

# Study of Headway and Lost Time at Single-Point Urban Interchanges

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The results of a recent study of the headway and lost time at three single-point urban interchanges (SPUIs) are summarized. The data base, containing more than 38,000 headway observations, was collected primarily in the Tampa, Florida, area. The data were used to calculate the minimum discharge headway and start-up lost time for the SPUI's three basic movements: cross road left-turn, off-ramp left-turn, and cross road through. It was found that traditional procedures for estimating the minimum discharge headway may be biased toward values higher than ultimately achieved by the traffic queue. Moreover, the degree of bias varied widely among the movements and sites studied because of unequal numbers of observations. As a result, initial attempts at a cause-and-effect analysis were clouded by a high degree of variability in the data. In recognition of the aforementioned bias, alternative statistical analysis techniques and regression models were used to identify significant effects and to calibrate predictive models of minimum discharge headway and start-up lost time. The results indicate that the minimum discharge headway of the SPUI's two left-turn movements are significantly lower than its through movements and lower than values traditionally used for protected left-turn movements under "ideal" conditions. In fact, the calibrated models predict minimum discharge headways that are generally lower, and start-up lost times that are higher, than those calculated by traditional procedures. Left-turn headway was also found to vary with turn radius.

Within the past two decades a new type of interchange, the single-point urban interchange (SPUI), has emerged in response to increasing urban traffic demands. In some ways this new interchange (shown in Figure 1) is similar to a diamond interchange, and in other ways it is similar to a high-type at-grade signalized intersection. The most distinctive feature of this interchange is the convergence of all through and left-turn movements into a single, signalized conflict area. The advantage of this feature is that all movements can be served by a single signal with, at most, one stop required to clear the intersection. In contrast, a diamond interchange requires two separate signalized junctions (one for each on/off ramp), which presents the possibility of being stopped twice while traveling through the interchange.

Messer et al. (1) indicate that the SPUI design was first considered in the United States in the mid-1960s and that the first SPUIs were constructed in the early 1970s. Messer et al. (1) also cite evidence that several European countries also constructed SPUIs in the early 1970s. To date, there are only about 40 operational SPUIs in the United States.

This paper summarizes a portion of the results of a larger study of the operational efficiency of the SPUI (2). In particular, this paper describes the statistical analysis of headway

and lost time data collected at three SPUIs. The analysis identifies and quantifies factors affecting the discharge headway and lost time of SPUI traffic queues; it also compares the SPUI data with similar data collected at two at-grade intersections (AGIs).

## BACKGROUND—CHARACTERISTICS OF SIGNALIZED JUNCTIONS

### Discharge Headway

Soon after the start of the signal phase, a traffic queue begins to discharge past the stop line. The time headways between vehicles are initially large but eventually they converge to a minimum discharge headway ( $H$ ). The basic trend of convergence to a relatively constant, minimum headway is recognized in the 1985 *Highway Capacity Manual* (HCM) (3, Chapter 2). Calculation of the minimum discharge headway is typically accomplished by averaging the headways of those queue positions that are relatively constant. In this regard, the 1985 HCM suggests that a constant headway is reached by the fifth queue position. Thus, the minimum discharge headway is calculated by averaging headways for the fifth and subsequent queue positions.

Another commonly used term to describe the service time of a traffic queue is saturation flow rate. Saturation flow rate is calculated as  $3,600/H$  and has units of vehicles per hour green per lane (vphgpl). Under ideal operating conditions (i.e., 12-ft lanes, all through vehicles, all passenger cars, level grade, no parking, and no pedestrian activity), the 1985 HCM (3, Chapter 9) recommends the use of 1,800 vphgpl for the saturation flow rate of a traffic lane at a signalized intersection, unless local field measurements prove otherwise. This value corresponds to a minimum discharge headway of 2.0 sec/veh.

In recognition of the difference between through and turning driver behavior, the 1985 HCM (3, Chapter 9) recommends a saturation flow rate for turn movements that is lower than that used for through movements. In particular, the 1985 HCM recommends that the saturation flow rates of right- and left-turn movements in exclusive lanes with protected phases be 85 and 95 percent, respectively, of the saturation flow rate for through movements. Similarly, the 1985 HCM recommends that dual-lane right- and left-turn movements be 75 and 92 percent, respectively, of the through saturation flow rate.

A recent study of the effect of radius on the saturation flow rate of turning vehicles was conducted by Kimber et al. (4).

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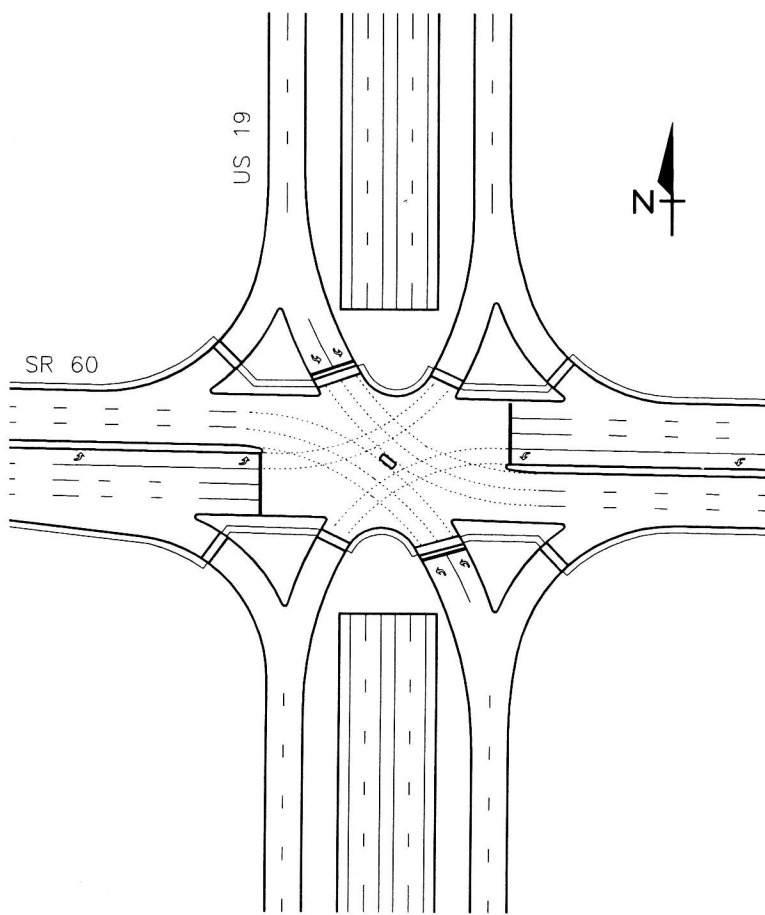


FIGURE 1 Typical geometric configuration of the SPUI.

On the basis of their research, Kimber et al. recommended the following relationship between radius and saturation flow rate for a left-turn movement:

$$S_t = \frac{2,080}{1 + \frac{4.92}{R}} \quad (1)$$

where  $S_t$  is saturation flow rate of a turn movement (vphgpl) and  $R$  is radius of curvature (feet).

**Start-Up Lost Time**

The first few vehicles in a traffic queue have headways in excess of the minimum discharge headway as their drivers accelerate to a desired speed. This excess time is commonly referred to as lost time because it represents time that is inefficiently used by the discharging traffic queue. Start-up lost time can be calculated by adding the individual lost time for these first few starting vehicles. The equation for start-up lost time is

$$K_s = \sum_{n=1}^N (h_n - H) \quad (2)$$

where

- $K_s$  = start-up lost time (sec/phase),
- $h_n$  = headway of the  $n$ th queued vehicle (sec),
- $H$  = minimum discharge headway (sec/veh), and
- $N$  = number of queue positions having headways larger than  $H$ .

Equation 2 indicates that the magnitude of start-up lost time is directly dependent on the value used for minimum discharge headway ( $H$ ).

As discussed previously, the 1985 HCM (3, Chapter 9) recommends that the minimum discharge headway be calculated as the average of the headways for the fifth through last queued vehicles. This approach implies that the first four vehicles incur all of the start-up lost time (i.e.,  $N = 4$ ). The 1985 HCM (3, Chapter 2) indicates that start-up lost time is generally about 2.0 sec/phase.

**EXPERIMENTAL DESIGN**

Headway and lost time for the three basic movement types found at the SPUI were examined. The basic movement types included the cross road left-turn movement, cross road through movement, and off-ramp left-turn movement.

## Study Sites

After a thorough review of candidate sites and consideration of all logistic and financial constraints, three SPUIs in the Tampa, Florida, area were identified for this study. All three SPUIs are located on an 8-mi section of US-19 in the Tampa-St. Petersburg area. US-19 is a heavily traveled, north-south thoroughfare that is being rebuilt to expressway standards. Two of the three SPUIs have been in operation for more than 15 years each, whereas the third has been open to the traffic for about 6 months (at the time of the study). Because the third site was located about midway between the two older sites, it was believed that the likelihood of having "first-time" drivers in the data set would be minimized.

Because one objective of this research was to identify the effect of SPUI geometry on selected traffic characteristics, it was decided that the field study should also include two typical, high-type AGIs for statistical control. One of the two AGIs is located in Florida, about 1 mi from the nearest SPUI. The second AGI selected for study is located on Wellborn Road in College Station, Texas. Details about each site are provided elsewhere (2).

## Data Collection System

The data collection system used for the field studies relied on a series of sensors strategically located around the interchange. One type of sensor used in the study to monitor vehicular motion was the tapeswitch. A tapeswitch is a plastic-encased pressure-sensing device placed flat on the roadway perpendicular to the direction of traffic flow.

Another type of sensor used was a light-sensitive switching device (photocell) that provides decreasing resistance to current flow as the intensity of light increases. Photocells were connected to the load switches inside the traffic signal controller cabinet and used to monitor the status of the signal indications.

These sensors were monitored by an Environmental Computer (EC) manufactured by the Golden River Corporation. This computer can monitor up to 24 sensors. When a circuit is closed because a vehicle passes or the signal indication changes, the EC records the number of the sensor and the time that it closed. This information is then uploaded to a portable personal computer (PC) for permanent storage. The EC can check the status of each sensor every 1/600 sec.

To collect the headway data for this study, a tapeswitch was located just past the point on the interchange approach where vehicles most frequently stopped (usually the stop line). For most sites, the tapeswitch was located about 3 ft beyond the stop line. Headways were measured relative to the back axle of each queued vehicle. A second tapeswitch was located about 50 to 150 ft downstream from the stop line tapeswitch (i.e., in the middle of the conflict area) to form a "trap" for obtaining vehicle speed.

## ANALYSIS METHODOLOGY

The statistical analysis methodology was composed of three tasks. First, the mean and standard deviation were quantified

for the headway and lost time data. Second, the factors affecting these variables were identified using analysis of variance (ANOVA) techniques and multiple comparison tests. Third, the effect of influential factors and model parameters were quantified using least-squares regression techniques.

All tasks of the analysis were conducted using the SAS System (5). The SAS System's general linear model (GLM) was used for the ANOVA because of its ability to provide statistics corrected for unbalanced data, that is, data with unequal sample sizes. The GLM effectively removes any confounding of factor effects due to differences in sample size (6). The significance tests for the ANOVA and regression modeling were based on a 95 percent confidence level ( $\alpha = 0.05$ ).

In general, the ANOVA model for each variable initially included factors for site, time of day, queue position, and traffic movement type. In addition, two measures of traffic pressure (queue length and total demand per cycle per lane) were independently examined as covariates.

## ANALYSIS RESULTS

Headways were collected for each of the basic movement types at three SPUIs and two AGIs. Headways were collected for 38,007 passenger vehicles at 5 through lanes and 17 left-turn lanes. The minimum discharge headway and start-up lost time, as calculated using the 1985 HCM procedure (3, Chapter 9), for each site and basic movement type are given in Tables 1 and 2. Because queues containing trucks were excluded from the data set, the values shown represent passenger car headways and start-up lost times.

### Initial Examination and Observations

Initial examination of the minimum discharge headways indicated some differences between the through movements at the SPUIs and AGIs. The SPUI through movement headways ranged from 1.97 to 2.13 sec/veh, whereas the AGI through movements ranged from 1.84 to 2.02 sec/veh. This suggests that drivers may not depart with the same efficiency at a SPUI as they would at an AGI; however, the wide range of observed headways at each junction type suggests that this trend may not be true for all AGIs and SPUIs.

Examination of the range of minimum discharge headways in Table 1 for the left-turn movements does not support the observation made in the preceding paragraph (i.e., there does not appear to be a difference in headway between junction types). The minimum discharge headways for the SPUI left-turn movements range from 1.81 to 1.96 sec/veh. This range completely embraces the range of headways found at the AGI left-turn movements (i.e., 1.90 to 1.91 sec/veh). In recognition of the relationship between saturation flow rate and radius recommended by Kimber et al. (4), the eight minimum headways in Table 1 were compared with radius, but no significant trend was found.

One interesting comparison that can be made from Table 1 is between the SPUI left-turn and through movements. The SPUI left-turn headways are, in all cases, smaller than the through movement headways. This trend is contradictory to

TABLE 1 Minimum Discharge Headway for the Basic Movement Types

Movement Type & Location	Cross Road Left-Turn			Cross Road Through			Off-Ramp Left-Turn		
	N	H	s	N	H	s	N	H	s
<b>SPUI:</b>									
US 19 & SR 60	2767	<b>1.84</b>	0.55	1406	<b>2.12</b>	0.70	913	<b>1.96</b>	0.60
US 19 & SR 686	750	<b>1.90</b>	0.54	1490	<b>1.97</b>	0.66	2770	<b>1.81</b>	0.57
US 19 & SR 694	<u>2985</u>	<u>1.90</u>	<u>0.57</u>	<u>1240</u>	<u>2.13</u>	<u>0.72</u>	<u>410</u>	<u>1.92</u>	<u>0.53</u>
SPUI Summary:	6502	<b>1.88</b>	0.56	4136	<b>2.07</b>	0.69	4093	<b>1.86</b>	0.58
<b>AGI:<sup>1</sup></b>									
SR 60 & Belcher Rd.	395	<b>1.91</b>	0.49	1306	<b>1.84</b>	0.62			
Wellborn & Old Main	<u>342</u>	<u>1.90</u>	<u>0.49</u>	<u>926</u>	<u>2.02</u>	<u>0.61</u>			
AGI Summary:	737	<b>1.91</b>	0.49	2232	<b>1.91</b>	0.62			

## Notes:

SPUI - Single-point urban interchange.

AGI - At-grade intersection.

1 - Statistics for the AGI correspond to the major road.

N - Number of observations.

s - Standard deviation, sec/veh.

H - Minimum discharge headway based on 1985 HCM procedure (i.e., the average of all observed headways for the fifth through last queue positions), sec/veh. The data include only passenger car headways (trucks were excluded).

TABLE 2 Start-Up Lost Time for the Basic Movement Types

Movement Type & Location	Cross Road Left-Turn			Cross Road Through			Off-Ramp Left-Turn		
	N	K <sub>s</sub>	s	N	K <sub>s</sub>	s	N	K <sub>s</sub>	s
<b>SPUI:</b>									
US 19 & SR 60	527	<b>2.76</b>	1.37	268	<b>2.01</b>	1.29	374	<b>2.42</b>	1.26
US 19 & SR 686	439	<b>2.19</b>	1.15	239	<b>2.02</b>	1.06	352	<b>2.80</b>	1.15
US 19 & SR 694	<u>614</u>	<u>2.50</u>	<u>1.20</u>	<u>293</u>	<u>2.23</u>	<u>1.24</u>	<u>202</u>	<u>2.19</u>	<u>0.99</u>
SPUI Summary:	1580	<b>2.50</b>	1.27	800	<b>2.09</b>	1.21	928	<b>2.52</b>	1.19
<b>AGI:<sup>1</sup></b>									
SR 60 & Belcher Rd.	167	<b>2.96</b>	1.33	142	<b>2.44</b>	1.15			
Wellborn & Old Main	<u>142</u>	<u>2.43</u>	<u>1.12</u>	<u>303</u>	<u>1.98</u>	<u>1.06</u>			
AGI Summary:	390	<b>2.71</b>	1.26	445	<b>2.13</b>	1.11			

## Notes:

SPUI - Single-point urban interchange.

AGI - At-grade intersection.

1 - Statistics for the AGI correspond to the major road.

N - Number of observations.

s - Standard deviation, sec/phase.

K<sub>s</sub> - Start-up lost time (based on the fourth queued vehicle's time of arrival at the stop line), sec/phase. The data include only passenger car arrival times (trucks were excluded).

that recommended by the 1985 HCM (3, Chapter 9). However, in support of this apparent trend, Poppe et al. (7) studied three SPUIs in Phoenix and also found the left-turn movement headways to be smaller than the through movement headways at two sites.

An initial examination of the start-up lost times in Table 2 was even less conclusive than the initial examination of minimum discharge headway. There does not appear to be any difference between the SPUI and AGI lost times, although the left-turn lost times appear to be larger than those of the through movements. In general, the left-turn movement start-

up lost times range from 2.19 to 2.96 sec/phase, whereas the through movement lost times range from 1.98 to 2.44 sec/phase. In comparing Tables 1 and 2, there is a trend toward larger start-up lost time for those movements with smaller minimum headways. This trend was anticipated because minimum headway is used in the calculation of start-up lost time (see Equation 2).

The results of this initial examination are helpful in that they present minimum headway and start-up lost time in a form that is comparable with other works using the widely adopted calculation procedure described in the 1985 HCM

(3, Chapter 9). However, the results are not totally satisfying because there are no obvious trends where trends are expected and, in one case, the trend found is contrary to recommended practice.

### Potential Bias in Headway and Lost Time Estimation

A closer examination of the data was undertaken to explore the causes of the wide variability in the tabulated results. This examination focused on the possibility that the method used to calculate minimum discharge headway had some inherent biases. In particular, headways averaged for each queue position indicated a trend toward decreasing values through the first 8 to 10 queue positions at most locations. This trend suggests that a minimum headway may not be achieved by the fifth queue position, as implied by the 1985 HCM procedure. Obviously, if the queue has not reached a minimum value by the fifth queue position, the minimum headway calculated using the HCM procedure would be biased toward a larger value than that ultimately achieved by the traffic queue.

This bias is further magnified when frequency of occurrence is considered. In this regard, the number of observed headways generally decreases with increasing queue position. As a result, the minimum headway calculated using the HCM procedure would be weighted toward the values observed in the lower queue positions. In effect, if headways for the lower queue positions are consistently larger than those of higher positions and if they are also observed with the greatest frequency, then the bias in the estimated average minimum headway will be even greater due to the unequal frequency of observations.

This bias will also affect the estimation of start-up lost time for two reasons. First, the minimum headway is needed to calculate start-up lost time (see Equation 2). A minimum headway biased toward a larger value will result in an estimated start-up lost time that is smaller than actually incurred. Second, the number of queue positions included in the sum ( $N$  in Equation 2) would need to include all of the positions that are incurring some added lost time because of start-up effects. If too few queue positions are included, the estimated start-up lost time would be biased toward a smaller value than actually incurred.

The magnitude of the potential bias resulting from the use of the 1985 HCM procedure is given in Table 3. The data in Column 1 represent an estimate of the minimum discharge headway with most of the bias by queue position (as magnified by unequal frequency) removed. This was accomplished by first averaging the headways for queue positions 13 and higher for the through movements. Positions 10 and higher were used for the left-turn movements because they tended to reach a minimum headway sooner than the through movements. These averages-by-queue-position were then averaged to yield the values given in Column 1. To add stability to the estimates, only queue positions having 20 or more observations were considered. Because of these restrictions, only 4 of the 5 through lanes and 6 of the 17 left-turn lanes had enough observations to calculate a minimum discharge headway by this procedure.

A comparison of Columns 1 and 2 in Table 3 (shown in Column 3) indicates that the 1985 HCM procedure always

overestimates the minimum discharge headway. Moreover, the overestimation appears to be greater for the left-turn (0.13) than the through (0.06) movements. The error over all movements and sites ranges from 0.02 to 0.20 sec/veh.

In some cases, this bias may not be large enough to compromise the results of a capacity analysis; however, it does tend to cloud any statistical analysis of cause and effect by introducing added variability in the data set. As a result, the true effect of a treatment or factor (e.g., lane width, percent trucks, etc.) may be obscured by data from sites having different amounts of bias by queue position and a different frequency of observations at each position.

### Factors Affecting Discharge Headway

Several precautions were taken to eliminate effects that might confound the analysis of discharge headway. To minimize differences in driver acceleration for the first few queue positions, the ANOVA tests only considered headways for the fifth and higher queued vehicles. In addition, the ANOVA tests included queue position as a blocking factor to preclude any bias that might be introduced by the different queue lengths found at each site. By "blocking" on queue position, all of the ANOVA comparisons are made on a queue-position-by-queue-position basis, thereby eliminating any bias by queue position. The data set used in the ANOVA analysis consisted of the individual passenger car headways recorded at each site for each movement studied, not the averages in Table 1.

One of the most interesting findings of the ANOVA tests is the significantly smaller headways of the SPUI left-turn movements compared with the SPUI through movements ( $p = 0.001$ ). This trend is contrary to the relationship suggested by the 1985 HCM (3, Chapter 9). Possible reasons for the lower left-turn headways at SPUIs are (a) a heightened awareness of left-turn (relative to through) drivers, (b) the ability of left-turning drivers to see preceding drivers in the queue complete the turn and thus anticipate the correct turn path, and (c) the provision of lane markings through the interchange for the left-turn (but not the through) movements at SPUIs. The trend toward smaller left-turn headways was also observed by Poppe et al. (7) at two of the three SPUIs they studied.

The ANOVA tests also indicated that the through movement headways at the SPUIs are significantly larger than those at the AGIs ( $p = 0.001$ ). An explanation for the larger through movement headways found at the SPUIs may be the extra caution exercised by drivers when entering the rather lengthy conflict area associated with the SPUI. Time of day was not found to have a significant effect on discharge headway.

The effect of traffic pressure was examined by considering both traffic volume per cycle per lane and queue length per cycle. Both measures were found to be significant; however, lane volume per cycle accounted for considerably more of the total sum of squared deviations from the mean ( $SS_v = 26.9$ ,  $p_v = 0.001$ ;  $SS_q = 15.0$ ,  $p_q = 0.001$ ). As a result, lane volume per cycle was determined to be the strongest measure of traffic pressure.

Increased traffic pressure was found to decrease headways at all queue positions. This trend is shown in Figure 2 for queue position five of the through movement at the Belcher

TABLE 3 Comparison of Different Methods of Estimating Minimum Discharge Headway

Move- ment	Site	Turn Radius, R (ft)	Traffic Pressure, v (vpchl)	Minimum Discharge Headway, sec/veh				
				Average by Posn. (1)	5th to Last (2)	Diff. (2)-(1) (3)	Equs. 4 & 6 (4)	Diff. (4)-(1) (5)
Thru	SR 60		10.3 <sup>a</sup>	2.06 <sup>b</sup>	2.12 <sup>c</sup>	0.06	2.00 <sup>d</sup>	-0.06
	SR 686		10.6	1.95	1.97	0.02	1.99	0.04
	SR 694		9.7	2.00	2.13	0.13	2.00	0.00
	Belcher		14.8	<u>1.82</u>	<u>1.84</u>	<u>0.02</u>	<u>1.73</u>	<u>-0.09</u>
		Average:		1.96	2.02	<b>0.06</b>	1.93	<b>-0.03</b>
		Standard Deviation:		0.10	0.14	<b>0.07<sup>e</sup></b>	0.13	<b>0.06<sup>e</sup></b>
Left	SR 60	180	8.3	1.69	1.82	0.13	1.79	0.10
		180	8.4	1.76	1.87	0.11	1.79	0.03
	SR 686	260	13.3	1.70	1.78	0.08	1.70	0.00
		275	8.5	1.82	1.97	0.15	1.76	-0.06
	SR 694	280	6.7	1.85	1.97	0.12	1.78	-0.07
		230	9.1	<u>1.66</u>	<u>1.86</u>	<u>0.20</u>	<u>1.76</u>	<u>0.10</u>
		Average:		1.75	1.88	<b>0.13</b>	1.76	<b>0.01</b>
		Standard Deviation:		0.08	0.08	<b>0.14<sup>e</sup></b>	0.03	<b>0.07<sup>e</sup></b>

Notes:

- a - Average traffic pressure for study period.
- b - Average minimum discharge headway calculated by first averaging the observed headways for each queue position. Then, the average of these averages-by-queue-position was calculated and is shown above. For through movements, this procedure considered average headways for queue positions 13 and higher ( $H_{13}$ ,  $H_{14}$ ,  $H_{15}$ , etc.). For left-turn movements, queue positions 10 and higher were considered because of a tendency to reach a minimum value at lower queue positions. Only those queue positions having 20 or more observations were considered. The number of queue positions included in the averages shown ranges from 3 to 14.
- c - Minimum discharge headway based on the 1985 HCM procedure (i.e., the average of all observed headways for the fifth through last queue positions).
- d - Minimum discharge headway predicted by Equations 4 and 6.
- e - Standard error, calculated as:  $s = \sqrt{(\sum \text{diff}^2) / n}$ .

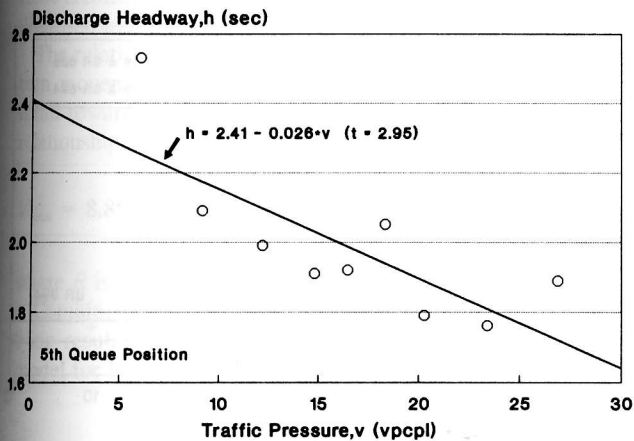


FIGURE 2 Discharge headway as a function of traffic pressure.

AGI. The data points in this figure represent the average of 15 observations each; however, the equation shown was determined from a regression analysis of the individual observations. As indicated by the *t*-statistic, the trend was highly significant ( $p = 0.004$ ). This finding is consistent with that of Stokes et al. (8) and Lee and Chen (9).

Other factors considered in the ANOVA tests include lane width and dual-versus-single-lane left-turn operation. Lane widths ranged from 10 to 18 ft with a median of 12 ft. The wider lane widths were found on the single-lane off-ramp left-turn bays. On the basis of this analysis, it was found that neither lane width nor number of left-turn lanes has a significant effect on headway at the five study sites ( $p_w = 0.110$  and  $p_n = 0.303$ , respectively).

#### Headway Model Development

As shown elsewhere (2), a linear speed-based acceleration model can be used to describe the dynamics of a starting traffic

queue. This model was extended to the discharge headway process, which led to the development of a discharge headway model that is sensitive to driver perception-reaction time, queue position, and vehicle speed.

Calibration of the discharge headway model was based on a least-squares regression of discharge headways averaged by site and queue position. Because the number of headways recorded varied widely among these factors, the headway data were averaged to remove the bias that an unequal sample size would have on model parameters. As a result, the statistics used to assess model fit to the data (i.e., standard deviation and  $R^2$ ) do not reflect the total variability in individual driver headways. Rather, these statistics indicate the ability of the model to predict the average discharge headway by queue position.

The calibrated discharge headway model is

$$h_n = \tau' * N_1 + T' + \frac{d'}{V_{max}} + b_3 * \left( \frac{V_{sl(n)} - V_{sl(n-1)}}{A_{max}} \right) + b_4 * v + b_5 * AGI \quad (3)$$

The model parameters are as follows:

- $\tau'$  = regressed additional response time of the first queued driver (sec),
- $T'$  = regressed driver starting response time (sec),
- $d'$  = regressed distance between vehicles in a stopped queue (ft),
- $V_{sl(n)}$  = stop line speed of the  $n$ th queued vehicle (fps),
- $V_{max}$  = common desired speed of queued traffic (fps), and
- $A_{max}$  = maximum acceleration (fpss).

The model variables are as follows:

- $h_n$  = headway of the  $n$ th queued vehicle (sec);
- $n$  = queue position,  $n = 1, 2, 3, \dots$ ;
- $v$  = traffic pressure (veh/cycle/lane);
- $N_1$  = indicator variable (1 for first queue position; 0 for all others); and
- AGI = indicator variable (1 for AGI, 0 for SPUI).

Regression results for through movements are as follows:

Parameter	Parameter Value	t-statistic
$\tau'(b_0)$	1.03	17.7
$T'(b_1)$	1.57	4.6
$d'(b_2)$	25.25	1.7
$b_3$	0.357	8.2
$b_4$	-0.0086	1.6
$b_5$	-0.23	4.3
Variable	Minimum Value	Maximum Value
$n$	1	18
$v$	0.0	16.8
$h$	1.6	3.8
Observations:	164	
Std. Deviation:	0.16	
$R^2$ :	0.88	

Regression results for left-turn movements are as follows:

Parameter	Parameter Value	t-statistic
$\tau'(b_0)$	0.76	14.5
$T'(b_1)$	1.58	20.5
$d'(b_2)$	9.82	4.8
$b_3$	0.538	17.9
$b_4$	-0.0121	5.2
$b_5$	0.00	
Variable	Minimum Value	Maximum Value
$n$	1	24
$v$	0.0	18.3
$h$	1.3	4.0
Observations:	215	
Std. Deviation:	0.14	
$R^2$ :	0.94	

In general, the parameter values for  $b_0$ ,  $b_1$ , and  $b_2$  are consistent with the definitions of the theoretical model parameters to which they correspond (i.e.,  $\tau$ ,  $T$ , and  $d$ , respectively). Since these values do not, however, represent actual physical measurements, a prime symbol (') has been added to each model parameter to denote that its value was established using regression analysis and that the relationship between this value and the theoretical definition may be distorted.

The statistical analysis revealed that traffic pressure, as measured by lane volume per cycle, was significant in reducing discharge headway. In using this component of the headway model, a one-to-one relationship between the duration of the volume average and the predicted average headway must be maintained. In other words, a lane volume representing a 1-hr average should be used in the regression model to predict discharge headways during the same 1-hr period.

In general, the significance of the calibrated parameter values combined with the theoretical basis of the discharge headway model suggests that the model adequately describes the headway process of queued vehicles. This ability is shown in Figure 3, which compares the calibrated model with the data for two SPUI left-turn movements.

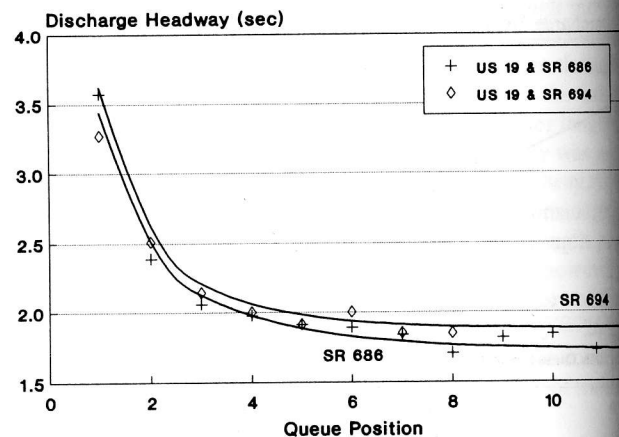


FIGURE 3 Discharge headway as a function of queue position

Figure 3 indicates that the predicted discharge headway does reach a relatively constant, minimum value after the eighth or ninth queue position for these particular movements. This trend suggests that the procedure recommended by the 1985 HCM for estimating the minimum discharge headway, if applied to these movements, would include queue positions that have not reached a minimum headway. As a result, the HCM procedure would result in estimates that are biased toward values larger than the minimum headways ultimately achieved.

*Minimum Discharge Headway Model*

As discussed previously, the minimum discharge headway is the constant headway reached by the traffic queue. Examination of Equation 3 indicates that a constant headway is not reached until the traffic queue reaches its common desired speed ( $V_{max}$ ), at which point the difference in stop line speeds (fourth term) equals zero. Furthermore, a study of the stop line speeds of the through movements indicated that  $V_{max}$  was relatively constant at 49.0 fps (2). As a result, Equation 3 can be simplified into the following model of minimum discharge headway for through movements:

$$H_{th} = 2.09 - 0.0086 * v_{th} - 0.23 * AGI \quad (4)$$

where

$H_{th}$  = minimum discharge headway for through movements (sec/veh),

$v_{th}$  = traffic pressure (veh/cycle/lane), and

AGI = 1 if the movement is at an AGI and 0 if it is at a SPUI.

Equation 4 implies that an AGI with a nominal through volume of 5.0 veh/cycle/lane should have an ideal minimum discharge headway of 1.81 sec/veh. This value suggests that the ideal minimum headway at these sites may be smaller than the 2.0 sec/veh recommended by the 1985 HCM (3, Chapter 9). Equation 4 also implies that the SPUI through movement headway is 0.23 sec/veh longer than that of the AGI. This trend is consistent with the findings from the ANOVA analysis discussed previously.

The relationship between turn radius and  $V_{max}$  for the left-turn movements studied indicated a statistically significant trend toward higher speeds on larger-radius turns (2). This relationship was quantified as

$$V_{max} = 8.85 * R^{0.245} \quad R^2 = 0.81 \quad (5)$$

where  $R$  is the radius of curvature (ft).

Combining this relationship with Equation 3 and simplifying results in the following minimum discharge headway model for left-turn movements:

$$H_{lt} = 1.58 + \frac{1.11}{R^{0.245}} - 0.0121 * v_{lt} \quad (6)$$

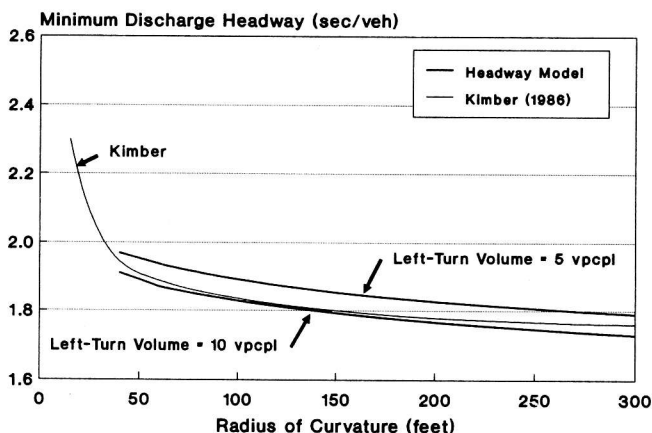


FIGURE 4 Minimum discharge headway of a left-turn movement as a function of curve radius.

where

$H_{lt}$  = minimum discharge headway for a left-turn movement (sec/veh),

$v_{lt}$  = traffic pressure (veh/cycle/lane), and

$R$  = radius of curvature (ft).

The relationship between radius and the minimum discharge headway for left-turn movements predicted by Equation 6 is shown in Figure 4. Figure 4 also shows the relationship between radius and headway predicted by Equation 1 (with proper conversion from saturation flow rate). For purposes of comparison, the headway model from this research is shown with a traffic pressure of 5 and 10 vehicles per cycle per lane. In general, the agreement appears to be good for the range of radii studied (i.e., 60 to 280 ft).

The ability of Equations 4 and 6 to predict the minimum discharge headway is shown in Table 3. A comparison of the predicted values in Column 4 with the average values in Column 1 indicates that the model is a better predictor than the 1985 HCM procedure. This ability is quantified in terms of the average difference and the standard error given in Column 5. These statistics indicate that the model predicts minimum headways closer to those in Column 1 (model: -0.03 throughs and 0.01 lefts versus HCM: 0.06 throughs and 0.13 lefts) and with less standard error (model: 0.06 throughs and 0.07 lefts versus HCM: 0.07 throughs and 0.14 lefts). Moreover, the model does not appear to have any bias toward overestimation, as does the 1985 HCM procedure.

*Start-Up Lost Time Model*

The theoretical start-up lost time can be calculated from the calibrated discharge headway model (Equation 3) and Equation 2 as

$$K_{s(th)} = 1.03 + 0.357 * \frac{V_{max}}{A_{max}} \quad (7)$$



$$K_{s(lt)} = 0.76 + 0.538 * \frac{V_{max}}{A_{max}} \quad (8)$$

where

$K_{s(th)}$  = start-up lost time for a through movement (sec/phase),

$K_{s(lt)}$  = start-up lost time for a left-turn movement (sec/phase), and

$A_{max}$  = maximum acceleration (equal to 6.63 fpss).

Driver acceleration data were also collected to validate the linear, speed-based acceleration model. Analysis of these data indicated that the acceleration profile of both the through and left-turn movements supported the use of a single value of  $A_{max}$  (2). This suggests that drivers initially accelerate in a similar manner, regardless of whether they are turning or traveling straight. This value of  $A_{max}$  was 6.63 fpss.

Equation 7 suggests that the start-up lost time for a through movement with  $V_{max}$  of 49 fps and  $A_{max}$  of 6.63 fpss is about 3.67 sec. This value is larger than the 2.0 sec suggested by the 1985 HCM (by about 80 percent) because it includes the lost time incurred by queue positions five and higher.

Combining Equation 5 with Equation 8 yields the following equation for estimating the start-up lost time for left-turn movements:

$$K_{s(lt)} = 0.76 + 0.718 * R^{0.245} \quad (9)$$

where  $K_{s(lt)}$  is start-up lost time for a left-turn movement (sec/phase) and  $R$  is the radius of curvature (ft). These start-up lost time relationships are not based directly on the data in Table 2. They were developed using the minimum discharge headway relationship in Equation 3. As a result, they should be used in conjunction with Equations 4 and 6.

## CONCLUSIONS AND RECOMMENDATIONS

This research found that traditional methods for estimating the average minimum discharge headway and start-up lost time may be biased toward values higher than ultimately achieved by the traffic queue. Moreover, the degree of bias varied widely among the movements and sites studied. As a result, initial attempts at a cause-and-effect analysis were clouded by a high degree of variability in the data.

In recognition of the aforementioned bias, alternative statistical analysis techniques and regression models were used to identify significant effects and to calibrate predictive models of minimum discharge headway and start-up lost time. On the basis of this research, it is recommended that statistical analyses of cause and effect in headway data use ANOVA techniques that account for unbalanced data (e.g., SAS System's general linear model) (6). It is also recommended that the ANOVA include queue position as a blocking factor.

Examination of the headway model components indicates that the minimum discharge headway may not always be reached by the fifth queue position. This suggests that traditional procedures for calculating the minimum discharge headway may not yield the value ultimately achieved by the traffic queue. It is recommended that minimum discharge headway be cal-

culated by first averaging headway observations by queue position and then averaging these averages-by-queue-position. Only those queue positions that appear to have stabilized at a constant value should be included in the overall average. Alternatively, the regression modeling approach described in this paper could be used.

The headway model calibration suggests that through movement headways at SPUIs are larger than those at AGIs (0.23 sec/veh larger for the SPUIs and AGIs studied). The SPUI through movements were also found to have minimum headways larger than those of the left-turn movements. The latter trend is supported by the results of another study (7); however, further studies are needed to fully verify these findings because they are so contrary to conventional trends found at AGIs.

Left-turn movement headways were found to vary with turn path radii. The larger radii of the SPUI left-turn paths resulted in minimum headways that are about 0.12 sec shorter (based on Figure 4) than those for the AGI left-turn paths. A comparison of this trend in left-turn headway with the results of other research (4) suggests that Equations 6 and 9 can be extended to other SPUIs and AGIs.

Traffic pressure, as measured by traffic volume per cycle, had a statistically significant effect on discharge headway. An increase in traffic pressure resulted in a decrease in discharge headway. This trend has been noted in other studies (8,9); however, all of these studies (including this study) are based on a small number of sites. In recognition of the potential significance and magnitude of this effect, it is recommended that traffic pressure be more fully examined in any future studies of discharge headway.

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