

**Evaluation of Traffic Signal Displays for  
Protected-Permitted Left Turn Control**  
NCHRP Project 3-54

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**NOTICE:** This report is being furnished to the traffic engineering community at the direction of NCHRP so to supply information about this research project and its findings. This report documents findings of the research project as of September 1999.

**TRAFFIC OPERATION STUDIES REPORT**  
**Working Paper 4**

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## TRAFFIC OPERATION STUDIES REPORT

### INTRODUCTION

Capacity and delay are two of the commonly used measure of effectiveness (MOEs) in evaluating signalized intersection operations (*I*). Capacity is defined as the maximum rate of flow at which vehicles can be reasonably expected to traverse a point or a uniform segment of a lane, or a roadway during a specific time period under prevailing roadway, traffic, and control conditions. Delay is the additional travel time experienced by a driver beyond what would reasonably be desired for a given trip.

Left-turn capacity at a signalized intersection is based upon the concept of saturation flow. The saturation flow rate is defined as the maximum rate of flow that can pass through a given lane group under prevailing traffic and roadway conditions, assuming that the lane group has 100 percent of green time available (*I*). Saturation flow is usually reached after the fourth vehicle in queue has entered the intersection.

At the beginning of each protected left-turn movement, the first several vehicles in the queue experience start-up time losses that result in their movement at less than the saturation flow rate (*I, 2*). This time loss is referred to as *start-up lost time*. Start-up lost time is made up of the perception and reaction time (response time) to the change in signal indication along with the vehicle acceleration time to free flow speed. Start-up lost time is important in evaluating left-turn lane capacity and driver's reaction to the traffic signal indication.

Gap acceptance and follow-up headway also effect left-turn capacity and delay. Gap acceptance refers to the time headways in the opposing traffic stream, measured between the front bumpers of two successive vehicles, that left-turn drivers are willing to turn through during the permitted left-turn phase. The minimum time headway between two successive vehicles in the opposing traffic stream that is accepted by left-turn drivers during the permitted phase is referred to as the critical gap. Follow-up headway is the

time span between the departure of a permitted left-turn vehicle and the departure of the next vehicle using the same gap under a condition of continuous queuing. Left-turn delay can be evaluated by quantifying each of the operational variables described and applying the procedures included in Chapter 9 of the HCM (1).

## **OBJECTIVE**

The traffic observation studies contained two components, the traffic conflict study and the operational analysis. The traffic operation study was conducted to evaluate and compare driver understanding associated with selected PPLT signal displays. The study included evaluation of the left-turn saturation flow rate, start-up lost time, response time, and follow-up headway associated with the PPLT signal displays. The details of the traffic operation study are described in the following sections.

## **BACKGROUND**

Several studies have been conducted which compared the change in operational conditions when signal phasing was changed from permitted- or protected-only to PPLT signal phasing. Researchers agree that PPLT signal phasing in a non-congested environment can improve capacity and reduce delay to the left-turn movement (3,4,5). The literature contains limited information on the operational advantages of PPLT signal phasing, signal displays, signal indications, or display placements. The literature does provide some general information related to operational effects of various types of PPLT signal phasing.

Bonneson evaluated the response time to the leading left-turn indication, considering only the first vehicle in queue (6). After evaluating 14 sites and 1,238 response times, Bonneson concluded that there was no significant differences among the five PPLT signal displays evaluated. Shorter response times were found with the five-section horizontal display and five-section cluster display when the displays were on a mast arm centered over the left-turn lane. In general, the difference in response times were less than 0.19 seconds.

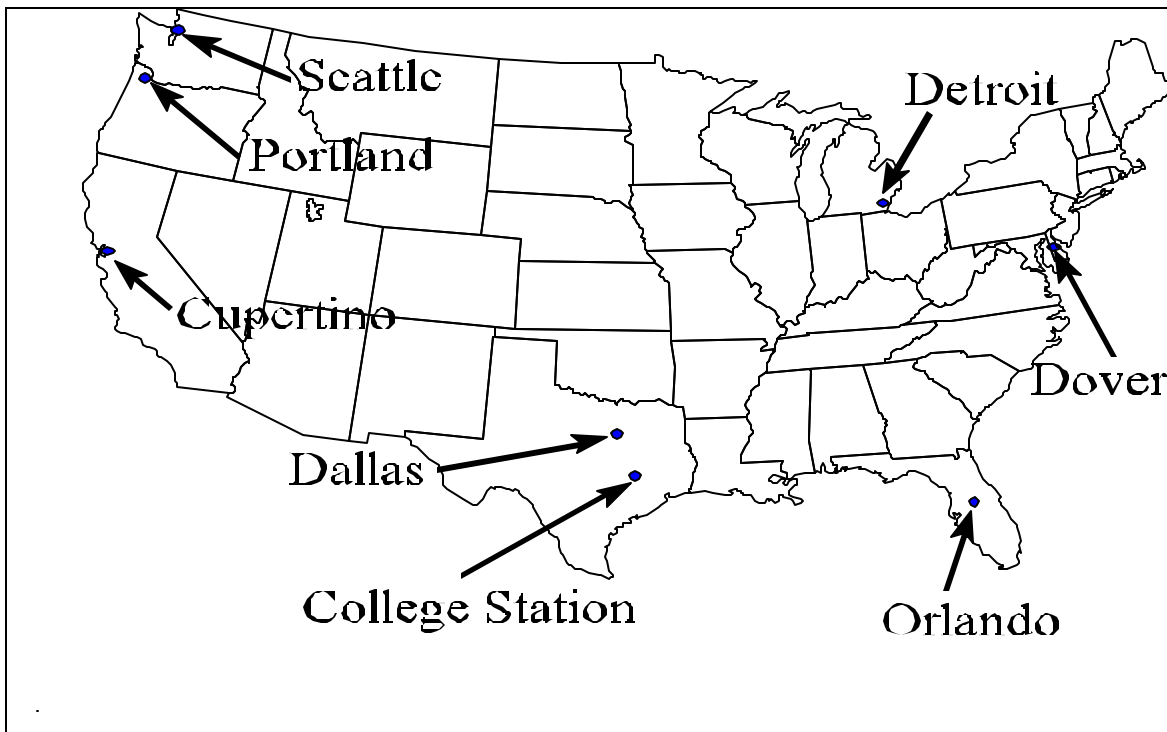
In a study of leading and lagging PPLT signal phasing, Lee found that intersection delay was significantly greater with lagging left-turn operation (7). These results were obtained during the afternoon peak period with no statistically significant differences in stops or travel time. Asante also found that the lag/lead PPLT phasing sequence resulted in higher delay values than lead/lag PPLT phasing (8).

Dallas phasing results in less delay for both the left-turning and through movements than the MUTCD PPLT phasing (1, 9). Dallas phasing resulted in less left-turn delay in a simulation of 60- and 90-second cycle lengths, with left-turn volumes of 300 vehicles per hour (vph), and opposing volumes ranging from 200 to 1,500 vph. Similar results were found by Asante (8).

## **TRAFFIC OPERATION STUDY**

Eight cities, in different geographic locations of the United States, were identified as potential study locations. Each city was selected using criteria related to protected-permitted left-turn control, permitted indication, and the geographic location. These locations include College Station and Dallas, Texas; Portland, Oregon; Seattle, Washington; Detroit, Michigan; Cupertino, California; Dover, Delaware; and Orlando, Florida. The geographical distribution of the study location are illustrated in Figure 1.

Seattle, Detroit, Cupertino, and Dover were selected because of the flashing permitted indications used in their representative PPLT signal displays. Dallas was selected because of its proximity to College Station and because Dallas Phasing was used with PPLT signal displays. College Station provided a local data collection site and Portland provided a site near members of the NCHRP 3-54 research team. Orlando was selected because of the large population of older and out-of-state drivers regularly in the Orlando area.



**Figure 1. Traffic Operation Study Data Collection Locations.**

### *Intersection Site Selection*

Within each of the cities identified as study locations, three intersections were selected for analysis. Table 1, a selection matrix, was used to select the potential study intersections. The matrix identified which permitted display type was being used in the study locations. Note that the PPLT signal display containing a flashing yellow arrow permitted indication used in the Reno, Nevada area had been removed and was not available for study.

Initially, the selection of the specific intersections was based on three variables, namely the left-turn lane geometry, display arrangement, and left-turn phasing. Left-turn lane geometry included exclusive lane, shared lane, and a combination of exclusive/shared lanes. Display arrangement included horizontal, vertical, and cluster displays. Left-turn phasing sequence included lead, lag, lead-lag, and Dallas Phasing.

**Table 1. Conflict Study Intersection Selection Matrix.**

Permitted Display Type	Location - Proposed Study Sites	Left-Turn Lane Geometry		
		Exclusive Lane	Shared Lane	Combination
MUTCD (green ball)	Dallas, TX College Station, TX Portland, OR	✓	✓	✓
Flashing Yellow Arrow	<i>Removed</i>	<i>No Sites Available</i>		
Flashing Yellow Ball	Seattle, WA	✓	✓	✓
Flashing Red Arrow	Cupertino, CA Dover, DE	✓	✓	✓
Flashing Red Ball	Detroit, MI	✓	✓	✓

In addition to the study variables, several additional selection criteria were established. The intersection had to be considered *typical*, meaning a right angle intersection with four approaches of two or three through lanes each, relatively flat grade, 12-foot lane width, no on street parking, and no additional variables that directly affect the left-turn movement being evaluated. Further, traffic volume, phasing sequence, and crash data were required to provide the necessary information for analysis.

Local transportation officials assisted in the select of intersections within each location. As expected, it was difficult to find intersections that met each of the selection criteria. In fact, several combinations in Table 1 did not exist. The limited number of sites which contained unique permitted indications resulted in several intersections being selected without applying all selection criteria. For example, there were only three intersections in Cupertino, California that used PPLT signal phasing and the flashing red arrow permitted indication. Therefore, all three intersections were selected.

The variable that could not be evaluated was left-turn lane geometry. Intersections with a shared or combination left-turn lane geometry that contained PPLT signal displays, had sufficient traffic volumes, and met the selection criteria, could not be located in any of the selected locations. Thus, all intersections evaluated contained a single exclusive left-turn lane. After removing left-turn lane geometry, PPLT display

arrangement and permitted indication became the primary selection criteria, considering typical geometry and availability of data. All selected intersections met this criteria.

Phasing sequence and PPLT signal displays were generally consistent within each location. Only intersections selected in Dallas and College Station contained different PPLT signal display arrangements. Table 2 lists the intersections selected in each location along with the PPLT signal display, the permitted indication (PI), and the left-turn phasing sequence found at each site. Note that the Michigan location is referred to as Oakland County because the selected intersections were located within several different municipalities.

Also note in Table 2, the Skillman Avenue at Mockingbird Lane and the Buckner Boulevard at Garland Road intersections in Dallas are listed twice, once for the leading and once for the lagging left-turn phase sequence. As part of the Dallas Phasing concept, these intersections changed phasing sequences by time-of-day. This change in phasing allowed for two distinct operational data sets to be obtained for a single intersection approach.

### *Sample Size*

For the purpose of estimating sample size, it was assumed that the data collection could be approximated by the normal distribution. The level of significance  $\alpha$  was set at 0.05 (Type I error), and where appropriate, the power of the statistical test ( $1 - \beta$ ) was set at 0.8 (type II error). Based on these assumptions, the following equation was used to estimate sample size:

$$n = \left( Z \frac{s}{d} \right)^2 \quad (1)$$

where:

- n = sample size;
- Z = constant from the standard normal distribution corresponding to a 95 percent ( $1 - \alpha$ ;  $\alpha = 0.05$ ) confidence level;
- s = sample standard deviation (vehicles-per-hour (vph)); and
- d = acceptable deviation from the true saturation flow rate (vph).

**Table 2. Intersections Selected for Study.**

City	Intersection	ID <sup>1</sup>	PPLT Display <sup>2</sup>	PI <sup>3</sup>	LT Phase <sup>4</sup>
Dallas, TX	Lovers Ln. @ Skillman Ave.	1	5-Vertical	GB	Lead
	Mockingbird Ln. @ Skillman Ave.	2	5-Horizontal	GB	D-lead
	Mockingbird Ln. @ Skillman Ave.	3	5-Horizontal	GB	D-lag
	Buckner Blvd. @ Garland Rd.	4	5-Horizontal	GB	D-lead
	Buckner Blvd. @ Garland Rd.	5	5-Horizontal	GB	D-lag
Dover, DE	Highway 13 @ Court St.	6	4-Cluster	FRA	Lead
	Highway 13 @ East Landing Rd.	7	4-Cluster	FRA	Lead
	Highway 113 @ Little Creek Rd.	8	4-Cluster	FRA	Lead
Oakland County, MI	Maple Ave. @ Orchard Lake Rd.	9	3-Vertical	FRB	Lag
	14 Mile Rd. @ Orchard Lake Rd.	10	3-Vertical	FRB	Lag
	13 Mile Rd. @ Orchard Lake Rd.	11	3-Vertical	FRB	Lag
College Station, TX	University Dr. @ College Ave.	12	5-Horizontal	GB	Lead
	Southwest Pkwy @ Texas Ave.	13	5-Horizontal	GB	Lead
	Southwest Pkwy @ Southwood Dr.	14	5-Cluster	GB	Lag
Seattle, WA	South Lander St. @ 1 <sup>st</sup> Ave.	15	4-Vertical	FYB	Lead
	South Lander St. @ 4 <sup>th</sup> Ave.	16	4-Vertical	FYB	Lead
	Fairview Ave. @ Republican St.	17	4-Vertical	FYB	Lead
Portland, OR	Oleson Rd. @ Vermont St.	18	5-Cluster	GB	Lead
	NW Murray Blvd. @ Science Park	19	5-Cluster	GB	Lead
	La Bonita Dr. @ 72 <sup>nd</sup> St.	20	5-Cluster	GB	Lead
Cupertino, CA	Pruneridge Dr. @ Hewlett Packard	21	4-Vertical	FRA	Lead
	Stevens Creek Blvd. @ Torre Dr.	22	4-Vertical	FRA	Lead
	Stevens Creek Blvd. @ Portal Ave.	23	4-Vertical	FRA	Lead
Orlando, FL	Orange Blossom Trail @ Princeton St.	24	5-Cluster	GB	Lead
	Orange Ave. @ Kaley St.	25	5-Cluster	GB	Lead
	Orange Ave. @ Michigan St.	26	5-Cluster	GB	Lead

1. Intersection Identification Number.

2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).

3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.

4. Left-turn phasing. D = Dallas phasing.

Standard deviation and acceptable deviation values were estimated based on the results of previous studies (2). For example, a typical value for  $s$  is 140 vph. Given this  $s$  value along with the desire to estimate mean saturation flow within 75 vph of the true saturation flow with 95 percent confidence ( $Z = 1.96$ ), 15 left-turn queue observations were required. Since start-up lost time is computed directly from the saturation flow rate results, this sample size applied to the start-up lost time evaluation as well.

A sample size of 15 valid left-turn queues represented the minimum amount of data needed to estimate the mean of each variable of interest with a reasonable degree of confidence. Whenever possible, data for more than 15 valid queues were collected. At locations where traffic volumes and operational conditions resulted in many left-turn queues, at least 30 left-turn queues were evaluated, doubling the required sample size.

Equation 1 was also used to calculate sample sizes for response time and follow-up headway, although several variables changed. Using the results of a previous study, a difference in response time of 0.2 seconds ( $d$ ) was determined to be sufficient to detect practical differences in driver behavior among signal display types (6). The standard deviation of the driver response time was estimated to be 0.6 seconds. Applying these values to Equation 1 resulted in a minimum sample size of 35 observations per left-turn signal display type.

Realizing that the use of similar equations for the determination of sample size may produce slightly different results, a minimum of 35 response time observations were obtained at each intersection studied to assure that the minimum sample size requirements were met. In fact, between 50 and 80 response time observations were obtained at all but the Fairview Avenue at Republican Street intersection in Seattle. One-hundred follow-up headway observations were obtained for each of the PPLT signal displays evaluated.

### ***Data Collection Equipment***

Headway data necessary to compute left-turn saturation flow rate, start-up lost time, response time, and follow-up headway were collected using a portable computer and the software program HEADWAY.

The program records the computer clock time with each computer key stroke (entry) and computes the time difference between the entries. The time differences represent the observed vehicle headways. A video camera was positioned at the intersection to record the left-turn traffic flow. As the tape was reviewed the traffic flow was entered into HEADWAY.

### ***Data Collection***

Headway data necessary to compute left-turn saturation flow rate, start-up lost time, response time, and follow-up headway was collected at each of the study intersection.

At each study intersection, a researcher with a laptop computer was positioned with a view of the stop bar (or similar reference point), the PPLT signal display, and the left-turn vehicle queue. Three signal cycles were carefully observed to determine approximate phase times, phase sequence, and duration of the all-red interval. Knowing the length of the phase preceding the protected left-turn phase allow the researcher to accurately anticipate the beginning of the protected left-turn phase.

To collect the headway data, the researcher initiated the headway program simultaneously with the beginning of the protected left-turn phase, and pressed the appropriate key as the front bumper of each vehicle in the queue (up to 10 vehicles) crossed the reference line (2).

Research has shown that saturation flow most often begins with the fifth vehicle in the queue (2). Thus, study procedures recommend that saturation flow rate estimates be obtained using headways from queued vehicle 5 through 10, and that queues of less than eight vehicles not be evaluated.

Using the two methods of data collection, direct input in the field and input from the review of video recordings, one hundred follow-up headways were recorded for each PPLT signal display being evaluated. The HEADWAY program was used to quantify the time values for each recorded headway.

Response time was considered to be the first left-turn driver's perception/reaction time of the onset of the protected phase of the PPLT control.

## STUDY FINDINGS

The traffic operation data collected using the HEADWAY program was reduced and analyzed. The following sections present the findings of the left-turn saturation flow rate, the start-up lost time and the follow-up headway data. The findings from the statistical analyses are included in the individual sections.

### *Saturation Flow Rate*

Using the collected traffic operation data, three observations of average saturation flow rate were calculated for each of the study intersections. Figure 2 shows a frequency histogram of the saturation flow rate data (in vehicles per hour green per lane) overlaid with an estimated normal distribution curve. The data appeared to approximate the normal distribution. A Shapiro-Wilk W statistic of 0.96 provided sufficient evidence to conclude that the data was normally distributed.

Table 3 presents the average saturation flow rates, standard deviations, and their corresponding rankings, found at each intersection. This table also presents the PPLT signal display type, permitted indication, and left-turn phasing type observed during data collection.

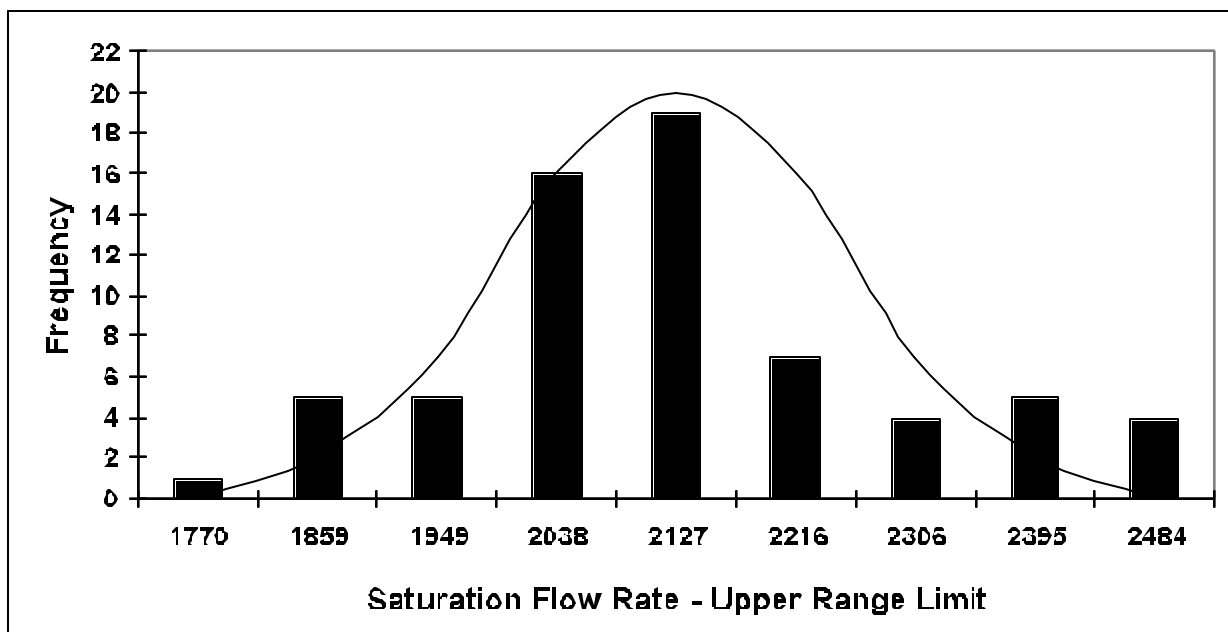


Figure 2. Frequency Distribution of Saturation Flow Rate Data.

**Table 3. Saturation Flow Rates (vphgpl).**

City	ID <sup>1</sup>	PPLT Display <sup>2</sup>	PI <sup>3</sup>	Left-Turn Phasing	Saturation Flow Rate		Rank
					Average	SD <sup>4</sup>	
Dallas, TX	1	5-Vertical	GB	Lead	2,201	36.55	6
	2	5-Horizontal	GB	Dallas-Lead	2,211	36.09	5
	3	5-Horizontal	GB	Dallas-Lag	2,320	97.50	3
	4	5-Horizontal	GB	Dallas-Lead	2,091	98.38	8
	5	5-Horizontal	GB	Dallas-Lag	2,063	58.97	12
Dover, DE	6	4-Cluster	FRA	Lead	2,214	151.91	4
	7	4-Cluster	FRA	Lead	1,977	19.75	16
	8	4-Cluster	FRA	Lead	1,999	118.21	15
Oakland County, MI	9	3-Vertical	FRB	Lag	2,168	111.09	7
	10	3-Vertical	FRB	Lag	2,399	86.51	2
	11	3-Vertical	FRB	Lag	2,402	52.54	1
College Station, TX	12	5-Horizontal	GB	Lead	1,973	60.65	18
	13	5-Horizontal	GB	Lead	2,025	78.42	14
	14	5-Cluster	GB	Lead	2,045	57.13	13
Seattle, WA	15	4-Vertical	FYB	Lead	1,773	3.00	22
	16	4-Vertical	FYB	Lead	---	---	23
	17	4-Vertical	FYB	Lead	---	---	23
Portland, OR	18	5-Cluster	GB	Lead	---	---	23
	19	5-Cluster	GB	Lead	1,871	40.13	21
	20	5-Cluster	GB	Lead	1,977	7.00	16
Cupertino, CA	21	4-Vertical	FRA	Lead	2,065	48.26	11
	22	4-Vertical	FRA	Lead	1,944	146.93	20
	23	4-Vertical	FRA	Lead	---	---	23
Orlando, FL	24	5-Cluster	GB	Lead	2,067	42.58	10
	25	5-Cluster	GB	Lead	2,072	61.87	9
	26	5-Cluster	GB	Lead	1,963	102.93	19

1. Intersection Identification Number.
2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).
3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.
4. Standard Deviation.

Note that intersections 16 and 17 in Seattle, 18 in Portland, and 23 in Cupertino did not have left-turn vehicles queues greater than seven vehicles during the data collection period. Therefore, saturation flow rates could not be measured.

To illustrate the results, Figure 3 presents a pictorial representation of average saturation flow rates by intersection. Alternating black and gray shading was used in Figure 3 to group intersections into location blocks. Left-turn saturation flow rates ranged from a high of 2,402 vphgpl at intersection 11 in Oakland County (three-section vertical display; lagging left-turn phasing) to a low of 1,773 vphgpl at intersection 15 in Seattle (four-section vertical display; leading left-turn phasing).

The average saturation flow rate for all intersections in the data set was 2,083 vphgpl. Average saturation flow rate for the 16 intersection approaches with a leading left-turn phasing sequence and for the six approaches with a lagging left-turn phasing sequence were 2,026 vphgpl and 2,233 vphgpl, respectively. Each of these saturation flow rate values exceeded the 1,900 vphgpl ideal saturation flow rate default value described in the HCM (1).

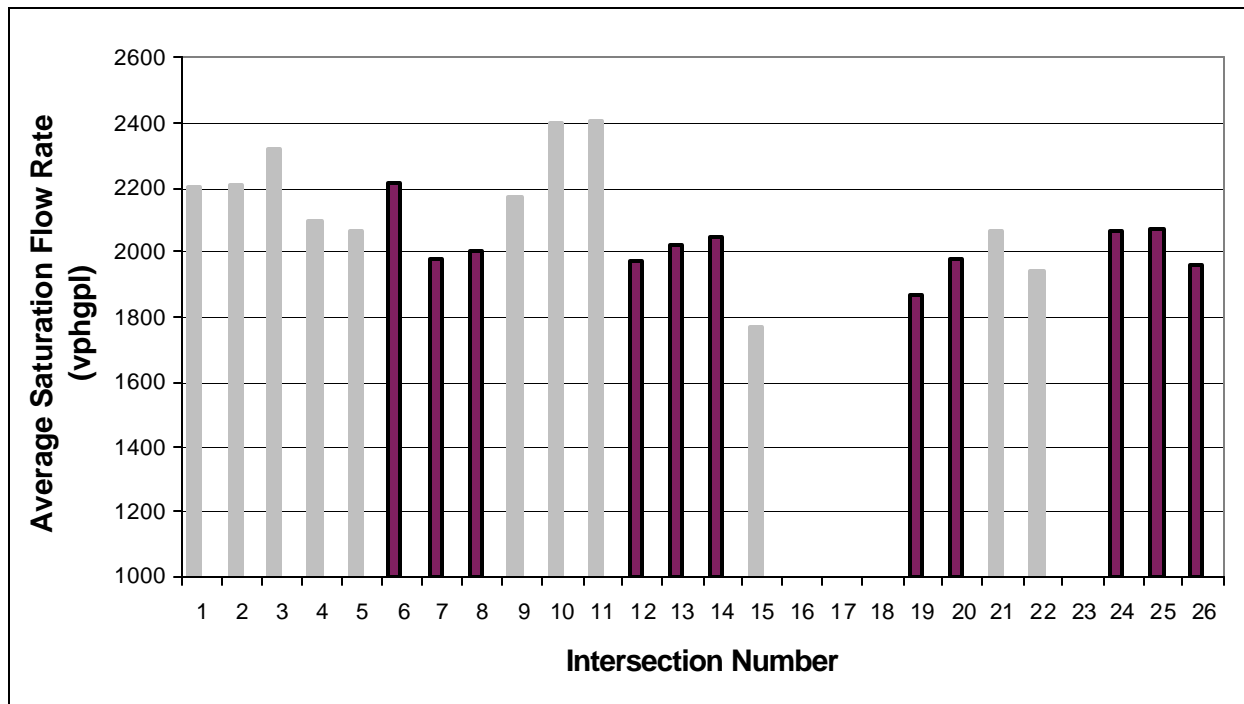


Figure 3. Average Saturation Flow Rates by Intersection.

**Statistical Analysis.** A statistical analysis was conducted to determine if a single factor significantly affected variability in the average saturation flow rates between intersections. Three factors were evaluated, namely the PPLT signal display, the PPLT signal phasing, and the location.

When considering the PPLT signal display as the single factor in the analysis, the saturation flow rate associated with the three-section vertical display was found to be significantly higher than that associated with other PPLT signal displays, except for the five-section vertical display. In addition, the average saturation flow rate associated with the five-section horizontal display was significantly higher than that associated with the four-section vertical display.

Considering only the PPLT signal phasing as a factor in the analysis, the average saturation flow rates at intersections with lagging dual left-turn signal phasing were found to be significantly greater than at intersections with leading or dual leading left-turn signal phasing.

When the study location was the single factor of analysis, the average saturation flow rates in Oakland County, Michigan was found to be significantly high and the average saturation flow rate in Seattle, Washington was found to be significantly low, as compared to that of the other locations.

Additional factors such as the placement of the PPLT signal display and the use of supplemental signs were considered. These factors were found to be correlated with one or more of the selected factors and therefore unable to perform a single variable analysis.

To further explore the findings of the initial statistical analysis, average saturation flow rates and their corresponding 95 percent confidence intervals (CIs) for each of the PPLT signal display, PPLT signal phasing, and location factors were computed and presented in Figures 4 through 6. Notice that the average saturation flow rate values in each figure are depicted by the horizontal dash line and the range of the CIs by the solid vertical line.

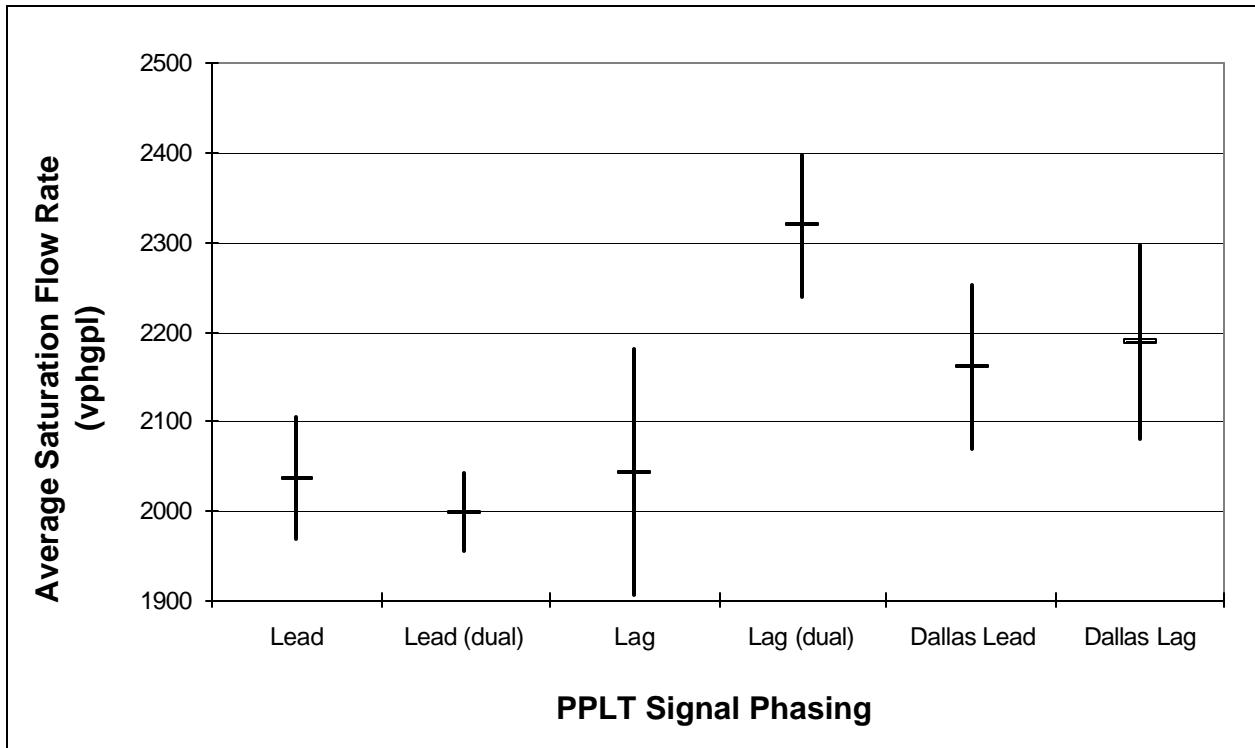


Figure 4. Average Saturation Flow Rate and 95 Percent CIs by PPLT Signal Display.

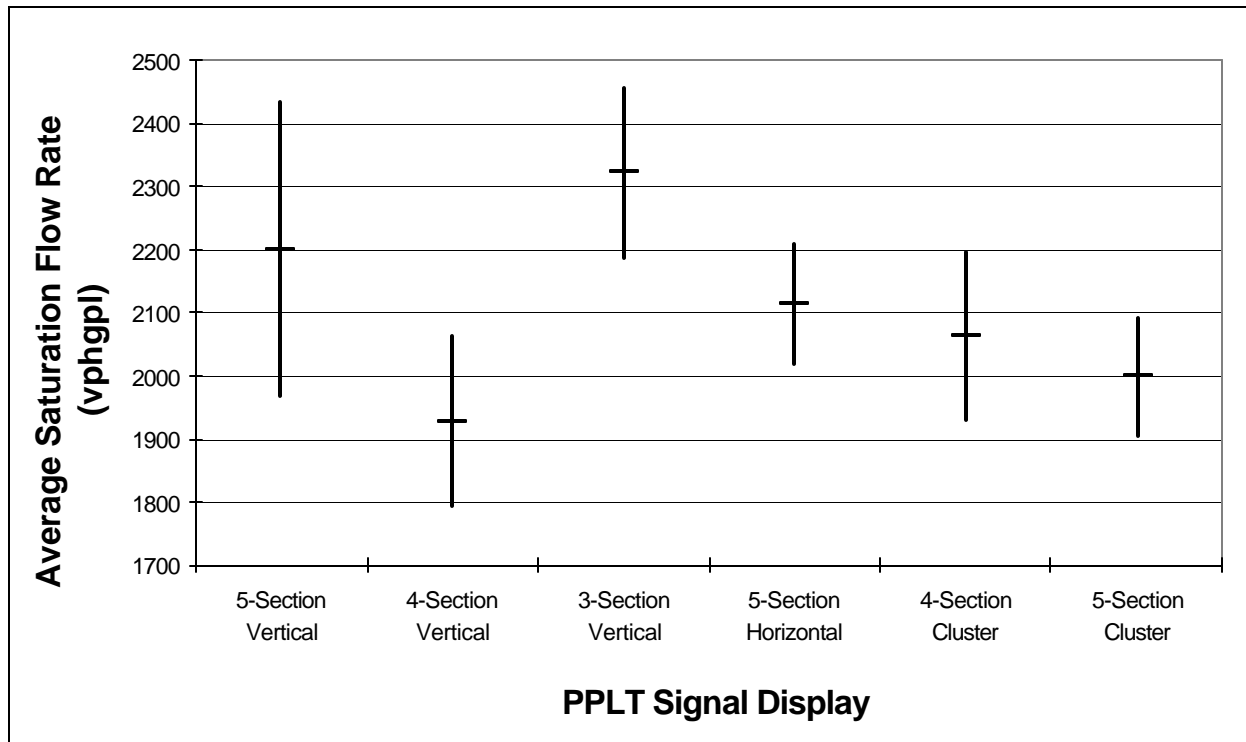
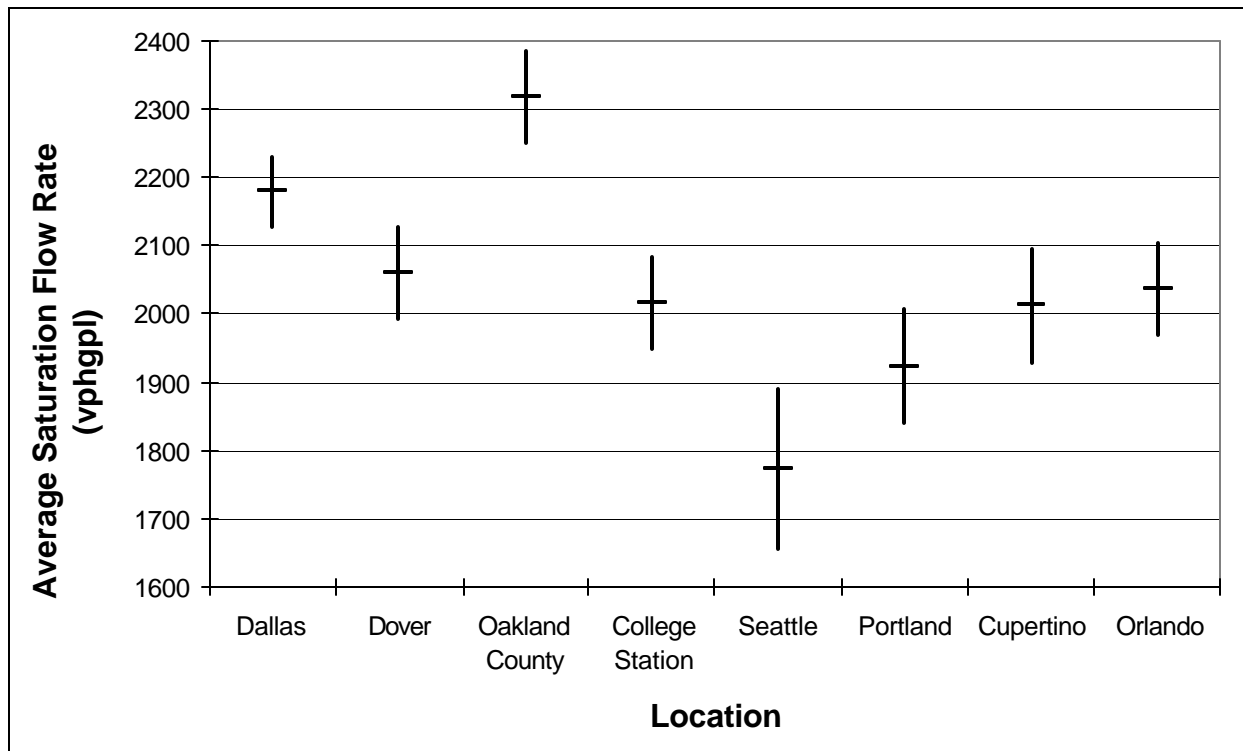


Figure 5. Average Saturation Flow Rate and 95 Percent CIs by Phasing.



**Figure 6. Average Saturation Flow Rate and 95 Percent CIs by Location.**

The results of the multiple comparison tests previously mentioned were consistent with intuitive expectations based on the CIs presented in each figure; however, additional analysis was required to determine the true source of variation in the average saturation flow rates.

The results of this statistical analysis found that the type of PPLT signal display and type of PPLT signal phasing, and their interaction effect, were significant contributors to the differences in average saturation flow rates. Further, the location factor was significant. However, the type of PPLT signal display was not significant nor was the signal display interaction with the location factor. Similarly, considering the combined effects of PPLT signal phasing and location, the location was significant; however, the type of PPLT signal phasing was not significant nor was the interaction between variables.

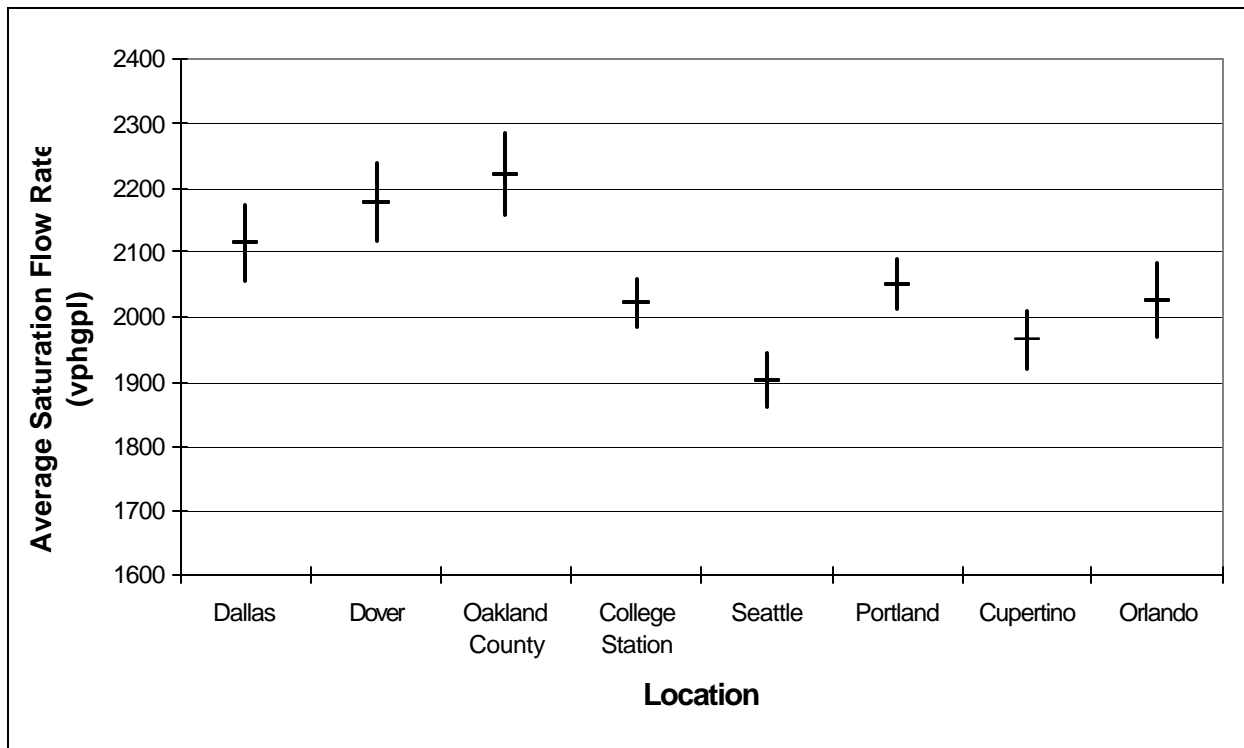
Based on this statistical analysis, the results suggested that the differences in average saturation flow rates were primarily due to differences in operational characteristics and driver behavior between each study location. The type of PPLT signal display and the PPLT signal phasing were not significant

contributors in the explaining the differences in average saturation flow rates from location to location.

**Through Movement Saturation Flow Rates.** A supplemental study was conducted on through movement saturation flow rates to determine if similar behavioral differences between locations existed. Eight intersections were randomly selected (one intersection from each location) and saturation headways from a minimum of 30 through movement vehicle queue of seven or more vehicles were measured. This methodology resulted in the evaluation of approximately 300 through movement saturation headways at each location.

Figure 7 presents the results of the through movement saturation flow rate analysis, including the 95 percent confidence intervals (CIs) for each location. The results of this analysis found that there was a statistically significant difference in through movement average saturation flow rates by location, similar to what was found in the left-turn movement analysis. In fact, a comparison of Figures 6 and 7 suggest that the relationship and rank order of average saturation flow rates by location nearly identical.

Oakland County, Michigan was found to have the highest average through movement saturation flow rate at 2,218 vphgpl and Seattle, Washington the lowest at 1,902 vphgpl. Duncan's multiple comparison test showed that the differences in through movement saturation flow rates between Oakland County and Dover were different but not statistically significant; however, both locations were significantly greater than the remaining locations. Therefore, it was concluded that the previous results found in the left-turn analysis were confirmed and the type of PPLT signal display and phasing were not significant contributors in differences in average saturation flow rates.

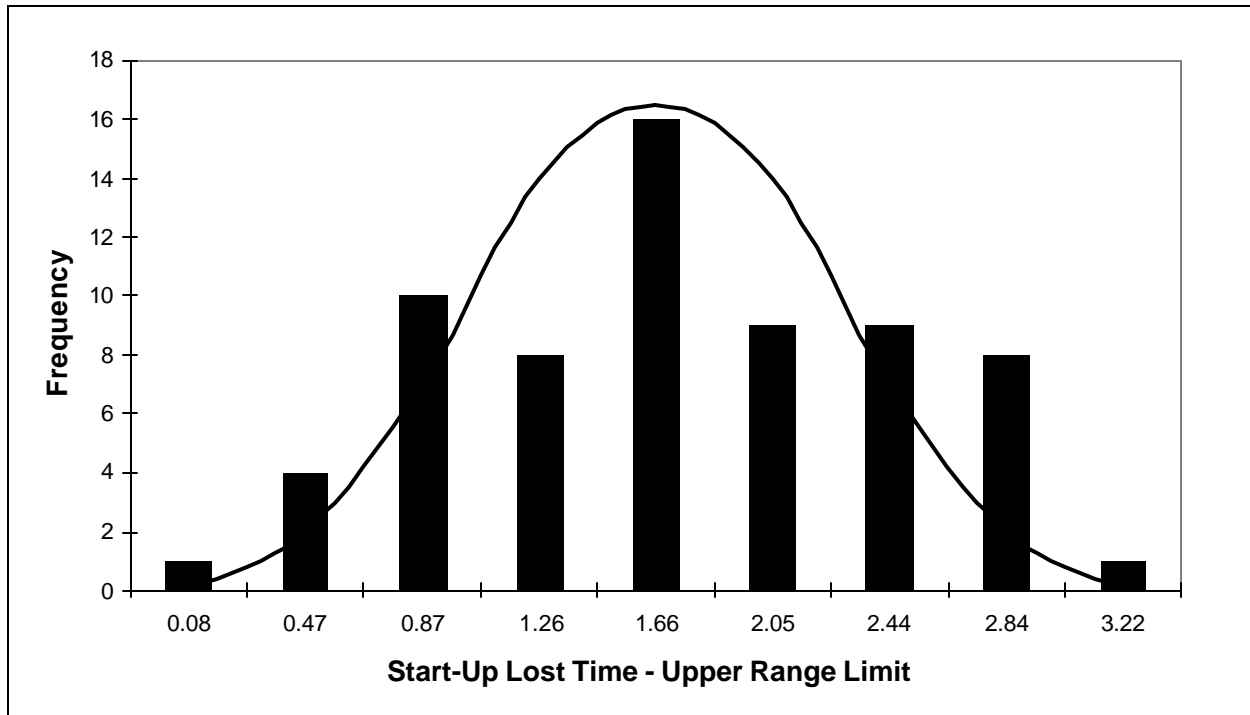


**Figure 7. Average Through Movement Saturation Flow Rate and CIs by Location.**

### *Start-Up Lost Time*

Identical to the saturation flow rate analysis, the evaluation of the start-up lost time data began by exploring the distribution of the data set. Figure 8 shows the relative frequency histogram of the start-up lost time data, overlaid with an estimate of the normal distribution. In visually examining the data, it was evident that the data was approximately normally distributed. In fact, a Shapiro-Wilk W statistic of 0.96 provided sufficient evidence to conclude that the start-up lost time data was normally distributed.

Table 3 presents the descriptive results of the start-up lost time analysis. The average start-up lost time and standard deviation is included along with information related to the left-turn signal display. The rank order of the average start-up lost times is also shown. As with the saturation flow rate data presented in the previous section, no data was available for intersections 16 and 17 in Seattle, intersection 18 in Portland, and intersection 23 in Cupertino.



**Figure 8. Cumulative Frequency Distribution of Start-Up Lost Times.**

Figure 9 presents a graphical depiction of the average start-up lost times for each study intersection. In order to visually group the intersections together, alternating black and gray shading was used. Start-up lost times ranged from 0.27 seconds in Pontiac (three-section vertical display; lagging left-turn phasing) to 2.70 seconds in Orlando (five-section cluster display; leading left-turn phasing).

Average start-up lost time for all locations was 1.56 seconds. Considering left-turn phase sequence, average start-up lost time was 1.87 seconds with a leading sequence (16 approaches) and 0.73 seconds with a lagging sequence (six approaches). The HCM default value for start-up lost time is 3.0 seconds/phase, although this includes clearance lost time.

**Table 3. Start-Up Lost Time.**

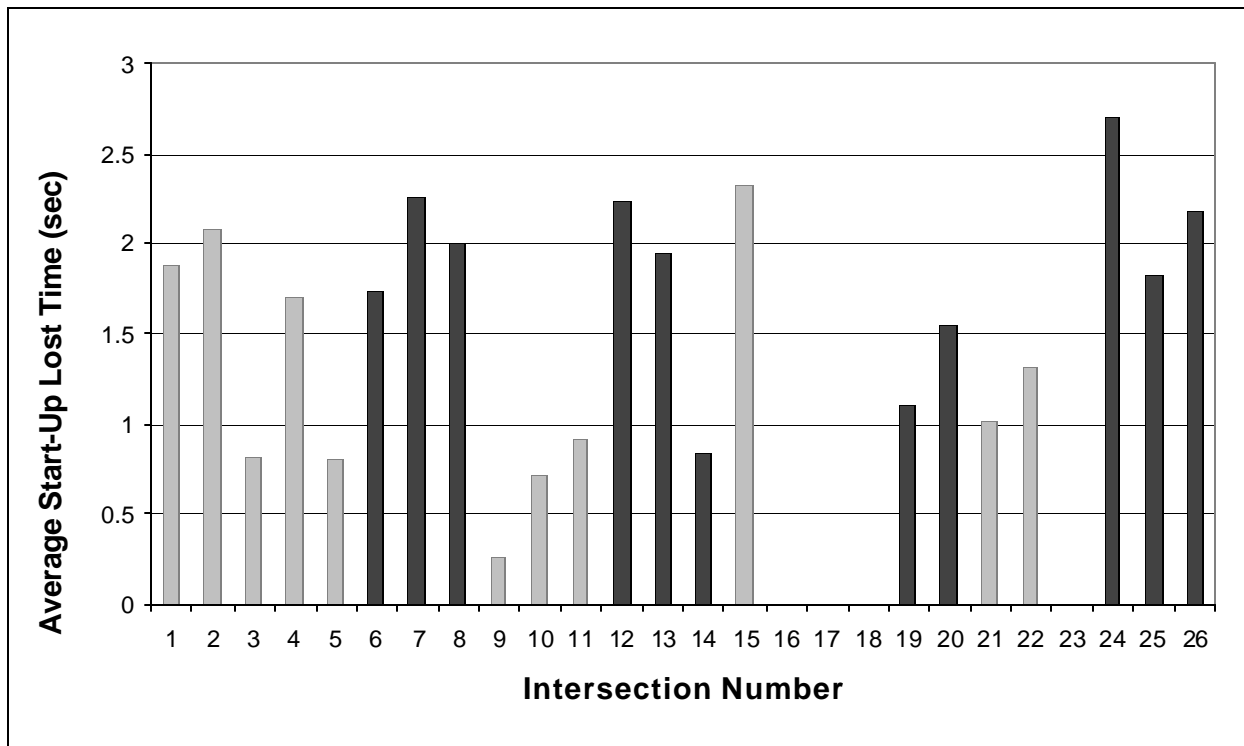
City	ID <sup>1</sup>	PPLT Display <sup>2</sup>	PI <sup>3</sup>	Left-Turn Phasing	Start-Up Lost Time (sec)		Rank
					Average	SD <sup>4</sup>	
Dallas, TX	1	5-Vertical	GB	Lead	1.89	0.28	14
	2	5-Horizontal	GB	Dallas-Lead	2.08	0.42	17
	3	5-Horizontal	GB	Dallas-Lag	0.82	0.68	4
	4	5-Horizontal	GB	Dallas-Lead	1.70	0.48	11
	5	5-Horizontal	GB	Dallas-Lag	0.81	0.17	3
Dover, DE	6	4-Cluster	FRA	Lead	1.74	0.23	12
	7	4-Cluster	FRA	Lead	2.26	0.45	20
	8	4-Cluster	FRA	Lead	2.01	0.80	16
Oakland County, MI	9	3-Vertical	FRB	Lag	0.27	0.16	1
	10	3-Vertical	FRB	Lag	0.72	0.13	2
	11	3-Vertical	FRB	Lag	0.91	0.31	6
College Station, TX	12	5-Horizontal	GB	Lead	2.23	0.34	19
	13	5-Horizontal	GB	Lead	1.95	0.41	15
	14	5-Cluster	GB	Lead	0.84	0.30	5
Seattle, WA	15	4-Vertical	FYB	Lead	2.33	0.13	21
	16	4-Vertical	FYB	Lead	---	---	23
	17	4-Vertical	FYB	Lead	---	---	23
Portland, OR	18	5-Cluster	GB	Lead	---	---	23
	19	5-Cluster	GB	Lead	1.11	0.04	8
	20	5-Cluster	GB	Lead	1.55	0.05	10
Cupertino, CA	21	4-Vertical	FRA	Lead	1.02	0.83	7
	22	4-Vertical	FRA	Lead	1.32	0.24	9
	23	4-Vertical	FRA	Lead	---	---	23
Orlando, FL	24	5-Cluster	GB	Lead	2.70	0.07	22
	25	5-Cluster	GB	Lead	1.83	0.57	13
	26	5-Cluster	GB	Lead	2.19	0.96	18

1. Intersection Identification Number.

2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).

3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.

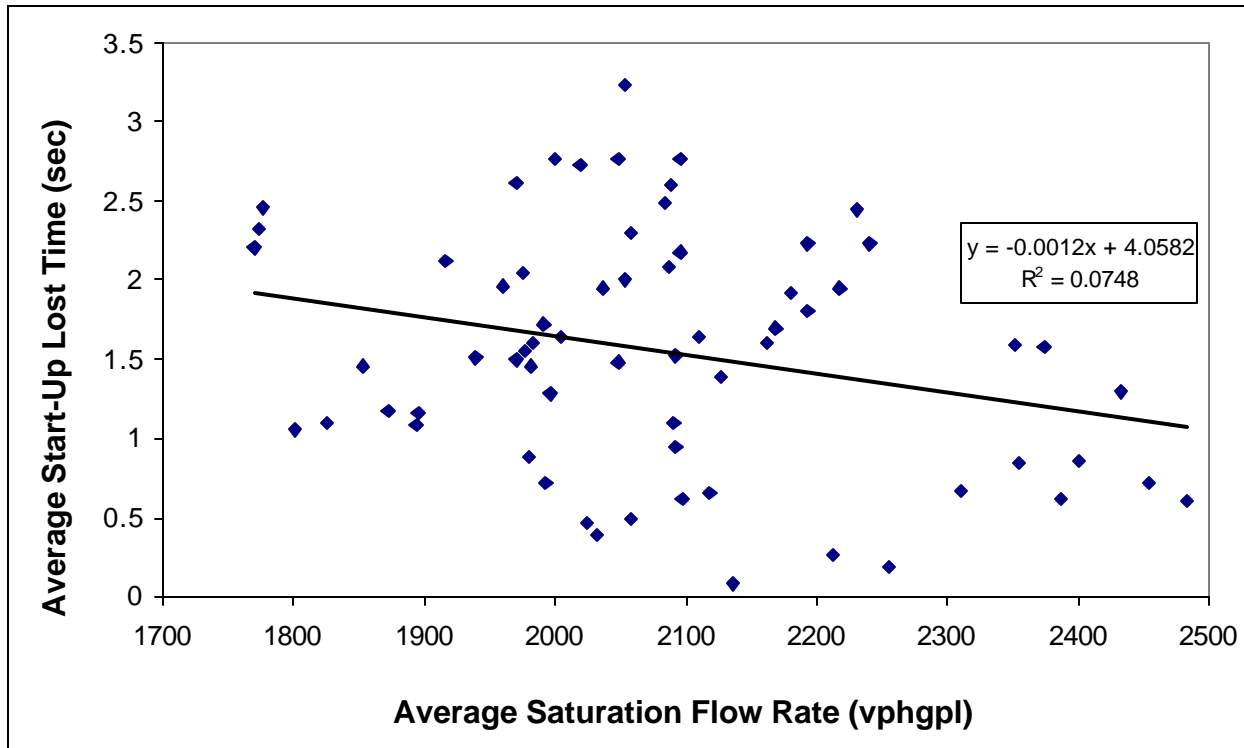
4. Standard Deviation.



**Figure 9. Average Start-Up Lost Time by Intersection.**

**Start-Up Lost Time and Saturation Flow Rate Relationship.** Since start-up lost time is dependent on the saturation flow rate, and both computed from the same headway data set, the relationship between these two variables was explored. A plot showing this relationship along with an approximate least squares regression line is presented in Figure 10.

The distribution of the start-up lost time and saturation flow rate data appeared to be quite random and showed little evidence of a linear relationship. The minimal slope of the least squares regression line and the coefficient of determination provided further evidence of the non-linear nature of the data. Because of the non-linear relationship between the two variables, it was concluded that the start-up lost time data could be evaluated independent of the saturation flow rate data.



**Figure 10. Saturation Flow Rate and Start-Up Lost Time Relationship.**

A review of both the Duncan and Tukey multiple comparison results showed that the three-section vertical display had a significantly lower average start-up lost time than all other PPLT signal displays. Average start-up lost times at intersections with lag, lag (dual), and Dallas lag left-turn signal phasing were found to be significantly less than at intersections with either leading or dual-leading left-turn signal phasing. Finally, average start-up lost times were significantly lower in Oakland County, Michigan while a group of locations including Dover, Delaware; Seattle, Washington; and Orlando, Florida had significantly higher results.

To illustrate the differences in start-up lost time by PPLT signal display, PPLT signal phasing, and location, the average start-up lost time and corresponding 95 percent CIs are shown for each of these factors in Figures 11 through 13, respectively.

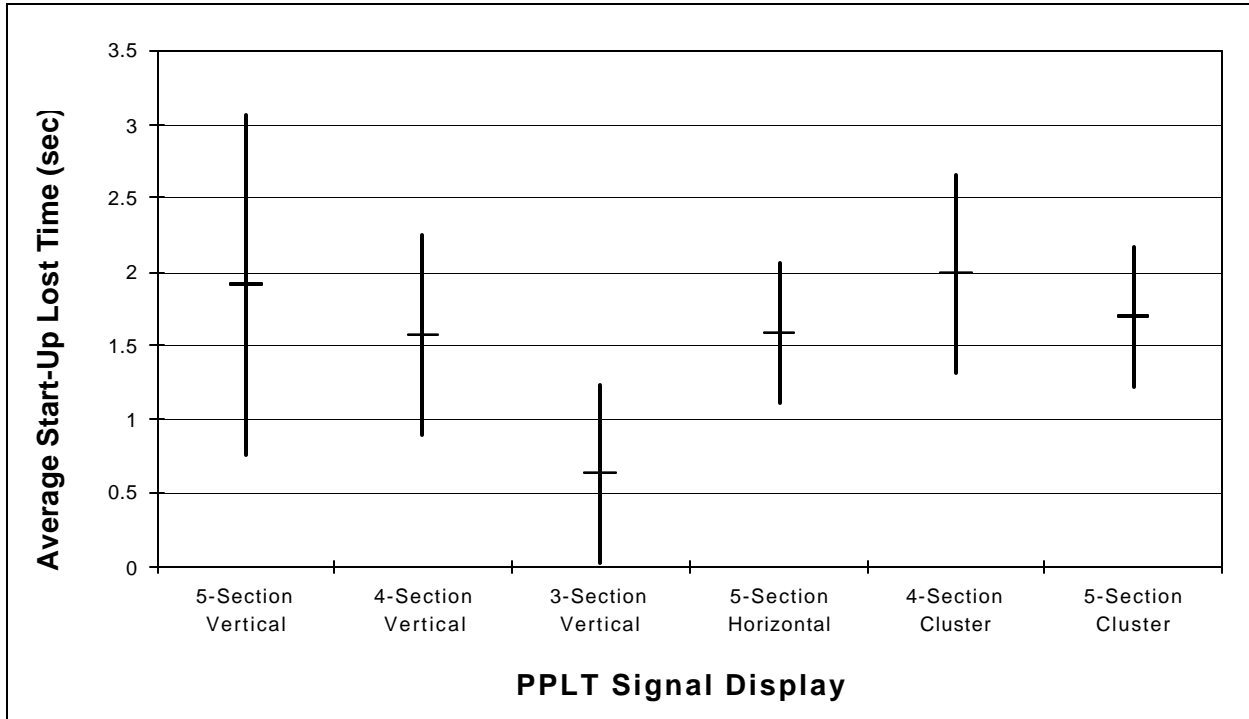


Figure 11. Average Start-Up Lost Time and 95 Percent CIs by Display.

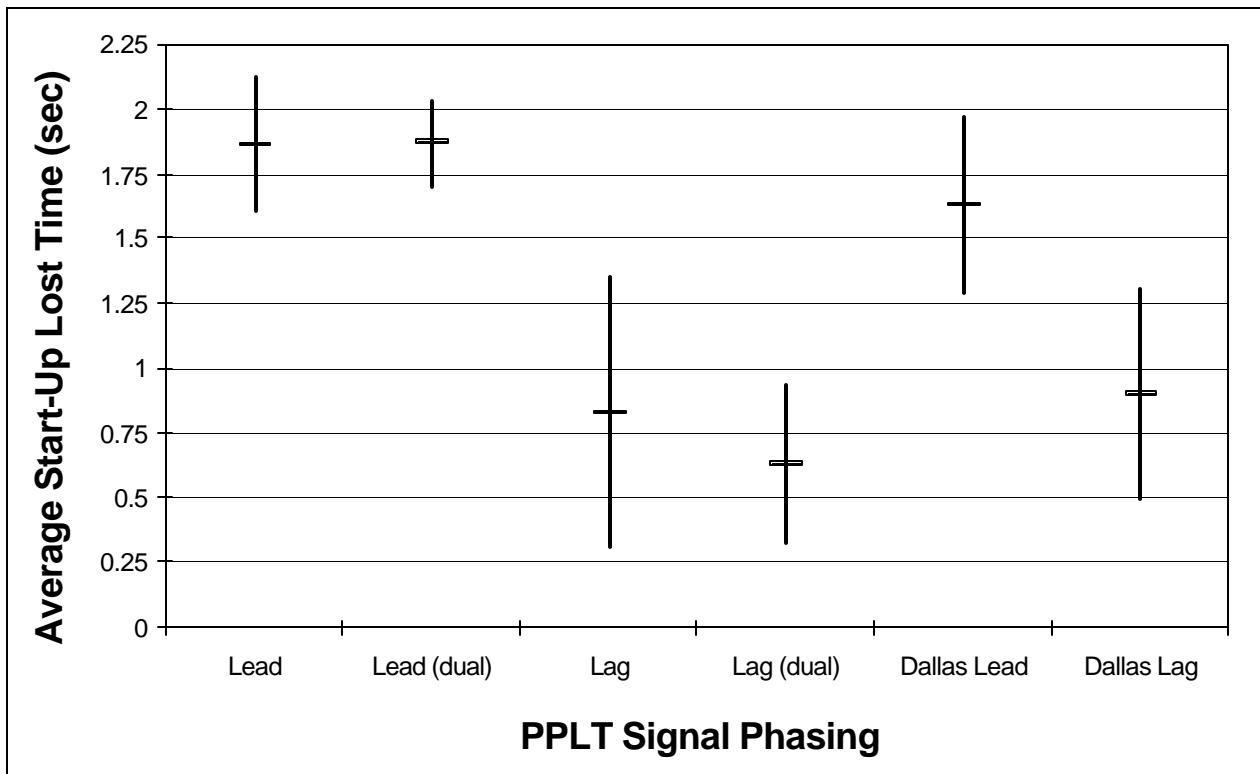
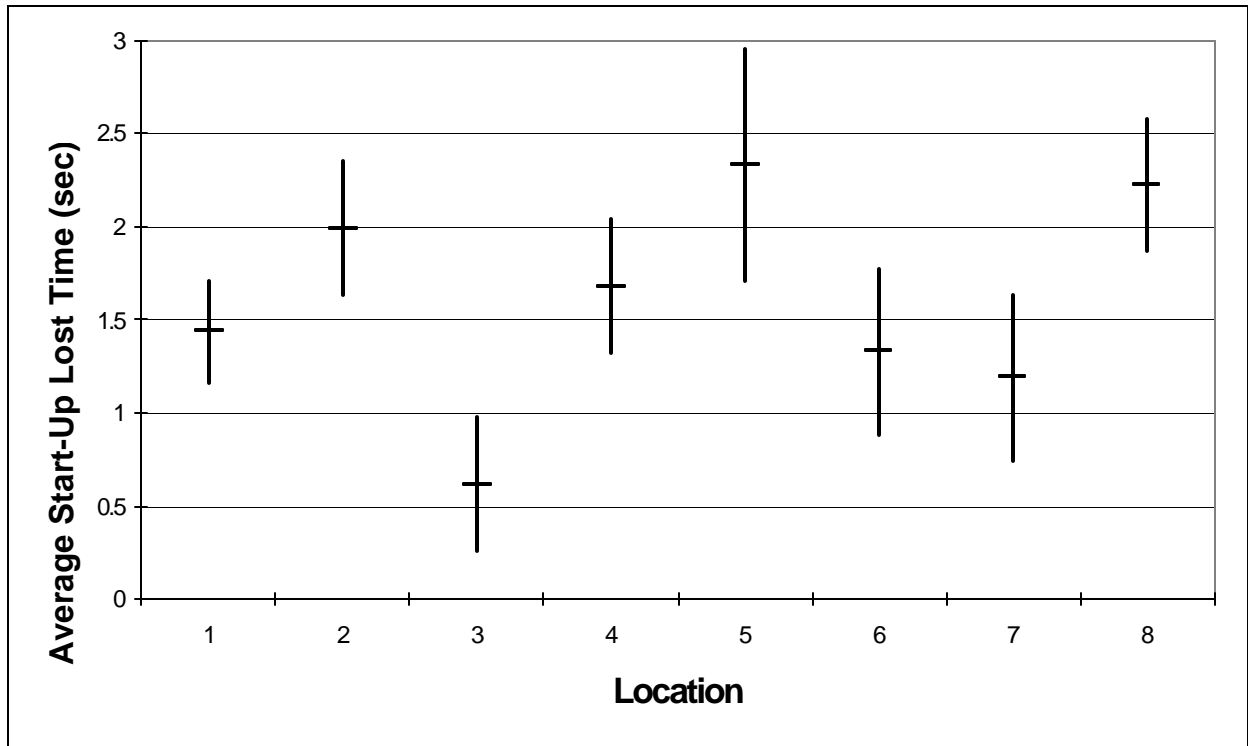


Figure 12. Average Start-Up Lost Time and 95 Percent CIs by Phasing.



**Figure 13. Average Start-Up Lost Time and 95 Percent CIs by Location.**

The results of a detailed statistical analysis indicate that the differences in average start-up lost time are primarily due to differences in PPLT signal phasing and are not significantly related to the type of PPLT signal display present or the location of the intersection.

The reason for the significantly lower start-up lost times in lagging left-turn phasing was driver's anticipation of the protected left-turn phase. Drivers in Oakland County and Dallas were quite knowledgeable concerning the left-turn phase sequence and often began the protected left-turn maneuver during the final seconds of the through movement clearance interval. This anticipation of the left-turn phase meant that the perception and reaction time component of start-up lost time were primarily consumed during the preceding yellow and all red intervals. By the time the left-turn green arrow indication was presented, the left-turn queue was moving at or near the saturation flow rate.

As with the saturation flow rate data, there was no statistical evidence to conclude that the type of PPLT left-turn signal display had a significant effect on left-turn start-up lost time. Differences in average start-up lost time between PPLT signal display types appear to be attributable to differences in PPLT signal phasing. It is possible that these differences could be significant with a larger sample size and balanced experimental design; however, it is again unlikely that start-up lost times would provide sufficient justification for the selection of one PPLT signal display over the other. Nevertheless, the three-section and four-section vertical PPLT signal displays in a lagging phase sequence appear to be associated with lower start-up lost times than the other PPLT displays.

### ***Response Time***

Consistent with the previous presentation, the analysis of the response time data began with an examination of the data set. As previously mentioned, response times was considered to be the time from the onset of the protected left-turn phase green arrow indication to the time the front bumper of the first left-turn vehicle in queue crossed the stop bar. Figure 14 shows a relative frequency histogram of the response time data, overlaid with an estimated normal distribution. A Shapiro-Wilk  $W$  statistic of 0.90 provided sufficient evidence to conclude that the response time data was approximated by the normal distribution. The slightly lower  $W$  value found in the response time analysis was due to the positive skewness of the curve as there were several response time data points at the upper end of the distribution.

Table 4 presents that average response time and standard deviation found at each intersection along with pertinent PPLT signal display information. The rank of the response time results from the lowest (rank = 1) to the highest (rank = 26) is also presented. To illustrate the average response time results, Figure 15 presents a pictorial representation of the average response time data, using alternating black and gray shading to group intersections within each location. Average response times ranged from 1.47 seconds in Pontiac (Three-section vertical display; lagging left-turn phasing) to a high of 3.24 seconds in Orlando (five-section cluster display; leading left-turn phasing). The average response time for all study locations was 2.46 seconds.

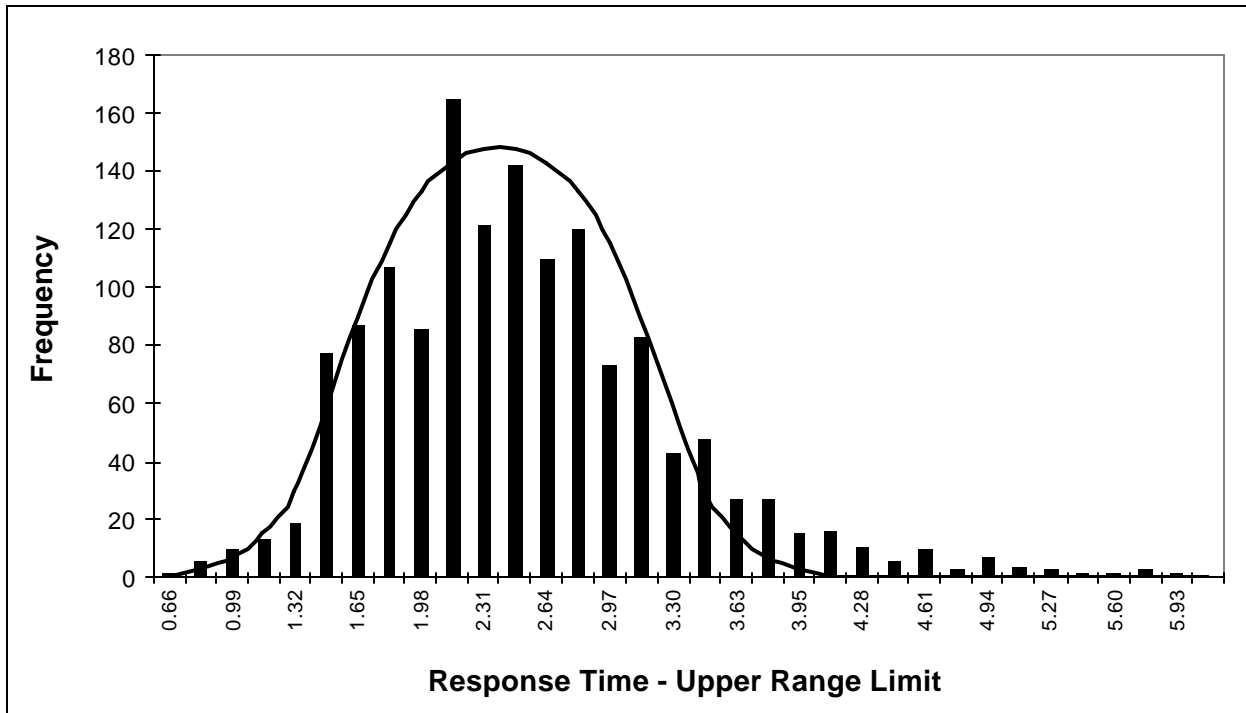


Figure 14. Cumulative Frequency Distribution of Response Time Data.

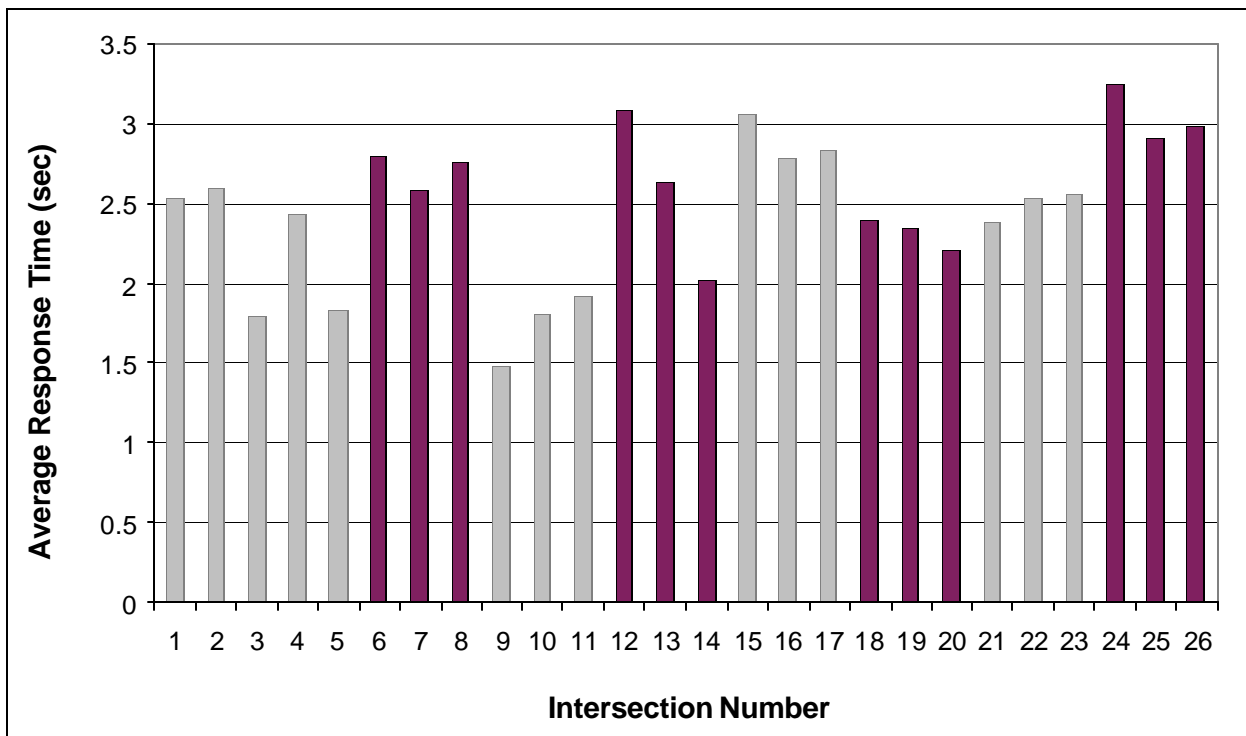


Figure 15. Average Response Time by Intersection.

**Table 4. Average Response Time by Intersection.**

City	ID <sup>1</sup>	PPLT Display <sup>2</sup>	PI <sup>3</sup>	Left-Turn Phasing	Response Time (sec)		Rank
					Average	SD <sup>4</sup>	
Dallas, TX	1	5-Vertical	GB	Lead	2.53	0.51	12
	2	5-Horizontal	GB	Dallas-Lead	2.60	0.62	16
	3	5-Horizontal	GB	Dallas-Lag	1.82	0.41	3
	4	5-Horizontal	GB	Dallas-Lead	2.43	0.49	11
	5	5-Horizontal	GB	Dallas-Lag	1.84	0.38	4
Dover, DE	6	4-Cluster	FRA	Lead	2.80	0.72	20
	7	4-Cluster	FRA	Lead	2.58	0.74	15
	8	4-Cluster	FRA	Lead	2.75	0.73	18
Oakland County, MI	9	3-Vertical	FRB	Lag	1.48	0.47	1
	10	3-Vertical	FRB	Lag	1.81	0.45	2
	11	3-Vertical	FRB	Lag	1.91	0.51	5
College Station, TX	12	5-Horizontal	GB	Lead	3.08	0.93	25
	13	5-Horizontal	GB	Lead	2.64	0.68	17
	14	5-Cluster	GB	Lead	2.02	0.49	6
Seattle, WA	15	4-Vertical	FYB	Lead	3.07	1.17	24
	16	4-Vertical	FYB	Lead	2.79	0.55	19
	17	4-Vertical	FYB	Lead	2.84	1.00	21
Portland, OR	18	5-Cluster	GB	Lead	2.39	0.90	9
	19	5-Cluster	GB	Lead	2.35	0.64	7
	20	5-Cluster	GB	Lead	2.19	0.58	9
Cupertino, CA	21	4-Vertical	FRA	Lead	2.38	0.70	8
	22	4-Vertical	FRA	Lead	2.53	0.79	12
	23	4-Vertical	FRA	Lead	2.55	0.51	14
Orlando, FL	24	5-Cluster	GB	Lead	3.24	0.88	26
	25	5-Cluster	GB	Lead	2.91	0.84	22
	26	5-Cluster	GB	Lead	3.00	0.90	23

1. Intersection Identification Number.

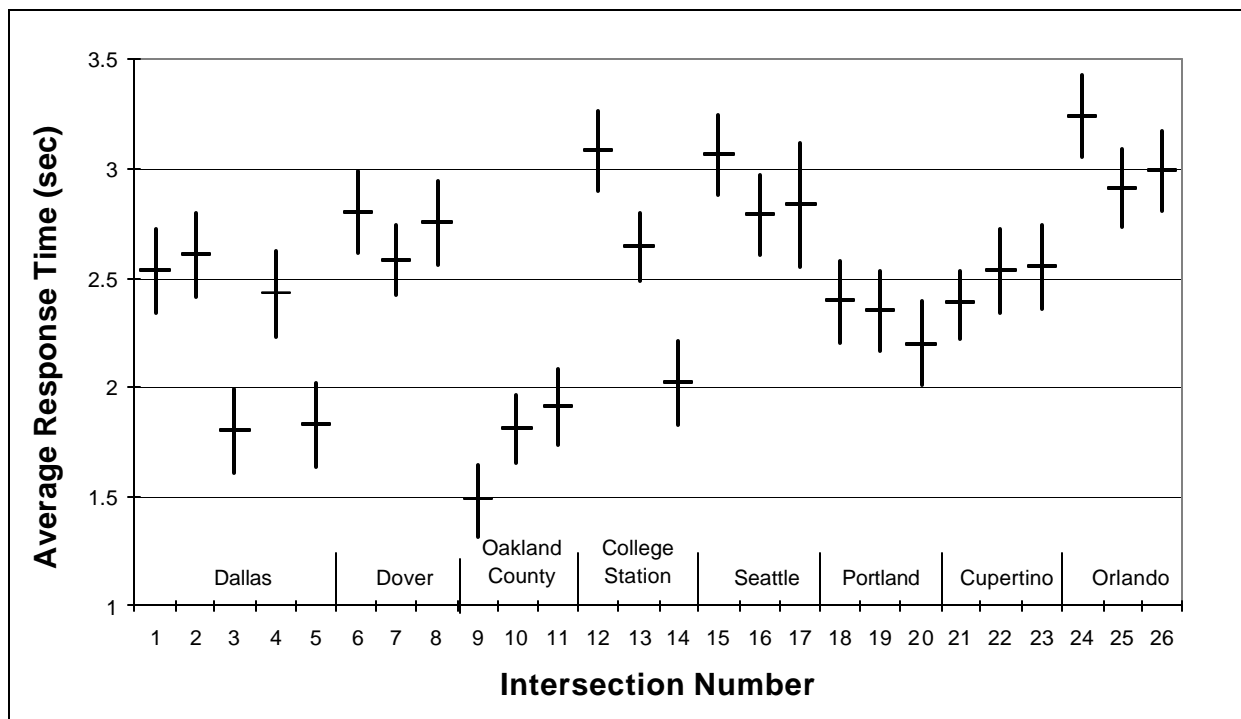
2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).

3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.

4. Standard Deviation.

**Statistical Analysis.** A statistical analysis showed that the three-section vertical display was associated with a significantly lower average response times than all other PPLT signal displays. Average response times at intersections with all types of lagging (lag, dual-lag, Dallas lag) left-turn signal phasing were found to be significantly less than at intersections with either leading or dual-leading left-turn signal phasing. Finally, average response times were significantly lower in Oakland County, Michigan while fairly consistent amongst the other locations.

To further illustrate the differences in response time by intersection and location, PPLT signal display, and PPLT signal phasing, the average response time and corresponding 95 percent confidence intervals (CIs) are shown in Figures 16 through 18. The results indicate that the differences in average response time were due to differences in both the PPLT signal display and the type of PPLT signal phasing present at each location. Although the PPLT signal phasing explained more of the variability in average response time than display type or location, each factor was significant.



**Figure 16. Average Response Time and 95 Percent CIs by Intersection.**

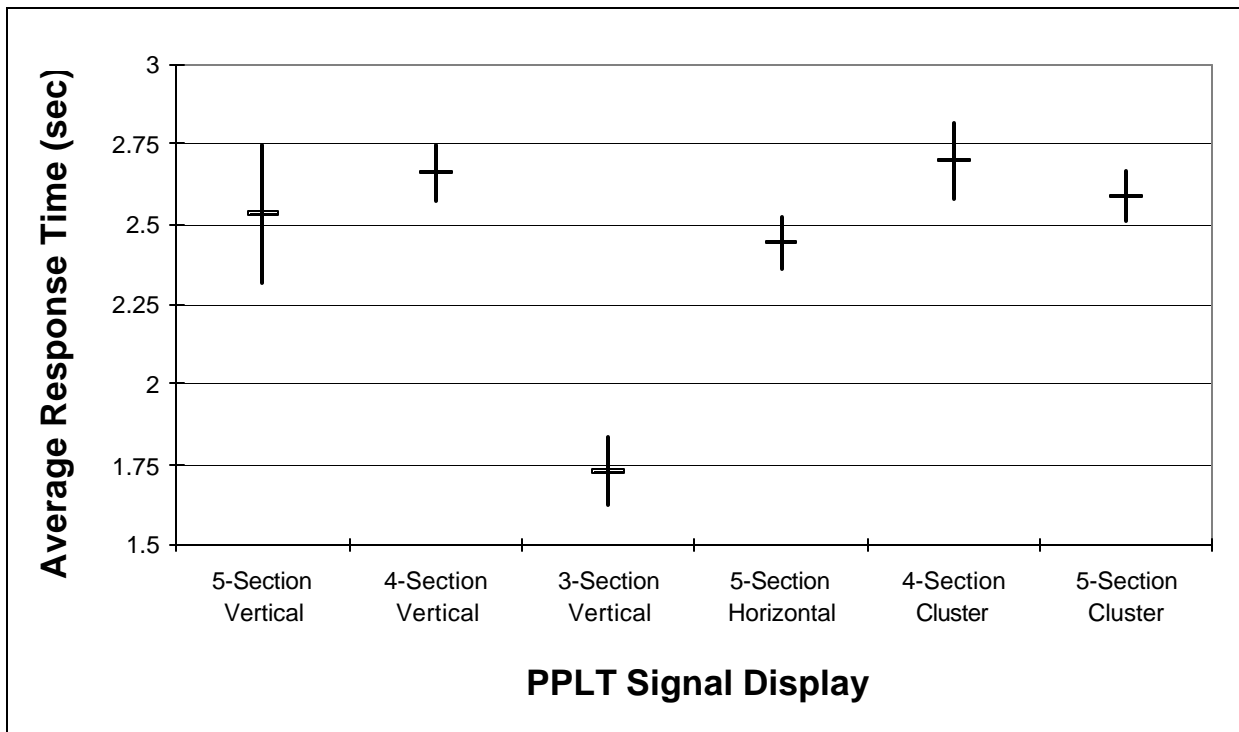


Figure 17. Average Response Time and 95 Percent CIs by Display Type.

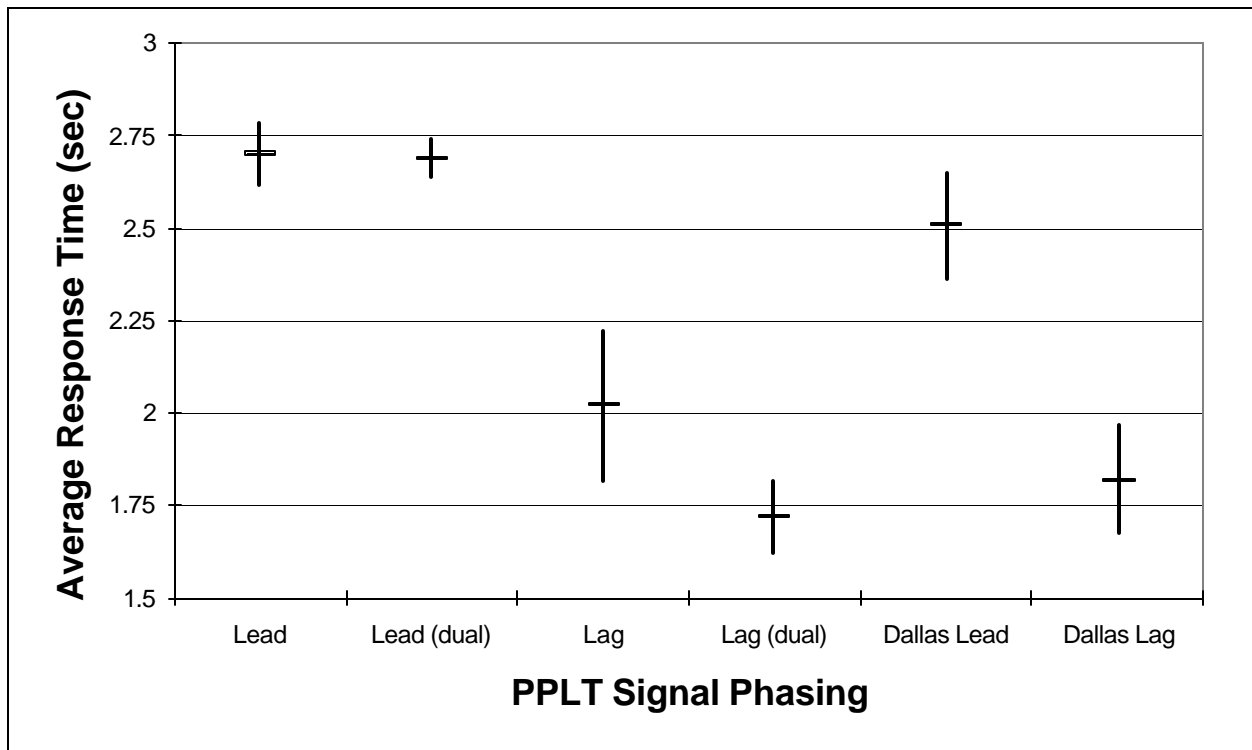


Figure 18. Average Response Time and 95 Percent CIs by Phasing.

The reason for the significantly lower response times in lagging left-turn phasing is again, driver's anticipation of the protected left-turn phase. Drivers in Oakland County and Dallas often began the protected left-turn during the final seconds of the through movement clearance interval. Drivers in Oakland County were also aware of the through movement clearance interval before the protected left-turn phase. As the adjacent through movement received a yellow ball indication, many left-turn drivers began their turning maneuver. This anticipation of the left-turn phase meant that the perception and reaction time component were primarily consumed during the preceding yellow and all red intervals. By the time the left-turn green arrow indication was presented, the left-turn queue was proceeding.

Although it is not clearly shown in the statistics, the longest response times were generally associated with the five-section horizontal displays using leading (dual) left-turn signal phasing. In the five-section horizontal display, the protected left-turn green arrow indication is located to the right of the red ball indication. Because the through movement continues to receive a red ball indication during the dual-leading protected left-turn phase, the red ball remains illuminated with the green arrow indication. In several instances, drivers seemed to be confused by this display which resulted in some of the longer response times.

**Signal Display Ranking.** Based on the average response time analysis, Table 5 presents a ranking of PPLT signal displays. The three-section vertical PPLT signal display was associated with the lowest average response time. The PPLT signal display is centered over the left-turn lane and a supplemental "LEFT" sign is used. The remaining PPLT signal displays had equal performance with the only differences associated with PPLT signal phasing.

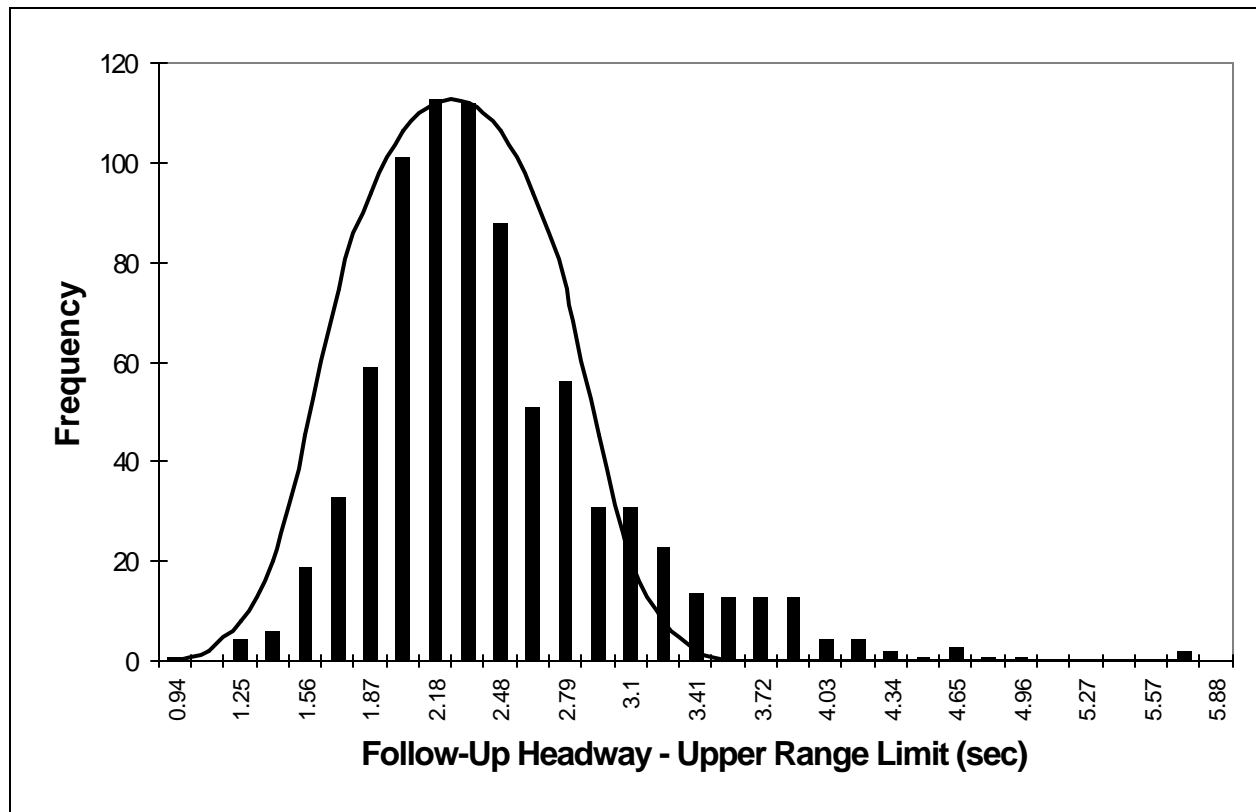
### ***Follow-Up Headways***

A final analysis was completed which looked at the follow-up headways at selected intersections. One intersection was analyzed in each of the eight cities selected representing every combination of PPLT signal display and permitted indication included in this research. The follow-up headway study was different than the previous studies in the fact that the permitted indication was of primary interest.

**Table 5 Ranking of PPLT Signal Display by Average Response Time.**

PPLT Signal Display	Permitted Indication	Rank
5-Section Vertical	Green Ball	5
4-Section Vertical	Flashing Yellow Ball	7
4-Section Vertical	Flashing Red Arrow	4
3-Section Vertical	Flashing Red Ball	1
5-Section Horizontal	Green Ball	3
5-Section Cluster	Green Ball	2
4-Section Cluster	Flashing Red Arrow	6

Consistent with the previous presentations, the analysis of the flow-up headway time data began by reviewing the data set. Figure 19 shows a cumulative frequency histogram of the response time data, overlaid with an estimated normal distribution. A Shapiro-Wilk W statistic of 0.90 provided sufficient evidence to conclude that the response time data was normally distributed.



**Figure 19. Cumulative Frequency Distribution of Follow-Up Headways.**

Table 6 presents that average response time and standard deviation found at each intersection along with pertinent PPLT signal display information. The rank of the follow-up headway results, from the lowest (rank = 1) to the highest (rank = 8), is also presented.

**Table 6 Average Follow-Up Headway by Intersection.**

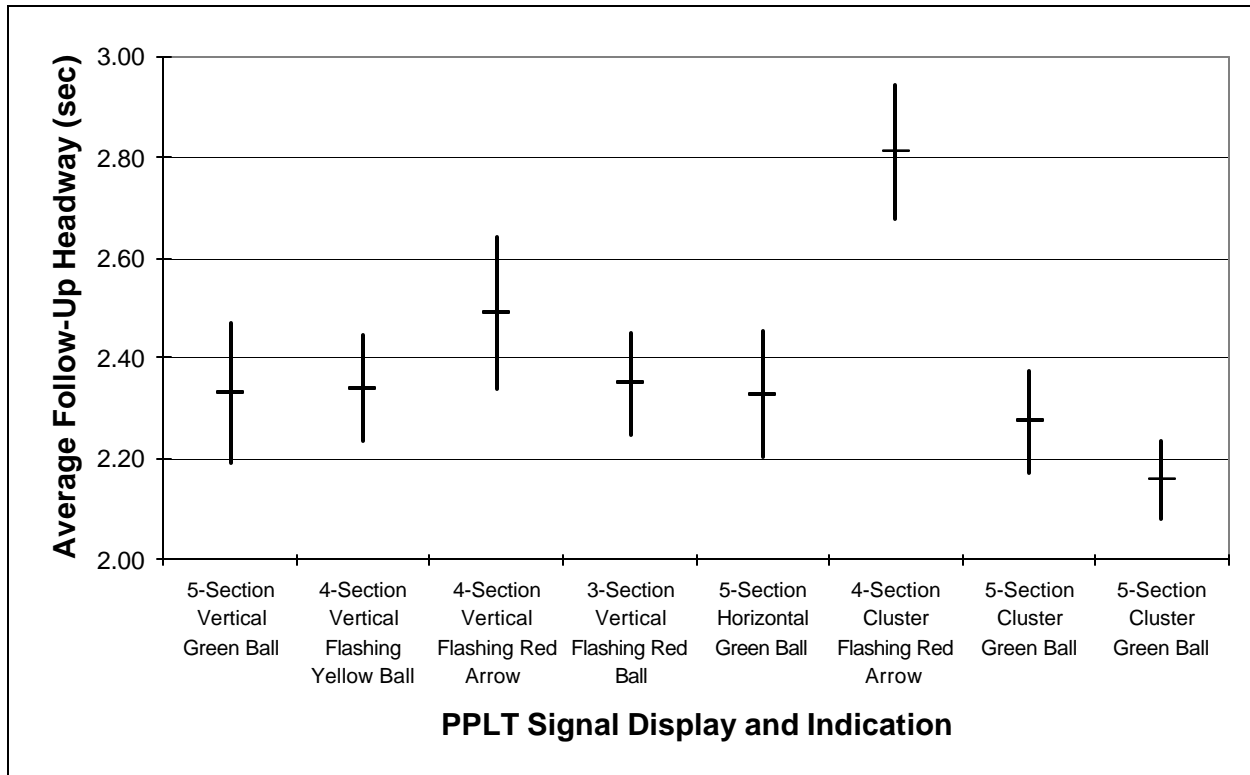
City	ID <sup>1</sup>	PPLT Display <sup>2</sup>	PI <sup>3</sup>	Left-Turn Phasing	Follow-Up Headways (sec)		Rank
					Average	SD <sup>4</sup>	
Dallas, TX	1	5-Vertical	GB	Lead	2.33	0.70	3
Dover, DE	6	4-Cluster	FRA	Lead	2.81	0.67	8
Oakland County, MI	9	3-Vertical	FRB	Lag	2.35	0.50	6
College Station, TX	12	5-Horizontal	GB	Lead	2.33	0.63	3
Seattle, WA	15	4-Vertical	FYB	Lead	2.34	0.54	5
Portland, OR	19	5-Cluster	GB	Lead	2.16	0.40	1
Cupertino, CA	22	4-Vertical	FRA	Lead	2.49	0.76	7
Orlando, FL	25	5-Cluster	GB	Lead	2.28	0.51	2

1. Intersection Identification Number.
2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).
3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.
4. Standard Deviation.

**Statistical Analysis.** Since the follow-up headways of interest occur only during the permitted phase of the signal cycle, the statistical analysis was focused completely on the variability in follow-up headway times between types of PPLT signal display and permitted indications.

Evaluation of the differences using statistical procedures found that the four-section cluster display with a flashing red arrow permitted indication had a significantly higher average follow-up headway time than all other PPLT signal display and permitted indication combinations. Further, the four-section vertical display with a flashing red arrow indication had a significantly higher average follow-up headway time than the five-section cluster display with a green ball permitted indication. Figure 20 presents the average follow-up headway for each PPLT signal display and indication combination along with the corresponding 95 percent confidence intervals (CIs) to further highlight these findings.

The five-section cluster display with a green ball permitted indication was associated with the lowest follow-up headway times. In contrast, the four-section cluster display with the flashing red arrow permitted indication had the highest follow-up headway times. At least part of the difference in follow-up headway times between the five-section and four-section cluster displays can be explained by the different requirements associated with the permitted indication. In other words, left-turn drivers are required to stop before making the permitted movement with a flashing red permitted indication while drivers facing a flashing yellow or green ball permitted indication are only required to yield. As expected, the four-section vertical display using a flashing red arrow permitted indication had the next highest average follow-up headway.



**Figure 20 Average Follow-Up Headway and 95 Percent CIs by Display Type.**

In general, there was no statistically significant difference between the five-section horizontal, the five-section vertical, and the five-section cluster displays using the green ball permitted indication. Similarly, there was no statistically significant difference between the PPLT signal displays that used either a flashing yellow ball or green ball permitted indication. Follow-up headways are greater with the flashing red ball and arrow permitted indications because drivers are required to stop before proceeding.

The exception to these results was the three-section vertical display with a flashing red ball permitted indication which is used in Oakland County, Michigan. Although drivers are legally required to stop before making a permitted left-turn, Oakland County drivers seemed to interpret the meaning of the flashing red ball permitted indication to be the same as the yellow or green permitted indications. Several law enforcement officers were observed during the data collection process, none of which found it necessary to enforce (i.e ticket) this legal requirements. In fact, many of these same law enforcement officers were observed violating the stop requirement themselves. Clearly, drivers in Oakland County have an implied

meaning of the flashing red ball permitted indication that is different than intended, which adds difficulty for non-local drivers.

**PPLT Signal Display Ranking.** Considering the results presented above, Table 7 presents a ranking of PPLT signal displays based on follow-up headways. The five-section cluster PPLT signal display was associated with the lowest average follow-up headway time. Also note that the green ball indication was associated the lowest follow-up headway times.

**Table 7 Ranking of PPLT Signal Display by Average Follow-Up Headway.**

<b>PPLT Signal Display</b>	<b>Permitted Indication</b>	<b>Rank</b>
5-Section Vertical	Green Ball	3
4-Section Vertical	Flashing Yellow Ball	4
4-Section Vertical	Flashing Red Arrow	6
3-Section Vertical	Flashing Red Ball	5
5-Section Horizontal	Green Ball	2
5-Section Cluster	Green Ball	1
4-Section Cluster	Flashing Red Arrow	7

## COMBINED ANALYSIS

The three different measures of saturation flow rate, start-up lost time, and response time yielded rank orders of locations with various PPLT signal displays. One way to determine whether there was any systematic relationship or consistency among these rankings is to apply the Kendall Coefficient of Concordance nonparametric test of association (10). Table 8 provides the three rankings for each location, plus the description of the display, permitted left-turn indication, and phasing.

A “W” value of 0.85 was computed for these data, yielding a chi-squared value of 53.55. The probability of obtaining such a chi-squared value under the null hypothesis of no association is <0.001. This finding supports a contention that these measures are highly associated. Reviewing the results shows that the highest ranking location pertained to the lagging left-turn phasing sequence.

**Table 8. Combined Analysis Considering Kendall Coefficient.**

Location <sup>1</sup>	Rank				Description		
	Flow Rate	Start-Up Lost Time	Response Time	Rank Sum	Arrange. <sup>2</sup>	Permitted Indication <sup>3</sup>	Phasing <sup>4</sup>
10	2	2	2	6	3V	FRB	Lag
9	7	1	1	9	3V	FRB	Lag
3	3	4	3	10	5H	GB	D-Lag
11	1	6	5	12	3V	FRB	Lag
5	12	3	4	19	5H	GB	D-Lag
14	13	5	6	24	5C	GB	Lag
21	11	7	8	26	4V	FRA	Lead
4	8	11	11	30	5H	GB	D-Lead
1	6	14	12	32	5V	GB	Lead
20	16	10	9	35	5C	GB	Lead
6	4	12	20	36	4C	FRA	Lead
19	21	8	7	36	5C	GB	Lead
2	5	17	16	38	5H	GB	D-Lead
22	20	9	12	41	4V	FRA	Lead
25	9	13	22	44	5C	GB	Lead
13	14	15	17	46	5H	GB	Lead
8	15	16	18	49	4C	FRA	Lead
7	16	20	15	51	5C	GB	Lead
24	10	22	26	58	5C	GB	Lead
26	19	18	23	60	5C	GB	Lead
12	18	19	25	62	5H	GB	Lead
15	22	21	24	67	4V	FYB	Lead

1. Intersection Identification Number.

2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).

3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.

4. Left-turn phasing. D = Dallas phasing.

## RESULTS

The analysis presented in this report found that there is no evidence to suggest that the type of PPLT signal display used has a significant effect on saturation flow rate and start-up lost time. There is some evidence to suggest that the PPLT signal display may have an effect on response time and follow-up headway although variation appears to be more a function of PPLT signal phasing and legal requirements of the permitted indication.

Variation in saturation flow rate was caused by differences in operational characteristics and driver behavior between locations. Variation in start-up lost time was primarily related to differences in PPLT signal phasing. The variation in response time between locations was found to be related to differences in PPLT signal phasing although there was a correlated effect between the signal phasing, location, and the PPLT signal display used.

A comparison of the average follow-up headway for each signal display an indication shows that with the exception of the four-section cluster with a flashing red arrow indication, there was no significant difference. The variation in follow-up headway associated with the four-section cluster with flashing red arrow indication was found to be related to the legal requirements associated with the flashing red indication. Drivers facing a flashing red display are required to stop before proceeding while drivers facing a steady green ball or flashing yellow indication are only required to yield. The four-section cluster display in Dover and the four-section vertical display in Cupertino were supported by a supplemental sign that told left-turn drivers to stop before making a permitted left-turn, which explains the larger follow-up headway.

Follow-up headway results in Oakland County, where a flashing red ball permitted indication is used, were not significantly different from locations using yellow or green permitted indications. Supplemental signs are not used in Michigan and the requirement to stop when approaching the flashing red ball permitted indication is not enforced.

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