Effect of Temporary Bridge on Parkway Performance

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● THE NEW ENGLAND floods of October 15, 1955, undermined a culvert on the Merritt Parkway at Norwalk, Connecticut, causing a pavement failure. Traffic on the parkway, a principal route between New York and New England, was rerouted with serious congestion and time losses. Because of the urgency of the situation, it was necessary to replace the culvert with temporary structures as rapidly as possible.

The structures used as emergency replacements are shown in Figure 1 as seen by westbound traffic. The bridge in the eastbound roadway is a steel beam span 22 ft wide. In order to conserve time, a pair of bailey bridges were installed in the westbound roadway, one for each lane. The bridge for the outside lane was offset 5 ft because of structural and foundation conditions. The bailey bridges were in use by October 19, four days after the flood.

Shortly after reopening the parkway to traffic, it was observed that the capacity of the bridges in the westbound lane was limited. During several hours of each weekend, traffic volumes were so great as to result in serious congestion, queues of 4 to 5 miles in length frequently being observed during each weekend.

The Bureau of Highway Traffic in cooperation with the Connecticut State Highway Department undertook an analysis of the effects of the temporary bridges on parkway traffic. The purposes of the study were as follows:

1. To determine what factors limited the capacity of the two bridges in the westbound lanes.
2. To analyze the characteristics of a rural freeway traffic stream operating under congested conditions caused by continuing speed-reducing roadway conditions.

STUDY SITE

The profile of the Merritt Parkway in the vicinity of the temporary bridge is shown in Figure 2. The bridge is located in a sag, with sight distance limitations as drivers approach the bridge. Traffic approached the bridge on a 7 percent downgrade and, after crossing the bridge, entered a 5 percent upgrade. There are no horizontal curves through the section shown on the profile. Eastbound and westbound lanes of the parkway are 26 ft wide with mountable curbs and a 21-ft medial divider except at structures. The area immediately preceding the bridge location (station 70 + 00 to station 76 + 00 on the profile) will be referred to as Zone A.

Traffic observed at Zone A was again observed at a point 0.75 mi beyond the bridges. Exit and entrance ramps beyond this point made it inadvisable to make measurements beyond 0.75 mi from the bridge. This second observation station will be referred to as Zone B.

Signing and Speed Zone Program

From station 110 + 00, the nearest parkway entrance before the bridge, there was an extensive sign program directing drivers to "Stay in Line" and informing them of "Temporary Bridge Ahead." The speed limit for the area from station 110 + 00 to the temporary bridge was set at 25 mph. The signs were placed on both the right shoulder and the medial divider at approximately 300-ft intervals as shown in Figure 3.

Bailey Bridge Details

Each bridge in the westbound lane was 80 ft long with a clear distance of 14 ft 6 in. between trusses and a paved roadway width of 12 ft 6 in. The trusses at the outside supports were 3 ft above the roadway and for the inside supports were 8 ft above the roadway. The right lane bridge was offset 5 ft because of structural clearance re-

Figure 1. Temporary bridge site (as seen by westbound traffic).

quirements. A transition zone 100 ft long was paved with asphalt to provide access to the decks of the bridges which were 24 in. above the established grade of the pavement at the bridge site.

COLLECTION OF FIELD DATA

Speed, volume, and headway data for each lane were collected by recording observations on an Esterline-Angus graphic recorder. Observations were made during the hours 4:00 p.m. to 8:00 p.m. on Sunday, July 8, 1956, and from 2:30 p.m. to 6:30 p.m. on Sunday, August 5, 1956. The recorder chart speed was such that time intervals were read to ± 0.02 sec. The pens of the graphic recorder were actuated in two ways. During observations made July 8, the pens were actuated by diaphragms as the

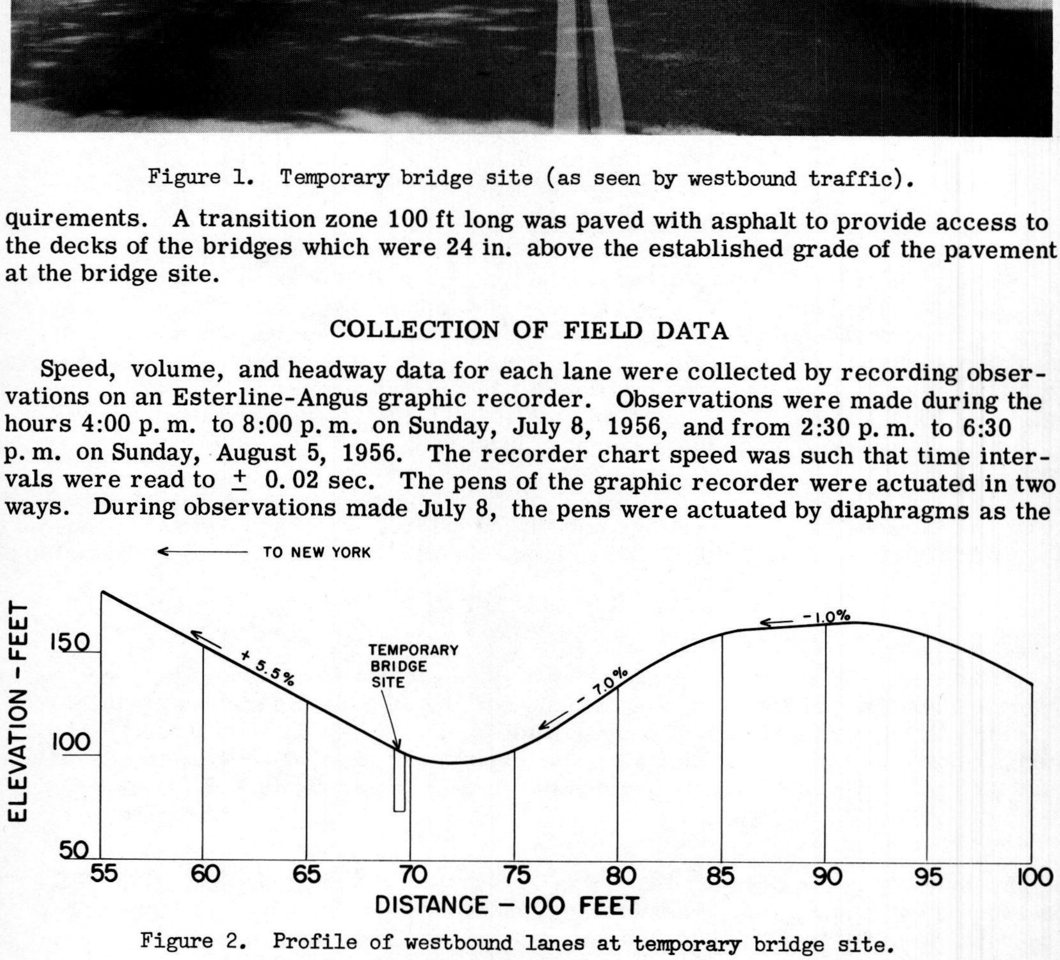

Figure 2. Profile of westbound lanes at temporary bridge site.

Figure 3. Signing program - approaching temporary bridge.

vehicles passed over air-hoses stretched across the roadway. To eliminate any adverse effect that the hoses would have on slow-moving traffic, the second group of observations on August 5 were made with manual actuation of the pens. Subsequent analysis of the data showed there was no significant difference in data collected by the two methods. Speeds were determined by finding the travel time between successive

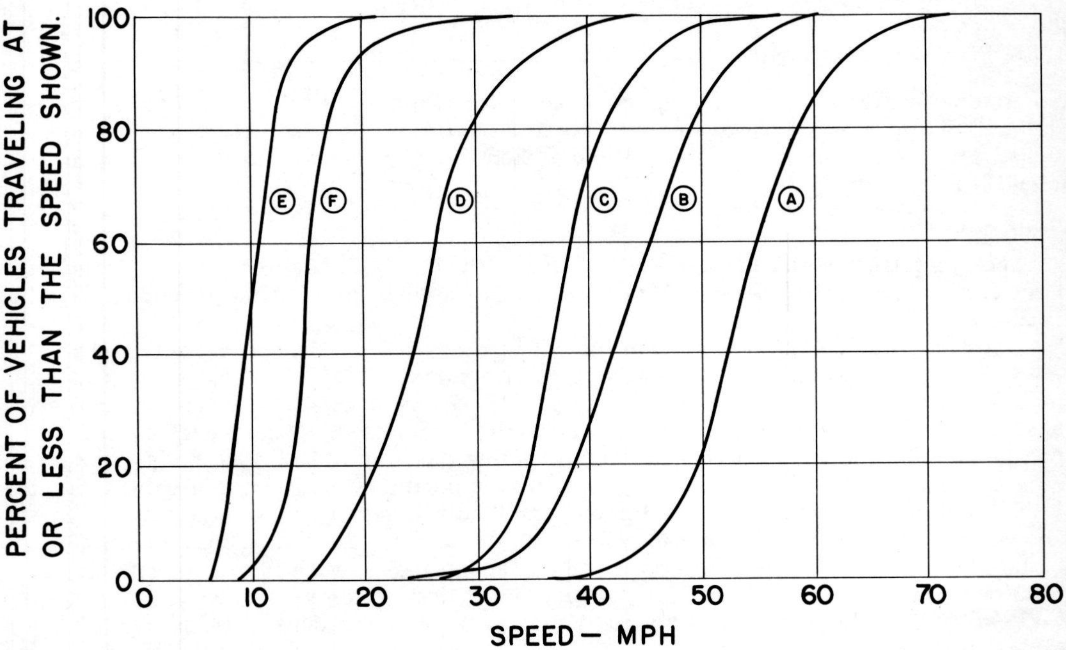

Figure 4. Speed distribution - Zones A and B.

TABLE 1

SUMMARY OF VOLUME, SPEED, DENSITY, HEADWAY, AND SPACING
INSIDE LANE - ZONE A

Date 1956	Time, p.m.	Volume, vph	Speed, mph	Density, veh/mi	Mean Headway, sec	Mean Spacing, ft
July						
8	5:00-5:05	876		No Record		
	5:15-5:20	1,044		No Record		
	5:40-5:45	1,044	7.8	133.8	3.45	39.5
	5:55-6:00	1,212	9.0	134.5	2.97	39.3
	6:15-6:20	876	8.1	108.2	4.11	48.8
	6:25-6:30	1,092	8.4	129.8	3.30	40.7
	6:35-6:40	1,116	9.9	112.4	3.23	47.0
	6:55-7:00	1,116	10.5	106.5	3.23	49.5
	7:05-7:10	1,080	9.2	117.7	3.33	44.9
	7:15-7:20	1,104	9.4	117.8	3.27	44.9
	7:25-7:30	1,128	9.4	121.0	3.19	43.6
	7:35-7:40	1,116	8.4	132.2	3.23	40.0
Aug.						
5	2:50-2:55	1,320	26.4	50.0	2.73	105.6
	2:55-3:00	1,032	25.7	40.2	3.49	131.5
	3:00-3:05	912	30.5	29.2	3.95	176.6
	3:05-3:10	1,020	21.9	46.6	3.53	113.2
	3:20-3:25	1,128	27.4	41.1	3.19	128.4
	3:37-3:42	1,068	10.5	101.9	3.37	51.8
	5:00-5:05	1,176	11.0	107.1	3.06	49.3
	5:10-5:15	1,164	12.0	96.8	3.09	54.5
	5:20-5:25	1,104	10.1	109.1	3.26	48.4
	5:49-5:54	1,128	12.4	91.3	3.19	57.8
	5:59-6:04	1,068	10.5	101.5	3.37	51.9
	6:09-6:14	1,140	12.1	94.6	3.16	55.8

points on the pavement. The lengths of the speed traps varied from 50 ft to 126 ft, as determined by location of pavement joints and traffic conditions. The same method of observation was employed at Zone A and at Zone B, although no attempt was made to identify individual vehicles.

Traffic Conditions

The Merritt Parkway is a limited-access, 4-lane, divided facility for passenger cars only. Generally, the speed limit, except as applied to the area preceding Zone A, is 55 mph.

Two vehicle actuated detectors of the overhead radar type had been previously installed over both westbound lanes at a point ¼ mi west of Zone A. The number of vehicles passing the detectors in each 2-min. period was automatically converted to an hourly volume rate, the results being placed on a graphic-recorder chart so that a continuous record of volume was available during the time of the field study. Total volume rates for both westbound lanes during the period of study ranged from 1,500 to 2,500 vehicles per hour. Peak volumes remained substantially constant between 2,000 and 2,250 vph for the two westbound lanes combined from 3:00 p.m. until 10:00 p.m. on both days that field work was conducted. During these hours the temporary bridges were operating at capacity with long queues of waiting vehicles.

Preliminary observations of traffic during periods of low density (less than 40 vehicles per mile) at Zone A indicated that drivers applied their brakes while still on the downgrade and continued to apply brakes until they passed the sag point in the vertical curve. Vehicles began to accelerate before reaching the transition pavement at the bridges. Maximum density of vehicular traffic occurred in the area from 100 to 600 ft before the bridge, so that measurements of volume, speed and density were made in this area rather than on the bridge itself.

Accident Experience

A complete record of type and severity of accident experience at the bridge was not

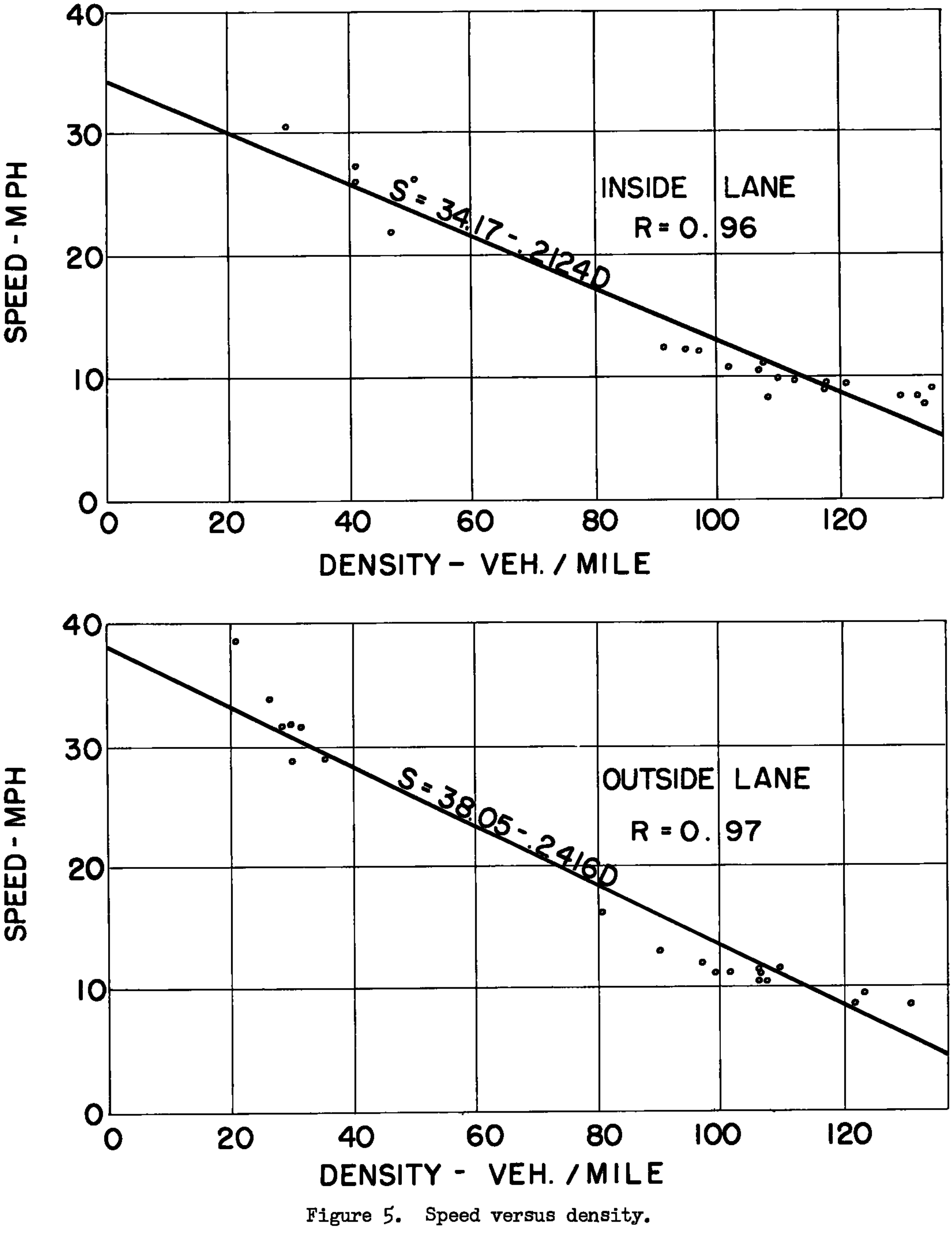

Figure 5. Speed versus density.

TABLE 2

SUMMARY OF VOLUME, SPEED, DENSITY, HEADWAY, AND SPACING
OUTSIDE LANE - ZONE A

Date 1956	Time, p.m.	Volume, vph	Speed, mph	Density, veh/mi	Mean Headway, sec	Mean Spacing, ft
July						
8	5:00-5:05	792	38.8	20.4	4.54	258.9
	5:15-5:20	864	31.5	27.4	4.17	192.5
	5:40-5:45	1,128	10.6	106.2	3.19	49.7
	5:55-6:00	1,296	16.1	80.4	2.78	65.7
	6:15-6:20	1,092	7.7	141.3	3.30	37.4
	6:25-6:30	1,092	8.3	130.9	3.30	40.3
	6:35-6:40	1,032	8.5	121.7	3.49	43.4
	6:55-7:00	1,176	11.1	106.5	3.06	49.5
	7:05-7:10	1,128	8.6	130.5	3.19	40.4
	7:15-7:20	1,116	11.1	101.1	3.23	52.2
	7:25-7:30	1,212	9.8	123.9	2.97	42.6
	7:35-7:40	1,128	7.8	144.2	3.19	36.6
Aug.						
5	2:50-2:55	936	31.8	29.5	3.85	179.3
	2:55-3:00	972	31.6	30.8	3.70	171.5
	3:00-3:05	900	34.0	26.5	4.00	199.2
	3:05-3:10	1,032	28.9	35.7	3.49	148.0
	3:20-3:25	864	28.8	30.0	4.17	176.0
	3:37-3:42	1,116	10.5	106.2	3.23	49.7
	5:00-5:05	1,188	12.3	97.0	3.03	54.4
	5:10-5:15	1,188	13.2	90.1	3.03	58.6
	5:20-5:25	1,212	11.4	106.7	2.97	49.5
	5:49-5:54	1,116	11.2	99.3	3.23	53.2
	5:59-6:04	1,104	10.3	107.2	3.26	49.2
	6:09-6:14	1,248	11.4	109.1	4.53	48.3

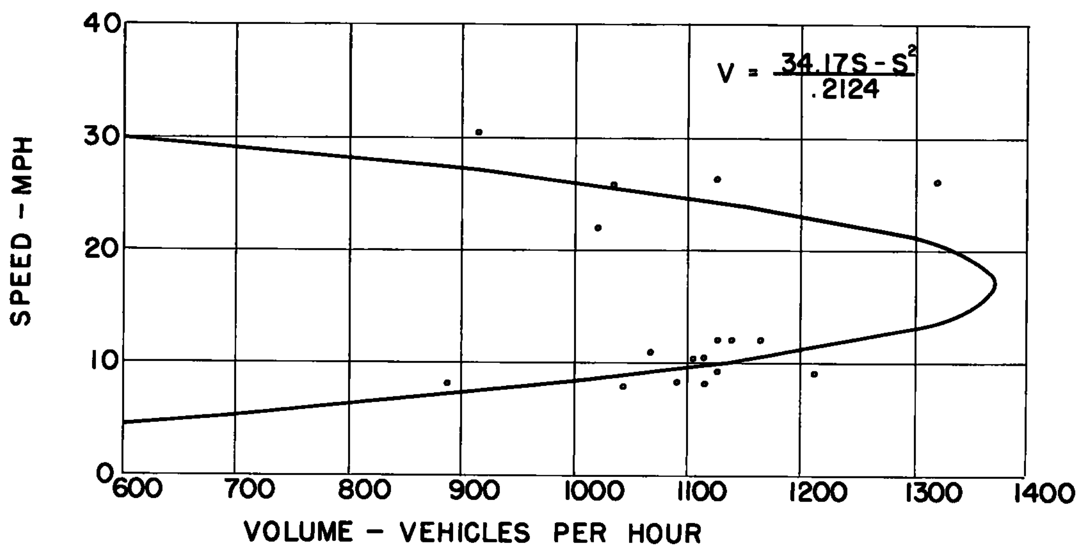

Figure 6. Speed versus volume - inside lane.

available at the time this paper was prepared although the number of accidents is known. During the period the bridges were in operation, October 1955 to October 1956, there were 3 accidents involving the bridge. Two of these were caused by sleeping or inattentive drivers and the other accident was caused by a driver, whose brakes had failed, ramming the bridge in order to come to a stop.

In the 2,000 ft preceding the bridge, there were 7 accidents, the majority being rear-end collisions involving two or three vehicles. The extensive signing program apparently alerted the drivers to the unusual conditions in the roadway and kept the accident frequency to a minimum.

ANALYSIS

In the following analysis various 5-min. volume counts have been expanded to an

TABLE 3

SUMMARY OF VOLUME, SPEED, DENSITY, HEADWAY, AND SPACING
INSIDE LANE - ZONE B

Date 1956	Time, p.m.	Volume, vph	Speed, mph	Density, veh/mi	Mean Headway, sec	Mean Spacing, ft
July 8	4:10-4:15	1,056	48.9	21.6	3.41	244
	4:25-4:30	1,230	46.4	26.5	2.93	199
	5:00-5:05	1,573	43.1	36.5	2.29	145
	5:14-5:19	1,254	45.8	27.4	2.87	193
	6:00-6:05	760	47.7	16.0	4.73	331
	6:15-6:20	1,244	43.2	28.8	2.89	183
	6:27-6:32	1,210	42.9	28.2	2.98	187
	7:16-7:21	1,334	44.1	30.3	2.70	174
	7:25-7:30	1,334	46.2	28.9	2.70	183
	7:45-7:50	1,329	48.9	27.2	2.71	194
	8:00-8:05	1,376	44.6	30.9	2.62	171
Aug. 5	2:40-2:45	1,355	56.6	23.9	2.66	221
	3:00-3:05	1,176	54.8	21.4	3.06	247
	3:45-3:50	1,176	52.5	22.4	3.06	235
	3:55-4:00	1,411	51.8	27.2	2.55	194
	4:05-4:10	1,317	50.5	26.1	2.73	202
	4:50-4:55	1,341	51.2	26.2	2.69	202
	5:00-5:05	1,388	44.1	31.5	2.59	168
	5:10-5:15	1,235	43.8	28.2	2.92	187
	5:35-5:40	1,211	47.0	25.8	2.97	205
	5:45-5:50	1,329	48.1	27.7	2.71	191

equivalent number of vehicles per hour. Mean speed, density and spacing were also calculated for each of these 5-min intervals. All mean speed calculations are based on space-mean speed according to the following formula:

$$\bar{S} = \frac{(L)\ (n)}{1.47\,\Sigma t} \qquad (1)$$

in which

$\bar{S}$ = space mean speed of all vehicles in mph;
L = length of trap in feet;
n = number of observed vehicles;
Σt = total time in seconds for passage of n vehicles through trap; and
1.47 = conversion factor (ft per sec to mph).

Wardrop (1) has shown that theoretical calculations involving volume, speed, and density relationships hold true only when the space mean speed is used.

In the following discussion the inside lane will refer to the left lane nearest the medial divider, and the outside lane will refer to the right lane as seen by the driver.

Distribution of Speeds

A comparison of vehicle speeds at Zone A with speeds at Zone B is shown in Figure 4. Curves A and B are representative speed distributions of the inside lane and outside lane, respectively, at Zone B. The speed limit in this zone is 55 mph. The mean speed of the inside lane is 53.9 mph and of the outside lane is 43.9 mph. Although vehicles may have not yet attained their maximum speed at Zone B, the curves shown here agree very well with the results of recent studies made by the Connecticut State Highway Department on the Merritt Parkway.

TABLE 4

SUMMARY OF VOLUME, SPEED, DENSITY, HEADWAY, AND SPACING
OUTSIDE LANE - ZONE B

Date 1956	Time, p.m.	Volume, vph	Speed, mph	Density, veh/mi	Mean Headway, sec	Mean Spacing, ft
July						
8	4:10-4:15	859	43.1	19.9	4.19	265
	4:25-4:30	894	41.8	21.4	4.03	247
	5:00-5:05	946	41.4	22.9	3.80	231
	5:14-5:19	832	43.6	19.1	4.33	277
	6:00-6:05	703	44.1	16.0	5.12	331
	6:15-6:20	991	40.9	24.2	3.63	218
	6:27-6:32	899	41.4	21.7	4.01	243
	7:16-7:21	775	42.3	18.3	4.64	288
	7:25-7:30	901	44.7	20.2	3.97	262
	7:45-7:50	929	45.0	20.6	3.87	256
	8:00-8:05	870	42.1	20.7	4.14	253
Aug.						
5	2:40-2:45	1,000	42.9	23.2	3.60	228
	3:00-3:05	835	48.0	17.4	4.31	303
	3:45-3:50	894	46.3	19.3	4.03	273
	3:55-4:00	870	46.3	18.8	4.14	281
	4:05-4:10	858	43.4	19.8	4.19	267
	4:50-4:55	847	46.8	18.1	4.25	292
	5:00-5:05	906	42.0	21.6	3.98	245
	5:10-5:15	847	42.5	19.9	4.25	265
	5:35-5:40	870	44.3	19.6	4.14	269
	5:45-5:50	964	44.8	21.5	3.73	245

The speed distribution of uncongested traffic flow (density less than 40 vehicles per mile) in the outside lane at Zone A is shown in curves C and D. Curve C represents the speed of vehicles at a point 560 ft before the bridge, and curve D represents speeds at a point 150 ft before the bridge. The mean speed for curve C is 37.9 mph and for curve D is 25.7 mph. The speed limit was 25 mph through this zone. As vehicles continued beyond the 150 ft point, the drivers maintained or increased speed slightly in crossing the bridge.

The combined effect of congestion and the bridge is shown in curves E and F. Under these conditions minimum speeds were observed 560 ft before the bridge, and drivers were accelerating when passing the point 150 ft before the bridge. Curve E with a mean speed of 10.3 mph represents the distribution of vehicle speeds 560 ft before the bridge, and curve F with a mean speed of 15.5 mph represents the distribution of vehicle speeds 150 ft before the bridge. Since minimum speeds were observed 560 ft before the bridge, all observations for Zone A were made at this point.

Vehicular Volumes and Lane Distribution

The hourly rate of volumes as estimated from 5-min periods for Zone A are shown in Tables 1 and 2 and for Zone B in Tables 3 and 4. An examination of volumes at Zone A indicates that when mean speeds exceed 20 mph and densities are less than 50 veh per mi, a greater percentage of the vehicles use the inside lane than the outside lane. The mean hourly volume rate, during those 5-min periods that satisfy the above conditions of speed and density is 1,936 vph for both lanes. Of these, an average 1,047 vph (54 percent) use the inside lane.

With increasing congestion, as measured by speed and density, the volumes by lanes become more nearly equal. Considering the volumes after 5:40 p.m., July 8, and after 3:37 p.m., August 5, the mean hourly volume was 2,253 vph for both lanes. Of these, an average of 1,102 vph (48.9 percent) used the inside lane and 1,151 vph used the outside lane.

A comparison of the estimates of hourly volume rates for the pair of lanes shows a significant difference in capacity of the two lanes at the 5 percent confidence level. If the period 6:15 p.m. - 6:20 p.m., July 8, is eliminated from the comparison, there is no longer a significant difference between the volumes of the two lanes. It is probable that some stoppage occurred beyond the limits of the study that reduced the volumes using the inside lane during the 6:15 p.m. - 6:20 p.m. period.

The lane distribution at Zone B shows a different pattern from that at Zone A. In this instance the average 5-min estimate of hourly volume for both lanes is 2,149 vph, of which 1,269 vph (59 percent) use the inside lane and 880 vph use the outside lane. Many drivers were observed to be making passing maneuvers in this area since passing had been restricted for several miles in the long queues delayed by the temporary bridge.

Speed, Volume, Density Relationships

The Highway Capacity Manual (2) points out that maximum volumes for a given facility occur at an optimum speed and that above and below this optimum speed there will be lesser volumes. Greenshields (3) showed that there was a straight line relationship between speed and density of traffic. Forbes (4) and Greenshields have shown that the relationship between volume and speed can be fitted with a parabolic curve. These relationships were applied to the data obtained at Zone A.

Hourly volume rates, space-mean speed, density, average headway and spacing of vehicles were computed for each 5-min sample (Tables 1-4). Density was found by dividing the hourly volume by the mean speed. Headways and spacings are based on averages for all of the vehicles in each 5-min sample.

The various points obtained for speed and density were plotted and straight lines fitted to them by the method of least squares. Each 5-min point was given equal weight in computing the least squares. The curves, one for each lane, are shown in Figure 5. The regression equation for the inside lane at Zone A is given by:

$$S = 34.17 - 0.2124\ D; \qquad (2)$$

and for the outside lane by:

$$S = 38.05 - 0.2416\ D \qquad (3)$$

in which

S = speed in miles per hour, and
D = density in vehicles per mile.

In the above equation 38.05 and 34.17 represent the speed as vehicles approached the bridge without congestion. These two values would be represented by the mean speed of curve C (Fig. 4) for which the mean speed was 37.9 mph. The coefficient of correlation for the inside lane is 0.97 and for the outside lane, 0.96.

The nature of the relationship between speed and volume follows from the relationship between speed and density. The above equations are of the form $S = a - mD$ and,

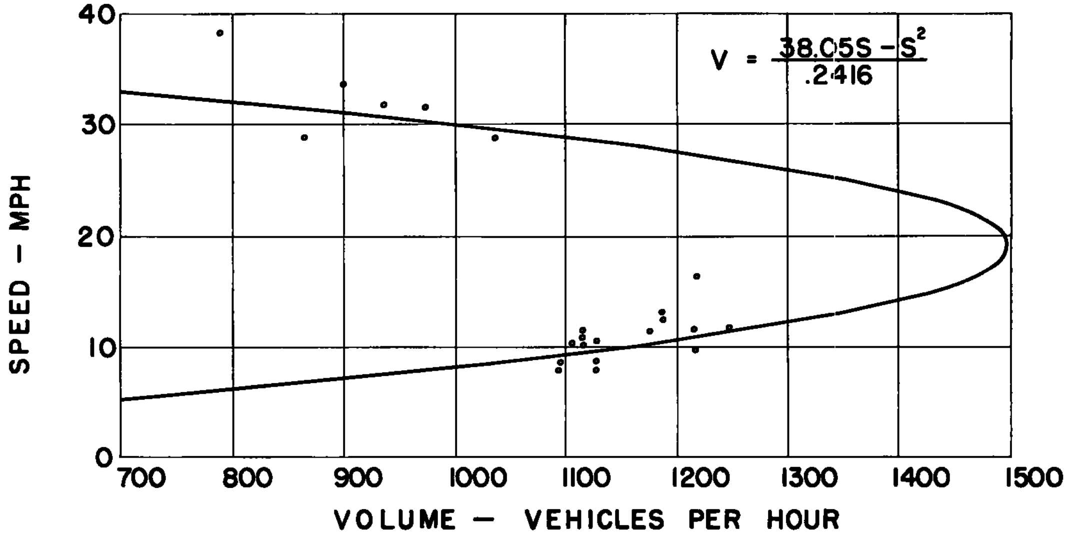

Figure 7. Speed versus volume - outside lane.

since D = V/S, the equation may be written as

$$S = a - m\,V/S \qquad (4a)$$

or

$$V = \frac{aS - S^2}{m} \qquad (4b)$$

in which

V = volume in vehicles per hour, and
S = space-mean speed in mph.

There are two values of speed which will satisfy a given volume.

The equation for the speed-volume relationship of the inside lane at Zone A is

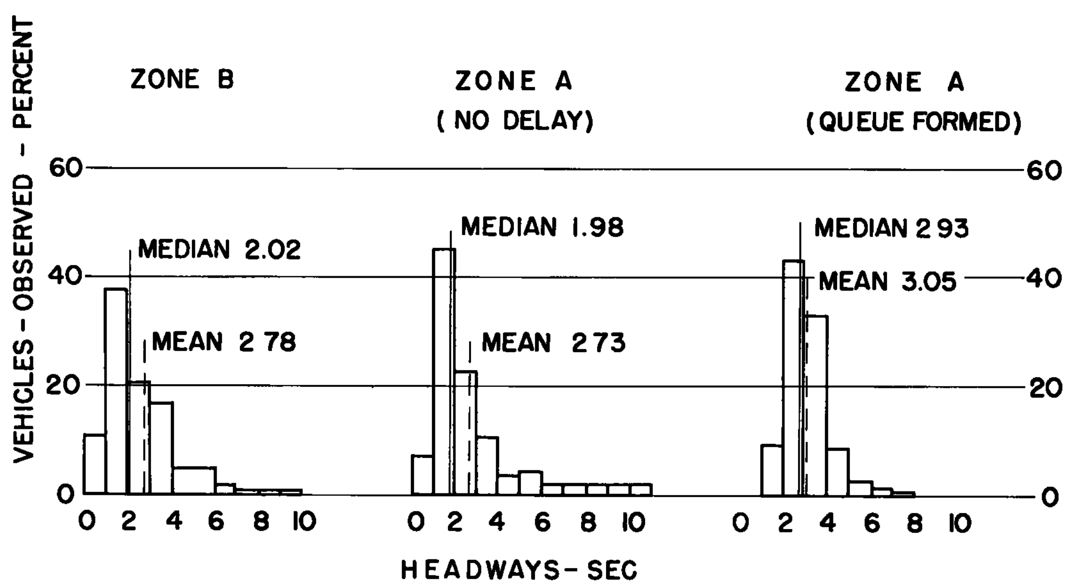

Figure 8. Headway distributions.

given by:

$$V = \frac{34.17\,S - S^2}{0.2124} \tag{5}$$

and for the outside lane by:

$$V = \frac{38.05\,S - S^2}{0.2416} \tag{6}$$

The curves of these two equations are plotted in Figures 6 and 7.

Under the existing roadway and traffic conditions, the possible capacity is represented by the apex of the curve. The critical speed, at which the maximum volume will occur, is 17 mph and 19 mph for the inside and outside lanes respectively. The critical densities corresponding to these critical speeds are 80.4 veh per mi and 78.7 veh per mi for the inside and outside lanes. The possible capacity of the inside lane is 1,375 vph and for the outside lane, 1,498 vph. The possible capacity as used here differs from the Highway Capacity Manual in that a lower operating speed is considered. Maximum observed volume for the outside lane was 1,248 vph and for the inside lane, 1,320 vph.

As volumes increased and speeds decreased (the upper limb of the parabola) the density also increased. Curve D (Fig. 4) showed that under conditions of free flow 15 percent of the vehicles were traveling at less than the critical speed of 19 mph. As the volume (and density) of the traffic increased, the mean speed decreased and increasing numbers of vehicles were operating at less than the critical speed. The volumes occurring at those points at which the mean speed fell below the critical speed are plotted on the lower limb of the parabolic curve.

The curves also indicate that if the volume per lane approaching the bridges had not exceeded 1,000 to 1,100 vph, the vehicles could have continued through the test section at speeds between 20 and 30 mph. As volumes per lane approaching the bridge exceeded 1,100 vph the average speed quickly dropped below the critical speed and, although greater volumes passed over the bridges, it was accomplished at the expense of considerable delay and congestion to the individual drivers.

Vehicle Spacing and Headways

Mean spacing, in feet, between vehicles in the same lane for each 5-min period was calculated from the relationship:

$$\text{Spacing} = \frac{5,280}{\text{Density (veh/mi)}} = 1.47 \text{ space-mean speed (mph) x mean headway (sec)} \tag{7}$$

Resulting values are found in Table 1 through Table 4. The minimum average spacing was 36.6 ft during the 5-min period beginning at 7:35 p.m., July 8, in the outside lane. Average spacings for those volumes on the lower limb of the curves (congested conditions) varied from 36.6 ft at a mean speed of 7.8 mph to 65.7 ft at a mean speed of 16.1 mph. The values of average spacing are in general agreement with extrapolated values of minimum spacings at various speeds as shown in Figure 2, page 28 of the Highway Capacity Manual.

The influence of congestion on headways is indicated in Figure 8. Headways shown are on a per lane basis. Each of the three distributions is based on a minimum of three 5-min samples. The headway distribution at Zone B is based on a volume of 1,290 vph per lane; at Zone A (no delay) on a volume of 1,320 vph per lane; and at Zone A (queue formed) on a volume of 1,190 vph per lane.

When traffic is not congested 48 percent of the headways at Zone B and 52 percent of the headways at Zone A (no delay) are less than 2 seconds. These values are in close agreement with the theoretical distribution as determined from the Poisson Series. The theoretical distribution of headways less than 2 seconds are 51.2 percent and 51.8 percent for Zone B and Zone A (no delay), respectively.

As density increased (and spacing decreased) the vehicles were required to maintain greater headways than normally expected. The effect on headways less than 2 seconds is shown by the histogram for Zone A (queue formed) in Figure 8. The theoretical distribution as determined from the Poisson Series indicates an expected value of 48.2 percent headways less than 2 seconds. Observed headways less than 2 seconds at Zone A (queue formed) were 9.8 percent of the total headways. The requirement that drivers maintain a minimum spacing would restrict the number of vehicles observed traveling at less than 2 seconds headway. The failure to maintain headways under 2 seconds increases the mean headway and limits the capacity at the bridges.

SUMMARY

1. The average speed of vehicles during uncongested periods was 37.9 mph at a point 560 ft before the bridge and 25.7 mph at a point 150 ft before the bridge. As density increased the mean speed of vehicles was 10.3 mph at 560 ft before the bridge and 15.5 mph at 150 ft. Mean speeds 0.75 mi beyond the bridge were 53.9 mph and 43.9 mph for the inside and outside lanes, respectively.
2. The mean estimate of hourly volumes passing the bridge during congested periods was 2,253 vph for both lanes. An average 1,102 vph (48.9 percent) used the inside lane and 1,151 vph, the outside lane. Under conditions of lesser congestion 54 percent of the vehicles used the inside lane at a total volume of 1,936 vph for both lanes.
3. As density increases, speed decreases in a straight-line relationship. The equation of the least-squares line for the inside lane is given by $S = 34.17 - 0.2124\, D$ and for the outside lane by $S = 38.05 - 0.2416\, D$. Coefficients of correlation were 0.96 and 0.97 for the inside and outside lanes.
4. Speed decreased as volume increased up to a point of critical speed and corresponding critical density. Below the critical speed a further decrease in speed resulted in a further decrease in volume. The relationship can be described by a parabolic curve the apex of which represents the possible capacity at the critical speed. Points were observed and plotted on both limbs of the parabola.
5. Minimum average spacings as low as 36.6 ft at 7.8 mph were observed. The requirement of maintaining a minimum spacing at low speeds resulted in a decrease in the number of headways under 2 seconds. This in turn increased the mean headway and consequently limited the volumes observed at the bridge.

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