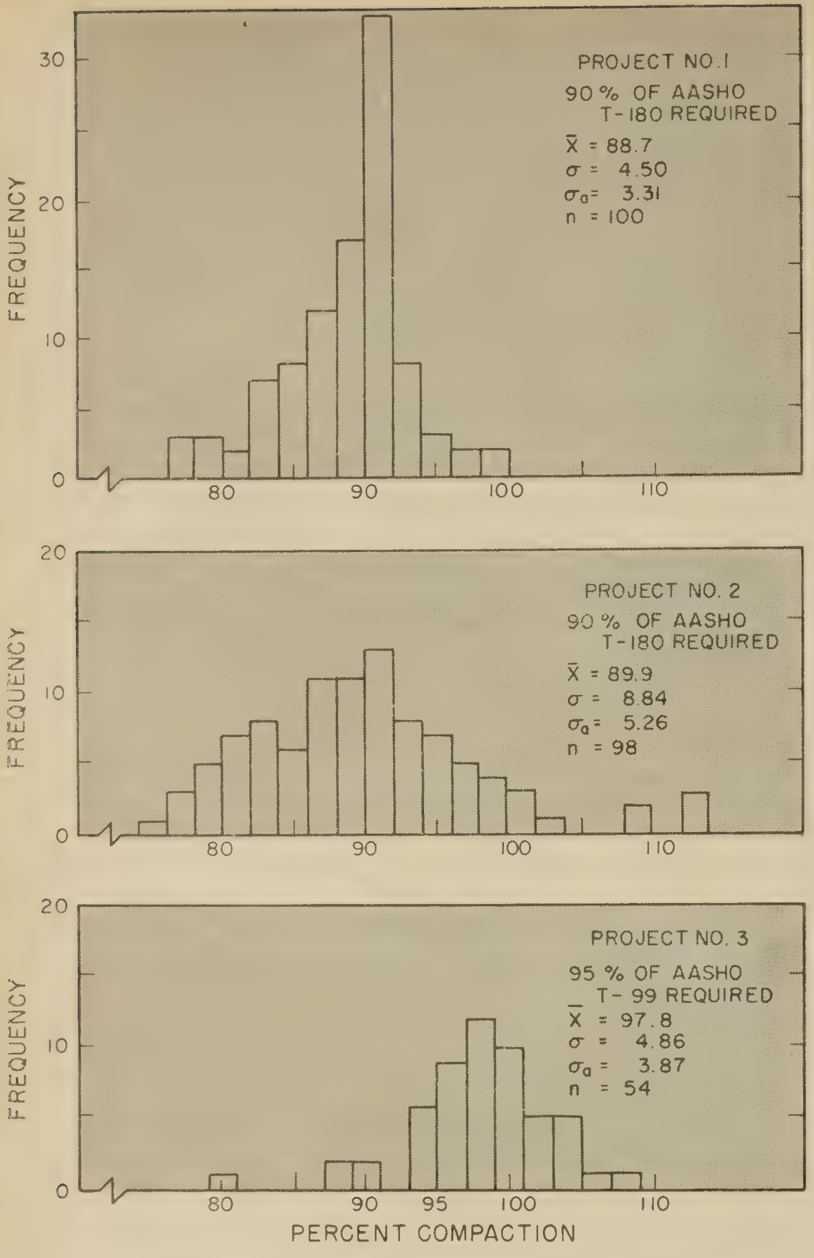


Figure 9.—Percent compaction—research data.

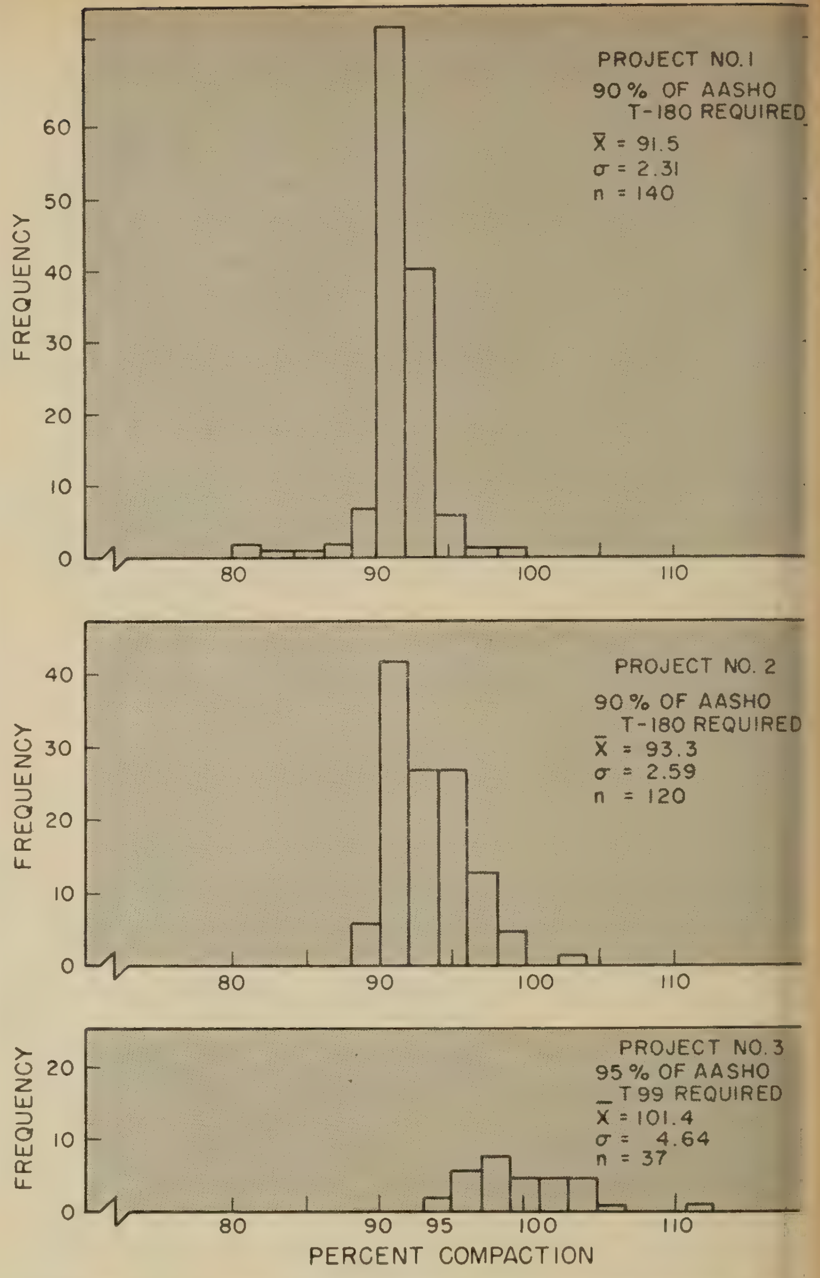


Figure 10.—Percent compaction—highway-department data

by California for compacted densities of embankment materials are corroborated by the data in figure 5, and variations in moisture content are shown in figure 6. The large variation in moisture content is probably a major cause of the large variation in density.

From a research study performed by Purdue University for the State of Indiana in March 1967 (*7*), information concerning average density, range, and standard deviation are shown in table 2 for three subgrade and three subbase projects. The data for the study were obtained after the projects had been accepted under normal acceptance procedures. The specifications for the projects required a minimum density of 100 percent of standard laboratory maximum density.

The wide ranges of results and large standard deviations reported in table 2 are, in part, due to variability contributed by test methods. The differences between replicate sand cone density tests on the study projects are shown in table 3. The entire difference cannot be attributed to test error as there may be actual differences in the materials or densities even when the tests are taken side by side as was done in this study. However, the results show the magnitude of differences when an effort was made to eliminate material differences within the limitations of practical construction conditions.

Another contributing factor to the variation of test results is the difference in results of laboratory maximum-density and optimum-moisture-content tests. These differences for duplicate samples from Project S-1 of the Purdue University study are shown in table 4.

The data obtained in the Purdue University study are shown in figures 7 and 8 which are histograms of the percent compaction for the six projects.

Figures 9 and 10 were extracted from a report of a study conducted by the Engineering Experiment Station of North Dakota State University for the North Dakota State Highway Department (*8*). In figure 9 is shown the variability of compaction in three embankment projects previously accepted under current control and acceptance procedures. The distribution of test results on random samples are presented in the histograms in the figure. The mean $\overline{X}$; the overall standard deviation, σ; and the sampling and testing standard deviation, σ_{α}, of the distributions are tabulated. These standard deviations must be changed to variances in order to obtain the relationship between the material and the sampling and testing variability, $\sigma^2-\sigma^2_{\alpha}=\sigma$. In figure 10, the information obtained during routine control and acceptance testing on the same three projects is presented. Comparison of the results presented in figures 9 and 10 emphasizes the advantages of random sampling in determining the true as-built conditions of any construction project and compliance with specifications.

Density-test results obtained with two types of nuclear gages and two different test methods on Project No. 1 of the North

Dakota study are shown in figure 11. These data substantiate the results of the Utah report in that the sampling and testing errors for the nuclear devices are smaller than those for the water-balloon method (fig. 9). It is of interest that the air-gap method indicates a higher average density than the water-balloon or contact-nuclear method. A similar nuclear study was performed on Project 2 with parallel results. In these tests, the manufacturer's calibration curves for the nuclear devices were verified before use.

Variations in Material Properties

Tables 5 and 6 were extracted from a California report (*9*) to show the variation f test results other than those of density tests. The data are from six projects selected s typical of material used for untreated base and subbase by the California Division of Highways. Again the data were obtained from random samples taken after the materials had been accepted as complying with the specifications for normal sampling methods. These materials were largely in substantial compliance with the specifications; however, there was considerable variation in the test results of the material properties, which may account for some of the variations in density and supporting capacity exhibited by the compacted material. The study did not include the determination of density variation f the in-place material.

Conclusions

The primary conclusion that can be drawn rom the data presented in this discussion is hat test results on base and embankment materials exhibit significant variation. These variations can be attributed to material variance, sampling variance, and testing variance. Many materials may be classified out-of-specification because of sampling and testing errors rather than failure of the material or construction to actually conform to specified requirements.

It should be apparent that improvement of mpling and testing methods must be a priority research and development item if field measurements on samples are to be used to ccept construction materials and structures. More tests results must be used in the decision rocess to increase the validity of decisions. Rapid sampling and testing methods, together ith random sampling and statistically valid ecision plans, will alleviate many of the roblems in current acceptance of construction.

The data and charts of this presentation early indicate a difference between the test sults on random samples and those on representative samples. A true estimate of the ctual quality of any material or construction n be obtained only when every item of the has a chance of being chosen as part of the mple. Sampling by choice cannot provide mples that will permit evaluation of both vel and variability of material or construction. Randomizing sampling locations is a simple matter and should cause no serious problems for the inspector, especially when rapid nondestructive test methods, such as the nuclear gage, are available. State highway departments should take immediate steps to implement random sampling in the control and acceptance of base and embankment construction.

The data reported here concerning the variations in base and embankment construction should not be taken as an indictment of present construction. Although there is adequate information to indicate that improvement is needed in the testing and analysis of data, there is no specific information available to indicate that construction being accepted

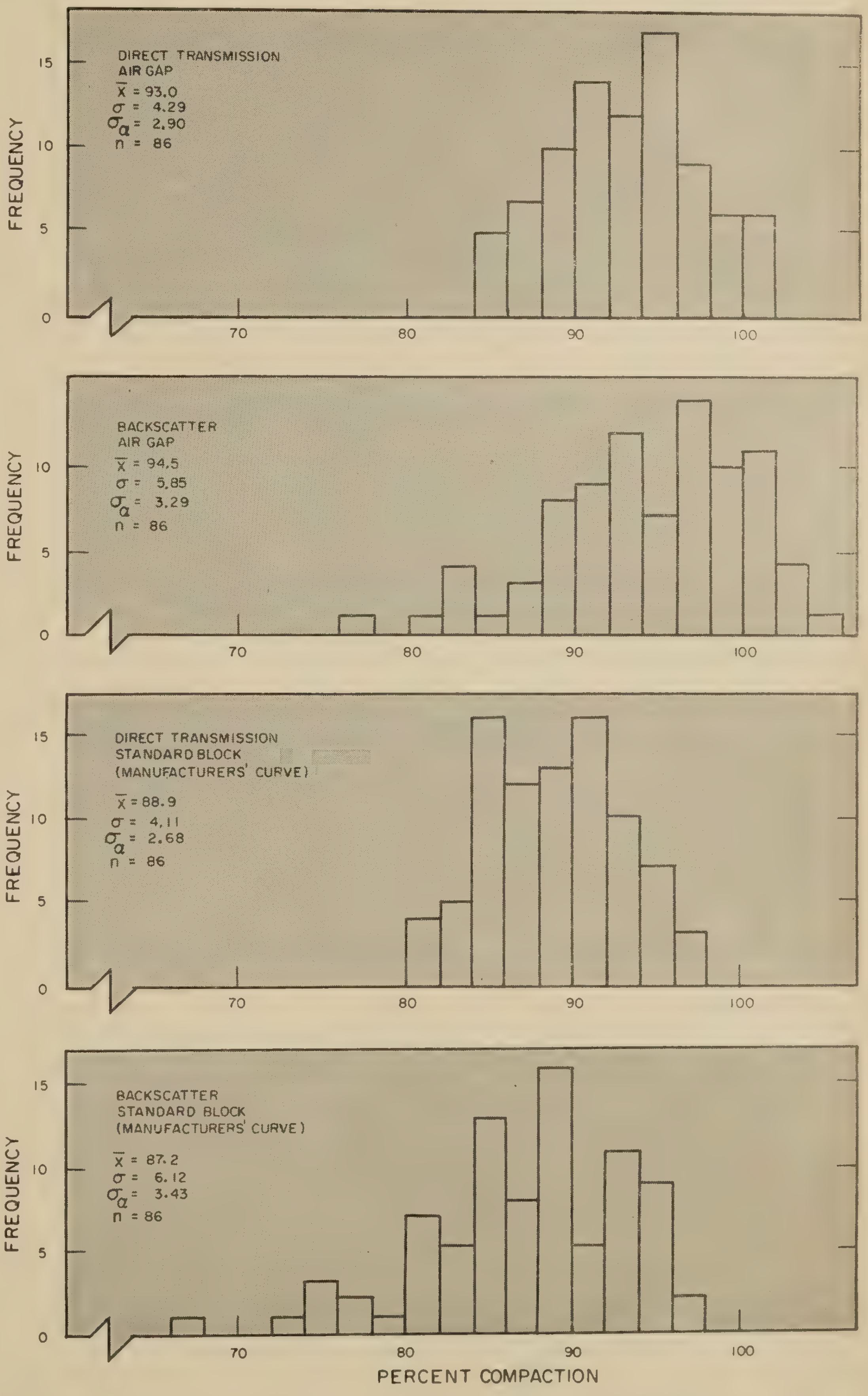


Figure 11.—Percent compaction—nuclear-instrument data.

Table 5.—Summary of test results, untreated aggregate base

Test	[1] n	[2] $\overline{X}$	[3] σ	Range of results	Specification requirement	Amount not complying with specification
PROJECT B-1						
						Percent
R value	200	81.9	1.3	78-85	[4] 78	0
Sand equivalent	200	42.9	4.0	33-58	[4] 30	0
Percent passing #4 sieve	200	50.9	3.1	35-55	35-55	0
Percent passing #30 sieve	200	23.8	2.5	15-30	10-30	0
Percent passing #200 sieve	200	6.0	0.7	4-8	3-9	0
PROJECT B-2						
R value	200	79.9	2.4	72-85	[4] 75	2.5
Sand equivalent	200	30.6	6.1	24-63	[4] 30	56
Percent passing #4 sieve	200	58.1	2.8	51-67	35-65	2.5
Percent passing #30 sieve	200	27.3	2.3	22-36	(5)	----------
Percent passing #200 sieve	200	7.9	1.1	4-10	3-12	0
PROJECT B-3						
R value	200	79.7	1.5	78-83	[4] 78	0
Sand equivalent	200	59.2	4.0	48-68	[4] 30	0
Percent passing #4 sieve	200	52.7	5.7	40-71	35-55	33
Percent passing #30 sieve	200	23.4	2.9	15-31	10-30	0.5
Percent passing #200 sieve	200	4.6	0.95	3-12	3-9	0.5

[1] n = Number of samples.
[2] $\overline{X}$ = Arithmetic mean.
[3] σ = Standard deviation.
[4] Minimum.
[5] None.

Table 6.—Summary of test results, untreated aggregate subbase

Test	[1] n	[2] $\overline{X}$	[3] σ	Range of results	Specification requirement	Amount not complying with specification
PROJECT S-1						
						Percent
R value	200	68.8	6.4	47-80	[4] 60	9.5
Sand equivalent	200	30.2	4.0	22-46	[4] 25	5.0
Percent passing #4 sieve	200	49.5	4.3	40-60	35-65	0
Percent passing #200 sieve	200	7.8	1.3	5-13	3-11	0.5
PROJECT S-2						
R value	188	77.2	3.1	66-83	[4] 60	0
Sand equivalent	188	36.2	8.5	14-69	[4] 25	2.0
Percent passing #4 sieve	188	72.6	6.5	60-91	30-100	0
Percent passing #200 sieve	188	10.0	1.8	5-16	0-20	0
PROJECT S-3						
R value	200	70.9	8.9	42-84	[4] 55	6.5
Sand equivalent	200	29.2	2.7	21-37	[4] 25	4.5
Percent passing #4 sieve	200	45.0	6.6	23-57	35-80	4.5
Percent passing #200 sieve	200	8.6	1.7	4-12	5-35	1.0

[1] n = Number of samples.
[2] $\overline{X}$ = Arithmetic mean.
[3] σ = Standard deviation.
[4] Minimum.

under present procedures is not performing t design expectations. However, if economi considerations do not allow an intensive effor to reduce sampling and testing variation, a well as actual variation in density and moisture content, it is imperative that recognitio be given the variations occurring in presen construction and that current specification be revised accordingly.

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(*3*) *Characteristics of Compacted Emban ments*, by Frank C. Van Houten, Utah Sta Highway Department, August 1967.

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(*5*) *A Statistical Analysis of Embankme Compaction*, by Geo. B. Sherman, Robert Watkins, and Rogel Prysock, State California, Department of Public Work Division of Highways, May 1966.

(*6*) *Quality Control of Construction Statistical Tolerances*, by J. H. David, Alaban Highway Department, May 1967.

(*7*) *An Investigation of Compaction Vari bility for Selected Highway Projects in India* by T. G. Williamson and E. J. Yoder, Purd University, Indiana State Highway Commission, December 1967.

(*8*) *The Statistical Approach to Quality Co trol in Highway Construction*, by Dr. James Jorgenson, North Dakota State Universit No. 15, Engineering Experiment Stati Series, November 1968.

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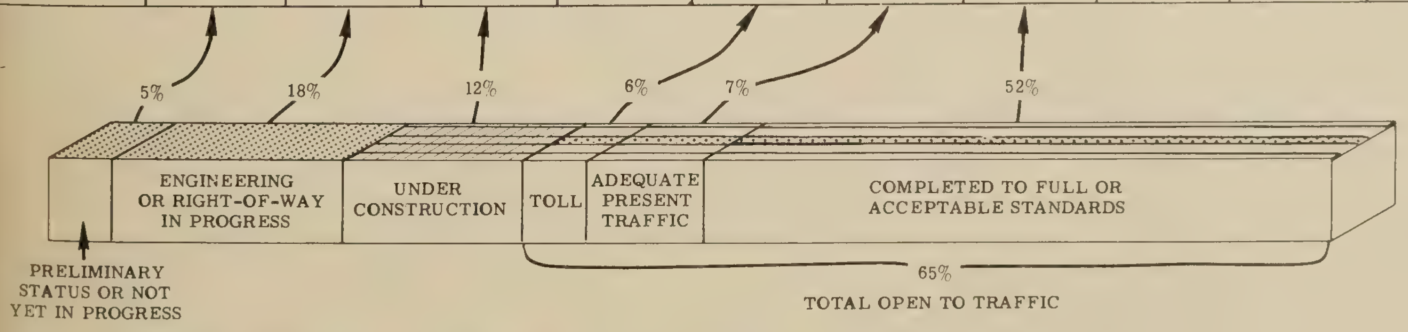
THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

IMPROVEMENT STATUS OF SYSTEM MILEAGE AS OF DECEMBER 31, 1968

TABLE I

STATE	PRELIMINARY STATUS OR NOT YET IN PROGRESS 1/	WORK IN PROGRESS			OPEN TO TRAFFIC				TOTAL DESIGNATED SYSTEM MILEAGE	STATE
		ENGINEERING OR RIGHT-OF-WAY	UNDER CONSTRUCTION	TOTAL UNDERWAY	TOLL FACILITIES	IMPROVED TO STANDARDS ADEQUATE FOR PRESENT TRAFFIC	COMPLETED TO FULL OR ACCEPTABLE STANDARDS	TOTAL OPEN TO TRAFFIC		
ALABAMA	19.2	211.2	181.4	392.6	-	141.1	343.7	484.8	896.6	ALABAMA
ARIZONA	5.9	162.2	218.3	380.5	-	240.8	545.0	785.8	1,172.2	ARIZONA
ARKANSAS	-	41.9	109.7	151.6	-	4.3	363.0	367.3	518.9	ARKANSAS
CALIFORNIA	108.8	412.8	304.2	717.0	10.2	304.4	1,133.3	1,447.9	2,273.7 2/	CALIFORNIA
COLORADO	158.6	112.2	60.4	172.6	-	112.8	531.9	644.7	975.9	COLORADO
CONNECTICUT	51.6	23.1	11.2	34.3	16.4	47.3	197.5	261.2	347.1	CONNECTICUT
DELAWARE	-	9.4	2.1	11.5	14.3	0.9	13.9	29.1	40.6	DELAWARE
FLORIDA	271.2	304.2	111.7	415.9	44.8	-	681.6	726.4	1,413.5	FLORIDA
GEORGIA	38.8	295.0	162.9	457.9	-	6.9	643.6	650.5	1,147.2	GEORGIA
HAWAII	11.6	22.4	5.7	28.1	-	1.6	10.5	12.1	51.8	HAWAII
IDAHO	-	133.7	80.8	214.5	-	96.3	300.8	397.1	611.6	IDAHO
ILLINOIS	118.8	291.9	232.2	524.1	155.7	143.0	780.8	1,079.5	1,722.4	ILLINOIS
INDIANA	14.0	197.6	141.8	339.4	156.9	15.4	603.4	775.7	1,129.1	INDIANA
IOWA	74.8	138.9	52.4	191.3	3.6	-	514.1	517.7	783.8	IOWA
KANSAS	19.6	80.5	70.1	150.6	185.9	0.3	464.1	650.3	820.5	KANSAS
KENTUCKY	-	153.4	107.9	261.3	39.2	4.2	433.9	477.3	738.6	KENTUCKY
LOUISIANA	30.0	186.3	179.6	365.9	-	6.4	301.0	307.4	703.3	LOUISIANA
MAINE	1.7	32.7	1.9	34.6	58.0	99.4	118.3	275.7	312.0	MAINE
MARYLAND	25.2	7.2	30.5	37.7	53.0	70.9	173.3	297.2	360.1	MARYLAND
MASSACHUSETTS	19.0	31.2	31.3	62.5	134.4	27.4	223.7	385.5	467.0	MASSACHUSETTS
MICHIGAN	92.6	165.0	25.9	190.9	4.8	44.4	841.1	890.3	1,173.8	MICHIGAN
MINNESOTA	9.4	240.4	210.8	451.2	-	30.3	422.5	452.8	913.4	MINNESOTA
MISSISSIPPI	-	125.6	85.4	211.0	-	19.2	448.1	467.3	678.3	MISSISSIPPI
MISSOURI	26.6	258.6	34.2	292.8	0.3	160.8	665.4	826.5	1,145.9	MISSOURI
MONTANA	24.6	465.3	101.8	567.1	-	301.8	292.5	594.3	1,186.0	MONTANA
NEBRASKA	1.9	72.8	31.8	104.6	0.2	13.6	359.2	373.0	479.5	NEBRASKA
NEVADA	-	128.7	32.5	161.2	-	5.3	368.1	373.4	534.6	NEVADA
NEW HAMPSHIRE	11.3	25.3	7.6	32.9	22.0	14.8	134.1	170.9	215.1	NEW HAMPSHIRE
NEW JERSEY	53.0	87.7	58.3	146.0	46.3	26.4	113.5	186.2	385.2 3/	NEW JERSEY
NEW MEXICO	37.5	185.5	91.7	277.2	-	61.1	622.6	683.7	998.4	NEW MEXICO
NEW YORK	152.4	44.0	81.2	125.2	491.8	53.3	532.5	1,077.6	1,355.2	NEW YORK
NORTH CAROLINA	67.2	195.4	108.3	303.7	-	17.0	449.3	466.3	837.2	NORTH CAROLINA
NORTH DAKOTA	62.6	38.8	77.2	116.0	-	51.9	340.3	392.2	570.8	NORTH DAKOTA
OHIO	12.3	162.1	226.9	389.0	206.4	55.0	871.4	1,132.8	1,534.1	OHIO
OKLAHOMA	9.3	53.9	144.4	198.3	174.1	23.3	401.7	599.1	806.7	OKLAHOMA
OREGON	19.2	65.5	2.5	68.0	-	111.2	537.7	648.9	736.1	OREGON
PENNSYLVANIA	39.1	115.9	275.6	391.5	360.2	8.3	781.6	1,150.1	1,580.7	PENNSYLVANIA
RHODE ISLAND	27.9	9.1	14.0	23.1	-	10.9	36.8	47.7	98.7	RHODE ISLAND
SOUTH CAROLINA	73.7	92.2	196.1	288.3	-	15.1	378.7	393.8	755.8	SOUTH CAROLINA
SOUTH DAKOTA	-	161.4	93.2	254.6	-	60.3	364.3	424.6	679.2	SOUTH DAKOTA
ENNESSEE	7.5	262.1	150.7	412.8	-	90.5	534.3	624.8	1,045.1	TENNESSEE
EXAS	139.0	559.3	395.9	955.2	-	285.9	1,786.1	2,072.0	3,166.2	TEXAS
TAH	50.8	374.0	208.0	582.0	-	22.6	277.7	300.3	933.1	UTAH
ERMONT	-	116.2	31.2	147.4	-	4.4	168.6	173.0	320.4	VERMONT
IRGINIA	9.8	216.5	158.6	375.1	37.6	44.9	600.8	683.3	1,068.2	VIRGINIA
ASHINGTON	76.8	125.5	79.5	205.0	-	196.0	276.9	472.9	754.7	WASHINGTON
EST VIRGINIA	29.5	158.6	54.4	213.0	87.2	0.3	184.7	272.2	514.7	WEST VIRGINIA
ISCONSIN	105.5	1.7	39.2	40.9	-	24.7	392.1	416.8	563.2	WISCONSIN
YOMING	82.4	76.3	101.2	177.5	-	30.3	623.8	654.1	914.0	WYOMING
ISTRICT OF COLUMBIA	9.9	7.9	1.7	9.6	-	2.9	7.2	10.1	29.6	DISTRICT OF COLUMBIA
PENDING	40.2 4/								40.2 4/	PENDING
TOTAL	2,240.8	7,439.1	5,215.9	12,655.0	2,303.3	3,109.9	22,191.0	27,604.2	42,500.0	TOTAL



Includes all routes and route segments added to the system under the 1,500 mile expansion authorized by the Federal-Aid Highway Act of 1968.

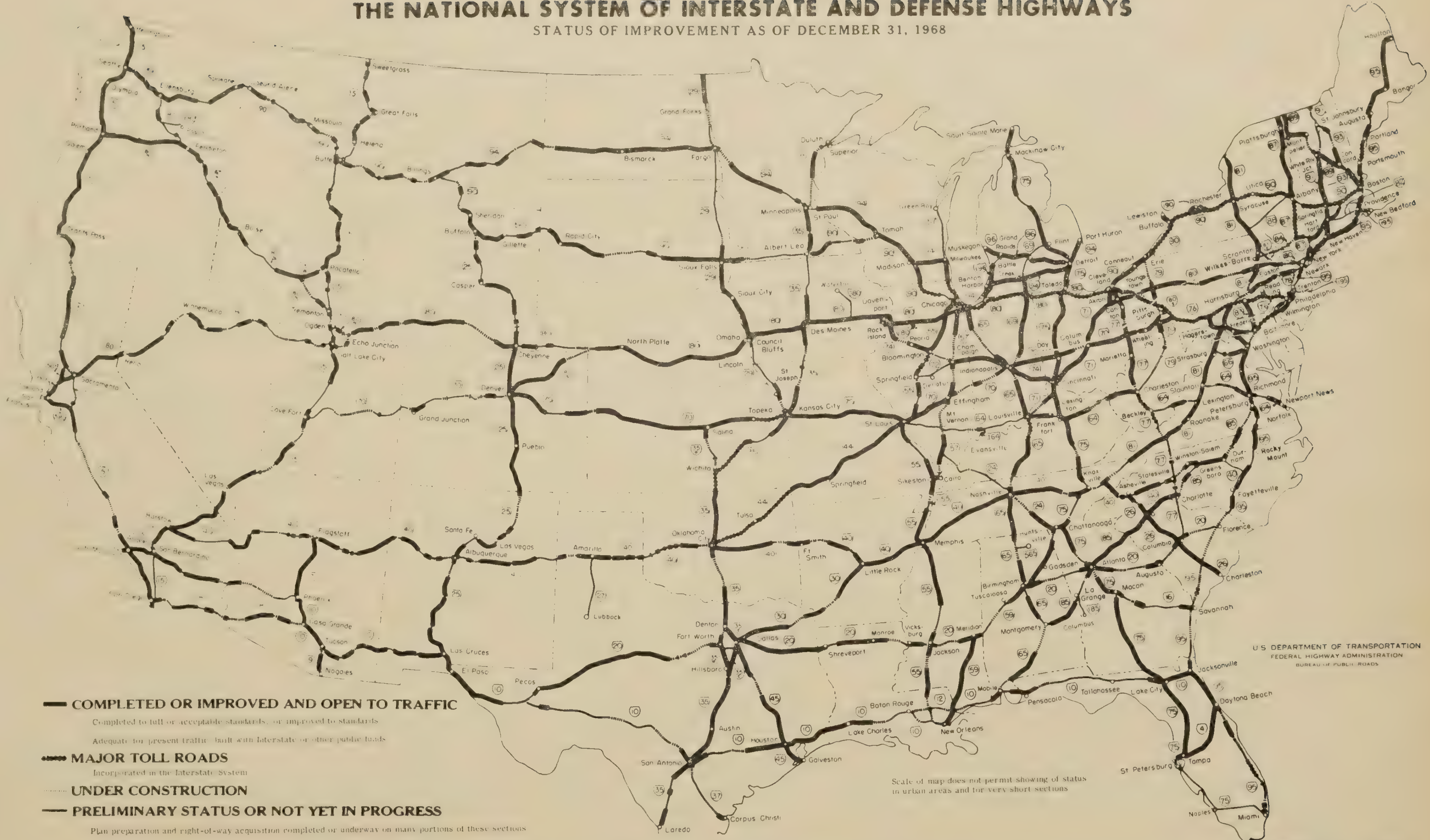
Excludes the 17.2 mile Century Freeway (I-105) which was added to the system under the "Howard Bill."

Excludes the 34.4 mile Trenton-Asbury Park Spur (I-195) which was added to the system under the "Howard Bill" but includes that portion of I-278 mileage (7.0) deleted under the same bill.

Consists of mileage which has not been assigned to any specific route and is a reserve for final measurement of the system.

THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

STATUS OF IMPROVEMENT AS OF DECEMBER 31, 1968



COMPLETED OR IMPROVED AND OPEN TO TRAFFIC

Completed to full or acceptable standards, or improved to standards

Adequate for present traffic, built with Interstate or other public funds

MAJOR TOLL ROADS

Incorporated in the Interstate System

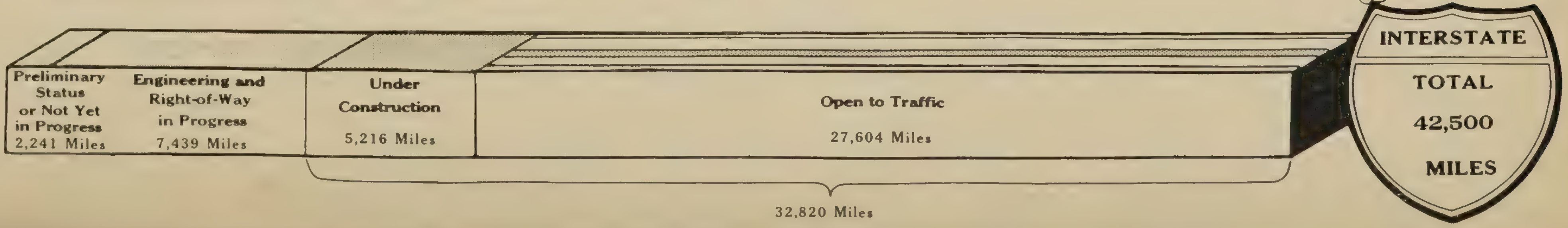
UNDER CONSTRUCTION

PRELIMINARY STATUS OR NOT YET IN PROGRESS

Plan preparation and right-of-way acquisition completed or underway on many portions of these sections

Scale of map does not permit showing of status in urban areas and for very short sections

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
BUREAU OF PUBLIC ROADS



U.S. GOVERNMENT PRINTING OFFICE: 1969

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- Standard Land Use Coding Manual (1965). 50 cents.
- Standard Plans for Highway Bridges:
  - Vol. I—Concrete Superstructures (1968). $1.25.
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  - Vol. IV—Typical Continuous Bridges (1962). $1.00.
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- 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.
- Study of Airspace Utilization (1968). 75 cents.
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