AVERAGE STOPPED DELAY FOR:

TABLE A-10

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.5
CAPACITY 1600

| V/C | U.D. | R.D. | FLOW RATE | QUALITY OF PROGRESSION 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| 0 | 11.40 | 0.00 | 0 | 21.09 | 15.39 | 11.40 | 8.21 | 6.04 |
| 0.1 | 12.00 | .00 | 160 | 22.20 | 16.20 | 12.00 | 8.64 | 6.36 |
| 0.2 | 12.67 | 0.01 | 320 | 23.45 | 17.11 | 12.68 | 9.13 | 6.72 |
| 0.3 | 13.41 | 0.03 | 480 | 24.87 | 18.15 | 13.45 | 9.68 | 7.13 |
| 0.4 | 14.25 | 0.09 | 640 | 26.53 | 19.36 | 14.34 | 10.33 | 7.60 |
| 0.5 | 15.20 | 0.22 | 800 | 28.52 | 20.81 | 15.42 | 11.10 | 8.17 |
| 0.6 | 16.29 | 0.46 | 960 | 30.98 | 22.61 | 16.75 | 12.06 | 8.88 |
| 0.7 | 17.54 | 0.97 | 1120 | 31.09 | 23.69 | 18.51 | 14.25 | 11.11 |
| 0.8 | 19.00 | 2.11 | 1280 | 31.67 | 25.76 | 21.11 | 17.31 | 14.15 |
| 0.9 | 20.73 | 5.30 | 1440 | 37.74 | 31.24 | 26.03 | 22.39 | 19.52 |
| 1 | 22.80 | 17.30 | 1600 | 56.14 | 47.32 | 40.10 | 36.09 | 32.88 |
| 1.1 | 25.33 | 51.27 | 1760 | 107.24 | 90.39 | 76.60 | 68.94 | 62.81 |

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

| LOS | MAXIMUM STOPPED DELAY | QP=1 MAX SV | QP=1 V/C | QP=2 MAX SV | QP=2 V/C | QP=3 MAX SV | QP=3 V/C | QP=4 MAX SV | QP=4 V/C | QP=5 MAX SV | QP=5 V/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 5 | | | | ERR | ERR | | | | | |
| | 10 | | | | ERR | ERR | | 559 | 0.35 | 1041 | 0.65 |
| B | 15 | | | | ERR | 738 | 0.46 | 1159 | 0.72 | 1305 | 0.82 |
| | 20 | | | 710 | 0.44 | 1212 | 0.76 | 1365 | 0.85 | 1446 | 0.90 |
| C | 25 | 492 | 0.31 | 1221 | 0.76 | 1406 | 0.88 | 1471 | 0.92 | 1506 | 0.94 |
| | 30 | 896 | 0.56 | 1404 | 0.88 | 1485 | 0.93 | 1529 | 0.96 | 1565 | 0.98 |
| | 35 | 1368 | 0.85 | 1477 | 0.92 | 1542 | 0.96 | 1587 | 0.99 | | |
| D | 40 | 1460 | 0.91 | 1527 | 0.95 | 1599 | 1.00 | | ERR | | |
| | 45 | 1503 | 0.94 | 1577 | 0.99 | | | | ERR | | |
| | 50 | 1547 | 0.97 | | | | | | ERR | | |
| | 55 | 1590 | 0.99 | | | | | | ERR | | |
| E | 60 | ERR | ERR | | | | | | ERR | | |

AVERAGE STOPPED DELAY FOR:

TABLE A-11

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.6
CAPACITY 1920

| V/C | U.D. | R.D. | FLOW RATE | QUALITY OF PROGRESSION 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|
| 0 | 7.30 | 0.00 | 0 | 13.50 | 9.85 | 7.30 | 5.25 | 3.87 |
| 0.1 | 7.76 | .00 | 192 | 14.36 | 10.48 | 7.76 | 5.59 | 4.11 |
| 0.2 | 8.29 | 0.01 | 384 | 15.35 | 11.20 | 8.30 | 5.97 | 4.40 |
| 0.3 | 8.90 | 0.03 | 576 | 16.51 | 12.05 | 8.93 | 6.43 | 4.73 |
| 0.4 | 9.60 | 0.08 | 768 | 17.90 | 13.06 | 9.68 | 6.97 | 5.13 |
| 0.5 | 10.42 | 0.18 | 960 | 19.61 | 14.31 | 10.60 | 7.63 | 5.62 |
| 0.6 | 11.40 | 0.39 | 1152 | 21.80 | 15.91 | 11.79 | 8.49 | 6.25 |
| 0.7 | 12.58 | 0.81 | 1344 | 22.50 | 17.14 | 13.39 | 10.31 | 8.03 |
| 0.8 | 14.03 | 1.77 | 1536 | 23.71 | 19.28 | 15.81 | 12.96 | 10.59 |
| 0.9 | 15.86 | 4.52 | 1728 | 29.56 | 24.46 | 20.39 | 17.53 | 15.29 |
| 1 | 18.24 | 15.79 | 1920 | 47.65 | 40.16 | 34.03 | 30.63 | 27.91 |
| 1.1 | 21.46 | 49.91 | 2112 | 99.92 | 84.22 | 71.37 | 64.24 | 58.53 |

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

| LOS | MAXIMUM STOPPED DELAY | QP=1 MAX SV | QP=1 V/C | QP=2 MAX SV | QP=2 V/C | QP=3 MAX SV | QP=3 V/C | QP=4 MAX SV | QP=4 V/C | QP=5 MAX SV | QP=5 V/C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 5 | | | | | | | | | 706 | 0.37 |
| | 10 | | | 46 | 0.02 | 835 | 0.43 | 1311 | 0.68 | 1492 | 0.78 |
| B | 15 | 316 | 0.16 | 1043 | 0.54 | 1472 | 0.77 | 1622 | 0.84 | 1716 | 0.89 |
| | 20 | 994 | 0.52 | 1563 | 0.81 | 1712 | 0.89 | 1764 | 0.92 | 1800 | 0.94 |
| C | 25 | 1578 | 0.82 | 1735 | 0.90 | 1793 | 0.93 | 1837 | 0.96 | 1876 | 0.98 |
| | 30 | 1733 | 0.90 | 1796 | 0.94 | 1863 | 0.97 | 1911 | 1.00 | | |
| | 35 | 1786 | 0.93 | 1857 | 0.97 | | | | | | |
| D | 40 | 1839 | 0.96 | 1918 | 1.00 | | | | | | |
| | 45 | 1892 | 0.99 | | | | | | | | |
| | 50 | | | | | | | | | | |
| | 55 | | | | | | | | | | |
| E | 60 | | | | | | | | | | |

# Saturation Flows of Exclusive Double Left-Turn Lanes

ROBERT W. STOKES, CARROLL J. MESSER, AND VERGIL G. STOVER

**The objectives of this study were to develop estimates of the saturation flows of exclusive double left-turn lanes, and to investigate the physical and operating characteristics of the intersection that may affect left-turn saturation flows. The results are based on observations of 3,458 completed left turns from exclusive double left-turn lanes on 14 intersection approaches in Austin, College Station, and Houston, Texas. Based on the results of this study and a review of the data from a limited number of related studies, an average double left-turn saturation flow rate of approximately 1,600 vehicles per hour of green per lane would appear to be a reasonable value for most planning applications. This flow rate can be assumed to be achieved for the third vehicle in the queue and beyond. Also, this flow rate appears to be applicable for mixed traffic conditions in which heavy vehicles constitute as much as 3 to 5 percent of the left-turn traffic volume.**

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The continuing emphasis on obtaining a more efficient utilization of the existing urban street infrastructure suggests that applications of the double left-turn lane concept will become increasingly widespread. Reliable estimates of double left-turn saturation flows have several important applications in traffic management and design. Such applications include the following *(1)*:

- Determination of optimum signal timing and phasing arrangements,
- Estimation of average queue lengths for use in the design of left-turn storage bays,
- Estimation of double left-turn lane capacity, and
- Estimation of the average and maximum delays experienced by left-turning vehicles.

Although double left-turn lanes have been in use for a number of years, basic research on the saturation flows of such facilities has been extremely limited. Consequently, current methods for estimating the capacities of double left-turn lanes are based on minimal amounts of data and none has been widely accepted as being truly representative of real-world conditions.

The capacity estimates derived from the limited data available on double left-turn lanes suggest a substantial range in flow rates. This range could be attributed to various physical, operating, and/or environmental factors that may vary within or between intersection approaches. This paper summarizes the results of a study directed at (*a*) estimating exclusive double left-turn lane capacity, which is easily computed from saturation flow; and (*b*) quantifying the relationships between double left-turn lane saturation flow and the physical and operating characteristics of the intersections studied *(2)*.

The use of the phrase "exclusive double left-turn lanes" in this paper refers to two contiguous lanes of an intersection approach that are designed solely for left-turning vehicles and protected from opposing through- and cross-traffic with separate signal phasing. In the study, double left-turn movement capacity is dealt with on a microscopic level; that is, in terms of the time headways of individual left-turning vehicles.

## OBJECTIVES

The primary objective of the study was to develop reliable estimates of exclusive double left-turn saturation flows. A secondary objective was to attempt to relate these flows to the physical and operating characteristics of the intersection approaches studied. Specific objectives were as follows:

1. Record, with an accuracy of ±0.1 sec, the time spacing between consecutive left-turning vehicles entering a signalized intersection from an exclusive double left-turn lane during saturated conditions (i.e., for queue lengths of five or more vehicles per lane).
2. Examine the variability in these time spacings between and within intersection approaches.
3. If possible, relate these time spacings and their variability in terms of the following physical and operating characteristics of the intersection approaches studied: (*a*) Width of turn lanes (ft); (*b*) Turn radius (ft); (*c*) Approach grade (percent); (*d*) Turn-bay storage length (ft); (*e*) Turn-bay taper length (ft); (*f*) Turn-bay queue lengths (veh/lane); (*g*) Turn-lane blockages, (*h*) Turn-lane green time (sec); and (*i*) Percentage of heavy vehicles in the left-turn traffic stream (i.e., percentage of vehicles with more than four tires).

## PREVIOUS RESEARCH

Double left-turn lanes have been in use for a number of years. However, basic research on the saturation (capacity) flows of such facilities has been extremely limited. A literature search revealed only seven references *(3–9)* on the subject of double left-turn lane capacity. Moreover, only five of the references treated double left-turn lanes in detail. With the exception of Kunzman's limited work in 1978 *(9)*, the literature search indicated that no fundamental research on double left-turn movement capacity has appeared in the literature in nearly 15 years.

Table 1 gives a summary of the estimates of double left-turn saturation flows reported in the research identified through the literature search. Also given is a summary of the efficiencies of double left-turn movements relative to single left-turns and straight-through movements. The average double left-turn saturation flows for the limited data available and given in Table 1 span a considerable range of values. However, with the exception of Ray's data *(4)*, and the Highway Capacity Manual (HCM) data for through-movements *(5)*, the efficiency factors appear to be fairly uniform. Also, note that with the exception of the HCM data, the left-turn flow rates do not appear to be substantially lower than through-lane flow rates. This suggests that the flows for all movements on a particular approach are equally affected by the physical and operating characteristics of the intersection. That is, those approaches with relatively low double left-turn flows also appear to have proportionately lower single left-turn and straight-through flows.

## DATA COLLECTION AND ANALYSIS

Based on an examination of the possible methods for obtaining the data required, it was decided that the most satisfactory and economical procedure, from both field study and data analysis time standpoints, was a combination of photographic and field measurement techniques.

By using time-lapse photography, more than 3,400 completed left turns were recorded on 14 intersection approaches with exclusive double left-turn lanes in College Station, Austin, and Houston, Texas. These three cities were selected for study because they represented a cross-section of Texas cities in terms of population and traffic conditions.

A filming speed of 9 frames/sec was used because this speed made it possible to estimate left-turn departure headways to within 0.1 sec. A total of approximately 4 hours of peak-period data was collected. This was considered a sufficient sample for estimating double left-turn saturation flows and for making statistical inferences concerning the factors affecting saturation flow.

The Statistical Analysis System (SAS) Computer Program Package was used in the statistical analysis phases of the study *(10)*. This package has been extensively tested and has been widely accepted for statistical analyses.

The sample data were used to test specific statistical hypotheses concerning the following:

1. The saturation flow region of the queue,
2. Variability in the estimates of left-turn departure headways, and

**TABLE 1 DOUBLE LEFT-TURN SATURATION FLOWS AND RELATIVE EFFICIENCY FACTORS**

| Source and Conditions | Double Left-Turn Saturation Flow (vphg) Inside Lane | Outside Lane | Average | Double Left-Turn Movement Efficiency Factor[a] Relative to Single Left-Turn | Relative to Through Movement |
|---|---|---|---|---|---|
| Capelle and Pinnell (3) | | | | | |
| Permissive Double Left-Turn[b] | 1500 | 1636 | 1568 | 0.91 | 0.91 |
| Ray (4) | | | | | |
| Permissive Double Left-Turn | 1240 | 1230 | 1235 | 0.75 | -[c] |
| Exclusive Double Left-Turn | 1375 | 1315 | 1345 | 0.82 | - |
| HCM (5) | | | | | |
| 10-foot Lanes | 1200 | 960 | 1080 | 0.90 | 0.72[d] |
| 11-foot Lanes | 1320 | 1056 | 1188 | 0.90 | 0.79[d] |
| 12-foot Lanes | 1440 | 1152 | 1296 | 0.90 | 0.86[d] |
| Assmus (7) | | | | | |
| Exclusive Double Left-Turn | 1540 | 1550 | 1545 | - | 0.97 |
| Kunzman (9) | | | | | |
| Queue $\leq$ 4 veh/lane | - | - | 1439 | 0.96 | 0.90 |
| Queue $\geq$ 5 veh/lane | - | - | 1581 | 0.92 | 0.93 |
| All Queue Lengths | - | - | 1523 | 0.93 | 0.91 |

[a] Efficiency factor defined as the ratio of average double left-turn flow to average single left-turn flow or average straight-through flow as indicated; all flows are per-lane flows.
[b] Left-Turn option in outside lane.
[c] Data not available.
[d] Assumes straight-through flow of 1500 vphg.

3. Some of the factors that may affect left-turn departure headways.

The statistical hypotheses were tested at the 5 percent significance level. The statistical procedures employed are discussed briefly in the following subsections.

## Saturation Flow Region of the Queue

The initial task in estimating double left-turn saturation flows was to identify the portion of the queue, in terms of vehicle storage positions, for which departure headways could be assumed to be uniform. Two basic statistical procedures were employed to accomplish this task: analysis of means and regression analysis.

In the analysis of means procedure, average left-turn headways were calculated by turn lane (Figure 1) for the entire sample (i.e., for all intersection approaches), by turn lane and approach, and by turn lane and city. The average headways were calculated for all vehicles observed entering the intersections, for selected segments of the queue, and by individual storage positions. In calculating the means by queue segments, the following regions of the queue were considered:

$$1 \leq n_i \leq n_{k(i)}, \ldots, 5 \leq n_i \leq n_{k(i)}$$

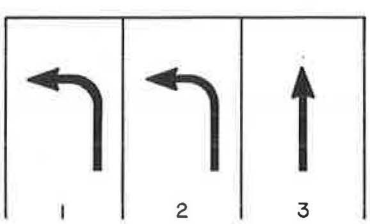


**FIGURE 1 Lane numbering scheme.**

where $n_i$ is the queue storage position for left-turning vehicles in Turn Lane i, for i = 1,2 (Figure 1); and $n_{k(i)}$ is the total number of vehicles queued in Lane i at the start of the left-turn green phase. Duncan's Multiple Range Test was used to test the hypothesis that average left-turn headways do not differ by vehicle storage position. Table 2 presents an aggregate summary of average left-turn headways for the total sample.

The regression analyses involved evaluating the following models:

$$T_{c(i)} = B_0 + B_1 n_I + e_i \quad (1)$$

$$h_{I,(i)} = B^*_0 + B^*_1 (1/n_i) + e^*_i \quad (2)$$

**TABLE 2 AVERAGE LEFT-TURN DEPARTURE HEADWAYS FOR THE TOTAL SAMPLE**

| Data Set and Lane | Sample Size | Mean Headway (sec/veh) | Standard Deviation | Standard Error of Mean |
|---|---|---|---|---|
| All Vehicles | | | | |
| Lane 1 | 1707 | 2.4 | 1.34 | 0.03 |
| Lane 2 | 1751 | 2.4 | 1.29 | 0.03 |
| $1 \leq n_i \leq n_{k(i)}$ | | | | |
| Lane 1 | 1500 | 2.3 | 0.81 | 0.02 |
| Lane 2 | 1598 | 2.3 | 1.04 | 0.03 |
| $2 \leq n_i \leq n_{k(i)}$ | | | | |
| Lane 1 | 1249 | 2.2 | 0.64 | 0.02 |
| Lane 2 | 1347 | 2.2 | 0.98 | 0.03 |
| $3 \leq n_i \leq n_{k(i)}$ | | | | |
| Lane 1 | 1000 | 2.1 | 0.60 | 0.02 |
| Lane 2 | 1101 | 2.1 | 1.00 | 0.03 |
| $4 \leq n_i \leq n_{k(i)}$ | | | | |
| Lane 1 | 752 | 2.0 | 0.58 | 0.02 |
| Lane 2 | 859 | 2.1 | 1.09 | 0.04 |
| $5 \leq n_i \leq n_{k(i)}$ | | | | |
| Lane 1 | 509 | 2.0 | 0.60 | 0.03 |
| Lane 2 | 623 | 2.1 | 1.17 | 0.05 |

where

| | | |
|---|---|---|
| $T_{c(i)}$ | = | time (sec) after the start of the left-turn green phase for the rear axle of the left-turning vehicle in queue storage position $n_i$ to cross the intersection stop line from Turn Lane i (i = 1,2); |
| $B_0$, $B_1$, $B^*_0$, $B^*_1$ | = | regression coefficients; |
| $e_i$, $e^*_i$ | = | random error terms; and |
| $h_{L(i)}$ | = | left-turn headway (sec) for vehicles in Turn Lane i (i = 1,2). |

In Equation 1, the parameter of interest is $B_1$, where the sample estimate of $B_1$, denoted by $b_1$, is an estimate of departure headway (sec/veh). The parameters of the model given in Equation 1 were estimated from the entire sample, as well as from subsets of the sample. The subsets of the sample used to estimate the parameters of the regression models were identical to those used in the analysis of means.

A less direct analysis of the saturation flow region of the queue was performed by evaluating regression models of the form given in Equation 2. The intent of the analyses involving Equation 2 was to find $n_i$ for which the hypothesis $B_1 = 0$ could not be rejected. In addition, the corresponding $b_0$'s should then be estimates of minimum average departure headways.

### Variability in Estimates of Left-Turn Departure Headways

The purpose of the second phase of the analysis was to determine whether the average left-turn headways for the saturation flow region of the queue differed significantly between or within intersection approaches, and/or by turn lane. The following three procedures were used to investigate the variability exhibited by the estimates of left-turn departure headways.

1. Duncan's Multiple Range Test was used to test the hypothesis that average left-turn departure headways do not differ significantly between intersection approaches.
2. A series of two-sample *t*-tests was performed to test the differences in departure headways between cities. The tests were performed on a per-lane basis by using the *t*-test (TTEST) procedure of the SAS Computer Program Package *(10)*. The TTEST procedure tests the significance of the difference between means from two independent samples. The TTEST procedure also performs an *F*-test on the hypothesis that the variances of the two samples are equal. The procedure then calculates two *t*-statistics: the usual two-sample *t* that assumes equal variances, and an approximate *t* that does not assume equal variances *(11)*.
3. A paired *t*-test was used to test the hypothesis that average left-turn departure headways do not differ between the two lanes of the double left-turn movements within each of the three cities studied.

### Factors Affecting Left-Turn Departure Headways

The intent of the final phase of the analyses was to examine some of the possible sources of the variability observed in the left-turn departure headway estimates. The potential headway-influencing factors investigated are summarized in Table 3.

The initial step in investigating the effects of the numeric factors (i.e., factors other than lane blockages) in the sample was to calculate the simple correlation coefficients (*r*) between the departure headways and the individual factors. The correlation (CORR) procedure of the SAS Computer Program Package was used to compute the sample correlation coefficients *(10)*.

Note in Table 3 that in the final analyses only three levels of lane blockages were considered. Specifically, only the blockage, no blockage, and blockage code 23 conditions were con-

**TABLE 3 HEADWAY-INFLUENCING FACTORS INVESTIGATED**

| Factor | Contraction | Definition |
|---|---|---|
| Lane blockage[a] | NOBLK | No lane blockages (code 00) |
| | BLOCK | Lane blockage codes 12, 21, and 23 combined |
| | BLK23 | Blockage code 23 |
| Headway compression[b] | COMPRES1 | Ratio of total queue length (veh) to available green time (sec) |
| | COMPRES2 | for Lane 1 and Lane 2, respectively |
| Approach grade | GRADE | Approach grade (%) |
| Green time | GRNTIME | Left-turn green time (sec) |
| Percent heavy vehicles | PERHV1 | Percentage heavy vehicles (veh with more than four |
| | PERHV2 | tires) in Lane 1, Lane 2, and Lanes 1 and 2 |
| | PERHVTOT | combined, respectively |
| Turn radius | RADIUS | Simple turn radius (ft) |
| Turn bay storage length | STORAGE | Turn-bay storage length (ft) |
| Turn bay taper length | TAPER | Turn-bay taper length (ft) |
| Turn lane width | WIDTH1 | Width (ft) of Turn Lane 1 |
| | WIDTH2 | Width of Lane 2 |
| | TOTWIDTH | Width of Lanes 1 and 2 combined |

[a]Code 00 = no blockage observed, code 12 = Lane 1 blocked by Lane 2, and so forth. See Figure 1 for lane numbering scheme.
[b]As the demand (queue length) per cycle increases relative to capacity (left-turn green time), there may be some compression, or shortening, of left-turn departure headways as vehicles attempt to fully utilize available capacity. It would be expected that the effects of this compression factor be more pronounced in those situations in which the available green time is not sufficient to fully serve the queue of vehicles waiting on the approach.

sidered in the analyses. These revised definitions of the blockage codes were formulated to facilitate the testing of statistical hypotheses suggested by the data. The effects of turn lane blockages on left-turn departure headways were evaluated by testing two hypotheses:

- The average departure headways for blockage codes 12, 21, and 23 combined do not differ significantly from those for the no-blockage condition (code 00).
- The average departure headways for blockage code 23 do not differ significantly from those for the no-blockage condition (code 00).

The first hypothesis was tested for each lane of the College Station and Houston sites. The second hypothesis was tested for Lane 2 of the College Station and Houston sites individually, as well as for Lane 2 of the two cities combined. No turn lane blockages were observed at the Austin sites. The *t*-test (TTEST) procedure of the SAS Computer Program Package was used to perform the statistical tests *(10)*.

## RESULTS

### Saturation Flow Region of the Queue

Three slightly different estimates of the saturation flow region of the queue were developed. The estimates of the saturation flow region of the queue and the corresponding headway estimates—developed from the analysis of means and the regression models given in Equation 1—were in fairly close agreement. In terms of the precision of the departure headway estimates, the estimates obtained from the regression models given in Equation 2 were inferior to those obtained from the other two estimation procedures. The estimates obtained from the analysis of means were selected as the best estimates. The results of the analysis of means suggest that the saturation flow region of the queue can be defined by the region $3 \le n_i \le n_{k(i)}$. The decision to use the estimates obtained from the analysis of means was based on the following considerations.

First, from a theoretical standpoint, it can be argued that the regression estimates (Equation 1) of departure headways should be more precise than those obtained from the analysis of means. However, it appears that at least one of the basic assumptions of regression analysis was not satisfied. Specifically, it was found that the variance of the error term in the regression models was not constant across the sample. The procedure used to test the constancy of the error variance was to

1. Array the observations by queue storage position and lane,
2. Divide the total observations into two equal data sets for each lane,
3. Fit separate regression functions to each half of the total observations,
4. Calculate the mean square errors (MSEs) for each, and
5. Test for equality of the error variances by the *F*-test.

The resulting variance ratios were significant at the 5 percent level.

Thus, evaluation of the constancy of the error variance suggests that the regression estimates of the departure headways may be biased. The data in Table 4 demonstrate the nature of the suspected bias. Note that, with the exception of Lane 2 for the Austin sites, the estimated headways (i.e., the slopes) are all less than or equal to 2.0 sec. The regression estimates suggest average flow rates in excess of 1,800 vehicles per hour of green per lane (vphgl) for the majority of the study sites. Relative to generally accepted straight-through flow rates of 1,700 to 1,800 vphgl, the regression models appear to have underestimated average left-turn departure headways. (See paper by Stokes, Stover, and Messer elsewhere in this Record for discussion.)

### Variability in Departure Headways

The results of Duncan's Test indicated significant differences in the average left-turn headways between the intersection approaches studied. However, there was a general pattern to the Duncan rankings of the headways; that is, the headways were generally grouped by city size. Specifically, the Houston sites (the large city studied) tended to exhibit significantly shorter average headways than did the College Station and Austin sites (the small- and medium-sized cities studied).

Table 5 presents the 95 percent confidence intervals for the average left-turn departure headways for the saturation flow region of the queue [i.e., for $3 \le n_i \le n_{k(i)}$] for each of the three cities studied. *F*-tests were performed on the hypothesis that the average headways do not differ between cities. The *F*-tests

**TABLE 4 EQUATION 1 REGRESSION MODELS BY CITY FOR $3 \le n_i \le n_{k(i)}$**

| | | Intercept | | Slope | | | |
|---|---|---|---|---|---|---|---|
| City and Lane | Sample Size | Estimate (sec) | Std. Err. | Estimate (sec/veh) | Std. Err. | Mean Sq. Err. (MSE) | $r^2$ |
| Austin | | | | | | | |
| Lane 1 | 175 | 2.2 | 0.37 | 1.9 | 0.06 | 2.79 | 0.84 |
| Lane 2 | 180 | 1.3 | 0.31 | 2.2 | 0.05 | 2.09 | 0.91 |
| College Station | | | | | | | |
| Lane 1 | 486 | 2.5 | 0.20 | 1.9 | 0.04 | 2.57 | 0.86 |
| Lane 2 | 592 | 2.2 | 0.26 | 2.0 | 0.04 | 5.07 | 0.80 |
| Houston | | | | | | | |
| Lane 1 | 339 | 2.4 | 0.22 | 1.8 | 0.05 | 1.04 | 0.79 |
| Lane 2 | 329 | 2.5 | 0.24 | 1.7 | 0.06 | 1.33 | 0.74 |

**TABLE 5 95 PERCENT CONFIDENCE INTERVALS FOR AVERAGE LEFT-TURN HEADWAYS ($h_L$) BY CITY FOR $3 \le n_i \le n_{k(i)}$**

| Lane | 95% Confidence Intervals for Average Headways (sec/veh) | | |
|---|---|---|---|
| | Austin | College Station | Houston |
| 1 | $2.1 \le \bar{h}_L \le 2.3$ | $2.0 \le \bar{h}_L \le 2.2$ | $1.9 \le \bar{h}_L \le 2.1$ |
| 2 | $2.1 \le \bar{h}_L \le 2.3$ | $2.1 \le \bar{h}_L \le 2.3$ | $1.8 \le \bar{h}_L \le 2.0$ |

indicated significant differences between the average headways of the double left-turn lanes of the three cities studied. A series of $t$-tests was performed to test the differences in average left-turn headways between cities. The following conclusions can be drawn from the tests:

- The average departure headways for the Austin and College Station sites are not significantly different for either turn lane for the saturation flow region of the queue. (Lane 1: $t$ = 1.92 and $p$-value = 0.06. Lane 2: $t$ = 0.81 and $p$-value = 0.42).
- The average departure headways for the Houston sites are significantly shorter than those for the Austin sites for each turn lane for the saturation flow region of the queue. (Lane 1: $t$ = 3.67 and $p$-value < 0.01. Lane 2: $t$ = 4.78 and $p$-value < 0.01).
- The average departure headways for the Houston sites are significantly shorter than those for the College Station sites for each turn lane for the saturation flow region of the queue. (Lane 1: $t$ = 2.22 and $p$-value = 0.03. Lane 2: $t$ = 3.72 and $p$-value < 0.01).

The differences in the average headways between the two lanes of the double left-turn movements within each city were also examined. As indicated by the data in Table 6, the average differences *(D)* between the Lane 1 and Lane 2 headways were generally positive, indicating that the Lane 1 headways tended to be slightly longer than the Lane 2 headways. Note, however, that none of the differences were significant at the 5 percent level. Thus, it can be concluded that any differences in the departure headways for vehicles in Lane 1 and Lane 2 within each city are not large enough to be detected with the given sample sizes.

## Factors Affecting Departure Headways

Two basic statistical procedures were used to investigate the factors in the sample that might have an effect on left-turn

**TABLE 6 $t$-TEST OF DIFFERENCES IN LEFT-TURN HEADWAYS BETWEEN LANES BY CITY FOR $3 \le n_i \le n_{k(i)}$**

| City | Variable | Mean | Std. Dev. | Std. Err. of Mean | t | Prob > \|t\| | Significant at 5% Level |
|---|---|---|---|---|---|---|---|
| Austin | D[a] | -0.08 | 1.30 | 0.10 | -0.81 | 0.4202 | NO |
| College Station | D | 0.10 | 1.79 | 0.08 | 1.29 | 0.1967 | NO |
| Houston | D | 0.07 | 0.95 | 0.05 | 1.19 | 0.2341 | NO |

[a] $D = h_{L(1)} - h_{L(2)}$.

saturation flows. Correlation analyses were used to assess the effects of the numeric factors in the sample. The effects of turn lane blockages were evaluated by using analysis-of-means procedures.

Table 7 gives a summary of those factors that exhibited significant linear correlations with departure headways in the saturation flow region of the queue. Note in the table that approach grade (GRADE), the headway compression factors (COMPRES1 and COMPRES2), and average left-turn green time (GRNTIME) exhibit significant correlations with both the Lane 1 and Lane 2 headways. Figure 2 shows these general relationships in terms of saturation flows.

**TABLE 7 SIGNIFICANT[a] SIMPLE CORRELATION COEFFICIENTS (r) FOR THE NUMERIC FACTORS IN THE SAMPLE FOR $3 \le n_i \le n_{k(i)}$**

| Factor[b] | Lane 1 Headway | | Lane 2 Headway | |
|---|---|---|---|---|
| | r | Prob > \|r\|[c] | r | Prob > \|r\| |
| TAPER | 0.0885 | (0.0082) | -[d] | |
| STORAGE | 0.0833 | (0.0084) | - | |
| GRADE | 0.0952 | (0.0026) | 0.0965 | (0.0013) |
| PERHV1 | 0.0778 | (0.0138) | - | |
| COMPRES1 | -0.1126 | (0.0004) | -0.1758 | (0.0001) |
| COMPRES2 | -0.0897 | (0.0048) | -0.1645 | (0.0001) |
| GRNTIME | 0.0977 | (0.0021) | 0.2235 | (0.0001) |
| WIDTH1 | - | | -0.0915 | (0.0024) |
| WIDTH2 | - | | -0.0827 | (0.0061) |
| TOTWIDTH | - | | -0.0941 | (0.0018) |

[a] Significance level = 0.05.
[b] See Table 3 for definitions.
[c] For hypothesis r = 0.
[d] Not significant at 5% level.

The positive relationship between saturation flow and approach grade (Figure 2*a*) is not surprising. It appears reasonable to expect departure headways to increase and saturation flows to decrease as the approach grade increases. However, given the limited range of approach grades in the sample (Figure 2*a*), the exact nature of the relationship remains open to question.

The relationships between saturation flow and the headway compression and green time factors (Figures 2*b*–2*d*) are not as easily interpreted as the other relationships examined. Although it appears reasonable to expect flow rates to increase as the turn lanes become busier, one should not lose sight of the implications of this assumption. Specifically, the effects of the compression and green time factors would appear to be related to driving behavior, not to quantifiable features of the turn lanes. That is, the observed effects of the compression and green time factors would appear to imply that drivers recognize

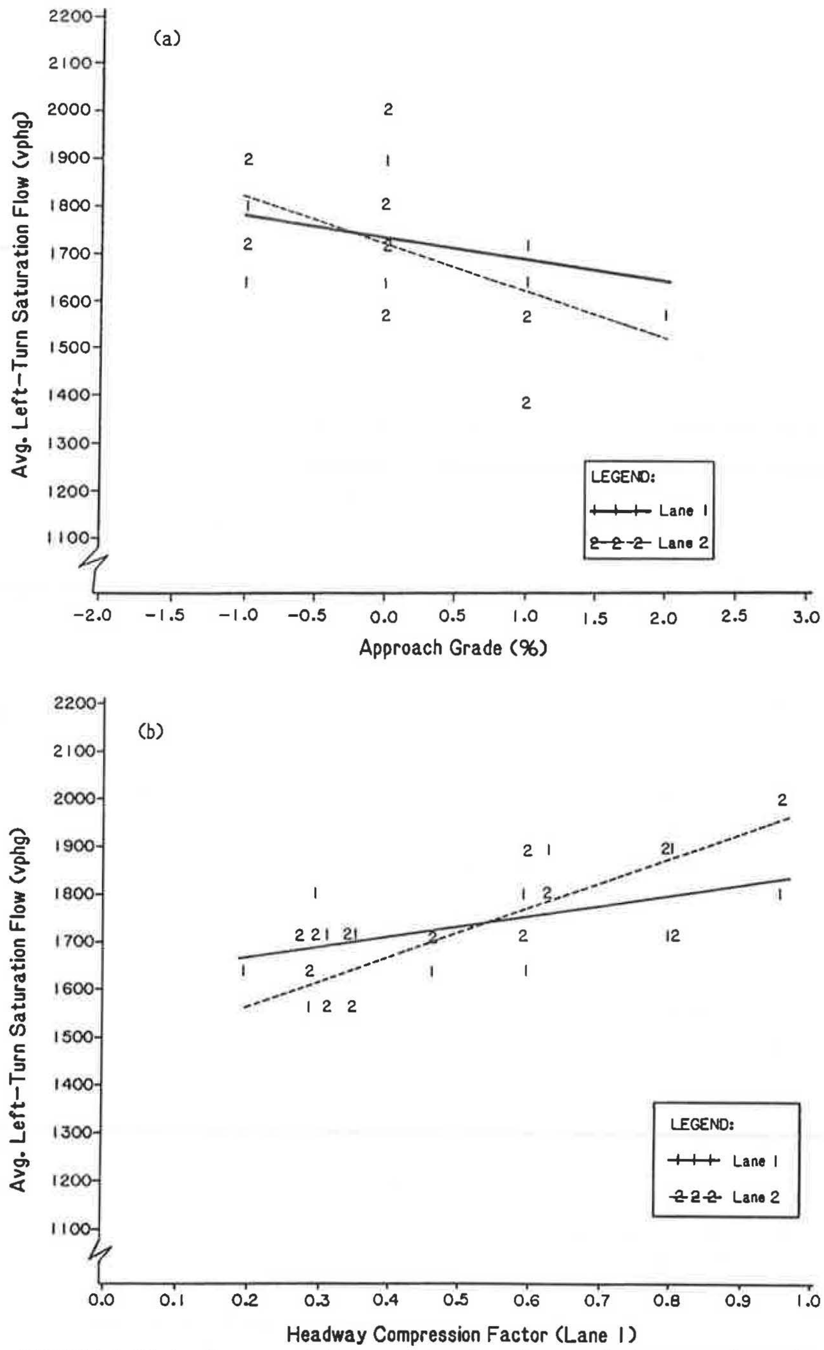


**FIGURE 2 Plots of average left-turn saturation flow against approach grade, headway compression factors, and average left-turn green time.**

that available green time is short (relative to the demand on the approach) and that they respond by assuming a relatively more aggressive driving posture. If the compression and green time factors are related to driving behavior, the magnitudes of the effects of these factors are probably highly variable.

The *t*-test was used to test the hypothesis that turn lane blockages have no effect on the average left-turn departure headways for the saturation flow region of the queue. The results of the tests for the saturation flow region of the queue are summarized as follows.

- Turn lane blockages have no significant effect on the left-turn departure headways of Lane 1 of the College Station sites ($t = -1.01$ and $p$-value = 0.31).
- Turn lane blockages have a significant effect on the left-turn departure headways of Lane 1 of the Houston sites ($t = 2.25$ and $p$-value = 0.02). Specifically, the departure headways of Lane 1 of the Houston sites for lane blockage conditions appear to be shorter than in the cases in which no lane blockage is encountered.
- Turn lane blockages have a significant effect on the left-

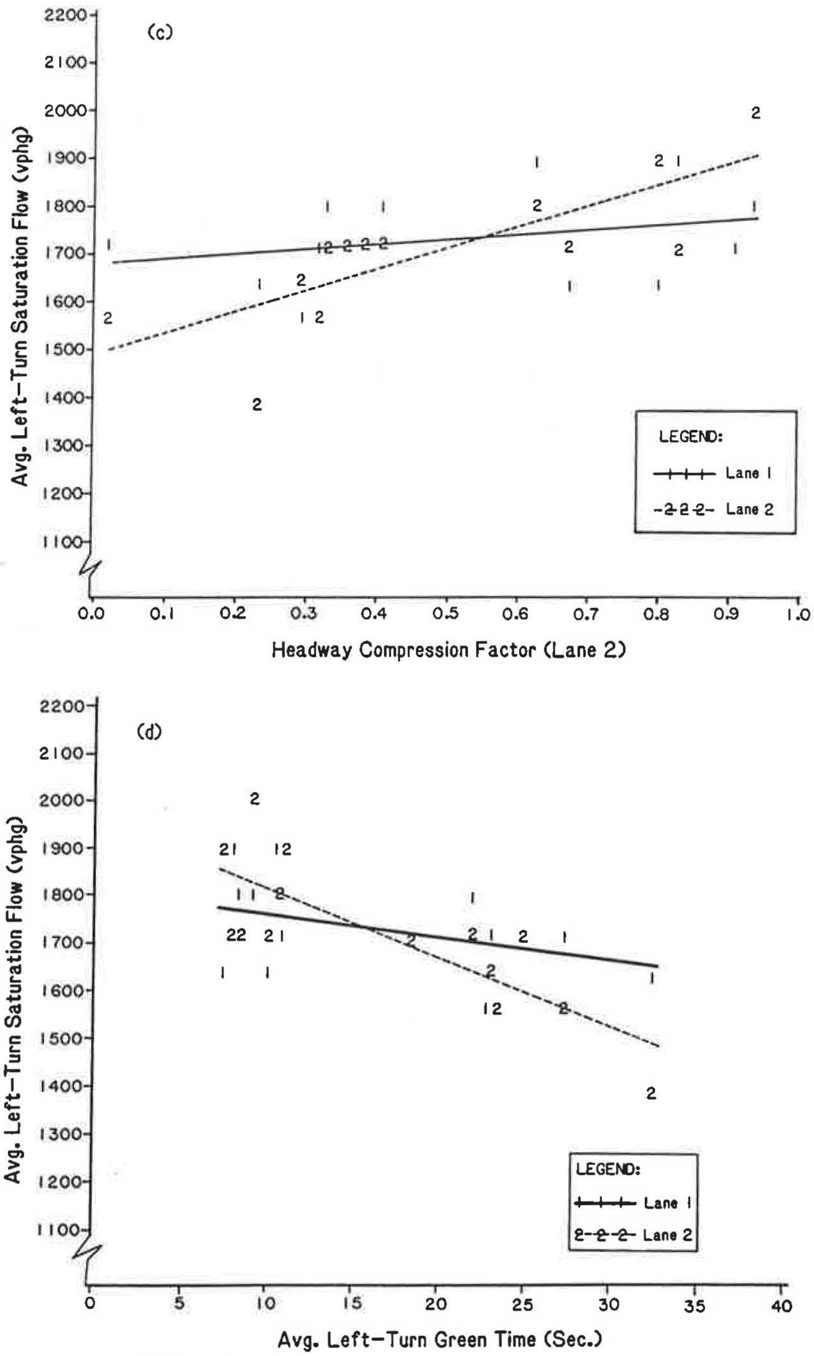


**FIGURE 2** *continued.*

turn departure headways of Lane 2 of the College Station sites ($t = -2.20$ and $p$-value = 0.03). The departure headways for the no-blockage conditions appear to be shorter than in the cases in which lane blockages are encountered.

- Turn lane blockages have no significant effect on the left-turn departure headways of Lane 2 of the Houston sites ($t = -0.33$ and $p$-value = 0.75).
- In the case in which Lane 2 of the double left-turn movement is blocked by the adjacent through lane (Lane 3), the left-turn departure headways for Lane 2 are not significantly different from those in which no blockage occurs, for either the Houston or College Station sites (Houston: $t = -0.74$ and $p$-value = 0.47; College Station: $t = -1.59$ and $p$-value = 0.12). For the two cities combined, the departure headways for Lane 2 for the no-blockage condition do not appear to be significantly different from the departure headways for the case in which Lane 2 is blocked by the adjacent through lane ($t = -1.88$ and $p$-value = 0.06).

## SUMMARY

It is indicated in the analyses that saturation flow for each lane of a double left-turn movement is obtained after the second vehicle in the queue. Vehicles, after the second in line, enter the intersection at the saturation flow rate until at least the last vehicle in the initial queue has entered the intersection or until the end of the effective left-turn green time.

It is suggested by the analyses that average left-turn departure headways vary significantly between the intersection approaches studied. However, much of the variability in the departure headways can be accounted for if the headways are grouped according to city size. Also, the study results indicate that, within each city, the departure headways do not differ significantly between the two lanes of a double left-turn movement.

Table 8 gives a summary of the 95 percent confidence intervals for average left-turn saturation flows ($\bar{s}_L$) estimated for the three Texas cities studied. As indicated by the data in the table, the left-turn saturation flow estimates developed in this study are generally higher than those that have been reported by other researchers (see Table 1). The average flow rates given for the Houston sites are on the same order of magnitude as the flows commonly reported for straight-through movements.

**TABLE 8 95 PERCENT CONFIDENCE INTERVALS FOR AVERAGE LEFT-TURN SATURATION FLOWS (vphgl) BY CITY FOR $3 \leq n_i \leq n_{k(i)}$**

| Lane | 95% Confidence Intervals[a] for Average Left-Turn Saturation Flow ($\bar{s}_L$) | | |
|---|---|---|---|
| | Austin | College Station | Houston |
| 1 | $1565 \leq \bar{s}_L \leq 1714$ | $1636 \leq \bar{s}_L \leq 1800$ | $1714 \leq \bar{s}_L \leq 1895$ |
| 2 | $1565 \leq \bar{s}_L \leq 1714$ | $1565 \leq \bar{s}_L \leq 1714$ | $1800 \leq \bar{s}_L \leq 2000$ |
| Grand Mean | 1636 | 1636 | 1800 |

[a] Calculated from $(1/\bar{h}_L) \times 3600$, using $\bar{h}_L$'s from Table 5.

The factors affecting left-turn departure headways were the subjects of some exploratory analyses. Although the results of these preliminary investigations were inconclusive, they suggest several complex relationships in the operating characteristics of double left-turn lanes. It is indicated by the investigations that approach grade, the headway compression factors, and average left-turn green time exhibit significant linear correlations with both the Lane 1 and Lane 2 departure headways.

Two general, and apparently contradictory, trends regarding the effects of turn lane blockages on left-turn departure headways are suggested by the study results. First, it appears that the effects of lane blockages vary by lane and city size. For College Station (the small city in the study), the effects of the lane blockages appear to be focused on the departure headways of Lane 2 (outside lane), where the blockages tend to increase the departure headways. For the large city in the sample (i.e., Houston), the effects of the lane blockages appear to be focused on the Lane 1 (inside lane) departure headways, where the blockages tend to reduce the departure headways. Second, for the specific lane blockage condition in which Lane 2 of the double left-turn movement is blocked by the adjacent through lane, it appears that this blockage condition has no significant effect on the Lane 2 headways for either the College Station or Houston sites individually, or the College Station and Houston sites combined.

Based on the results of this study and a review of the data from a limited number of related studies, an average double left-turn saturation flow rate of approximately 1,600 vphgl would appear to be a reasonable value for most planning applications. This flow rate can be assumed to be achieved for the third vehicle in the queue and beyond. Also, this flow rate appears to be applicable for mixed traffic conditions in which heavy vehicles constitute as much as 3 to 5 percent of the left-turn traffic volumes.

The double left-turn saturation flows observed at the Houston sites were approximately 1,800 vphgl. When compared with the flow rates typically reported in the literature for left-turn and straight-through movements, the Houston flow rates appear to be high. However, the Houston flow rates may be indicative of the maximum flows that can be realized on double left-turn lanes in an urban environment.

It is suggested by the results of this study that average double left-turn saturation flows may be substantially higher than previously believed. However, the results are based on data from only three cities in Texas. Consequently, in assessing a site-specific problem, engineers and planners may find it useful to collect local data to spot-check the applicability of the flow rates reported in this study.

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# Use and Effectiveness of Simple Linear Regression To Estimate Saturation Flows at Signalized Intersections

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**In this paper, data from 14 intersection approaches with exclusive double left-turn lanes in three Texas cities are used to illustrate the use of simple linear regression to estimate saturation flows. Some theoretical considerations and potential bias in saturation flows estimated by simple linear regression are also briefly discussed. Average left-turn saturation flows in excess of 1,800 vehicles per hour of green per lane for the majority of the study sites within each city are suggested by the regression estimates. Relative to generally accepted straight-through flow rates, the regression models appear to have substantially underestimated average left-turn departure headways.**

When a queue of vehicles is released by a traffic signal, the departure flow rate quickly increases until after the first few vehicles, when a uniform average departure rate is reached. This uniform departure rate is called the saturation flow rate of the intersection approach. Because the flow at signalized intersections is controlled by the amount of green time allotted, saturation flow under these conditions is defined as the flow rate that would result if there were a continuous queue of vehicles and they were given 100 percent green time *(1)*. Saturation flow is generally expressed in vehicles per hour of green time (vphg).

A method commonly used to estimate saturation flows at signalized intersections is the headway method. In this method, interarrival times (headways) of all saturated vehicles are measured at the intersection stop line, a saturated vehicle being one that has had to stop or almost stop in the queue behind the traffic signal. In the headway method, saturation flow is calculated directly as the reciprocal of the average headway of saturated vehicles.

One of the problems in estimating saturation flows from observed headways is accurately defining the saturation flow region of the queue. This problem is usually addressed by one of two procedures. The first and more straightforward of the procedures is to simply plot the average time headways of a queue of vehicles entering an intersection from a stopped position. These plots typically take the form shown in Figure 1. The saturation flow region of the queue can be identified by examining the plot and making a subjective determination of the vehicle storage positions for which departure headways could be assumed to be equal. Formal statistical procedures such as analysis-of-variance and multiple comparisons can be used to examine the departure headways in a more objective manner (e.g., see paper by Stokes, Messer, and Stover elsewhere in this Record).

A second approach to the problem of determining the saturation flow region of the queue involves the use of a formal optimization process such as simple linear regression. The regression models used in this process are typically of the following form:

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