Evaluation of Traffic Signal Displays for Protected-Permitted Left Turn Control

NCHRP Project 3-54

TRAFFIC CONFLICT STUDIES REPORT

Working Paper 5

Prepared for:

National Cooperative Highway Research Program

Project Panel Members

August, 1999

Date submitted to the Project Web page: February 2000

Prepared by:

KITTELSON & ASSOCIATES, INC.
2200 W. Commercial Boulevard, Ste 304
Ft. Lauderdale, FL 33309
(954) 735-1245, FAX (954) 735-9025

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University System
College Station, TX 77843-3135
(409) 845-1717, FAX (409) 845-6481

TRAFFIC CONFLICT STUDIES

INTRODUCTION

Traffic conflicts are traffic events involving the interaction of two or more drivers where one or both drivers take evasive action to avoid a collision (*1, 2, 3*). Traffic conflict studies provide one of the most effective ways to supplement crash studies in estimating the crash potential of various PPLT signal displays. In addition, traffic conflict studies can provide measures of traffic safety when crash rates are not available. The collection of traffic conflict data can also be valuable in identifying whether unsafe vehicle maneuvers are prevalent at an intersection. Conflict studies also provide an effective way to study specific geometric applications at PPLT intersections.

Conflicts can be considered to be vehicle interactions which may lead to crashes. For a conflict to occur, the road users must be on a collision course, i.e., attempting to occupy the same space at the same time (*1, 2, 3*). The primary requirement of a traffic conflict is that the action of the first user places the other user on a collision path unless evasive action is taken. Collisions and near miss situations that occur without evasive maneuvers, or when the evasive action is inadequate or inappropriate for conditions, are also recorded as conflicts.

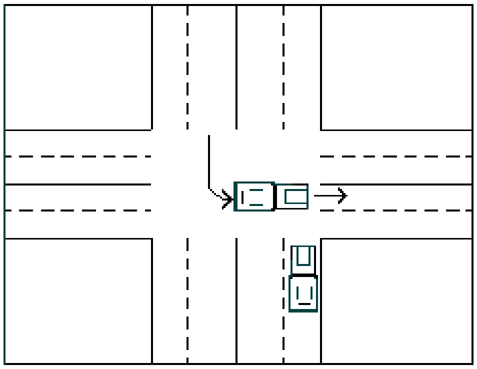
Conflict studies are not only used to evaluate safety, but are also used to select signal phasing. An ITE study found that 33 percent of the reporting agencies used a left-turn conflict rate of four conflicts per 100 left-turn vehicles as a warrant for implementing PPLT signal phasing (*4*).

Conflict Types

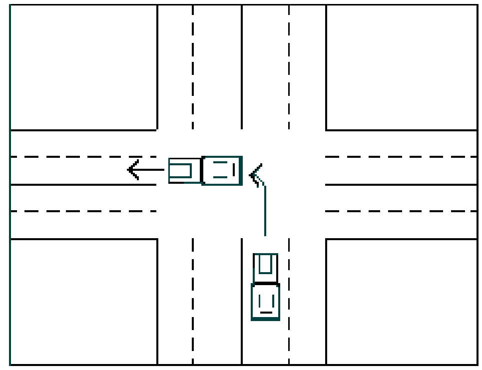
Traffic conflicts are generally categorized by type of maneuver (*2, 3*). Specific conflicts related to PPLT signal phasing include:

- **Opposing Left-Turn Conflict:** Occurs when an oncoming vehicle makes a left turn, placing a second vehicle, going in the opposite direction, in danger of a head-on or broadside collision. It applies only when the second vehicle has the right-of-way.
- **Left-Turn, Same-Direction Conflict:** Occurs when the first vehicle slows to make a left turn, thus placing a second following vehicle in danger of a rear-end collision.
- **Lane-Change Conflict:** Occurs when the first vehicle changes from one lane to another, thus placing a second following vehicle in danger of a rear-end or sideswipe collision.
- **Opposing Right-Turn-on-Red Conflict:** Occurs during the protected left-turn phase when an opposing vehicle makes a RTOR placing a left-turning vehicle in danger of a broadside or rear-end collision.
- **Left-Turn, Pedestrian/Bicycle Conflict:** Occurs when a pedestrian or bicycle crosses in front of a vehicle who has the right-of-way, causing the vehicle to brake or swerve to avoid a collision.
- **Left-Turn Lane Overflow:** Occurs when left-turn vehicle storage overflows the left-turn lane and blocks a through lane.
- **Secondary Conflict:** Occurs when a second vehicle makes a maneuver to avoid the first vehicle, placing a third vehicle in danger of a collision.

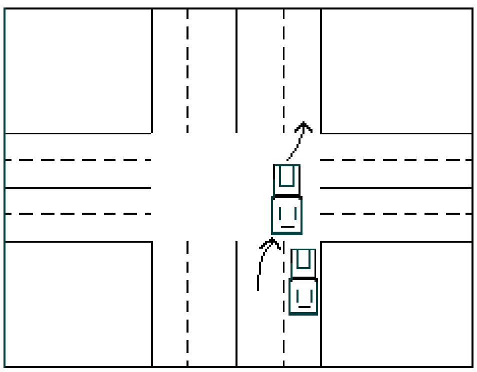
Pictorial examples of the first six conflict types are presented in Figure 1.



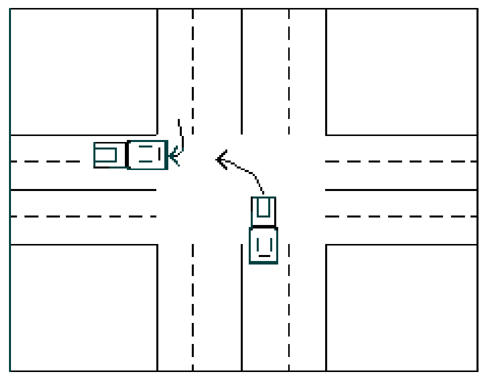
Opposing left-turn conflict.



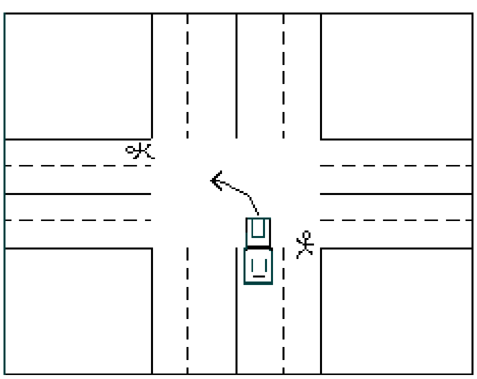
Left-turn, same-direction conflict.



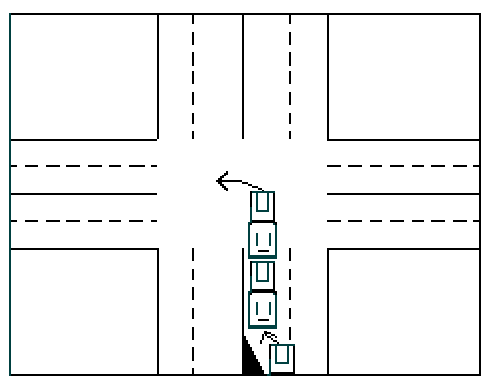
Lane-change conflict.



Opposing right-turn-on-red conflict.



Left-turn, ped/bicycle far/near side conflict.



Left-turn lane overflow.

Figure 1. PPLT Conflict Types.

Traffic Events

Traffic events are unusual, dangerous, or illegal non-conflict maneuvers (*2*, *3*). Typical traffic events include red indication violations, backing, hesitation on signal change, and slowing considerably in a traffic lane. Although traffic events do not fit within the definition of traffic conflicts, traffic events can provide a measure of driver understanding of traffic signal displays at the intersection under investigation. Traffic events related to PPLT signal phasing include:

- **Indecision Left:** A left-turning vehicle hesitates on the protected left-turn indication, starts and then stops suddenly when presented with a permitted left-turn indication, or does not turn left on the permitted indication when there is no oncoming traffic.
- **Left-Turn Red-Light Violation:** Occurs when a vehicle crosses the stop line and enters the intersection on the red ball indication.
- **Yellow (Left-Turn) Trap:** Occurs when a vehicle enters the intersection during the green or yellow ball indication and gets caught past the stop line at the red ball. The driver is forced to back-up, or attempt to back-up, to clear the space until the next protected or permissive phase.

OBJECTIVE

The traffic observation studies contained two components, the traffic conflict study and the operational analysis. The traffic conflict study was conducted to determine and compare the traffic conflict and event rates related to different PPLT signal display arrangements and permitted indications. The operational analysis was conducted to determine the operational characteristics associated with each PPLT signal display. The details of the traffic conflict study are described in the following sections.

METHODOLOGY

To accomplish the objective of the traffic conflict study, several tasks were conducted. The tasks are listed below:

- perform a literature review to provide background information on traffic conflict study techniques and to review the results of previous studies;
- select the study sites and identify the individual study intersections;
- develop the data collection procedures and identify the equipment requirements and required sample size;
- collect the conflict data at the identified study intersections; and
- reduce the data and analyze the results.

BACKGROUND

The traffic conflict study technique for both conflicts and events has been used since the 1960's (*5*). Traditionally, a traffic conflict study is performed by a trained observer stationed along one of the signalized intersection approaches for an 11-hour period (*2*). Data is collected for 20 to 25 minutes in each 30 minute segment. Conflict data is generally obtained when traffic volumes are the heaviest; however, periods of congested conditions are avoided. Conflicts and events are most often quantified in units of conflicts/events-per-hour or conflicts/events-per-1,000 entering vehicles. The latter is used to normalize conflict and event rates for different traffic volume conditions.

Glauz, Bauer, and Migletz completed a study with the objective of establishing a relationship between conflicts and crashes (*6*). Specifically, the goal of the study was to establish a relationship that would allow conflict rates to be used to predict expected crash rates. The results of this study were inconclusive because of the large variance in the collected data. Glauz recommended that conflict data not be used to predict crash rates, but rather as a surrogate measure of safety when crash data is insufficient.

A limited number of studies have been completed that evaluate traffic conflicts and events related to PPLT signal displays. Hummer conducted a study in Indiana in an effort to evaluate and compare the safety afforded by leading and lagging left-turn signal sequences (*7*). The largest difference between the leading and lagging sequence was in the left-turn/pedestrian conflict where the leading sequence was associated with three times as many conflicts as the lagging sequence. The lagging sequence was associated with significantly lower rates of left-turning/opposing through movement conflicts and a higher number of indecision conflicts. The leading sequence resulted in drivers entering the intersection during and after the yellow clearance phase creating a through movement conflict.

Asante and Williams evaluated conflict rates at 47 intersection approaches within Texas (*8*). A mean conflict rate of 176 conflicts per million squared vehicles per lane (cpmsvl) was found at approaches with PPLT signal phasing. This conflict rate was slightly higher than protected-only left-turn signal phasing (146 cpmsvl) but considerably less than permitted-only left-turn phasing (914 cpmsvl). Leading PPLT phasing sequences had a higher conflict rate than lagging sequences.

Agent evaluated conflicts rates in Kentucky at 58 approaches to 29 PPLT signalized intersections (*9*). Conflict rates varied from 0 to 12 conflicts per hour during the peak hour. Attempts to correlate the conflict rate with peak hour left-turn traffic volume and opposing traffic volume were unsuccessful.

TRAFFIC CONFLICT STUDY

The following sections detail the development of the traffic conflict study, including the site selection, data collection process and the reduction of the traffic conflict data.

Site Selection

Eight cities, spread throughout the United States were identified as potential study locations, based on the protected-permitted left-turn control, permitted indication and the geographic location of the city. These locations include College Station and Dallas, Texas; Portland, Oregon; Seattle, Washington; Detroit, Michigan; Cupertino, California; Dover, Delaware; and Orlando, Florida.

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. The geographical distribution of these eight sites is shown in Figure 2.

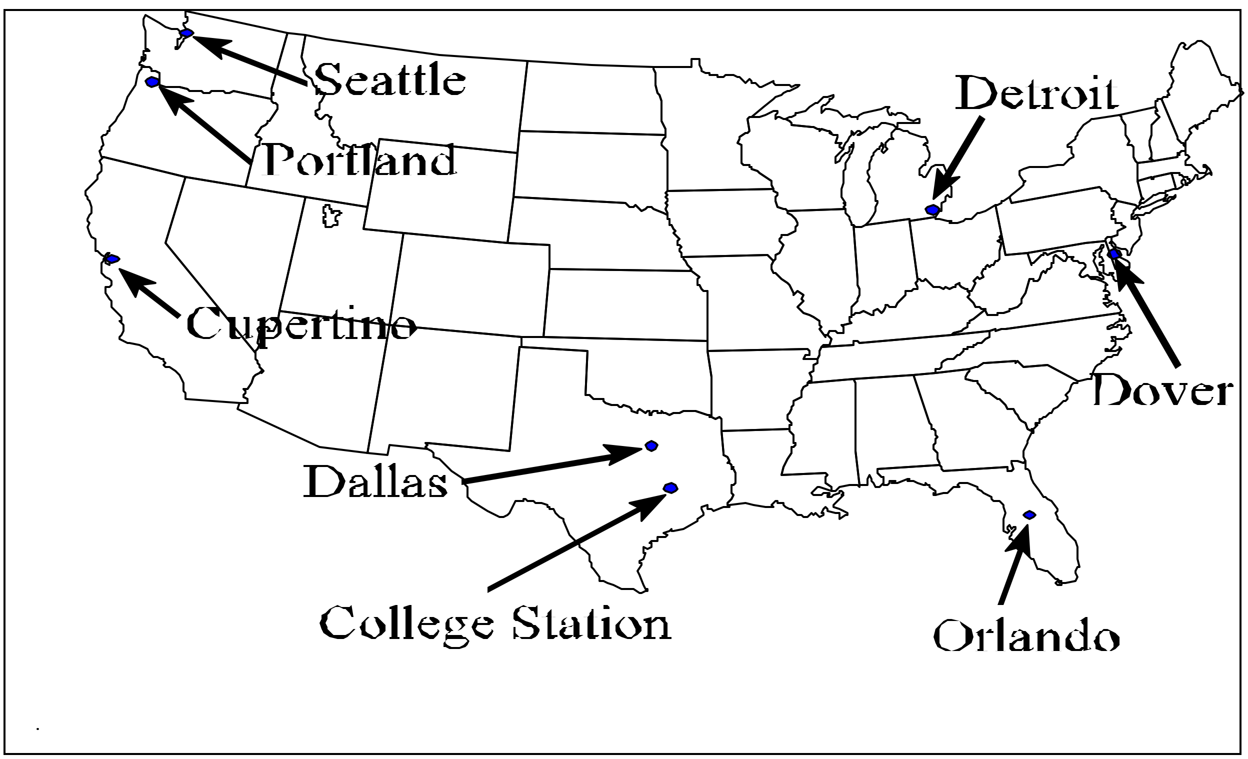


Figure 2. Traffic Conflict Study Data Collection Locations.

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.

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 arrangements included horizontal, vertical, and cluster displays. Left-turn phasing sequences 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	*Removed*	*No Sites Available*		
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, signal phasing, and crash data were required to provide the necessary information for analysis.

Local transportation officials assisted in the selection 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 most significant 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. Fortunately, the remaining criteria were satisfied.

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.

Table 2. Intersections Selected for Study.

City	Intersection	ID[1]	PPLT Display[2]	PI[3]	LT Phase[4]
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 Parkway @ Texas Ave.	13	5-Horizontal	GB	Lead
	Southwest Parkway @ Southwood Dr.	14	5-Cluster	GB	Lag
Seattle, WA	South Lander St. @ 1st Ave.	15	4-Vertical	FYB	Lead
	South Lander St. @ 4th 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. @ 72nd 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.

Also note in Table 2 that 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

The procedure outlined in the ITE *Manual of Traffic Engineering Studies* was used to determine the number of hours of data collection required (*1*). Conflicts per unit time were selected because many intersection traffic volumes were not known at the time of study and they could be compared with rates per unit time previously established. These rates are presented in Table 3.

After selecting conflicts per unit time as the parameter of interest, the required sample size was calculated. Hours of data collection depended on the type of conflict(s) to be studied, the desired accuracy, and the traffic volume at the intersection. When the traffic volumes were not known, it was assumed that each intersection had entry volumes greater than 10,000 vehicles-per-day (vpd). The following equation was used to estimate the number of observation hours needed (*1*):

$$NT = [(100 * \frac{t}{PC})^2] * \frac{var}{mean^2} \qquad \textbf{(1)}$$

where:

NT = number of units of time that must be observed;
t = a constant corresponding to the desired level of confidence;
PC = permitted error in the estimate of the mean conflict rate (percent);
var = expected variance of the conflict rate; and
mean = expected mean of the conflict rate.

Table 3. Typical Conflict Rate Statistics for Intersections with Four Approaches.

Conflict Type	Conflicts/Hour		Conflicts/Day			
					Percentile	
	Mean	Variance	Mean	Variance	90th	95.0
	Signalized with Entry Volumes Greater Than 25,000					
Left-turn same direction	8	22	83	12000	270	360
Slow vehicle	61	34	670	24000	870	940
Lane change	2	C	18	160	35	43
Right-turn same direction	20	11	220	7600	470	510
Opposing left-turn	2	1.2	22	380	48	60
All same direction[a]	90	74	990	67000	1300	1500
	Signalized with Entry Volumes 10,000 to 25,000 Vehicles/Day					
Left-turn same direction	12	22	130	10000	270	340
Slow vehicle	34	11	380	4900	470	500
Lane change	0.7	c	8	53	17	22
Right-turn same direction	11	12	120	2400	190	220
Opposing left-turn	2.6	1.2	29	210	49	56
All same direction[a]	59	95	640	25000	860	930
	Unsignalized with Entry Volumes 10,000 to 25,000 Vehicles/Day					
Left-turn same direction	12	21	130	12000	270	350
Slow vehicle	14	5.2	150	5900	260	290
Lane change	5.6	11	62	1200	100	120
Right-turn same direction	0.8	1.2	9	40	17	21
Opposing left-turn	0.8	1.1	9	99	21	29
All same direction[a]	29	77	320	29000	540	640
Through cross traffic[b]	0.6	c	7	16	12	14
	Unsignalized with Entry Volumes 2,500 to 10,000 Vehicles/Day					
Left-turn same direction	6.4	22	71	1000	110	130
Slow vehicle	9.3	5.5	100	9600	220	300
Lane change	5.3	11	58	2200	120	150
Right-turn same direction	0.3	c	4	8	8	9
Opposing left-turn	0.5	1.1	6	12	10	12
All same direction[a]	21	77	230	18000	410	490
Through cross traffic[b]	1.1	c	12	75	24	29

[a] All same direction includes left-turn same direction, slow vehicle, lane change, and right-turn same direction

[b] Through cross traffic includes cross traffic from left and cross traffic from right conflict

[c] Data not available

Mean and variance values were selected from Table 3. The *opposing left-turn* conflict type was of primary interest and mean and variance (2.6, 1.2) were selected accordingly. A *PC* value of 30 was selected which provided for a range of +/- 30 percent in the precision of the estimate. This relatively broad range in precision was considered acceptable because of the low number of expected left-turn conflicts. Based on the mean conflict rates presented in Table 3 for opposing left-turn conflicts, an error of 30 percent resulted in an error of less than one conflict/hour. Each of the numerical values selected were consistent with previous research results.

A *t* value of 1.96 was selected which represented a 95 percent level of confidence. Applying a *t* of 1.96, *PC* of 30, variance of 1.2, and mean of 2.6 to Equation 1, the results indicated that approximately eight hours of conflict study data was required at each site. Due to the infrequency of the conflict types of interest in this research, attempts to improve the precision of the estimate were explored but not accepted due to the impracticality of the result. For example, to improve the permitted error of the estimate from 30 to 10 percent, hours of observation increased from 8 to 68. Given this result, it was determined that a minimum of eight hours of conflict data would be obtained at each intersection.

Data Collection Equipment

Data collection equipment consisted of two items: a data collection form and a video camera. Primarily, conflict data were recorded using a data collection form, based on field observations. During the conflict studies, a Sony Steady Shot™ 8 mm video camera was used to record vehicle maneuvers on videotape. The videotape provided a visual record of the intersections observed and was used to review several intersections where questionable conflicts and events were observed. The videotape data were also used to compute traffic volumes when other volume information was not available and to observe specific intersection operations.

Data Collection

A one day (8 hour minimum) traffic conflict study was conducted at each of the intersections selected. Data was collected between the hours of 7:00 A.M. and 6:00 P.M. on weekdays. No traffic breakdowns (congestion, signal failure, crashes) or weather conditions were experienced that inhibited data collection efforts.

The data collection procedure included a 10 minute set-up period before the start of the conflict study followed by data collection for 25 minutes in each 30 minute segment. Conflict study techniques generally recommend that a short break be taken every 30 minutes to regain concentration and allow for changes in data collection forms and videotapes (*1*). This recommendation was followed.

Both traffic conflict and traffic event data were recorded during the data collection period. The researcher was positioned approximately 300 feet from the intersection in a location concealed from the approaching traffic. Only conflicts and events that happened in relation to the features of the PPLT signal display and the approach of interest were recorded. The video camera was mounted on a tripod near the location of the researcher allowing video data to be collected simultaneously with the traffic conflict study as a backup to the manual data collection.

For each conflict or event observed, the time, vehicle position, vehicle movement, conflict and/or event number, and comments to help define the actions observed were recorded. Appropriate coding was used, as indicated on the data collection form, to expedite the recording process and to provide consistency between locations.

Traffic volume, intersection geometry, and signal phasing data were obtained for each intersection in the conflict study. Generally, this information was provided by the local traffic engineer. Traffic volume was used to provide an additional rate measurement of conflicts and events. Intersection photographs were taken to supplement this information.

Data Reduction

At the completion of each conflict study, the conflict and event data were reduced by summing the totals of each type. Since both conflicts per hour and conflicts per day were of interest, the data was adjusted for unobserved time periods to an equivalent 11-hour day. This adjustment also allowed observed conflict rates to be compared to conflict rates presented in Table 3.

No weighted adjustments were used as it was assumed that there was little difference in counts from period to period. To account for differences in traffic volumes and exposure, conflict and event rates per 1,000 entering vehicles were computed. Entering vehicles were considered to be the sum of the left-turn vehicles and opposing through vehicles observed in the 11-hour study period.

DATA ANALYSIS

The analysis of traffic conflicts and events at a signalized intersection provides a relative measure of crash potential and safety. Specific traffic movements can be isolated, and the safety effects of those movements evaluated. The purpose of the conflict study was to isolate the left-turn movement and evaluate the safety effects of the PPLT signal display and associated attributes. Because the study was focused only on the left-turn maneuver, and more specifically, on driver understanding or lack of understanding of the left-turn signal display, only conflicts and events directly related to left-turns were recorded and evaluated. The conflicts of primary interest were:

- Type 1 - Opposing left-turn conflict;
- Type 2 - Left-turn same-direction conflict;
- Type 3 - Left-turn lane change conflicts; and
- Type 4 - Secondary conflicts (pedestrians, bicycles, lane overflow, etc.).

Similarly, the events of primary interest were:

- Type 1 - Hesitate on green arrow;
- Type 2 - Hesitate on the permitted indication;
- Type 3 - Ran through the red ball indication; and
- Type 4 - Back-up out of the intersection into the left-turn lane.

Evaluation of Observed Traffic Conflicts

Conflicts were stratified according to conflict types and then pooled to determine the conflict frequencies at each intersection evaluated. The results of the pooled conflict frequency analysis is presented in Table 4 showing the total number of conflicts observed, the conflict rate (per 1,000 entering vehicles), and the rank of the conflict rates by intersection. Conflict rate per time can also be computed by considering total conflicts over an 11 hour evaluation period. PPLT signal display, permitted indication, and left-turn phasing information is also presented.

Conflict rates were generally consistent with the average rates presented in Table 3. Opposing left-turn conflicts (Type 1) ranged from 0 to 1.5 conflicts per hour and from 0 to 1.3 conflicts per 1,000 entering vehicles. The average rates were slightly below those of Table 3 but well within the variance presented. When the observed conflicts from all 24 intersections were added, there was a total of 166 left-turn conflicts. Only 11 conflicts (7 percent) were Type 2, Type 3, or Type 4. Specifically, nine Type 2 conflicts, two Type 3, and no Type 4 conflicts.

Type 1 Conflicts. Focusing on the 155 Type 1 conflicts, 146 conflicts appeared to be caused by aggressive driving. Two occurrences were quite common. First, left-turn drivers continued to make left-turn maneuvers during the yellow and all-red intervals following a protected left-turn phase. In essence, drivers tried to extend the green period. Left-turn drivers who continued to turn left after the protected left-turn phase often found themselves in conflict with the opposing through vehicles. Through drivers were forced to hesitate at the onset of the through movement green ball indication to avoid a collision.

Table 4. Cumulative Conflicts.

City	ID[1]	PPLT Display[2]	PI[3]	LT Phase	Conflicts		Rank
					Total	Rate[4]	
Dallas, TX	1	5-Vertical	GB	Lead	8	0.8	19
	2	5-Horizontal	GB	Dallas-Lead	17	1.3	22
	3	5-Horizontal	GB	Dallas-Lag	17	1.3	22
	4	5-Horizontal	GB	Dallas-Lead	9	0.7	15
	5	5-Horizontal	GB	Dallas-Lag	9	0.7	15
Dover, DE	6	4-Cluster	FRA	Lead	3	0.3	6
	7	4-Cluster	FRA	Lead	9	0.9	21
	8	4-Cluster	FRA	Lead	2	0.2	5
Oakland County, MI	9	3-Vertical	FRB	Lag	8	0.5	12
	10	3-Vertical	FRB	Lag	4	0.7	15
	11	3-Vertical	FRB	Lag	3	0.3	6
College Station, TX	12	5-Horizontal	GB	Lead	20	1.4	24
	13	5-Horizontal	GB	Lead	9	1.4	24
	14	5-Cluster	GB	Lag	5	1.4	24
Seattle, WA	15	4-Vertical	FYB	Lead	0	0.0	1
	16	4-Vertical	FYB	Lead	3	0.3	6
	17	4-Vertical	FYB	Lead	0	0.0	1
Portland, OR	18	5-Cluster	GB	Lead	3	0.8	19
	19	5-Cluster	GB	Lead	3	0.3	6
	20	5-Cluster	GB	Lead	3	0.3	6
Cupertino, CA	21	4-Vertical	FRA	Lead	3	0.7	15
	22	4-Vertical	FRA	Lead	1	0.1	4
	23	4-Vertical	FRA	Lead	0	0.0	1
Orlando, FL	24	5-Cluster	GB	Lead	8	0.6	13
	25	5-Cluster	GB	Lead	10	0.6	13
	26	5-Cluster	GB	Lead	9	0.4	11

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. Conflicts per 1,000 entering Vehicles.

The second common occurrence of the Type 1 conflict involved left-turn drivers accepting a very small gap in the opposing traffic stream during the permitted left-turn phase. This conflict appeared to be a function of the level of congestion and the availability of acceptable gaps. As congestion increased and the number of available gaps decreased, left-turn drivers became more willing to accept smaller gaps and take greater risks. Each of these conflicts required the through movement driver to brake and/or change lanes to avoid a collision.

The remaining nine Type 1 conflicts appeared to be directly related to a lack of driver understanding of the PPLT signal display. In each case, the misunderstanding occurred during the permitted left-turn phase. Table 5 presents of summary of these conflicts including location, permitted indication, and a brief description of the apparent cause.

Although the numbers are few, several trends are identified in Table 5. First, eight of the nine conflicts appeared the result of left-turn drivers assuming right-of-way during the permitted left-turn (green ball indication) phase. The two Type 1 conflicts associated with Dallas phasing were a result of left-turn drivers receiving a green ball indication opposite the opposing protected left-turn and assuming right-of-way. Second, more Type 1 conflicts were associated with the five-section cluster display than all other displays.

Type 2 Conflicts. A review of Type 2 conflicts found that each occurred at an intersection using a five-section display and the green ball permitted indication. In each case, the conflict was caused by the lead left-turn driver making an abrupt hesitation, forcing the following left-turn drivers to brake sharply in avoidance of a rear-end collision. There were several reasons for the abrupt movement which caused the conflict to occur. Primarily, Type 2 conflicts seemed to be a result of indecision by the lead left-turn driver. In several instances, the driver began to turn left during the permitted phase, then, abruptly rejected the gap. In other instances, a driver began to turn left at the onset of the green ball permitted phase, and then stopped, presumably because they realized that they did not have right-of-way. There appeared to be a relationship between driver misunderstanding of the permitted green ball indication and the Type 2 conflict.

Table 5. Type 1 Conflicts Due to Driver Misunderstanding of the PPLT Signal Display.

ID[1]	PPLT Display[2]	PI[3]	Left-Turn Phasing	Type 1 Conflict Cause
5	5-Horz.	GB	Dallas-Lag	Assumed right-of-way at the onset of the green ball permitted indication.
5	5-Horz.	GB	Dallas-Lag	Assumed right-of-way at the onset of the green ball permitted indication.
7	4-Cluster	FRA	Lead	Assumed right-of-way after stopping at flashing red arrow permitted indication.
19	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.
25	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.
25	5-Cluster	GB	Lead	Assumed right-of-way and turned left without gap during the green ball permitted indication.

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.

Type 3 Conflicts. Type 3 conflicts were a result of driving error not related to drivers' understanding of the signal displays. Therefore, Type 3 conflict provided little information related to driver understanding of the signal display and were not included for further analysis.

Statistical Analysis of Conflicts. Because of the limited number of conflicts that can be correlated to driver's misunderstanding of PPLT signal displays, applying a statistical procedure in an attempt to identify significance was not feasible. Thus, the results of the conflict study are strictly observational and are presented in the following section.

Conflict Study Results

Several results of the conflict study can be noted. First, the number of left-turn opposing conflicts (Type 1) observed were consistent with the average rates identified in Table 3, although generally on the lower end of the variance.

Second, the green ball permitted indication was associated with nearly all of the conflicts caused by breakdowns in driver understanding. There remains a tendency for drivers to assume that the green ball indication provides right-of-way in all instances, albeit infrequent.

Third, only one conflict associated with an apparent lack of driver understanding was observed with the flashing red arrow permitted indication and no conflicts were observed with the flashing yellow ball and flashing red ball permitted indications. This result is consistent with the argument supporting flashing permitted indications.

Finally, the Type 1 conflicts were observed more often at intersections using five-section cluster displays. The five-section cluster display appeared to be successful in identifying its association with the left-turn movement, but drivers may have been more prone to assume that the indication illuminated in the cluster display pertained only to the left-turn movement.

PPLT Signal Display Ranking. There was not sufficient evidence in the conflict study results to provide a ranking of PPLT signal display based on their safety performance. Nevertheless, it was concluded that the flashing yellow and red ball permitted indications performed better than both the flashing red arrow indication and the green ball permitted indication, as identified in Table 6.

Table 6. Ranking of Conflict Rates by Indication.

Permitted Indication	Rate[1]	Rank
Green Ball	0.9	4
Flashing Yellow Ball	0.1	1
Flashing Red Arrow	0.4	2
Flashing Red Ball	0.5	3

1. Conflicts Per 1,000 Entering Vehicles.

Evaluation of Traffic Events

Along with traffic conflicts, traffic events were identified and recorded during the data collection process. Unlike traffic conflicts, traffic events provided a more direct observational measure of driver understanding related to PPLT signal displays. Each event was associated with a driver error related to interpretation and understanding of the PPLT signal display and its intended message.

Similar to the evaluation of traffic conflict data, traffic event data was stratified according to event type and then pooled to determine event frequencies. A direct comparison of the frequency of traffic events (driver error) with each type of PPLT signal display was completed. The findings are shown in Table 7.

The total number of events observed at each study intersection was calculated. These total were used to calculate the event rate (per 1,000 vehicles entering) and to rank the performance of the intersection with respect to event occurrence. These findings are shown in Table 8.

The number of events observed ranged from 0 to 3.3 events per 1,000 entering vehicles. College Station, Texas (five-section horizontal/cluster PPLT signal displays; green ball permitted indication) had the highest average event rate at 2.0 followed by Seattle, Washington (four-section vertical PPLT signal display; flashing yellow ball permitted indication) and Portland, Oregon (five-section cluster PPLT signal display; green ball), both at 1.5. Cupertino, California had the lowest average event rate at 0.3. The following sections explore each of the four event types individually.

Table 7. Observed Event Frequency by Type.

City	ID[1]	PPLT Display[2]	PI[3]	LT Phase	Event Type			
					1	2	3	4
Dallas, TX	1	5-Vertical	GB	Lead	3	2	2	0
	2	5-Horizontal	GB	Dallas-Lead	0	0	0	0
	3	5-Horizontal	GB	Dallas-Lag	0	0	0	0
	4	5-Horizontal	GB	Dallas-Lead	5	5	0	0
	5	5-Horizontal	GB	Dallas-Lag	5	5	0	0
Dover, DE	6	4-Cluster	FR	Lead	11	5	0	0
	7	4-Cluster	FR	Lead	2	4	0	0
	8	4-Cluster	FR	Lead	8	2	0	7
Oakland County, MI	9	3-Vertical	FR	Lag	4	0	0	2
	10	3-Vertical	FR	Lag	2	0	0	0
	11	3-Vertical	FR	Lag	9	9	0	0
College Station, TX	12	5-Horizontal	GB	Lead	34	4	0	2
	13	5-Horizontal	GB	Lead	13	0	0	0
	14	5-Cluster	GB	Lag	2	2	0	0
Seattle, WA	15	4-Vertical	FY	Lead	12	2	0	11
	16	4-Vertical	FY	Lead	6	0	3	7
	17	4-Vertical	FY	Lead	0	0	0	0
Portland, OR	18	5-Cluster	GB	Lead	8	5	0	0
	19	5-Cluster	GB	Lead	5	2	0	0
	20	5-Cluster	GB	Lead	2	2	0	0
Cupertino, CA	21	4-Vertical	FR	Lead	0	1	0	0
	22	4-Vertical	FR	Lead	0	0	0	3
	23	4-Vertical	FR	Lead	0	0	0	3
Orlando, FL	24	5-Cluster	GB	Lead	7	1	0	0
	25	5-Cluster	GB	Lead	3	2	0	2
	26	5-Cluster	GB	Lead	6	0	0	0

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.

Table 8. Cumulative Events.

City	ID[1]	PPLT Display[2]	PI[3]	LT Phase	Events		Rank
					Total	Rate[4]	
Dallas, TX	1	5-Vertical	GB	Lead	7	0.7	13
	2	5-Horizontal	GB	Dallas-Lead	0	0.0	1
	3	5-Horizontal	GB	Dallas-Lag	0	0.0	1
	4	5-Horizontal	GB	Dallas-Lead	10	0.8	15
	5	5-Horizontal	GB	Dallas-Lag	10	0.8	15
Dover, DE	6	4-Cluster	FRA	Lead	16	1.5	19
	7	4-Cluster	FRA	Lead	6	0.6	12
	8	4-Cluster	FRA	Lead	17	1.5	19
Oakland County, MI	9	3-Vert.	FRB	Lag	6	0.4	8
	10	3-Vert.	FRB	Lag	2	0.4	8
	11	3-Vert.	FRB	Lag	18	2.0	22
College Station, TX	12	5-Horizontal	GB	Lead	40	2.9	25
	13	5-Horizontal	GB	Lead	13	2.0	22
	14	5-Cluster	GB	Lag	4	1.2	18
Seattle, WA	15	4-Vertical	FYB	Lead	25	2.7	24
	16	4-Vertical	FYB	Lead	16	1.7	21
	17	4-Vertical	FYB	Lead	0	0.0	1
Portland, OR	18	5-Cluster	GB	Lead	13	3.3	26
	19	5-Cluster	GB	Lead	7	0.8	15
	20	5-Cluster	GB	Lead	4	0.4	8
Cupertino, CA	21	4-Vertical	FRA	Lead	1	0.3	5
	22	4-Vertical	FRA	Lead	3	0.3	5
	23	4-Vertical	FRA	Lead	3	0.3	5
Orlando, FL	24	5-Cluster	GB	Lead	9	0.7	13
	25	5-Cluster	GB	Lead	7	0.5	11
	26	5-Cluster	GB	Lead	6	0.2	4

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. Events per 1,000 entering Vehicles.

Type 1 Events. Type 1 events involved left-turn vehicles hesitating or not turning left while the green arrow was illuminated, during the protected left-turn phase. This event type accounted for 60 percent of all of the events observed.

College Station, Texas had the highest average number of Type 1 events. The largest numbers were found at intersections containing a five-section horizontal PPLT signal display, located over the lane line, using a leading (dual) left-turn signal phasing sequence. With a dual lead left-turn phasing sequence, the protected green arrow indication was illuminated after the conclusion of the side street phase, while the adjacent through movements continued to receive a red ball indication. Subsequently, the green arrow and red ball indications were simultaneously illuminated in the five-section horizontal signal display. With the green arrow indication placed to the right of the red ball indication in the five-section horizontal display, drivers appeared either to miss the initial illumination of the green arrow indication or hesitate for several seconds to be assured that making the left-turn maneuver was safe.

Type 1 events associated with the five-section horizontal PPLT signal display in Dallas, Texas were much less frequent. As part of the Dallas phasing concept, left-turn drivers received either a green arrow or green ball indication throughout the entire time that the opposing left-turn and adjacent arterial through movement was serviced. In addition, the city of Dallas was opposed to displaying the green arrow and red ball indication simultaneously in a five-section signal display as required by the MUTCD. Therefore, a green arrow and green ball indication were simultaneously illuminated in the PPLT signal display regardless of the current through movement indication.

Dallas' effort to overcome driver confusion associated with the simultaneous illumination of the green arrow and red ball indication for the protected left-turn movement actually created additional driver confusion. Left-turn drivers received a green arrow and green ball indication during the protected left-turn phase, accompanied by a supplemental sign that read *left-turn yield on green (ball)*. Drivers were forced to assume that the green arrow indication took precedence over the green ball indication and to ignore the supplemental sign during the protected left-turn phase.

No Type 1 events were observed in Cupertino, California. Cupertino used two four-section vertical PPLT signal displays, one centered over the lane line and one far side pole mounted. Drivers appeared to focus on the far side signal display knowing that this display pertained only to the left-turn movement. Oakland County, Michigan also used two PPLT signal displays including a far side pole mounted display. Several Type 1 events were observed in Oakland County; however, some noticeable differences were identified.

Oakland County used a lagging (dual) left-turn signal phasing sequence. The lead vehicle in the left-turn queue often moved into the intersection searching for a gap during the permitted left-turn phase. By moving into the intersection, drivers had moved under the overhead PPLT signal display making it no longer visible. If the vehicle had not accepted a gap before the onset of the protected left-turn phase, drivers had to rely on the far side signal display or a secondary queue, such as the stoppage of the through movement vehicles, for notification of the protected phase. In addition, Oakland County has an extremely high occurrence of red light violations. Several Type 1 events observed in Oakland County were a result of drivers hesitating and being overly cautious in making sure that the through movement vehicle(s) was stopping on red.

In general, Type 1 events were highest with the five-section horizontal display when dual lead left-turn signal phasing was used. Further, more Type 1 events were observed with the leading left-turn phasing sequence than the lagging left-turn sequence. The addition of a secondary left-turn signal display provided drivers a second source of left-turn information which appeared to have a positive effect in reducing Type 1 events.

Type 2 Events. Type 2 events involved drivers hesitating on the permitted indication and/or not accepting a gaps of sufficient size in the opposing traffic stream. Type 2 events represented 22 percent of all events observed, equally distributed among the study intersections.

The primary cause of Type 2 events was driver overcautiousness in gap selection during the permitted left-turn phase. Several drivers involved in a Type 2 event did not accept any of the large gaps available during the permitted left-turn phase, but waited until the protected phase before turning. These were random occurrences with no PPLT display or signal phasing concept exhibiting more than the others; however, elderly drivers were most often involved. The remaining Type 2 events observed provided no evidence of deficiencies in either the PPLT signal display, phasing sequence, or indication.

Type 3 Events. Type 3 events involved drivers running the red ball indication or, in other words, red light violations. Data collection for Type 3 events began in earnest with the first several intersections observed; however, it soon became apparent that red light violations were occurring at the end of almost every signal phase, none of which were related to driver's understanding of the PPLT or through movement signal displays. Most often, red light violations appeared to be related to aggressive driving and avoidance of delay. Because of this, only Type 3 events that were clearly a function of driver misunderstanding were recorded.

As defined, only five Type 3 events were observed during data collection, representing two percent of the total events observed. In each instance, it appeared that the left-turn driver may have observed the through movement green ball indication, while the left-turn indication was red, and assumed the green ball indication applied to the left-turn movement. In any event, there were very few occurrences of Type 3 events related to driver understanding and there were no consistent patterns among PPLT signal display types.

Type 4 Events. Type 4 events occurred when drivers found themselves in the intersection at the end of the left-turn phase, forcing them to back into the left-turn lane, behind the stop bar, to clear the intersection and wait for the next left-turn opportunity. The largest number of Type 4 events occurred in Seattle, Washington. No PPLT signal display related reasons were observed to explain this high number of Type 4 events. This result was attributed to a lack of acceptable gaps near the end of the permitted left-turn phase and the lack of opportunity to make a *sneaker* left-turn.

The next largest occurrence of Type 4 events were in Dover, Delaware and Cupertino, California. In each location, the flashing red arrow permitted indication terminated directly to a solid red ball indication, without any form of clearance interval. Because of this, drivers in the intersection waiting to make a permitted left-turn suddenly found that the flashing red arrow left-turn signal display indication had changed to a solid red ball leaving the driver with limited options, the safest of which was backing up and waiting for the next left-turn opportunity.

In general, Type 4 events were associated with the flashing permitted indications. Only four of the 37 Type 4 events observed occurred at a location which used the permitted green ball indication. As previously mentioned, the difficulties in providing a clearance interval with several of the flashing permitted indications can explain some of the differences observed. Oakland County, Michigan was an exception since they used a lagging protected left-turn phase as part of the clearance interval, regardless of the left-turn demand at the end of the permitted left-turn phase.

Statistical Analysis. The event rate were analyzed using the variance (ANOVA) procedure using the Minitab™ statistical software package (*10*). All statistical tests were based on a 95 percent confidence level (i.e. the probability of false rejection α is 5 percent). The ANOVA was also extended into multiple comparison tests, which were conducted using two procedures (*11*).

Since the events observed were consolidated into a single event rate per intersection, only one analyzable observation per intersection was available. A comparison of means procedure confirmed that there was a statistically significant difference in event rates between intersections. Pooling the results by PPLT signal display type and applying an ANOVA procedure, the difference in averaging rates was not significant. Similarly, signal phasing sequence and location were not significant. Non-significant differences in location implies that differences in permitted indications used and the location of the PPLT signal display were not significant. The results suggested that the differences in event rates between intersections were either due to random variation or were a function of specific event types. Therefore, each event type was explored individually.

Applying the ANOVA procedure to the Type 1 event data found that the differences in PPLT signal phasing sequence was not significant; however, the PPLT signal display type and location were significant. A comparison of displays using Tukey's pairwise procedure found that the five-section horizontal display used in College Station had a significantly higher event rate than all other displays. College Station was the only location that used the five-section horizontal display with leading (dual) left-turn signal phasing. The phasing sequence resulted in the simultaneous presentation of the protected green arrow and through movement red ball indications. Analysis of event Types 2, 3, and 4 did not find any significant factors.

Event Study Results

Evaluating each event type individually found that the five-section horizontal display was associated with a significantly higher rate of Type 1 events. The simultaneous illumination of the green arrow and the red ball indications, increases the complexity of the signal display and appears to increase the associated driver workload. The increase in driver workload ultimately leads to an increase in driver error.

There was not sufficient evidence to determine whether the placement of the PPLT signal display affected safety. During the field studies, it appeared that the use of a secondary far side PPLT signal display had a positive affect, although this observation was not evident in the data. The permitted indication was not found to have a significant effect on safety; however, a significantly higher event rate was found with the five-section horizontal display which implied that the complexity of the signal display arrangement could affect safety, although there was dependence on the indications shown. Left-turn lane geometry was identical for all locations and could not be evaluated.

PPLT Signal Display Ranking. Based on the results of traffic event evaluation, Table 9 provides the ranking of PPLT signal display by average event rate (per 1,000 vehicles entering). Note that the rankings combine signal displays with left-turn phasing sequence due to their interdependence. In addition, Table 10 provides a rank by permitted left-turn indication.

Table 9. Ranking of PPLT Signal Displays by Event.

PPLT Signal Display	Permitted Indication	LT Phasing	Rate[1]	Rank
5-Section Vertical	Green Ball	Lead	13.0	5
4-Section Vertical	Flashing Yellow Ball	Lead	15.3	7
4-Section Vertical	Flashing Red Arrow	Lead (dual)	5.0	1
3-Section Vertical	Flashing Red Ball	Lag (dual)	12.7	4
5-Section Horizontal	Green Ball	Lead (dual)	23.5	11
5-Section Horizontal	Green Ball	Dallas	8.0	2
5-Section Cluster	Green Ball	Lag	18.0	9
5-Section Cluster	Green Ball	Lead	8.0	2
5-Section Cluster	Green Ball	Lead (dual)	13.8	6
4-Section Cluster	Flashing Red Arrow	Lead	19.0	10
4-Section Cluster	Flashing Red Arrow	Lead (dual)	15.5	8

1. Events per 1,000 entering vehicles

Table 10. Ranking of PPLT Signal Display Indications by Event.

Permitted Indication	Rate[1]	Rank
Green Ball	14.1	3
Flashing Yellow Ball	15.3	4
Flashing Red Arrow	13.2	2
Flashing Red Ball	12.7	1

1. Events per 1,000 entering vehicles

REFERENCES

1. Robertson, H.D., J.E. Hummer, and D.C. Nelson. *Manual of Traffic Engineering Studies*. ITE, Prentice Hall, Englewood Cliffs, NJ, 1994, pp. 69-87, 219-235.

2. Parker, M.R. Jr., and C.V. Zegeer. *Traffic Conflict Techniques for Safety and Operations: Engineers Guide*. Report FHWA-IP-88-026, FHWA, U.S. Department of Transportation, Washington, DC, 1988.

3. Parker, M.R. Jr., and C.V. Zegeer. *Traffic Conflict Techniques for Safety and Operations: Observers Manual*. Report FHWA-IP-88-027, FHWA, U.S. Department of Transportation, Washington, DC, 1988.

4. *Recommended Warrants for the Use of Protected/Permissive Left-Turn Phasing*. Technical Committee Project 4A-30, Institute of Transportation Engineers, Washington, DC, 1994.

5. Perkins, S.R., and J.I. Harris. Traffic Conflict Characteristics - Accident Potential at Intersections. In *Transportation Research Record 225*, TRB, National Research Council, Washington, DC, 1968, pp. 35-43.

6. Glauz, W.D., K.M. Bauer, and D.J. Migletz. Expected Traffic Conflict Rates and Their Use in Predicting Accidents. In *Transportation Research Record 1026*, TRB, National Research Council, Washington, DC, 1985, pp. 1-12.

7. Hummer, J.E., R.E. Montgomery, and K.C. Sinha. Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing. In *Transportation Research Record 1324*, TRB, National Research Council, Washington, DC, 1991, pp. 11-20.

8. Asante, S.S., S.A. Ardekani, and J.C. Williams. *Selection Criteria for Left-Turn Phasing, Indication Sequence, and Auxiliary Sign*. Report 1256-1F, Civil Engineering Department, University of Texas at Arlington, Arlington, TX, 1993.

9. Agent, K.R., N. Stamatiadis, and B. Dyer. *Guidelines for the Installation of Left-Turn Phasing*. Research Report KTC-95-23, Kentucky Transportation Center, University of Kentucky, Lexington, KY, Dec., 1995.

10. MINITAB *Reference Manual*. Release 10 for Windows. Minitab, Inc., State College, PA, 1994.

11. Wadsworth, H.M. *Statistical Methods for Engineers and Scientists.* McGraw-Hill Inc., New York, 1990.