Detailed Observations of Saturation Headways and Start-Up Lost Times

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The analyses conducted in this research were based on three methodologies for the field measurement of saturation headways. The first method (M1), the one on which most past studies were based, measured the characteristics of Vehicles 4 to 12 in a standing queue. M2, the method found in the *Highway Capacity Manual* (HCM), counted all vehicles in a standing queue, regardless of queue length. M3 included arrivals that joined the standing queue as long as vehicles were up to 140 ft from the stop line. This study focused on one approach of a high-design intersection with heavy, random arrivals. The large number of observations and the practically ideal traffic conditions enabled the acquisition of several statistically significant results on saturation flow (*s*), start-up lost time (SULT), and start-up response time (SRT): (*a*) when long queues are present, the typical field measurement of *s* based on the first 12 vehicles is an overestimate of *s* for through vehicles and an underestimate of *s* for protected left-turning vehicles; (*b*) the type of movement had a more dominant role in determining *s* than the level of saturation (or queue length); (*c*) SRT displayed a bigger variation than headways—the left-turning movement had a significantly shorter SRT than the through movement did; and (*d*) much higher SULTs were estimated in this study compared with those in the HCM.

Saturation headways are typically estimated from field measurements of the elapsed time between the 4th and 10th to 12th vehicles in a queue (*1*). The results of these measurements have been used widely under two questionable assumptions:

1. The difference in saturation headway between a short queue and a long queue does not exist or is negligible, and
2. The average headway estimated from the first 4 to 10 or 4 to 12 vehicles is representative of long queues. Since in reality standing queues longer than 12 vehicles are ubiquitous, an analysis of discharge behavior was undertaken including start-up lost time (SULT) for short and long queues in order to obtain a clearer picture of the discharge process of long queues.

It has been observed that the last few vehicles in a long queue may produce compressed or elongated headways. Usually, compressed headways are observed when vehicles tailgate to achieve passage during the phase change interval. Elongation may be observed on long queues of through movements because by the time vehicles reach the stop line, speeds may exceed 40 mph, and longer headways are observed either because drivers increase their spacing for safety or because conservative drivers generate large gaps by driving at a lower speed. The larger spacings also increase the motorists' propensity to change lanes, which affects the discharge process of each lane. In addition, the evolution of headways along a queue is important in microsimulation because it often contains large fluctuations that affect both signal timings and throughput.

This study is based on one through-movement lane and one protected left-turn-movement lane; three methods for describing the discharge process of a standing queue at an approach of a signalized intersection are described. The first method (M1) is the one on which most past studies were based and entails measurements of headways based on the first 12 vehicles in a standing queue. The second method (M2) is the one found in the *Highway Capacity Manual* (HCM) and entails measurements of headways based on all vehicles in a standing queue (up to 28 vehicles in this case). By definition, M2 gives a more extensive picture of the queue discharge process. The third method (M3) extends M2 by including arrivals that join the standing queue; M3 extended measurements to 36 vehicles. Strictly speaking, M3 no longer measures saturation headways because vehicles added to the queue may not have come to a complete stop. However, M3 practically represents saturation headways resulting from "field arrivals." It gives a more complete picture of the discharge process and provides data for the development of a distribution of the discharge process.

The analyses presented in this paper attempt to validate existing knowledge and enrich it with data produced from long queues at a busy signalized intersection. Specific questions answered herein include the following:

- Are saturation headways derived by methods M1, M2, and M3 significantly different?
- If so, what is the implication of these differences?
- Do selected intermediate headways vary with respect to the size of the queue?
- What roles do the turning movement and saturation condition play in determining headway?
- Is there an elongation or compression of headways for the last vehicles in queue?
- If there is an elongation or compression, is it the same for through and protected left-turn movements?
- Is the SULT affected by length of queue (which may serve as a proxy for the amount of prevailing congestion)?
- What is the distribution of SULTs and headways?

BACKGROUND

According to HCM 2000, the fifth vehicle in a standing queue is the ending point for estimating SULT and the starting point for estimating saturation headway. The saturation headway is estimated by averaging the headways from the fifth vehicle to the last vehicle in

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a standing queue. HCM 1994 suggests a base saturation flow rate of 1,800 passenger cars (pc)/h/ln, which corresponds to a saturation headway of 2 s. HCM 1997 and 2000 suggest a base saturation flow rate of 1,900 pc/h/ln, which corresponds to a saturation headway of 1.895 s.

The saturation flows suggested in the HCM 1994 for protected left turns translate into saturation headways equal to 2.11 and 2.17 s for single and dual exclusive lanes, respectively. A saturation headway of 2 s, which corresponds to a saturation flow rate of 1,800 pc/h/ln, is mentioned in the HCM 2000; there is no differentiation by number of lanes.

The SULT can be derived by measuring the elapsed time for the first four vehicles, including the start-up response time (SRT) of the first vehicle, and adjusting it with the average saturation headway. HCM 2000 mentions that typical observed values range from 1.0 to 2.0 s. No SULT for protected left-turn movements is mentioned in either HCM 1994 or 2000 (*1, 2*).

Several studies are concerned with the definition and measurement of saturation headway and SULT in the HCM. Teply and Jones (*3*) indicated that the HCM, the *Canadian Capacity Guide for Signalized Intersections,* and an Australian Road Research Board special report have a similar definition and measurement method for saturation headway. Bonneson (*4*) developed a discharge headway model based on SRT for all subsequent drivers in the queue, distance between vehicles in a queue, speed of queued vehicles at the stop line, desired speed of traffic, and maximum acceleration. This model, however, is sensitive to variables that are hard to measure. Niittymaki and Pursula (*5*) used both the HCM and simulation to update Finland's basic saturation flow values. Their estimate for the ideal saturation flow for through lanes was 1,940 pc/h/ln, corresponding to a saturation headway of 1.86 s.

Queue length may affect saturation flow because the discharge headway may increase when a long green is displayed (*6*). This effect implies that saturation headways estimated from long queues may be lower than those estimated from the first 10 to 12 vehicles. In studying headways and lost time at single-point urban interchanges, Bonneson (*4*) indicated that traffic pressure (lane volume and queue length per cycle) has a negative effect on the saturation headway of the first 12 vehicles, which implies that the saturation headway of the front part of a long queue is smaller because of the higher traffic pressure of a long queue.

The distribution of headways has not been examined in detail in the literature. Some studies based on observed data have not been sufficiently rigorous. There are, however, some simple distributions in stochastic models, for example, decile distribution in NETSIM (*7*). Thus, an examination of distributions of the SRT and headways was undertaken and is presented herein.

METHODOLOGY

Figure 1 details the flow of tasks for the research described here. It consists of three major layers: data collection and basic data manipulation form the top layer; research questions to be addressed form the middle layer; and statistical analyses, tests, and answers are provided in the third layer. There are also three levels of complexity for several of the analyses: by method (M1, M2, and M3); by movement, through (TH) and left turn (LT); and by measure (*h*, SRT, and SULT).

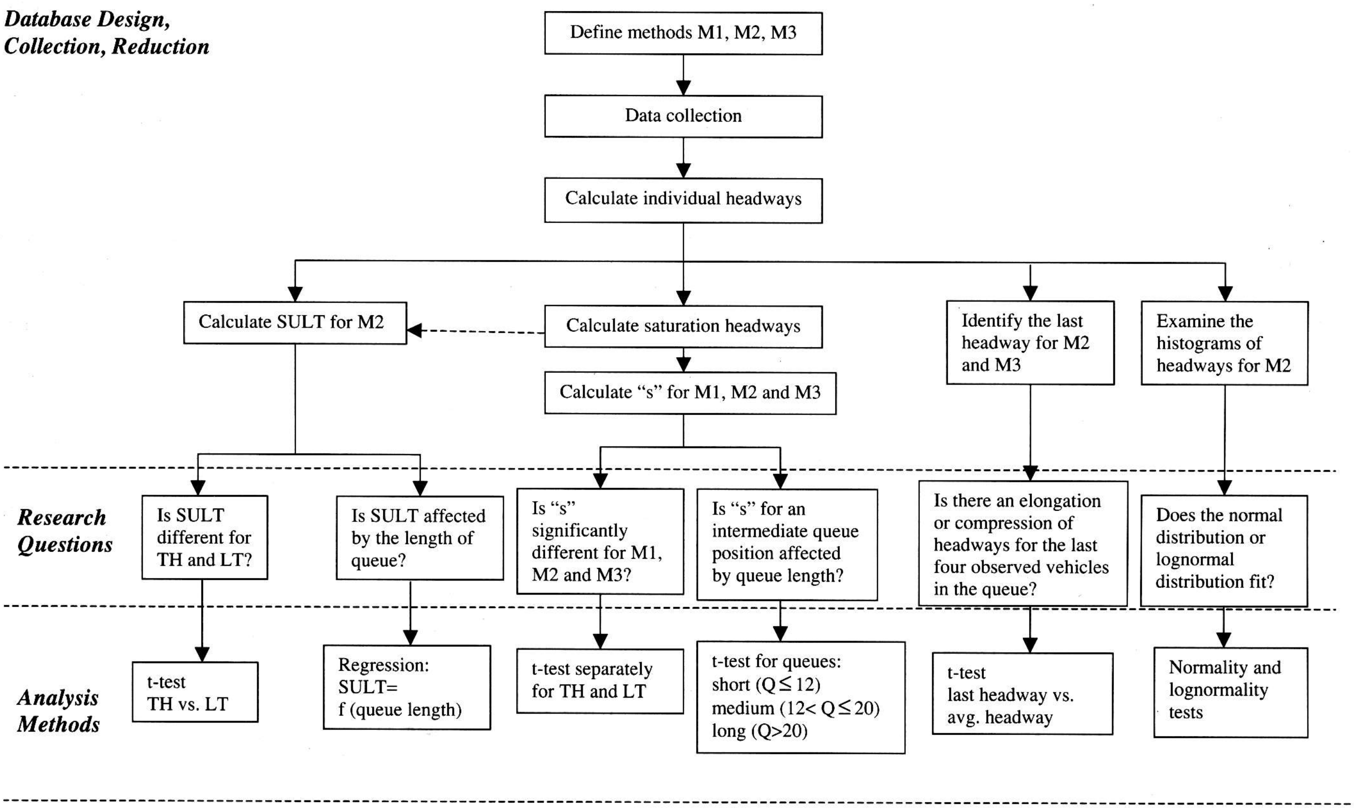


FIGURE 1 Research methodology.

Site Description

The Vineyard Boulevard approach at the signalized intersection with Punchbowl Street in downtown Honolulu, Hawaii, was the site of data collection. It was selected for the following reasons:

- It is a typical example of a high-design arterial. It is fully actuated with a downstream signalized intersection 750 ft away. The subject approach has five lanes: all lanes have two detectors before the stop line, and the three through lanes have additional advance detectors 140 ft before the stop line. Three signal phases provide green for the subject movements as shown in Figure 2.
- This intersection approach is representative of heavy traffic flow in a typical central business district fringe or crowded suburban location. The traffic is composed almost exclusively of daily commuters. The proportion of large vehicles is lower than 3%.
- A large amount of data was available, specifically, five videotapes with 40 h of data from a well-oriented and focused traffic surveillance camera. At the time of the tapings, this approach was supplied not only by a very busy two-lane freeway off-ramp [e.g., >2,000 vehicles per hour (vph)] but also by a heavily loaded (e.g., >1,600 vph) upstream on-ramp, which was diverted to this approach as part of a ramp-closure experiment. This setup generated a unique opportunity to study heavy, randomly arriving flows at a signalized approach during typical weekday commuting periods.

The through lane (*TH* in Figure 2) and one exclusive left-turn lane (*LT* in Figure 2) were selected for this study because their operation can be considered to be practically ideal (standard lane width, no significant grade, no bus stops, no parking, etc.) Although a few heavy vehicles were present, queues with heavy vehicles were dropped from the final analysis. The specific through lane was selected because it was the busiest. The other left-turn lane was excluded from the analysis because it contains a considerable number of U-turn movements.

The data were manually collected from the videotapes between the times of 6:00 and 10:00 a.m. The operation of the through movement varied between undersaturation and near-saturation, whereas for the left-turn movement, traffic became oversaturated shortly after 7:00 a.m. because of the absence of advance detectors.

Survey Methods

This study was designed to be consistent with the field measurement for saturation flow in the HCM: it was considered that a vehicle was discharged when its rear axle passed the stop line. It was determined that other reference points such as the front bumper or the front axle of a vehicle were not appropriate because a number of vehicles stopped partially past the stop line. The first author collected all the data from the videotapes; this minimized biases due to different perceptions of multiple observers. The authors were aware that instrument errors were unavoidable; for example, the speed of the videotape being played may produce a small error. In comparing 90 min of tape playing with a digital chronometer and the precise timer imprinted on the surveillance tape of the traffic control center, a less than 1-s error was observed. This minute error is constant in the comparison of M1, M2, and M3 database statistics and does not on affect the results.

The SRT of the first vehicle in queue and the subsequent headways were measured on a cycle-by-cycle basis as follows:

- The SRT of the first vehicle is the elapsed time from the display of the green to the time when the first vehicle begins to move. The SRT for the TH was measured from 6:00 to 10:00 a.m. For the

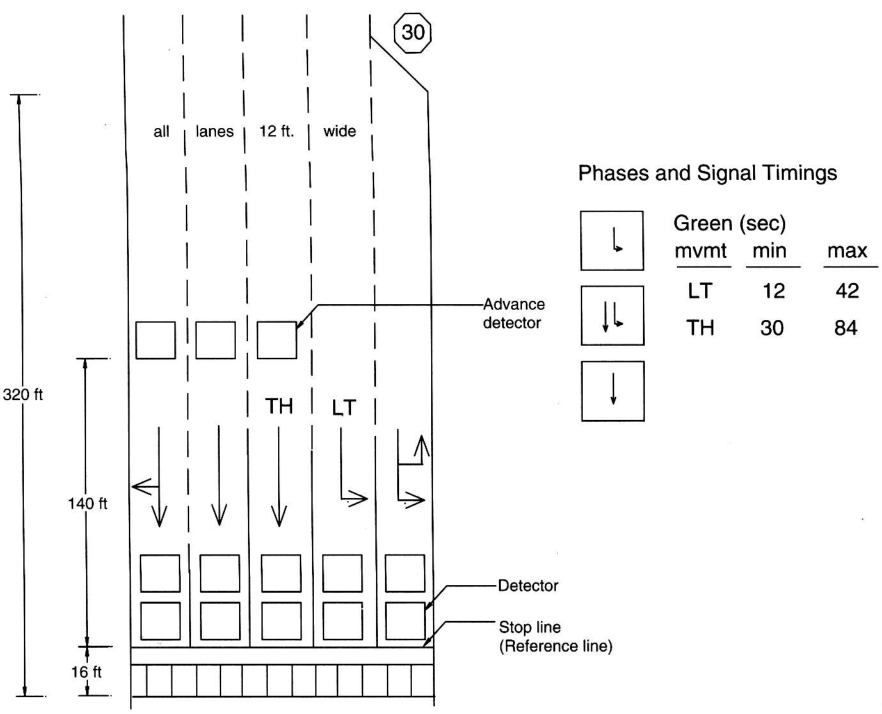


FIGURE 2 Geometric and signal characteristics of study approach.

protected LT, it was measured from 6:00 to 7:30 a.m. because the display of the LT green was obscured by the glare of sunlight.

- For subsequent headways, the stopwatch was started when the first vehicle in queue began to move, and the time when every fourth vehicle's rear axle passed the stop line was recorded (e.g., the elapsed time for the fourth, eighth, . . . , Nth vehicle was recorded). An assistant to the measurer recorded the spoken stopwatch readings. The measurement stopped when the following events occurred:
  - The rear axle of the last vehicle in a standing queue passed the stop line. Queues up to 28 vehicles were measured for TH. Queues up to 20 vehicles were measured for the protected LT. The total set of headway measurements formed the M2 database, and the set of the headways for the first 12 vehicles formed that for M1.
  - The rear axle of a newly arriving vehicle passed the stop line and there were no other new arriving vehicles between the stop line and the advance detector (a distance of 140 ft or 2.4 s at 40 mph). This measurement was conducted for TH only, and queues up to 36 vehicles were measured. This measurement produced the M3 database.

Observations containing fewer than four vehicles at the end of a queue were not included.

Calculation of Headways and SULT

The individual headways were calculated as follows:

$$H_1 = SRT + H_4 \tag{1}$$

$$H_i = \frac{T_i - T_{i-4}}{4} \tag{2}$$

where

i = queue position, $i = 4, 8, \ldots, 36$;
SRT = starting response time of first vehicle;
H_i = average headway from $(i - 3)$ to (i) vehicles;
T_i = time recorded when the rear axle of vehicle (i) passed the stopline, $T_0 = SRT$.

Headways were measured for groups of four vehicles not only because measurement errors were relatively smaller (e.g., a 0.2-s error in a 1.6-s individual headway measurement is much larger than the same error in a 7-s four-vehicle headway measurement) but also because these measurements are consistent with the four-vehicle step procedure in the HCM.

The saturation headway (h) is obtained by averaging headways beyond the first four vehicles:

$$h = \frac{T_N - T_4}{N - 4} \tag{3}$$

where N is the last vehicle in a queue, $N = 8, \ldots, 36$.

The saturation flow rate (s) is

$$s = 3600/h \tag{4}$$

SULT is the sum of the SRT of the first vehicle in the queue and the additional time it took the first four vehicles to discharge. The latter is estimated by taking the difference between H_4 and the saturation headway (h). Thus,

$$SULT = SRT + 4 * (H_4 - h) \tag{5}$$

SATURATION HEADWAY

A number of statistical comparisons were made to answer the questions set as the objectives of this study. The statistical significance level used throughout is 5%.

The number of observations for SRT and headways for each measuring method is shown in Table 1, and the number of observations for queues is shown in Table 2. The saturation headways (h) were first obtained for M1, M2, and M3, and then saturation flow rates (s) were derived using Equation 4. The results are shown in Table 3. The three measurement methods, M1, M2, and M3, generated three databases, which are also referred to as M1, M2, and M3.

Two-way t-tests between the h estimates for the TH movement by M1, M2, and M3 showed that all were significantly different from each other. M1 produced a saturation headway of 1.90 s, close to that in the HCM 2000. The significantly larger h by M2 indicates that long queues do not discharge as efficiently as short queues, which was also observed by Teply et al. (*6*). The h by M3 may be the most appropriate value for determining the saturation flow rate because it represents the complete discharge of entire queues, including arrivals that join the queue. It corresponds to a saturation flow rate of 1,818 pc/h/ln.

The means and standard deviations of SRT and h by M2 are displayed in Figure 3*a* and *b* for TH and protected LT, respectively. Note that the results (Table 1) for SRT, H_4, H_8, and H_{12} for M2 are

TABLE 1 Basic Data Analysis: Number of Observations

Movement	TH			LT	
Database	M1	M2	M3	M1	M2
SRT	354	354	865	342	342
H_4	344	344	850	975	975
H_8	312	312	811	892	892
H_{12}	261	261	734	649	649
H_{16}	--	189	613	--	408
H_{20}	--	110	427	--	212
H_{24}	--	63	263	--	--
H_{28}	--	42	202	--	--
H_{32}	--	--	155	--	--
H_{36}	--	--	84	--	--

NOTE: Lower SRT for LT is due to signal glare.

TABLE 2 Basic Data Analysis: Number of Observations and Basic Statistics by Queue Size

Movement	TH			LT	
Database	M1	M2	M3	M1	M2
Short queue (Q≤ 12)	155	155	237	567	567
Medium queue (12<Q≤ 20)	--	126	350	--	408
Long queue (Q>20)	--	63	263	--	--
Mean	9.0	15.9	19.5	9.1	12.9
Std. dev.	3.12	8.09	8.9	2.81	5.12
Minimum	4	4	4	4	4
Maximum	12	28	36	12	20

identical to the results for M1. Headways for the protected LT decrease as the queue position increases. A possible reason for the decreasing headway trend is that motorists are aware of the limited duration of the LT arrow and tailgate in order not to miss the cycle. This behavior is often observed in oversaturated conditions. (The signal allows only protected LTs.)

Another interesting finding was that measurements for both movements showed that the minimum headway was not reached until the 9th to 12th vehicle instead of the 5th vehicle as implied in the HCM. The fact that the minimum headway is reached at a higher queue position was also observed by Bonneson (*8*). The means and standard deviations of SRT and *h* of M3 are shown in Figure 3*c*. Means and standard deviations of headways after the 12th vehicle increased when measured by M3 because of the inclusion of vehicle arrivals joining the standing queue.

The *t*-test for the protected LT showed that *h* by M2 was significantly smaller than *h* of M1 because of the decreasing trend of headways shown in Figure 3*b*. This statistically significant difference indicates that queues of medium length discharge more efficiently than do short queues.

Inspection of saturation flow rate by queue position in Figure 4 gives a clearer picture. For TH of M2 in Figure 4*a*, the saturation flow rate reached a maximum between Vehicles 9 and 12 and decreased slightly after the 12th vehicle. The saturation flow rate of 1,900 pc/h/ln suggested by the HCM 2000 fits well for queue positions 5 to 20. However, after the 20th vehicle, which corresponds to a green time longer than 40 s, the 1,900 pc/h/ln is an overestimate. All saturation flow rates are less than 1,900 pc/h/ln for TH of M3, and the magnitude of the difference is considerable after the 20th vehicle.

These findings have important implications for

1. Capacity analysis because the actual *s* is likely to be considerably lower than the input *s* when long greens and long cycles prevail (the subject intersection operates in a 160-s cycle);
2. Signal timing analysis because the findings support the scattered evidence in the literature that overlong greens and cycles are unproductive; and
3. Microsimulation, for similar reasons of accuracy as those in Item 1.

In contrast to the findings for TH, saturation flow rates for the protected LT of M2 continued to increase significantly as shown in Figure 4*b*. After the first 12 vehicles, the saturation flow rate remained well above 1,800 pc/h/ln. This finding may serve as evidence that "tight" signal timings may act as queue condensers with major benefits in terms of hourly throughput. It should be noted that after the 16th vehicle in queue, the saturation flow rates of the protected LT were larger than those for TH.

ANOVA tests were conducted for H_8 and H_{12} estimates for short queues, medium queues, and long queues, separately for databases M2 and M3 and for TH and LT. H_8 and H_{12} for both movements were not significantly affected by queue length (M2 data). There was also no significant difference between medium and long queues (M3 data). Similar results were observed by Bonneson (*4*), who found that queue size was not a strong measure of traffic pressure to the headways for TH.

HEADWAY ELONGATION OR COMPRESSION

In order to investigate the potential elongation or compression, only headways after the 12th vehicle were examined. The last headway was compared with the average headway of the queue excluding H_4. The results of a *t*-test are shown in Table 4. For TH of M2, the tests showed that the observed last headway was not significantly different from the preceding average headway. These observations are consistent with the HCM, in which it is essentially assumed that the saturation headway remains stable until the end of a standing queue.

TABLE 3 Basic Data Analysis: Analysis by Movement and Database

Movement	Database	*h* (s)	Std. dev. (s)	Observations	s (pc/h/ln)
TH	M1	1.90	0.21	312	1895
	M2	1.92	0.20	312	1875
	M3	1.98	0.22	811	1818
LT	M1	2.04	0.23	892	1765
	M2	2.01	0.23	892	1791

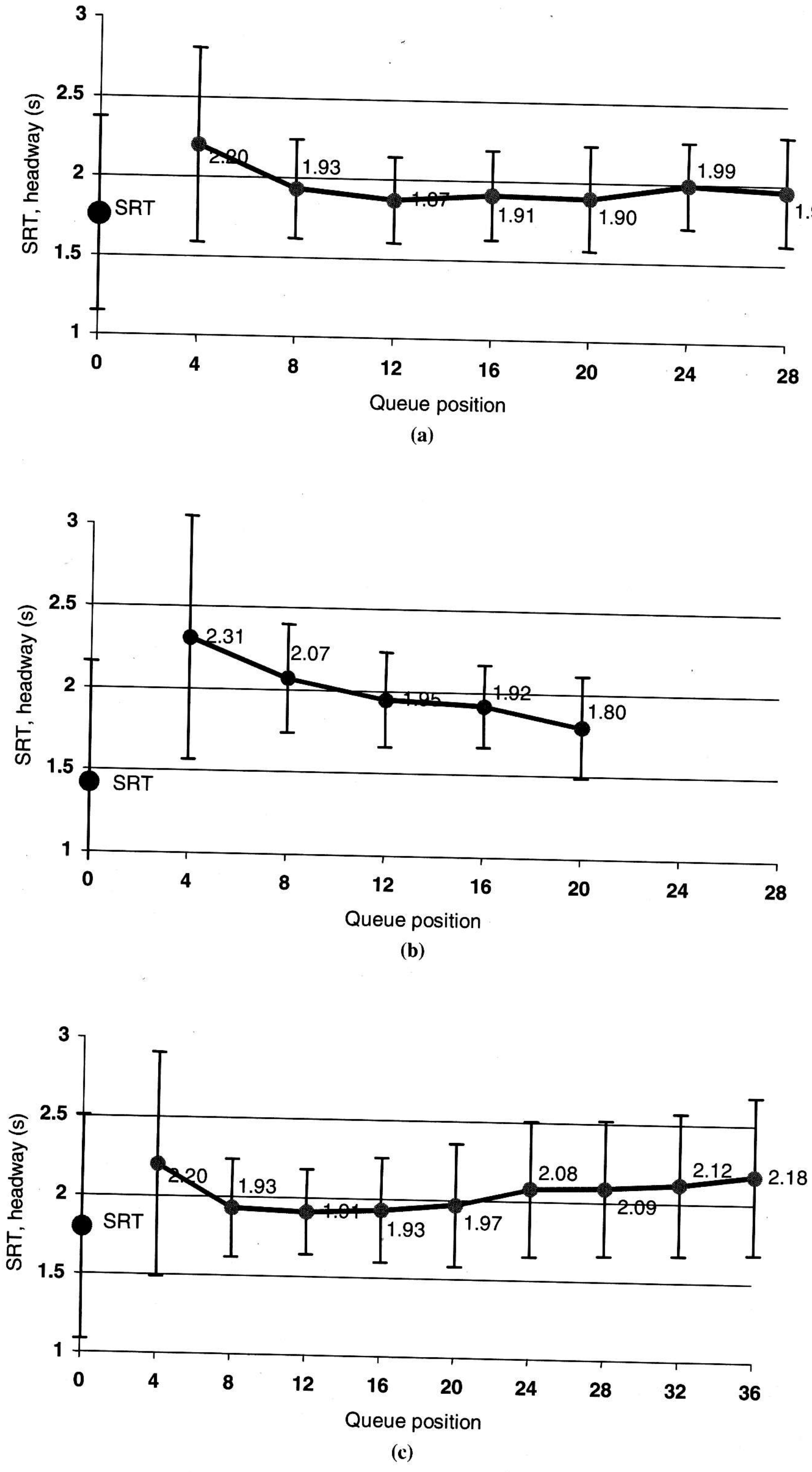
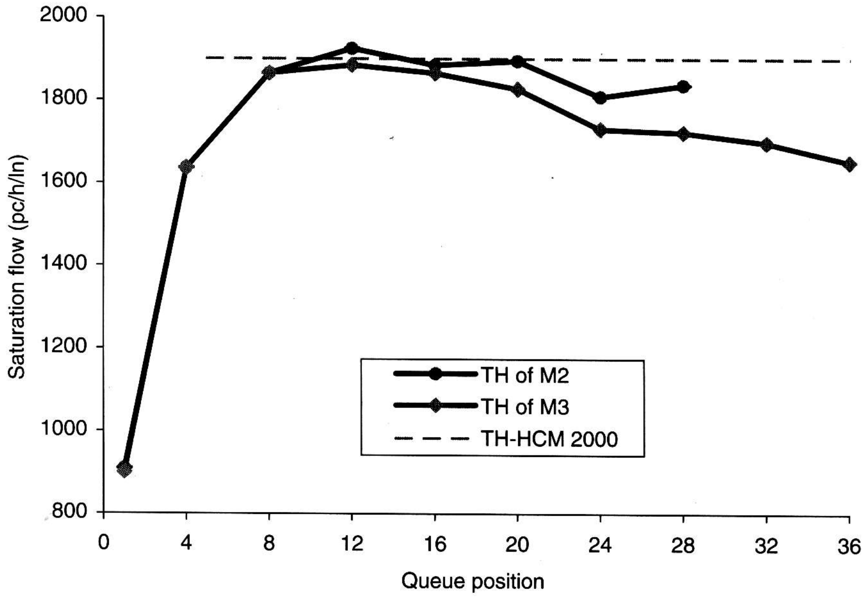
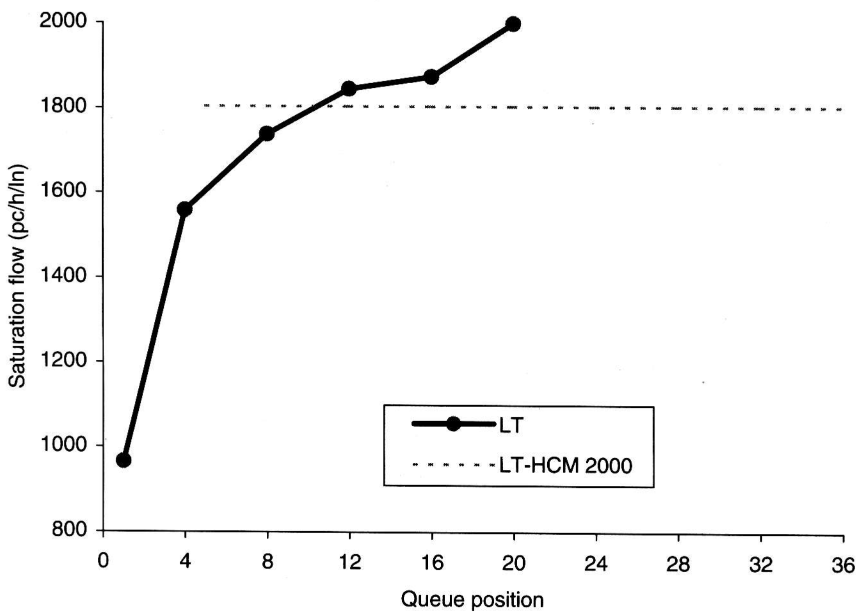


FIGURE 3 SRT and headway plots: (*a*) M2, TH movement; (*b*) M2, LT movement; and (*c*) M3, TH movement.



(a)



(b)

FIGURE 4 Saturation flow by method for (*a*) TH movement, (*b*) protected LT movement.

TABLE 4 Basic Data Analysis: Statistical Significance Tests

Last observed headway	Are they significantly different from the average headway before it?		
	TH in M2	TH in M3	LT in M2
H_{16}	No	Yes	Yes
H_{20}	No	Yes	Yes
H_{24}	No	Yes	--
H_{28}	No	Yes	--
H_{32}	--	Yes	--
H_{36}	--	Yes	--

However, for TH of M3, the last observed headway was larger than the preceding average headway because of the inclusion of arrivals joining the standing queue. The tests showed than those differences were significant. For the protected LT of M2, the observed last headway was smaller than the preceding average headway. The tests showed than those differences were also significant. Therefore for a congested LT, the last four drivers compressed their headways to take advantage of the expiring green. In contrast, the overlong green for TH caused higher speeds, resulting in elongated headways.

The last headways of M2 and M3 represent the headway of the last foursome. An additional one, two, or three vehicles may have been discharged before expiration of the green. Thus, a clearer picture may have been drawn if individual headways were measured, which would have allowed the inclusion of the true last vehicle that was discharged from every queue. However, such measurements by a human observer are extremely tedious, and errors are larger in number and proportion (e.g., a 0.2-s error in a 1.6-s individual headway measurement is much larger than the same error for a 7-s foursome headway measurement). Thus, these measurements provide a reasonable compromise between accuracy and comprehensiveness and are consistent with the HCM.

START-UP LOST TIME

SULT was examined on the basis of M2. As a part of SULT, the SRT of the first vehicle (Figure 3*a* and *c*) was examined first; the results are shown in Table 5. Three interesting findings about SRT are as follows:

1. The SRT of TH is larger than that of the protected LT. The *t*-test indicated that the difference was significant. The smaller value of the protected LT reflects the heightened awareness of left-turning drivers to the display of green. The time-of-day factor was not considered because both TH and LT data were collected simultaneously during normal morning peak periods.
2. High standard deviations of SRT are observed for both movements and reflect a big variation of SRT among drivers.
3. ANOVA tests indicate that SRT is not sensitive to queue length. The result shows that SRT had similar means and variance for any queue size level.

SULT was calculated by using Equation 5. The results are summarized in Table 5. SULT for both movements is well above the range in the HCM (1 to 2 s) but close to the lost time used in Webster's optimal cycle length estimation formula (3 to 4 s). Off-peak SULT statistics are larger, as shown in Table 5. This finding is intuitive because off-peak drivers typically exhibit less driving aggression. Also, a *t*-test indicated that the SULT for TH is significantly larger than the SULT for LT.

To investigate if queue length affects SULT, a regression analysis was conducted for both movements. Because of the high variance in the measurements, R^2 was low (1 to 5%), but the models were significant and intuitive. The models are as follows:

$$SULT(\text{TH}) = 3.08 - 0.0123 * (\text{queue size})$$

The intercept is significant at the 99% level, and the slope is significant at the 85% level.

$$SULT(\text{LT}) = 2.89 - 0.0357 * (\text{queue size})$$

The intercept is significant at the 99% level, and the slope is significant at the 98% level. These (weak) models indicate that there is a negative correlation between SULT and queue length. The actual relationship is likely to be nonlinear.

SRT AND HEADWAY DISTRIBUTIONS

The distribution of the SRT and headways was examined with M2 data. The histograms of SRT and headway showed that they were bell-shaped with strong positive skewness (skewness >1.0), which implies that the lognormal distribution may be a good fit (*9, 10*).

A commonly used normality test, the Lilliefors test, a variation of the Kolmogorov-Smirnov test, was used. The advantages of Lilliefors tests over other tests are discussed by Tulle (*11*) and Norusis (*12*). Lilliefors tests were conducted before and after a log transformation of SRT and headways. The shifted lognormal distribution was also tested, and the shift was obtained on the basis of the minimum value in the data. It should be noted that whenever the sample size is large, almost any goodness-of-fit test is likely to reject the hypothesis of normality (*12*). Therefore, for those variables whose sample size exceeded 200, 200 observations were randomly selected for these tests.

The observed minimum was 0 s for SRT, so the shifted lognormality test was not needed. The observed minimum for headways was 1 s, so lognormality tests were conducted twice, without and with a shift of 1 s. The test results for TH are shown in Table 6. The Lilliefors test suggested that the SRT of the first vehicle is normally distributed; it failed the lognormality test. The Lilliefors test suggested that the lognormal distribution without shift was the best fit for headways.

The results for the protected LT are shown in Table 6. The Lilliefors test suggests that the SRT for the first vehicle is normally

TABLE 5 M2 Data for Vehicle 1 for SRT, for SULT Calculated by Equations 5, and Off-Peak SULT

SRT	Mean (s)	Std. Dev. (s)	Minimum (s)	Maximum (s)	Observations
TH	1.76	0.61	0.74	4.02	354
LT	1.42	0.74	0.00	6.70	342
SULT					
TH	2.89	1.36	-0.45	8.93	344
LT	2.38	1.32	-0.39	8.59	341
Off-peak	SULT				
TH	3.03	1.5	-0.45	8.93	155
LT	2.53	1.3	-0.22	6.93	146

TABLE 6 Distribution of SULT and Headways: Results for TH and LT Movements

TH	Observations	Normality Test	Base Lognormality Test	Shifted Lognormality Test
SRT	200	Pass	Fail	--
H_4	200	Fail	Pass	Pass
H_8	200	Fail	Pass	Fail
H_{12}	200	Pass	Pass	Pass
H_{16}	189	Pass	Pass	Pass
H_{20}	110	Fail	Pass	Pass
H_{24}	63	Pass	Pass	Pass
H_{28}	42	Pass	Pass	Pass
LT				
SRT	200	Pass	Fail	--
H_4	200	Fail	Fail	Pass
H_8	200	Fail	Fail	Pass
H_{12}	200	Fail	Pass	Pass
H_{16}	200	Fail	Fail	Pass
H_{20}	200	Pass	Pass	Pass

distributed; it failed the lognormality test. The Lilliefors test suggests that a shifted lognormal distribution with a shift of 1 s is the best fit for headways.

CONCLUSIONS

The results are presented of a detailed analysis of headways, SRTs, and SULTs on short, medium, and long queues with random arrivals at a busy approach of a high-design, fully actuated signalized intersection with heavy random arrivals. The large number of observations and the practically ideal traffic conditions enabled the acquisition of several statistically significant results. The analyses conducted in this research were based on three methodologies for the field measurement of saturation headways: M1, M2, and M3.

The research attempted to answer a number of questions. These questions and their answers are as follow:

- Are saturation headways derived by methods M1, M2, and M3 significantly different? The saturation headways derived by the three methods are significantly different. For TH, the saturation headways based on M1, M2, and M3 were 1.90 s, 1.92 s, and 1.98 s, respectively. These values correspond to saturation flow rates of 1,895 pc/h/ln, 1,875 pc/h/ln, and 1,818 pc/h/ln, respectively. The significant differences between them indicate that (*a*) the saturation flow rate based on the first 12 vehicles is likely an overestimate of the real saturation flow rate applicable to a long standing queue and (*b*) in near-saturated conditions the more traditional methods, M1 and M2, produce higher saturation flow rates, which do not represent the discharge process well.

The saturation flow rates for the protected LT based on M1 and M2 were 2.04 s and 2.01 s, respectively. These values correspond to saturation flow rates of 1,765 pc/h/ln and 1,791 pc/h/ln, respectively. The significant difference between them indicates that during oversaturated conditions the saturation flow rate based on the first 12 vehicles (M1) underestimates the saturation flow rate actually achieved by the whole standing queue (M2).

- What is the implication of these differences? The significant differences for TH have the following important implications: (*a*) for capacity analysis because the actual saturation headway *s* may be considerably lower than the input *s* based on partial queue observations (this potential error is larger when long greens and long cycles prevail); (*b*) for signal timing analysis because overlong green and cycles appear to be less productive; and (*c*) for microsimulation for reasons similar to those in Item a.
- Do selected intermediate headways vary with respect to the size of the queue? ANOVA tests suggest that the selected headways of the 5th to 12th vehicles were not significantly affected by the queue size for both movements.
- What roles do the turning movement and saturation condition play in determining headway? The turning movement has a more dominant role in determining the saturation headway than does the saturation condition. However, the trend of headways along the queue position is affected more by the saturation condition than by the turning movement.
- Is there an elongation or compression of headways for the last vehicles in queue? Is it the same for TH and protected LT movements? The *t*-test comparisons revealed that for TH of M3, the last headway was elongated. The *t*-tests showed that for the protected LT of M2, the last headway was compressed.
- Is the SULT affected by the length of queue (which is a proxy for congestion)? A weak negative correlation between SULT and queue length was revealed. However, more sophisticated, nonlinear models are required for accurate modeling. In addition, peak and off-peak conditions may need to be modeled separately.
- What is the distribution of SRT and headways? Distribution tests showed that headways of TH were lognormally distributed without a shift. Headways of the protected LT were lognormally distributed with a shift of 1 s. SRT was normally distributed for both movements.

In addition, the following observations were made:

1. SRT displayed a bigger variation than do headways. The difference between SRT (TH) and SRT (LT) was significant and reflected the left-turn-on-green driver's greater awareness to the display of the green.

2. There is statistically significant evidence that drivers on left-turn bays anticipate the onset of the green and a negative start-up time was observed in several cycles (1%).

3. Much higher SULTs were estimated in this study compared with those in the HCM.

4. Measurements for both movements showed that the minimum headway was not reached until the 9th to 12th vehicle.

Future endeavors on this subject include the enrichment of the databases with data from other intersection approaches, which will reduce potential local effects from this single-approach analysis. The effect of clues of phase change on SULT may also be investigated.

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