Relationship of Signal Design to Discharge Headway, Approach Capacity, and Delay

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The rate at which a queue at a signalized approach discharges vehicles has a major effect on the capacity of the approach. To determine the relative effectiveness of various signal configurations and lens sizes in dissipating queues, queue discharge headway measurements were made at 38 sites in five states. Four major classes of signal configurations and two lens sizes were analyzed. The results show that, except for lens size, no class of configurations can be considered better than any other class for any queue position. Estimates are made of expected delay and approach capacity as functions of configuration class and lens size.

Traffic control signals represent an unavoidable impedance to traffic flow. No matter how well a signal is timed and no matter how well that timing is maintained and adapted to instantaneous conditions, some vehicles arrive during the red interval. These vehicles form a queue that must be dissipated during the ensuing green interval. The rate of queue dissipation has a major effect on the capacity of the approach; also, the rate of queue dissipation greatly determines smoothness of flow of the primary platoon.

As part of a major study of traffic signal design configuration (NCHRP Project 3-23, Guidelines for Uniformity in Traffic Signal Design Configurations) queue discharge behavior was investigated. A nationwide program of empirical testing was undertaken to determine the absolute values of the queue discharge headway distribution and the influence of various factors on this distribution. The main emphasis was to determine how number, size, and location of traffic signal heads could be changed to improve the queue discharge headway distribution.

DATA COLLECTION

Characteristics of Data Collection Sites

The sites at which queue discharge headway data were collected are listed in Table 1. The signal configuration number refers to a combination of number, location, and mounting height of traffic signal head. Many combinations are possible, and nearly 50 have been identified (1). The 18 signal configuration numbers used in Table 1 are sketched in Figure 1.

Data Collection and Reduction

Queue discharge headway data were recorded by manual input to a chart recorder. The observer pressed a button when the signal changed to green and when a vehicle passed the stop line (or a screen line established as the location of the front wheels of the first car in queue). Data were recorded for all passenger cars on each cycle that

1. Were stopped in queue at the beginning of the green interval;
2. Proceeded straight through the intersection; and
3. Were not impeded by pedestrians, cross traffic, or opposing left turns.

Data were collected for approximately 30 cycles at each location. Figure 2 shows a typical recorder chart.

This manual input method has an element of error because of the observer's reaction time. To compensate for this error the reaction time was assumed to be almost uniform for all the inputs. This assumption was validated by film. Queue discharge data were manually collected at one location by using a chart recorder while, at the same time, the queue discharge process was filmed at 5 frames/s. Both sets of data were reduced, and the queue discharge distribution was determined. No significant differences between the two distributions were detected.

The filmed data were reduced on a frame-by-frame basis. The queue discharge headway data recorded on the charts were reduced by measuring the times between the onset of green spike and the first vehicle spike. Then the time between each succeeding vehicle passage was measured. The sample size at each queue position decreased from approximately 30 at the first position to zero at more distant queue positions.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

Table 1. Data collection sites and characteristics.

Number	Location	Intersection	Approach[a]	Equivalent Lanes	Median[b]	Left Turn Lane[c]	Control Type[d]	Lens Size[e]	Signal Configuration Number	Posted Speed Limit (km)	85th Percentile Speed (km)
1	Somerville, Mass.	Highland and Lowell	NB	1	0	0	1	3	13	48	43
2	Brookline, Mass.	Beacon and Dean	EB	2	1	0	1	2	13	48	62
3	San Francisco	California and 25th	WB	1	0	0	1	1	13	40	50
4	San Francisco	California and 25th	EB	1	0	0	1	1	13	40	48
5	Lansing, Mich.	Michigan and Penn	WB	2	0	1	1	1	4	40	50
6	East Lansing, Mich.	Mt. Hope and Hagadorn	EB	2	0	0	1	1	4	72	78
7	Augusta	Greene and 7th	WB	3	1	0	1	1	36	48	43
8	Augusta	Telfair and 5th	EB	2	0	0	1	1	7	48	45
9	Augusta	Broad and 5th	WB	3	1	0	1	1	35	48	48
10	Atlanta	Blvd. and Angier	SB	2	0	0	1	1	45	48	61
11	Atlanta	Juniper and 10th	EB	3	2	—	1	1	34	48	48
12	Muttontown, N.Y.	Route 106 and Muttontown Road	NB	2	1	1	2	2	6	88	91
13	East Lansing, Mich.	Mt. Hope and Farmlane	EB	2	0	1	2	2	2	72	83
14	Sacramento	Watt and Whitney	NB	3	1	1	2	2	32	64	74
15	Brookline, Mass.	Beacon and Dean	WB	3	1	1	1	2	13	48	58
16	Brookline, Mass.	Kent and Aspinwall	EB	1	0	0	1	1	13	48	51
17	Lansing, Mich.	Michigan and Shepard	WB	2	0	1	1	1	4	40	50
18	Cambridge, Mass.	Main and Windsor	WB	1	0	0	1	1	13	48	48
19	Brookline, Mass.	Beacon and Dean	NB	1	0	0	1	2	33	48	48
20	San Francisco	Alemany and Geneva	WB	2	1	0	1	1	43	40	45
21	San Francisco	Alemany and Geneva	NB	3	1	0	1	1	43	40	61
22	San Francisco	Alemany and Geneva	SB	3	1	0	1	1	43	40	61
23	Sacramento	El Camino and Fulton	EB	3	1	1	2	2	23	56	66
24	Sacramento	Howe and Arden	WB	3	1	1	3	3	23	56	58
25	Augusta	Reynolds and 13th	WB	2	0	0	1	1	1	48	54
26	Atlanta	Ponce de Leon and Highland	EB	3	0	1	1	1	8	48	59
27	Boston	Beacon and Mass.	WB	3	2	—	3	2	13	48	56
28	Brookline, Mass.	Chestnut Hill and Dean	NB	1	0	0	3	2	44	48	58
29	Huntington, N.Y.	Oakwood and Pulaski	NB	2	0	0	1	1	6	64	72
30	Queens, N.Y.	Parsons and 77th	NB	1	0	0	2	1	39	48	50
31	Queens, N.Y.	Parsons and 78th	SB	1	0	0	2	1	31	48	53
32	Hicksville, N.Y.	Route 106 and West John (day)	SB	2	1	1	1	1	6	64	56
33	Hicksville, N.Y.	Route 106 and West John (night)	SB	2	1	1	1	1	6	64	59
34	Glen Head, N.Y.	Glen Cove and Glenhead Road	NB	2	1	1	2	3	6	88	88
35	Huntington, N.Y.	Oakwood and Pulaski	EB	1	0	0	1	1	2	80	78
36	Huntington, N.Y.	Park Avenue and Maplewood Road	SB	1	0	0	1	1	1	64	—[f]
37	Huntington, N.Y.	Park Avenue and Broadway	NB	1	0	0	1	1	1	64	—[f]
38	Huntington, N.Y.	Pulaski Road and Lake Road	SB	1	0	0	1	1	1	56	—[f]
39	Huntington, N.Y.	DeForest Road North and East Deer Park Avenue	WB	1	0	0	1	1	1	48	—[f]

Note: 1 km = 0.6 mile.

[a]NB = northbound, EB = eastbound, WB = westbound, and SB = southbound.
[b]0 = no, 1 = yes, and 2 = one way.
[c]0 = no, and 1 = yes.
[d]1 = fixed time, 2 = vehicle actuated, and 3 = pedestrian actuated.
[e]1 = 200 mm, 2 = 300 mm, and 3 = 300 mm, 200 mm, and 200 mm.
[f]Data not collected.

Figure 1. Signal configurations at data collection sites.

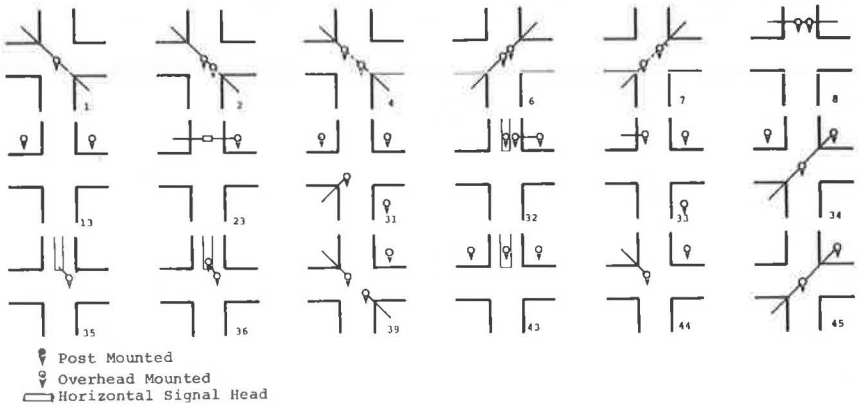
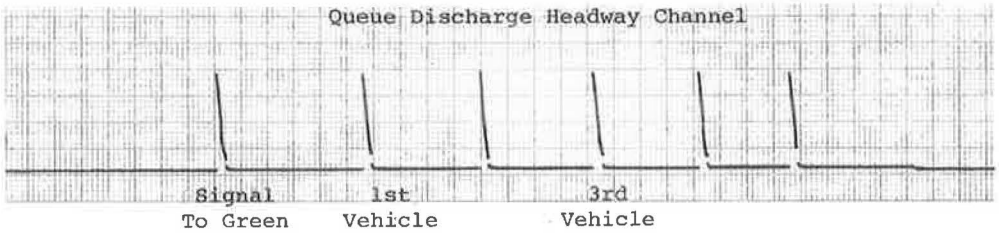


Figure 2. Sample recorder output showing queue discharge headway.



ANALYSIS OF QUEUE DISCHARGE HEADWAY DATA

The computed mean and standard deviation of the discharge headways for each queue position for each approach are shown in Table 2. The data were analyzed in general and then specifically for signal design configuration, signal lens size, and number of signal heads.

Overall Analysis

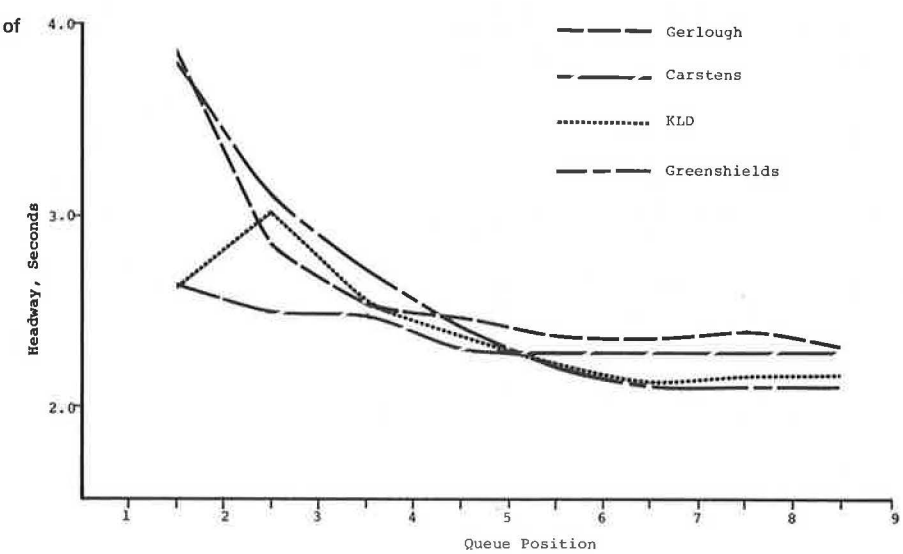
Queue discharge behavior has been studied by many investigators including Gerlough (2), Greenshields (3), Kell as reported by Gerlough (2), Berry and Gandhi (4), Capelle and Pinnell (5), and Carstens (6). Many researchers, however, have reported their results in average headway for the entire queue. The results of a number of studies that reported headways for individual queue positions are plotted in Figure 3.

Most of the previous studies support present results except for the first queue position. This lack of support is undoubtedly due to the definition of the measuring screen line used in the present study. Data on the important effect that this definition has on the results have been quoted by Berry and Gandhi (4). Since the present study is concerned with reactions to traffic signal configurations, a definition has been adopted that emphasizes the reaction time rather than the acceleration el-

Table 2. Overall analysis of queue discharge headways.

Location No.	Configuration No.	Position 1			Position 2			Position 3			Position 4			Position 5			Positions 6 to 8		
		No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
1	13	28	2.26	0.55	28	2.49	0.76	23	2.70	0.64	22	2.64	0.87	15	2.64	0.83	22	2.58	0.89
2	13	31	2.32	0.79	31	2.90	0.81	29	2.48	0.51	24	2.22	0.52	15	2.22	0.77	18	2.17	0.80
3	13	29	3.36	0.97	29	3.17	0.78	28	2.72	0.64	17	2.60	0.40	10	2.22	0.78	4	2.05	0.55
4	13	28	3.67	1.56	28	3.09	0.83	28	2.71	0.52	16	2.51	0.68	7	2.59	0.56	1	2.00	0.00
5	4	36	2.30	0.88	35	3.00	0.68	30	2.40	0.55	23	2.20	0.58	17	2.29	0.69	20	2.19	0.63
6	4	33	2.31	0.69	33	2.78	0.60	22	2.27	0.31	11	2.79	0.63	4	1.85	0.39	2	2.45	0.35
7	36	29	2.73	0.92	29	3.48	0.73	23	2.53	0.63	18	2.52	0.67	13	2.33	0.55	4	2.30	0.73
8	7	30	2.87	1.26	29	3.04	0.79	20	2.65	0.60	16	2.27	0.67	2	1.85	0.21	0	0.00	0.00
9	35	30	2.85	1.29	29	3.40	0.67	20	3.08	0.62	7	3.04	0.87	5	2.26	0.24	3	2.03	0.49
10	45	30	2.82	0.95	30	3.09	0.66	28	2.89	0.75	23	2.53	0.62	14	2.38	0.88	10	2.41	0.60
11	34	31	2.58	1.02	29	3.08	0.85	20	2.69	0.73	12	2.65	0.62	2	2.50	0.71	0	0.00	0.00
12	6	41	1.80	0.66	41	2.79	0.66	24	2.23	0.51	14	1.95	0.52	7	1.76	0.38	7	1.63	0.72
13	2	30	2.19	0.70	30	2.79	0.56	30	2.16	0.57	24	2.13	0.43	19	1.98	0.38	19	2.07	0.76
14	32	30	3.31	1.33	29	3.47	0.90	28	2.63	0.91	22	2.47	0.45	11	2.32	0.67	4	1.93	0.46
15	13	27	2.61	1.17	27	2.70	0.66	27	2.51	0.54	20	2.57	1.26	10	2.23	0.45	4	2.83	1.09
16	13	37	2.64	0.79	32	2.53	0.43	18	2.57	0.81	9	3.21	1.09	4	2.23	0.17	2	2.70	0.28
17	4	33	2.55	0.96	32	2.75	0.50	31	2.45	0.59	28	2.22	0.37	18	2.34	0.53	14	2.49	0.65
18	13	30	2.14	0.69	20	2.81	0.58	11	2.56	0.55	7	2.64	0.82	4	2.00	0.36	2	1.50	0.71
19	33	20	2.13	0.98	20	2.88	0.69	20	2.25	0.58	16	2.08	0.46	12	1.99	0.46	21	2.20	0.66
20	43	31	2.78	1.44	31	3.25	0.58	31	2.62	0.64	21	2.22	0.55	15	2.21	0.68	9	2.01	0.35
21	43	29	2.97	1.16	29	3.29	0.76	29	2.30	0.32	22	2.52	0.89	14	2.05	0.30	8	2.54	0.58
22	43	31	3.33	1.22	31	3.05	0.81	31	2.44	0.51	22	2.66	0.54	12	2.22	0.67	7	2.27	0.56
23	23	30	3.07	1.31	30	2.87	0.74	30	2.40	0.75	21	2.24	0.55	11	2.57	0.81	2	1.55	0.35
24	23	29	2.94	0.87	29	3.22	0.78	29	2.36	0.72	20	2.20	0.61	13	2.12	0.56	8	2.06	0.50
25	1	28	2.24	0.71	23	3.42	0.68	17	3.21	1.06	11	3.05	0.65	7	2.51	0.61	2	2.05	0.21
26	8	30	2.11	0.90	30	2.79	1.39	28	2.39	0.64	26	2.30	0.62	14	2.19	0.64	13	2.19	0.50
27	13	27	2.09	0.78	27	2.66	0.68	25	2.30	0.71	24	2.27	0.60	22	2.25	0.82	34	2.08	0.55
28	44	35	2.28	0.87	35	2.83	0.80	32	2.42	0.81	30	2.18	0.47	20	2.25	0.57	19	1.89	0.47
29	6	30	2.15	0.73	19	3.05	0.52	13	2.79	0.65	9	2.16	0.30	2	2.00	0.99	1	1.50	0.00
30	39	30	2.82	1.43	19	2.93	0.58	11	2.45	0.45	7	2.39	0.43	4	1.93	0.30	1	2.10	0.00
31	31	30	2.54	1.03	20	3.30	0.58	13	2.79	0.70	7	2.73	0.66	0	0.00	0.00	0	0.00	0.00
32	6	30	4.02	1.04	18	3.41	0.97	13	2.84	0.62	5	2.44	0.50	3	2.87	0.46	0	0.00	0.00
34	6	30	2.96	1.14	21	3.10	0.98	17	2.76	0.65	9	2.02	0.45	4	2.23	0.53	4	1.85	0.42
35	2	30	2.72	1.01	19	3.62	0.93	14	2.34	0.52	8	2.05	0.48	6	2.33	0.37	3	2.30	0.90
36	1	33	2.57	1.31	23	3.04	0.55	19	2.57	0.59	10	2.23	0.70	4	2.25	0.24	2	2.30	0.71
37	1	31	2.23	0.61	27	2.99	0.79	20	2.29	0.56	9	2.22	0.47	5	1.60	0.20	5	2.22	0.60
38	1	31	2.25	1.15	27	2.85	0.50	20	2.42	0.51	14	2.18	0.36	9	1.83	0.43	10	1.96	0.46
39	1	30	2.04	0.88	30	2.63	0.52	27	2.37	0.50	25	2.15	0.54	23	1.99	0.41	59	1.96	0.55

Figure 3. Comparison of various research results of queue discharge headway.



ement. Carstens (6), who adopted a similar definition, obtained similar results.

Aside from this difference in the first queue position, most data sets including the present show the same general trend: a decrease of discharge headway as queue position increases and then a leveling off to approximately 2.2 s by the fifth position.

Analysis by Configuration Class

Table 3 gives queue discharge headway data aggregated by signal configurations. Since only 2 of the 18 configurations were represented by five or more approaches, no separate analysis by individual signal design configurations was made. The major analysis was a comparison of four classes of signal design configuration: all post, single overhead, multiple overhead, and mixed.

Table 4 gives the data on queue discharge headway aggregated by configuration class. The same information is shown in Figure 4. These data reveal that there are differences in efficiency between the various configuration classes and the rank order of the configuration classes changes among queue positions.

For each queue position all possible duplicate comparisons were evaluated for statistical significance and yielded the following results at the $p = 0.05$ level.

1. At queue position 1 single overhead and multiple overhead configurations were better (i.e., lower value of start-up loss) than the all post or mixed configuration.
2. At queue position 2 the queue discharge headways were close together for all configuration classes (Figure 4). The only significant differences were between mixed and all post or multiple overhead.
3. At queue position 3 multiple overhead was better (i.e., queue discharge headway was lower) than the single overhead configuration. There were no other significant differences.
4. At queue position 4 the multiple overhead configurations were significantly better than at the other three. Also the mixed configurations were better than the all post configurations.
5. At queue position 5 the single overhead configurations were better than the all post or mixed configuration. There was, however, only a small sample available for this configuration.
6. At other queue positions data for all queue positions higher than five were merged for analysis because of the small number of data points and the fact that queue discharge headways tend to be constant beyond the fifth queue position. For these queue positions, single overhead configurations were significantly better than all post configurations. There were no other significant differences.

Analysis by Lens Size

Figure 5 shows the effect of lens size on queue discharge headway. The data set was partitioned according to size of the green signal lens in each configuration. The figure shows that the 300-mm (12-in) lens performs better for all queue positions. Statistical tests show that these differences are significant for the third and all subsequent queue positions. The hypothesis that the larger signal size is more likely to be used in the better performing overhead configurations was tested. For the third queue position a two-way analysis of variance showed that both configuration class and lens size were significant. The third position was selected for this test because it was the position at which significant differences first became apparent. Furthermore, for the same queue position, a comparison of 200-mm (8-in) and 300-mm (12-in) green lens sizes for all post configurations showed only that the larger lens performed significantly ($p = 0.01$) better than the smaller one.

Analysis by Number of Signal Heads

Figure 6 shows the apparent effect of the number of signal heads, without regard to configurations, on discharge headway. None of the three possibilities tested dominates, although the two-signal head combination appears to perform well.

The apparent good performance of the single overhead configuration can probably be explained by the fact that for both the two-head and three-head configuration groups more than half of each data set applied to all post configurations.

IMPACT ON DELAY AND CAPACITY

The separate analyses discussed in the previous section indicate that, except for lens size, no configuration-related factor can be considered better or worse at all queue positions. Also delay of a vehicle in a given queue position is not linearly related to the queue discharge headway for that position. If H_i is the discharge headway for the i th queue position, then the total delay (D_i) occurring to a vehicle in that position is given by

$$D_i = \sum_{j=1}^{j=i} H_j \qquad (1)$$

The total delay (D_s) accrued by a queue of length k is then given by

$$D_{s(k)} = \sum_{j=1}^{j=k} D_j \qquad (2)$$

or

$$D_{s(k)} = kH_1 + (k - 1)H_2 + \ldots + 2H_{k-1} + H_k \qquad (3)$$

Table 5 gives the total delay, estimated by using this equation, for all vehicles in queue for some representative queue sizes. The units of delay in this table are expressed as vehicle•s/cycle. For a 60-s cycle, this is equivalent to vehicle•min/h.

Examination of this table shows that all post and mixed configurations accrue more delay for all four queue lengths. When the queue lengths are reached, the better performance of overhead configurations, both single and multiple, becomes more apparent. Improvement can also be expected with the use of the larger signal lens.

The computational method used to develop this table does not permit an assessment of significance that has a practical meaning because the variance for a linear combination of variables is the sum of the variances of the individual variables. For a queue of length k this represents $[k(k + 1)]/2$ items.

Although the differences in aggregate delay are not very striking, they indicate a definite improvement in approach capacity as the queue discharge headways decrease.

Table 6 gives computed capacities as a function of cycle length for two lens sizes and three basic configuration classes. Single overhead configurations were not included because of a shortage of data in the fourth to sixth queue position. These capacities were computed under the following conditions.

1. The maximum number of vehicles that can be serviced during a green interval are in queue at the beginning of the green signal. This condition means continu-

ous cycle failure or that both peak-hour factor and load factor are assumed to be equal to 1.0 as stated in the Highway Capacity Manual (HCM) (7).

2. The yellow interval is fully used for discharging vehicles.

3. The queue discharge headway is constant for all vehicles beyond the sixth queue position.

The capacity computation consists of discharging vehicles according to measured headways during the entire green-plus-yellow interval and multiplying the number discharged per cycle by the number of cycles in an hour. Because of the probabilistic nature of the individual headway values, fractional discharges per cycle were permitted. The algorithm used is as follows:

$$Q = \left\{ [(C/2) - \sum_{i=1}^{6} H_i] / H_7 + 6 \right\} (3600/C) \tag{4}$$

Table 3. Analysis of queue discharge headway by signal configuration.

Configuration No.	Number of Locations	Position 1			Position 2			Position 3			Position 4			Position 5			Positions 6 to 8		
		No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
1	5	153	2.27	0.96	130	2.96	0.38	103	2.54	0.42	69	2.32	0.30	48	2.02	0.18	78	1.99	0.29
2	2	60	2.46	0.76	49	3.11	0.52	44	2.20	0.31	32	2.11	0.20	25	2.06	0.14	22	2.10	0.60
4	3	102	2.38	0.73	100	2.85	0.37	83	2.38	0.28	62	2.31	0.27	39	2.27	0.39	36	2.32	0.44
6	4	131	2.65	0.83	99	3.02	0.63	67	2.59	0.30	37	2.08	0.24	16	2.12	0.39	12	1.69	0.91
7	1	30	2.87	1.26	29	3.04	0.79	20	2.65	0.60	16	2.27	0.67	13	2.33	0.55	00	0.00	0.00
8	1	30	2.11	0.90	30	2.79	1.39	28	2.39	0.64	26	2.30	0.62	14	2.19	0.64	13	2.19	0.50
13	8	237	2.63	0.93	222	2.79	0.52	189	2.57	0.40	139	2.51	0.68	87	2.32	0.59	87	2.26	0.60
23	2	59	3.01	1.29	59	3.04	0.60	59	2.38	0.56	41	2.22	0.35	24	1.15	0.52	10	1.96	0.31
31	1	30	2.54	1.03	20	3.30	0.58	13	2.79	0.70	7	2.73	0.66	00	0.00	0.00	00	0.00	0.00
32	1	30	3.31	1.33	29	3.47	0.90	28	2.63	0.91	22	2.47	0.45	11	2.32	0.67	40	1.93	0.46
33	1	20	2.13	0.98	20	2.88	0.69	20	2.25	0.58	16	2.08	0.46	12	1.99	0.46	21	2.20	0.66
34	1	31	2.58	1.02	29	3.08	0.85	20	2.69	0.73	12	2.65	0.62	2	2.50	0.71	00	0.00	0.00
35	1	30	2.85	1.29	29	3.40	0.67	20	3.08	0.62	7	3.04	0.87	5	2.26	0.24	3	2.03	0.49
36	1	29	2.73	0.92	29	3.48	0.73	23	2.53	0.63	18	2.52	0.67	13	2.33	0.55	4	2.30	0.73
39	1	30	2.82	1.43	19	2.93	0.58	11	2.45	0.45	7	2.39	0.43	4	1.93	0.30	10	2.10	0.00
43	3	91	3.03	1.70	91	3.19	0.54	91	2.46	0.27	65	2.47	0.49	41	2.16	0.36	24	2.26	0.29
44	1	35	2.28	0.87	35	2.83	0.80	32	2.42	0.81	30	2.18	0.47	20	2.25	0.57	19	1.89	0.47
45	1	30	2.82	0.95	30	3.09	0.66	28	2.89	0.75	23	2.53	0.62	14	2.38	0.88	10	2.41	0.60

Table 4. Analysis of queue discharge headway by signal configuration classes.

Class	Number of Locations	Position 1			Position 2			Position 3			Position 4			Position 5			Positions 6 to 8		
		No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
All posts	11	328	2.74	1.05	313	2.91	0.75	280	2.53	0.59	204	2.50	0.78	128	2.27	0.68	111	2.26	0.71
Mixed	10	294	2.73	1.12	270	3.12	0.77	234	2.53	0.75	176	2.36	0.57	100	2.27	0.64	69	2.10	0.58
Multiple overhead	11	353	2.51	1.07	307	2.96	0.93	242	2.43	0.59	173	2.22	0.54	96	2.17	0.56	83	2.15	0.67
Single overhead	6	183	2.37	1.05	159	3.02	0.68	123	2.63	0.72	76	2.39	0.67	53	2.04	0.47	81	1.99	0.53
All	—	1158	2.61	1.11	1049	3.00	0.77	879	2.52	0.66	629	2.37	0.66	377	2.21	0.62	344	2.14	0.64

Figure 4. Effect of configuration on queue discharge headway.

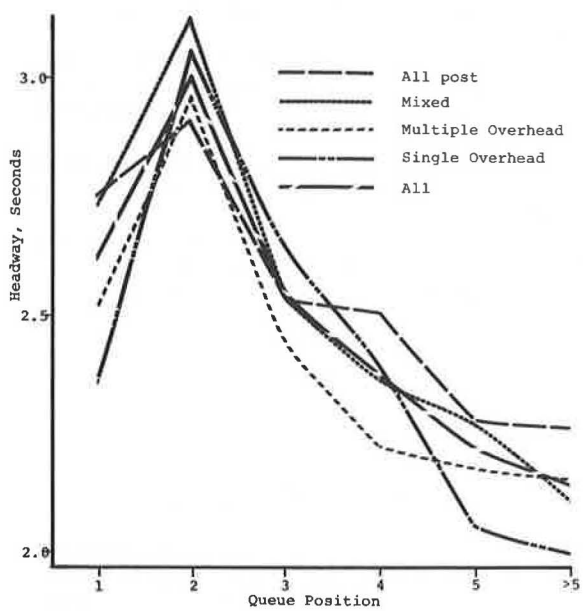
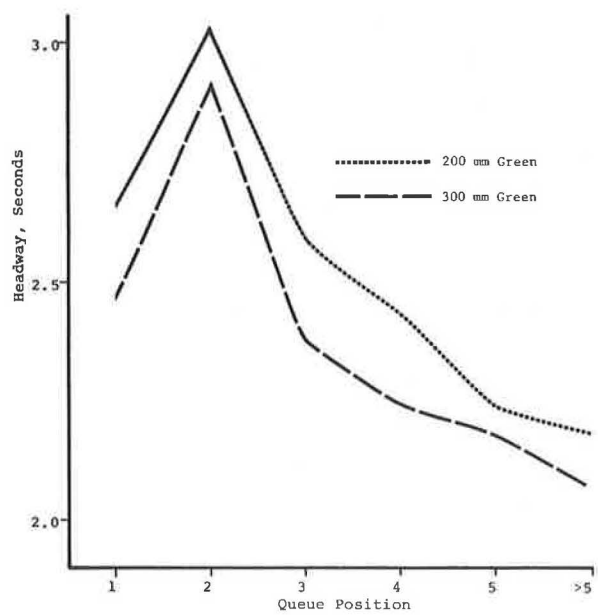


Figure 5. Effect of lens size on queue discharge headway.



where

Q = capacity in vehicles per hour,
C = cycle lengths in seconds (50 percent split assumed),
H_i = discharge headway of i th vehicle (i < 7), and
H_7 = average discharge headway of seventh and following vehicles.

Figure 6. Effect of number of signal heads on queue discharge headway.

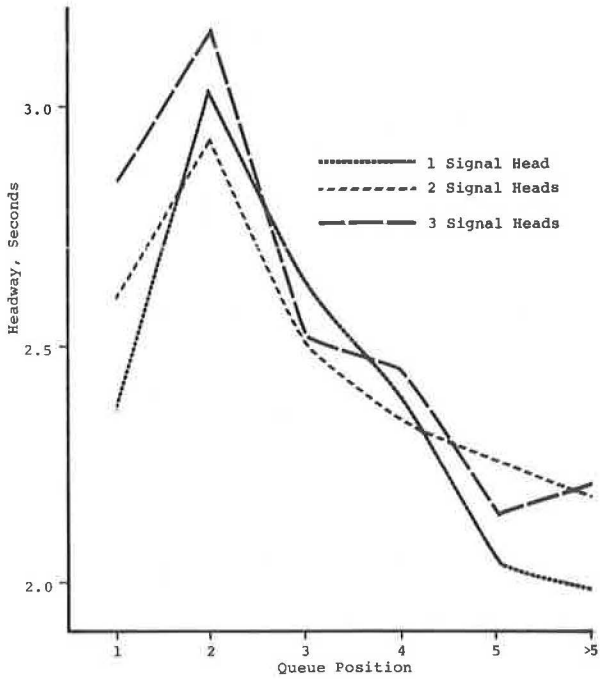


Table 5. Estimated total delay in queue.

Signal	Delay (vehicles/s/cycle) by Queue Length			
	2 Vehicles	4 Vehicles	6 Vehicles	8 Vehicles
All post	8.4	27.2	55.4	92.6
Mixed	8.6	27.7	55.8	92.3
Multiple overhead	8.0	26.0	52.7	88.1
Single overhead	7.8	26.2	53.2	88.1
30.5-cm green lens	7.8	25.6	52.0	86.7
20.3-cm green lens	8.4	27.3	55.4	92.2
Two heads	8.1	26.5	53.9	90.1
Three heads	8.8	28.3	56.8	94.1
All approaches	8.2	26.9	54.4	90.5

Note: 1 cm = 0.39 in.

Table 6. Signal configuration and approach capacity.

Signal	Capacity (vehicles/h/lane) by Cycle Length		
	45 s	60 s	90 s
All post	742	748	755
Mixed	774	792	810
Multiple overhead	805	817	829
30.5-cm green lens[a]	809	824	839
20.3-cm green lens[a]	770	780	790
All approaches[a]	786	799	812

Note: 1 cm = 0.39 in.
[a] Data for single-overhead configurations are included.

The data in Table 6 show that the difference in computed capacity between all post and multiple overhead configurations averages 9 percent for the three cycle lengths or nearly 70 vehicles/h. The computed values of 1442 to 1658, averaging 1572 vehicles/h of green per lane, compare well with the capacities for signalized approaches computed according to the procedures of chapter 6 of the HCM. For example, the computed capacity of a signalized approach where there are two 3.4-m (11-ft) lanes, parking is permitted, and turns and trucks are prohibited is 1566 vehicles/h of green per lane.

ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program, which is administered by the Transportation Research Board of the National Research Council.

The opinions and conclusions expressed or implied in the report are ours and are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or of the individual states participating in the National Cooperative Highway Research Program.

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Discussion

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The conclusions given in this paper are based primarily on analysis of differences in queue discharge behavior in relation to differences in traffic signal configurations;

queue discharge measurements were made at 38 different signal approaches in five states.

My discussion deals primarily with the selection of the screen lines where queue discharge headways are measured and with differences that can be expected in headways when different screen line definitions are used. The authors used two different screen-line definitions in collecting their data. They state that data on queue discharge behavior for each cycle were recorded as each vehicle passes the stop line or a screen line, which was established as the location of the front wheels of the car first in queue.

Figure 7 shows use of a screen line located at the position of the stopped front wheels of the first vehicle in queue. In alternative IA, the first vehicle would be considered to have started when it begins motion. The elapsed time from the beginning of the green interval would include reaction time, but no acceleration time. In alternative IB, vehicle 1 would be considered discharged when its rear wheels crossed the screen line as established by the stopped front wheels. The start-up time thus would include reaction time and the time to accelerate a distance equivalent to the wheelbase length of vehicle 1. Alternative IB apparently was used by the authors for a portion of their cycles for some or all of their signal configuration groupings.

In alternative II the stop line is used as the screen line. The two versions relate to whether the front or the rear wheels were used to identify when the vehicle passed the stop line. The authors used the stop line for some of the observations (presumable alternative IIA). In alternative III, the crosswalk line is the screen line for measuring queue discharge behavior. The entry to the intersection is the screen line in alternative IV.

In 1973, Kittelson (8) investigated the effect of two screen lines on queue discharge headways. Time-lapse photography was used at 5 frames/s at a single-lane approach adjacent to the Evanston campus of Northwestern University. His films have data for analyzing effects of five screen-line definitions on starting delay for the first vehicle and on headways for subsequent vehicles.

Figure 8 shows average starting delays for the first vehicle and average headways for the next three vehicles for five screen-line definitions; data from the same eight queues of vehicles (eight cycles) were used (30-cycle averages for start-up delay for vehicle 1 are as follows for three screen lines: IB, 2.71 s; IIIB, 3.30 s; and IV, 4.25 s). The choice of a screen-line definition affects headways for both queue position 1 (starting delay) and queue position 2.

Figure 7. Alternative screen lines for measuring queue discharge headings at signals.

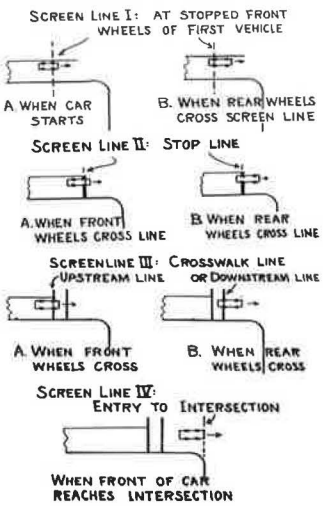
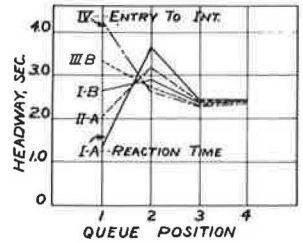


Figure 8. Start-up delays and headways for five screen-line types.



King and Wilkinson use both screen-line definitions IIA and IB and give no indication of the proportion of cycles for which each screen-line type is used. Reexamination of their data would be desirable to determine the proportion of cycles in each grouping of signal configurations that used each of the two screen-line types.

Other location factors that affect the length of the start-up time for the first queued vehicle for different screen-line definitions include

1. The distances between the stop line, the crosswalk lines, and the point of intersection entry;
2. The extent to which drivers tend to stop behind the stop and crosswalk lines when stopping;
3. The extent to which the side-street yellow signal is visible to the drivers; and
4. Whether a yellow signal is displayed after the red and just prior to the green, as in some European countries.

Schwarz (9) studied starting delays in 1961 at seven intersections in Chicago before and after elimination of a "get ready to go" yellow varying from 1.7 to 2.6 s. Using screen-line definition IIIB, he found that starting delays with the advance yellow averaged 1.20 s lower (2.97 versus 4.17) than with the red-green sequence. The differences were significantly different. Distances from stop lines to his crosswalk screen lines varied from 5.6 to 11.5 m (18.4 to 37.8 ft).

George and Heroy (10) studied starting reaction times at five signalized intersection approaches and found average start-up times per intersection varying from 1.5 to 2.0 s. His criterion, corresponding to screen-line definition IA, probably would have been preferable for an analysis of differences in response to different signal configurations. Greenshields (3) used definition IV for his headway studies, but he also reported reaction times for screen-line definition IA.

For capacity analysis in which measuring use of the yellow for loaded cycles is also desirable (4), I would recommend making queue discharge measurements at the entry to the intersection, corresponding to screen-line definition IV.

Authors' Closure

Berry's discussion of the influence of screen-line selection on the numerical values of queue discharge headway is a valuable and necessary contribution to the subject. He correctly points out that this selection is important in the relationship of acceleration and reaction time to the correct computation of queue discharge headway measurements.

First, we would like to clarify the exact measurement technique used to obtain the data presented in our paper. In keeping with the overall purpose of the research, we attempted to define a screen line that would emphasize the reaction time element. Furthermore, since manual

Figure 9. Comparison of queue discharge headway data.

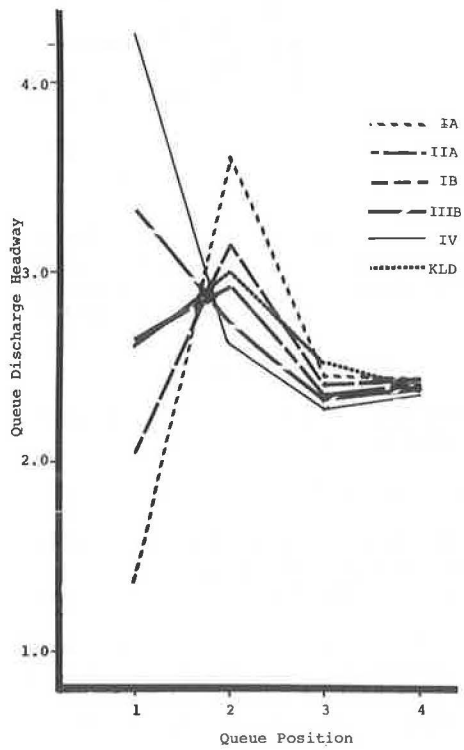
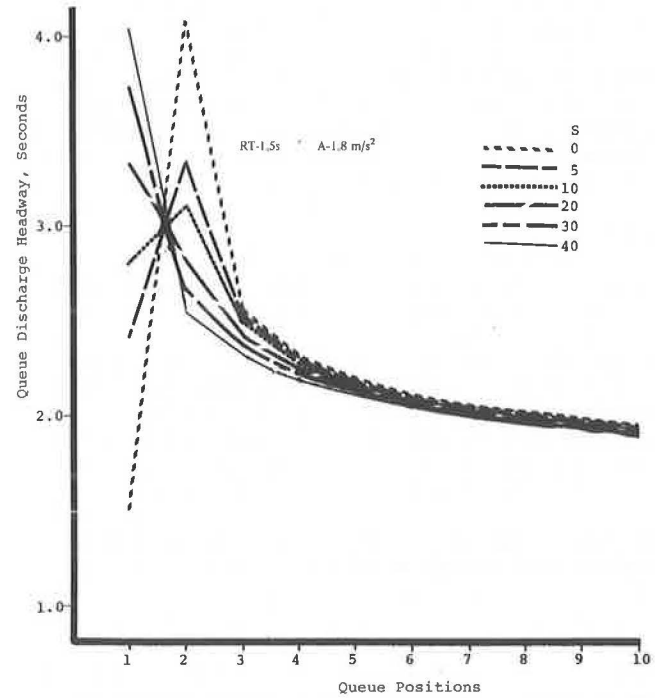


Figure 10. Relation of distance of first vehicle to screen line and queue discharge headway.



data inputs were used, a screen line visible in the field had to be selected. We therefore chose the stop line as the primary screen line on the assumption that most vehicles would be stopped with their front wheels only a short distance behind that line. However, an appreciable number of vehicles came to a stop straddling the stop line. For those vehicles, the stop line was retained as the screen line, but the passage of the rear wheels over that line was recorded. All measurements were consistent for any one queue. Either the front or rear wheels were used depending on the stopped position of the first vehicle. The entire data base is thus a random mixture of those two types; no records were kept of individual queues. The data base thus represents a mix of Berry's definitions IB and IIA, as he points out and as shown in Figure 9, in which our data are superimposed on Berry's data shown in Figure 8.

The empirical results presented by Berry in Figure 7 can be supported by theoretical analysis. Starting with the basic laws of motion, one can show that the discharge time of the nth vehicle (T_n) in queue can be computed by equation 5 if the simplifying assumptions of uniform space headways in queue, uniform acceleration, and constant reaction time are made.

$$T_n = \sqrt{2\left\{[S + H(n-1)]a\right\}} + RTS + (n-1)\,RTV \qquad (5)$$

where

RTS = signal perception-reaction time in seconds,
RTV = vehicle motion perception-reaction time in seconds,
H = space headway in queue in meters,
S = distance from first vehicle to screen line in meters, and
a = acceleration in meters per second squared.

The queue discharge headway (ΔT_n) represents the difference in queue discharge times of the nth and (n - 1)th vehicle and is given by

$$\Delta T_n = RTV + \sqrt{(2/a)}\left[\sqrt{S + H(n-1)} - \sqrt{S + H(n-2)}\right] \qquad n > 1$$

$$\Delta T_n = RTS + \sqrt{2S/a} \qquad n = 1 \qquad (6)$$

Figure 10 shows this relationship for the following representative parameters: RTV = RTS = 1.5 s, a = 1.8 m/s² (6 ft/s²), and H = 6.1 m (20 ft). The generic resemblance to Berry's data is apparent.