Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays

By

David A. Noyce
Assistant Professor
Department of Civil and Environmental Engineering
University of Massachusetts
Amherst, MA 01003-5205
Telephone: (413) 545-2509
Fax: (413) 545-2840
Email: noyce@ecs.umass.edu

Daniel B. Fambro
Associate Professor
Department of Civil Engineering
Texas A&M University System
College Station, TX 77843-3135
Telephone: (409) 845-1717
Fax: (409) 845-6481
Email: d-fambro@tamu.edu

Kent C. Kacir
Senior Associate Engineer
Kittelson & Associates
2200 W. Commercial Blvd., Suite 304
Ft. Lauderdale, FL 33309
Telephone: (954) 735-1245
Fax: (954) 735-9025
Email: kkacir@kittelson.com

Paper Number: 00-1698 Sponsoring Committee: A3A02
Prepared for the 79th Annual Meeting of the
Transportation Research Board, Washington, D.C.
January, 2000

Length of Paper:
5,375 words, 2 figures + 6 tables @ 250 words each
7,375 equivalent words

Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays

ABSTRACT

Several different protected/permitted left-turn (PPLT) signal displays are used in the United States, varying in configuration and permitted indication. Questions remain as to the safety implications of using each type of display. Since left-turn crash data do not contain information related to the type of signal display and permitted indication at the intersection, conflict studies are often used as a surrogate measure. This paper describes a study of 24 intersections in eight U.S. cities to evaluate traffic conflicts and events (safety implications) associated with selected PPLT signal displays.

Based on the results of this study, there was no difference in the conflict rates associated with the PPLT signal displays evaluated. Conflict rates varied from 0.0 to 1.4 conflicts/1,000 entering vehicles. Conflicts attributed to driver misunderstanding of the signal display or indication were primarily associated with the green ball permitted indication.

Most left-turn events were related to hesitation at the onset of the protected green arrow indication. Evaluating each event type individually suggested that the five-section horizontal display with both the green arrow and red ball illuminated was associated with a significantly higher rate of Type 1 (hesitate on green arrow indication) events. Currently, the Manual on Uniform Traffic Control Devices (MUTCD) requires simultaneous illumination of the green arrow and adjacent through movement indication in the PPLT signal display during the protected left-turn phase. This result demonstrated the increase in signal display complexity and driver workload with the simultaneous illumination of the green arrow and red ball indications.

Keywords: Protected/Permitted Left-Turn, Safety, Conflict, Event, Signal Display

INTRODUCTION

One relatively new type of left-turn signal phasing, designed to minimize the exclusive left-turn phase time requirements without decreasing capacity, is protected/permitted left-turn (PPLT) phasing. PPLT signal phasing provides an exclusive phase for left-turns as well as a permissive phase during which left-turns can be made if gaps in opposing through traffic allow, all within the same signal cycle (*1*). PPLT signal phasing is currently used at approximately 29 percent of the signalized intersections in the United States (*2*).

Guidance in the selection of signal displays has been provided in the Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) since 1935 (*3*). Currently, the MUTCD allows the use of several five-section PPLT signal display arrangements, the most common being the five-section horizontal, vertical, and cluster. The MUTCD also states that a green arrow indication shall be used with the protected left-turn phase and a green ball indication with the permitted left-turn phase.

Many traffic engineers believe that the MUTCD green ball permitted indication is adequate and properly presents the intended message to the driver; however, other traffic engineers argue that the green ball permitted indication is not well understood and therefore inadequate. The latter argument is based on the belief that drivers in a left-turn lane may interpret the green ball permitted indication as a protected indication, creating a potential safety problem. These same traffic engineers believe that a different and/or unique permitted indication is needed.

At least four variations of the PPLT permitted indication have been developed in an attempt to improve the level of driver understanding and safety. These variations replace the green ball permitted indication with either a flashing red ball, flashing yellow ball, flashing red arrow, or flashing yellow arrow indication. Additionally, variations in signal display arrangement, signal display placement, and the use of supplemental signs are also applied. This variability in display types and indications has led to a myriad of PPLT signal displays and permitted indications throughout the United States.

Questions remain as to the safety implications of using each type of PPLT display. Since left-turn crash data do not contain information related to the type of signal display and permitted indication at the intersection, conflict studies are often used as a surrogate measure. This paper describes a study of 24 intersections in eight U.S. cities to evaluate traffic conflicts and events (safety implications) associated with selected PPLT signal displays.

BACKGROUND

Traffic conflicts are interactions between two or more drivers where one or both drivers take evasive action to avoid a collision (*4*, *5*, *6*). For a conflict to occur, the road users must be on a collision course, i.e., attempting to occupy the same space simultaneously. 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. Traffic conflict studies are generally considered one of the most effective ways to supplement crash data in estimating the crash potential of various PPLT signal displays and can provide a measure of traffic safety when crash rates are not available.

Traffic conflicts are generally categorized by type of maneuver (*5*, *6*). 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 the 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 the 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 Conflict:** 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.

Traffic events are unusual, dangerous, or illegal *non-conflict* maneuvers (*5*, *6*). 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, they 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 to clear the space until the next protected or permitted phase.

The conflict study methodology for both conflicts and events has been used since the 1960's (*7*). 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 (*5*). The latter is used to normalize conflict and event rates for different traffic volume conditions. Conflict rates for various maneuvers have been quantified by the Institute of Transportation Engineers (ITE) and are presented in Figure 1 (*4*).

	Conflicts/Hour		Conflicts/Day			
					Percentile	
Conflict Type	*Mean*	*Variance*	*Mean*	*Variance*	*90th*	*95th*
Signalized with Entry Volumes Greater Than 25,000 Vehicles/Day						
Left-turn same direction	8	22	83	12,000	270	360
Slow vehicle	61	34	670	24,000	870	940
Lane change	2	[b]	18	160	35	43
Right-turn same direction	20	11	220	7,600	470	510
Opposing left turn	2	1.2	22	380	48	60
All same direction	90	74	990	67,000	1300	1500
Signalized with Entry Volumes 10,000 to 25,000 Vehicles/Day						
Left-turn same direction	12	22	130	10,000	270	340
Slow vehicle	34	11	380	4,900	470	500
Lane change	0.7	[b]	8	53	17	22
Right-turn same direction	11	12	120	2,400	190	220
Opposing left turn	2.6	1.2	29	210	49	56
All same direction	59	95	640	25,000	860	930
Unsignalized with Entry Volumes 10,000 to 25,000 Vehicles/Day						
Left-turn same direction	12	21	130	12,000	270	350
Slow vehicle	14	5.2	150	5,900	260	290
Lane change	5.6	11	62	1,200	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	29	77	320	29,000	540	640
Through cross traffic	0.6	[b]	7	16	12	14
Unsignalized with Entry Volumes 2500 to 10,000 Vehicles/Day						
Left-turn same direction	6.4	22	71	1,000	110	130
Slow vehicle	9.3	5.5	100	9,600	220	300
Lane change	5.3	11	58	2,200	120	150
Right-turn same direction	0.3	[b]	4	8	8	9
Opposing left turn	0.5	1.1	6	12	10	12
All same direction	21	77	230	18,000	410	490
Through cross traffic	1.1	[b]	12	75	24	29

[a]

"All same direction" includes left turn same direction, slow vehicle, lane change, and right-turn same direction. "Through cross traffic" includes cross traffic from left and cross traffic from right conflict types.

[b] Not available.

Figure 1 Typical Conflict Rate Statistics for Intersections with Four Approaches.

At least one study has been completed which compared conflict rates and crash rates at the same location. Glauz completed a study with the objective of establishing a relationship between conflict and crash rates (*8*). Specifically, the goal of the study was to establish a relationship that would allow conflict rates to be used to predict expected crash rates. Study results 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.

Few studies have evaluated traffic conflicts and events related to PPLT signal displays. Hummer conducted a study in Indiana to evaluate and compare the safety afforded by leading and lagging left-turn phasing sequences (*9*). 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 different intersection approaches in Texas (*10*). 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). Lagging PPLT sequences had a lower conflict rate than leading sequences. Similarly, Agent evaluated conflict rates in Kentucky at 58 approaches at 29 signalized intersections containing PPLT signal phasing (*11*). Conflict rates varied from zero to 12 conflicts per hour during the peak hour.

STUDY DESIGN

To determine whether PPLT signal displays had an effect on conflict rates required a study that measured conflicts at several intersections. Therefore, a study was designed to field measure conflict rates at each type of PPLT signal display and at different geographical regions of the United States.

College Station and Dallas, Texas; Cupertino, California; Dover, Delaware; Portland, Oregon; Oakland County, Michigan; Orlando, Florida; and Seattle, Washington were selected as data collection locations. Cupertino, Dover, Oakland County, and Seattle were selected because of the flashing permitted indications in their PPLT signal displays. College Station, Dallas, Orlando, and Portland were selected because of their use of five-section PPLT signal displays and green ball permitted indications. Examples of the PPLT signal displays evaluated are shown in Figure 2.

Three intersections were studied at each of the eight cities selected. In Dallas, two of the three intersections contained a lead-lag phasing sequence using Dallas Phasing. Dallas phasing is a unique phasing scheme designed to eliminate the yellow trap. The left-turn phasing sequence changed from leading (AM peak) to lagging (PM peak) during each day of the study period. Therefore, each intersection approach was evaluated twice, under each phasing sequence, creating five study intersections in Dallas.

Criteria were established to qualify a *typical* intersection, 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. The intersections selected for study met these criteria. Intersections were different in PPLT display arrangement and corresponding permitted indication.

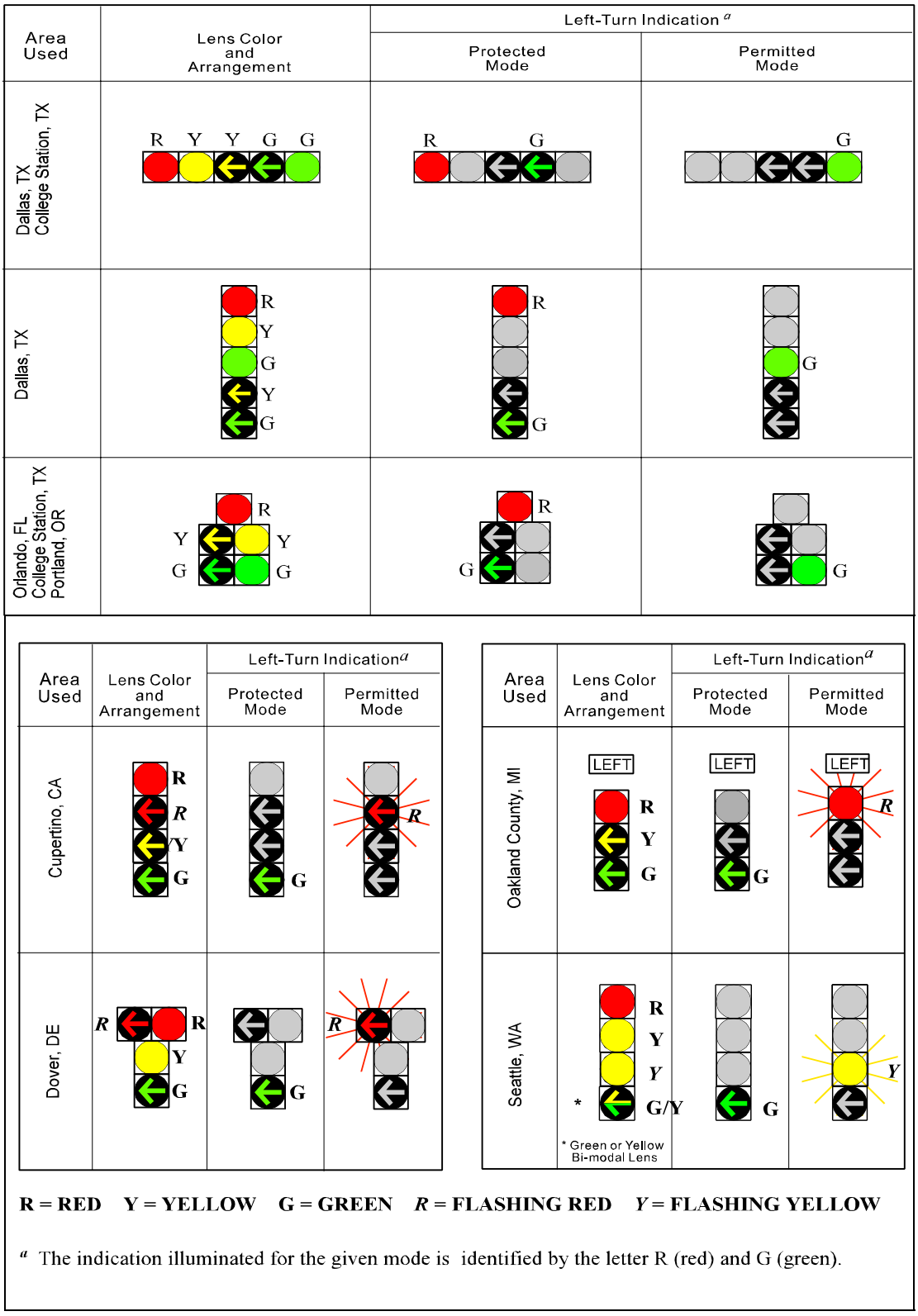

Figure 2 PPLT Signal Display Arrangements and Indications.

Table 1 lists the intersections selected in each location along with the PPLT signal display, permitted indication (PI), and left-turn phasing sequence at each site. Data collection equipment consisted of two items: a data collection form and a video camera (*4*). Conflict data were recorded using the data collection form. 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 was also used to compute traffic volumes when other volume information was not available, and to observe specific intersection operations.

The purpose of the conflict study was to isolate the left-turn movement and evaluate the effects of the PPLT signal display and associated attributes. Because the study was focused only on the left-turn maneuver, and more specifically, on drivers' 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 conflict; 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 (red violation); and
- Type 4 - Back-up out of the intersection into the left-turn lane.

Table 1 Intersections Selected for Study

City	Intersection	ID [a]	PPLT Display [b]	PI [c]	LT Phase [d]
Dallas TX	Lovers Ln. @ Skillman Ave.	1	5-Vert.	GB	Lead
	Mockingbird Ln. @ Skillman Ave.	2	5-Horz.	GB	D-Lead
	Mockingbird Ln. @ Skillman Ave.	3	5-Horz.	GB	D-Lag
	Buckner Blvd. @ Garland Rd.	4	5-Horz.	GB	D-Lead
	Buckner Blvd. @ Garland Rd.	5	5-Horz.	GB	D-Lag
Dover DE	Highway 13 @ Court St.	6	4-Cluster	FR	Lead
	Highway 13 @ East Landing Rd.	7	4-Cluster	FR	Lead
	Highway 113 @ Little Creek Rd.	8	4-Cluster	FR	Lead
Oakland County MI	Maple Ave. @ Orchard Lake Rd.	9	3-Vert.	FR	Lag
	14 Mile Rd. @ Orchard Lake Rd.	10	3-Vert.	FR	Lag
	13 Mile Rd. @ Orchard Lake Rd.	11	3-Vert.	FR	Lag
College Station TX	University Dr. @ College Ave.	12	5-Horz.	GB	Lead
	SW Parkway @ Texas Ave.	13	5-Horz.	GB	Lead
	SW Parkway @ Southwood Dr.	14	5-Cluster	GB	Lag
Seattle WA	South Lander St. @ 1st Ave.	15	4-Vert.	FY	Lead
	South Lander St. @ 4th Ave.	16	4-Vert.	FY	Lead
	Fairview Ave. @ Republican St.	17	4-Vert.	FY	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-Vert.	FR	Lead
	Stevens Creek Blvd. @ Torre Dr.	22	4-Vert.	FR	Lead
	Stevens Creek Blvd. @ Portal Ave.	23	4-Vert.	FR	Lead
Orlando FL	Orange Blossom Trail @ Princeton	24	5-Cluster	GB	Lead
	Orange Ave. @ Kaley St.	25	5-Cluster	GB	Lead
	Orange Ave. @ Michigan St.	26	5-Cluster	GB	Lead

[a] Intersection Identification Number.
[b] Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).
[c] Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.
[d] Left-turn phasing. D = Dallas Phasing.

A one day traffic conflict study was conducted on one intersection approach at each of the study sites. Data was collected between the hours of 7:00 AM and 6:00 PM on weekdays. No occurrences of traffic breakdowns (congestion, signal failure, crashes) or weather conditions were experienced that inhibited data collection efforts.

The data collection itinerary 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. Both traffic conflict and traffic event data were recorded. The observer was positioned approximately 300 feet from the intersection in a location concealed from the approaching traffic. Only conflicts and events related to the features of the PPLT signal display and the approach of interest were recorded.

For each conflict or event observed, the time, vehicle position, vehicle movement, conflict and/or event type, and comments to help define the actions observed were recorded. Left-turn conflict/event codes were recorded to expedite the data collection process and provide consistency between locations. At the completion of each study, the conflict and event data were reduced by summing the totals of each type. No weighted adjustments were used as it was assumed that there was little difference in traffic volumes throughout the study period. Actual conflict and event totals were adjusted for unobserved time periods to obtain 11-hour values (*3*).

Conflict and event rates per 1,000 entering vehicles were computed at each location. Entering vehicles were considered to be the sum of the left-turn vehicles and opposing through and right-turn vehicles in the 11-hour study period. The analysis plan included the use of the General Linear Model (GLM) methodology in the Analysis of Variance procedure (ANOVA) to evaluate significant differences in conflict and event rates (*12*). The GLM ANOVA method was selected because it is suitable for analyzing a data set with an unequal number of observations for each treatment level. Factors related to signal display, phasing sequence, intersection, and location were included in the analysis as explanatory variables. The test for significance was completed using the *F* statistic and was based on a 95 percent confidence level.

RESULTS

Table 2 shows the number of hours analyzed, the total number of conflicts observed, the conflict rate (per 1,000 entering vehicles), and the Type 1 conflict rate by intersection. Opposing left-turn conflicts (Type 1) ranged from 0.0 to 1.4 conflicts per 1,000 entering vehicles. The average rates were slightly below those presented in Figure 1 but well within the expected variability. A total of 166 left-turn conflicts were observed at the 26 study sites. Of the 166 conflicts observed, only 11 conflicts (7 percent) were Type 2, Type 3, or Type 4. Specifically, nine Type 2 conflicts, two Type 3 conflicts, and no Type 4 conflicts were observed.

Focusing on the 155 Type 1 conflicts, nine (6 percent) appeared to be directly related to driver error while the other 146 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 drivers at the onset of their green ball indication. Through movement drivers were forced to hesitate at the onset of the through movement green ball indication to avoid a collision.

The other common occurrence was the left-turn driver accepting a very small gap in the opposing traffic stream during the permitted phase. This conflict appeared to depend on the level of congestion and the availability of acceptable gaps. As demand flow rates 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.

Table 2 Cumulative Conflicts

City	ID [a]	PPLT Display [b]	PI [c]	LT Phase	Total Traffic Volume [d]	Conflicts		
						Total	Rate [e]	Type 1
Dallas TX	1	5-Vert.	GB	Lead	9,515	8	0.8	0.6
	2	5-Horz.	GB	Dallas-Lead	13,380	17	1.3	1.3
	3	5-Horz.	GB	Dallas-Lag	13,380	17	1.3	1.3
	4	5-Horz.	GB	Dallas-Lead	12,730	9	0.7	0.5
	5	5-Horz.	GB	Dallas-Lag	12,730	9	0.7	0.5
Dover DE	6	4-Cluster	FRA	Lead	10,630	3	0.3	0.3
	7	4-Cluster	FRA	Lead	10,150	9	0.9	0.9
	8	4-Cluster	FRA	Lead	10,980	2	0.2	0.2
Oakland County MI	9	3-Vert.	FRB	Lag	16,950	8	0.5	0.5
	10	3-Vert.	FRB	Lag	5,415	4	0.7	0.7
	11	3-Vert.	FRB	Lag	8,925	3	0.3	0.3
College Station TX	12	5-Horz.	GB	Lead	13,880	20	1.4	1.2
	13	5-Horz.	GB	Lead	6,600	9	1.4	1.1
	14	5-Cluster	GB	Lag	3,650	5	1.4	1.4
Seattle WA	15	4-Vert.	FYB	Lead	9,250	0	0.0	0.0
	16	4-Vert.	FYB	Lead	9,365	3	0.3	0.3
	17	4-Vert.	FYB	Lead	7,210	0	0.0	0.0
Portland OR	18	5-Cluster	GB	Lead	3,960	3	0.8	0.8
	19	5-Cluster	GB	Lead	8,925	3	0.3	0.3
	20	5-Cluster	GB	Lead	9,000	3	0.3	0.3
Cupertino CA	21	4-Vert.	FRA	Lead	4,000	3	0.7	0.7
	22	4-Vert.	FRA	Lead	10,000	1	0.1	0.1
	23	4-Vert.	FRA	Lead	9,500	0	0.0	0.0
Orlando FL	24	5-Cluster	GB	Lead	13,950	8	0.6	0.6
	25	5-Cluster	GB	Lead	15,550	10	0.6	0.6
	26	5-Cluster	GB	Lead	25,800	9	0.4	0.4

[a] Intersection Identification Number.
[b] Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).
[c] Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.
[d] Total left-turn plus opposing through and right-turn volumes over the 11-hour study period.
[e] Conflicts per 1,000 entering Vehicles.

As previously mentioned, nine of the Type 1 conflicts appeared to be directly related to driver confusion. In each case, the misunderstanding occurred during the permitted left-turn phase. Eight of the nine conflicts were the apparent 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 at the same time as the opposing left-turn had a green arrow indication and assuming right-of-way. Table 3 presents a summary of these Type 1 conflicts including the location, permitted indication, and a brief description of the apparent cause.

Type 2 conflicts occurred at intersections with a five-section display and the green ball permitted indication. The conflicts were caused by the lead left-turn driver hesitating, forcing the following left-turn drivers to brake sharply to avoid a rear-end collision. Most often, Type 2 conflicts were a result of indecision by the lead left-turn driver. In several instances, the driver began to accept a gap, then, abruptly rejected the gap. In at least one instance, a left-turn driver began to execute the turn at the onset of the green ball phase, and then realized that they did not have the right-of-way. There appeared to be a relationship between driver misunderstanding of the permitted green ball indication and the Type 2 conflict.

Type 3 conflicts were a result of driving error, not related to drivers' understanding of the signal displays, and provided little information related to driver understanding of the signal display. No further analysis was completed on Type 3 conflicts. No Type 4 conflicts were observed.

Because of the limited number of conflicts that could be directly correlated to drivers' misunderstanding of PPLT signal displays, statistical procedures were not feasible. Therefore, the results of the conflict study were based on a comparison of average rates. Combined conflict rates for each permitted indication are summarized in Table 4.

Table 3 Type 1 Conflicts Due to Driver Misunderstanding of the PPLT Signal Display

ID [a]	PPLT Display [b]	PI [c]	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 the flashing red arrow permitted indication.
19	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball
24	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball
25	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball
25	5-Cluster	GB	Lead	Assumed right-of-way and turned left (without gap) during the green ball

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

Table 4 Conflict Rates by Indication

Permitted Indication	Phase Sequence	Average Conflict Rate [a]
Green Ball	Lead	0.8
Green Ball	Lag	1.1
Flashing Yellow Ball	Lead	0.1
Flashing Red Arrow	Lead	0.4
Flashing Red Ball	Lag	0.5

[a] Per 1,000 Entering Vehicles.

The opposing left-turn conflict (Type 1) rate observed was consistent with the rates identified in Figure 1, although generally on the low end of the range. The green ball indication was associated with nearly all of the conflicts that appeared to be caused by breakdowns in driver understanding. Although infrequent, there remains a tendency for drivers to assume that the green ball indication provides right-of-way for the left-turn movement. Only one conflict associated with driver misunderstanding 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. Although the flashing permitted indications appeared to be associated with high levels of driver understanding, the low number of conflicts related to the flashing permitted indications may have been partially due to the small sample size in the database.

Traffic Events

The frequency of each event type is presented in Table 5. In addition, the results of the pooled event frequency analysis are presented in Table 5 including the total events and the event rate. Events ranged from 0.0 to 3.3 events per 1,000 entering vehicles (eptev). College Station had the highest average event rate at 2.0 eptev followed by Seattle and Portland, both at 1.5 eptev. Cupertino had the lowest average event rate at 0.3 eptev.

Table 5 Observed Event Frequency by Type

City	ID [a]	PPLT Display [b]	PI [c]	LT Phase	Event Type				Events	
					1	2	3	4	Total	Rate [d]
Dallas TX	1	5-Vert.	GB	Lead	3	2	2	0	7	0.7
	2	5-Horz.	GB	Dallas-Lead	0	0	0	0	0	0.0
	3	5-Horz.	GB	Dallas-Lag	0	0	0	0	0	0.0
	4	5-Horz.	GB	Dallas-Lead	5	5	0	0	10	0.8
	5	5-Horz.	GB	Dallas-Lag	5	5	0	0	10	0.8
Dover DE	6	4-Cluster	FRA	Lead	11	5	0	0	16	1.5
	7	4-Cluster	FRA	Lead	2	4	0	0	6	0.6
	8	4-Cluster	FRA	Lead	8	2	0	7	17	1.5
Oakland County MI	9	3-Vert.	FRB	Lag	4	0	0	2	6	0.4
	10	3-Vert.	FRB	Lag	2	0	0	0	2	0.4
	11	3-Vert.	FRB	Lag	9	9	0	0	18	2.0
College Station TX	12	5-Horz.	GB	Lead	34	4	0	2	40	2.9
	13	5-Horz.	GB	Lead	13	0	0	0	13	2.0
	14	5-Cluster	GB	Lag	2	2	0	0	4	1.2
Seattle WA	15	4-Vert.	FYB	Lead	12	2	0	11	25	2.7
	16	4-Vert.	FYB	Lead	6	0	3	7	16	1.7
	17	4-Vert.	FYB	Lead	0	0	0	0	0	0.0
Portland OR	18	5-Cluster	GB	Lead	8	5	0	0	13	3.3
	19	5-Cluster	GB	Lead	5	2	0	0	7	0.8
	20	5-Cluster	GB	Lead	2	2	0	0	4	0.4
Cupertino CA	21	4-Vert.	FRA	Lead	0	1	0	0	1	0.3
	22	4-Vert.	FRA	Lead	0	0	0	3	3	0.3
	23	4-Vert.	FRA	Lead	0	0	0	3	3	0.3
Orlando FL	24	5-Cluster	GB	Lead	7	2	0	0	9	0.7
	25	5-Cluster	GB	Lead	3	2	0	2	7	0.5
	26	5-Cluster	GB	Lead	6	0	0	0	6	0.2

[a] Intersection Identification Number.
[b] Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster).
[c] Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball; A = Arrow; F = Flashing.
[d] Events per 1,000 entering Vehicles (eptev).

Type 1 Events

Type 1 events involved left-turn vehicles hesitating or not turning left during the protected left-turn phase. This event type accounted for 60 percent of all events observed. College Station had the highest number of Type 1 events. Most of these events where found at intersections containing a five-section horizontal signal display, located over the lane line, using a leading (dual) left-turn signal phasing sequence.

With a leading dual left-turn sequence, the 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 PPLT 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, be confused by its meaning, or hesitate for several seconds to be assured that making the left-turn maneuver is safe.

Type 1 events at the five-section horizontal PPLT signal display in Dallas were much less frequent. As part of the Dallas Phasing concept, left-turn drivers see either a green arrow or green ball indication during the entire time that the opposing left-turn and adjacent through movement were serviced. Note that the green arrow and red ball are not presented simultaneously as in College Station. 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 during the protected left-turn phase, even when the through movement had a red ball indication.

Dallas' effort to overcome driver confusion with the simultaneous illumination of the green arrow and red ball indication for the protected left-turn movement may also cause 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 required 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. Despite this potential confusion, Dallas drivers were involved in very few events.

No Type 1 events were observed in Cupertino. Cupertino used two four-section vertical PPLT signal displays, one centered over the lane line and one pole mounted on the far side of the intersection, and a leading (dual) left-turn phase sequence. Drivers appeared to focus on the far side signal display knowing that this display pertained to the left-turn movement.

Oakland County 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 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 lagging protected left-turn phase, drivers had to rely on the far side signal display or a secondary cue, such as the stoppage of opposing vehicles, for notification of the protected phase. In addition, Oakland County had a high occurrence of red light violations. Several Type 1 events 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 gave drivers a second source of information that appeared to have a positive effect in reducing Type 1 events.

Type 2 Events

Type 2 events involved hesitating on the permitted indication and/or not accepting a gap of sufficient size in the opposing traffic stream. Type 2 events represented 22 percent of all events

observed, equally distributed among intersections.

The primary cause of Type 2 events appeared to be 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 during the permitted left-turn phase, but waited until the protected phase before turning. These were random occurrences with no PPLT signal display or phasing sequence exhibiting more than the others; however, elderly drivers were most often involved. There was no evidence to suggest that the PPLT signal display, phasing sequence, or permitted indication had an affect on Type 2 event rates.

Type 3 Events

Type 3 events involved running the red ball indication or, in other words, red light violations. Data collection for Type 3 events began in earnest at the first intersections studied; 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 drivers' understanding of the PPLT or through movement signal displays. Most often, red light violations were simply due to aggressive driving. Because of this, only Type 3 events that were clearly a function of driver misunderstanding were recorded.

Five Type 3 events were observed during data collection, representing two percent of the total events. 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 a non-flashing red ball, and assumed the green ball indication applied to the left-turn movement. Nevertheless, there were very few Type 3 events related to driver understanding and there were no consistent patterns among PPLT signal displays.

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 up 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. 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 number of Type 4 events were in Dover and Cupertino. In each location, the flashing red arrow permitted indication terminated directly to a solid red ball indication, without any form of clearance interval. Drivers in the intersection waiting to make a permitted left-turn suddenly found that the flashing red arrow 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.

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

A statistical analysis of the event data showed that the five-section horizontal display 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 left-turn signal phasing. This 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 suggest any significant factors.

To explore the differences in event rates due to display type further, the results of the event study were summarized by PPLT signal display and permitted indication. These results are presented in Table 6.

Table 6 PPLT Signal Displays by Event

PPLT Signal Display	Permitted Indication	LT Phasing	Events Average [a]
5-Section Vertical	Green Ball	Lead	0.7
4-Section Vertical	Flashing Yellow Ball	Lead	1.6
4-Section Vertical	Flashing Red Arrow	Lead (dual)	0.3
3-Section Vertical	Flashing Red Ball	Lag (dual)	0.8
5-Section Horizontal	Green Ball	Lead (dual)	2.6
5-Section Horizontal	Green Ball	Dallas	0.4
5-Section Cluster	Green Ball	Lag	1.2
5-Section Cluster	Green Ball	Lead	0.4
5-Section Cluster	Green Ball	Lead (dual)	1.1
4-Section Cluster	Flashing Red Arrow	Lead	1.6
4-Section Cluster	Flashing Red Arrow	Lead (dual)	1.1

[a] Events per 1,000 entering vehicles.

CONCLUSIONS

Based on the results of this study, there was no difference in the conflict rates associated with the PPLT signal displays evaluated. Left-turn conflict rates were low for all PPLT signal displays evaluated. Only nine of the conflicts observed could be attributed to driver confusion related to the signal display. In addition, conflict study results provided little information concerning the affect of PPLT signal displays on safety. Although there appeared to be small differences between PPLT signal display types, the results do not imply that safety is not a concern with PPLT phasing. Instead, the results may simply highlight the difficulty in detecting small variances among rare occurrences.

Conflicts attributed to driver misunderstanding of the signal display or indication were primarily associated with the green ball permitted indication. Although this sample size is too small to make inferences regarding the entire population of signal displays, there is evidence to suggest that drivers will occasionally assume that the green ball permitted indication provides right-of-way for the left-

turn movement. Since left-turn drivers facing a green ball permitted indication are required to yield to opposing traffic, this misunderstanding of the green ball indication may lead to a safety problem.

Most left-turn events were related to hesitation at the onset of the protected green arrow indication. Evaluating each event type individually found that the five-section horizontal display was associated with a significantly higher Type 1 event rate. This result may demonstrate an increase in signal display complexity and driver workload with the simultaneous illumination of the green arrow and red ball indications in the horizontal display, ultimately leading to increased driver error.

RECOMMENDATIONS

The National Committee on Uniform Traffic Control Devices should give consideration to the potential problems in driver understanding and signal display complexity when two indications are simultaneous illuminated within a signal display. The five-section horizontal display with a green arrow and red ball simultaneously illuminated was found to have a high number of Type 1 events, increasing driver workload and the probability for driver error. Additional study is recommended to corroborate the findings of this research.

ACKNOWLEDGMENTS

The data collection and reduction were performed as part of National Cooperative Highway Research Program (NCHRP) Project 3-54 entitled *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control* being conducted jointly by Kittelson & Associates and the Texas Transportation Institute (TTI) for the Transportation Research Board.

REFERENCES

1. Fambro, D.B., G.D. Gaston, and C.M. Hoff. *Comparison of Two Protected-Permitted Lead-Lag Left-Turn Phasing Arrangements.* Report 989-1F. Texas Transportation Institute, Texas A&M University System, College Station, TX, 1991.

2. Noyce, D.A. *Development of a Uniform Traffic Control Device For Protected/Permited Left-Turn Control*. Doctoral Dissertation, Texas A&M University System, College Station, TX, 1999.

3. *Manual on Uniform Traffic Control Devices*. FHWA, U.S. Department of Transportation, Washington, DC, 1988.

4. 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.

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

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

7. 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.

8. 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.

9. 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.

10. Asante, S.A., 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.

11. 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.

12. Neter, J., W. Wasserman, and M.H. Kutner. *Applied Linear Statistical Models*. Third Edition, Richard D. Irwin, Inc, Homewood, IL, 1990.