TECHBRIEF

Pedestrian and Bicycle Safety

Safety Evaluation of Protected Left-Turn Phasing on Pedestrian Safety

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This document is a technical summary of the Federal Highway Administration report *Safety Evaluation of Protected Left-Turn Phasing and Leading Pedestrian Intervals on Pedestrian Safety* (FHWA-HRT-18-044).

Introduction and Objective

Pedestrian safety is an important issue for the United States, with pedestrian fatalities representing approximately 16 percent of all traffic-related fatalities in 2016.[1] In recognition of the magnitude of this problem, the Federal Highway Administration (FHWA) funded a study to evaluate promising infrastructure improvements to increase pedestrian safety. Following a literature review that summarized the existing knowledge on 18 countermeasures, FHWA and a Technical Advisory Panel selected 2 as the highest priorities for detailed evaluation in this study—the provision of protected and protected/permissive left-turn phasing and the provision of leading pedestrian intervals (LPIs). The objective of the study was to develop statistically rigorous crash modification factors (CMFs) for these countermeasures using state-of-the-art analytical methods.

This TechBrief summarizes the evaluation of protected left-turn phasing. FHWA wrote a separate TechBrief for the evaluation of leading pedestrian intervals.[2] The safety effectiveness of the countermeasure was measured by crash frequency of vehicle–pedestrian crashes (all severities combined), vehicle–vehicle crashes (all severities combined), and vehicle–vehicle injury crashes (K, A, B, and C severities on the KABCO scale, where K is fatal injury, A is incapacita-ting injury, B is nonincapacitating injury, C is possible injury, and O is property damage only). The analysis was conducted using an empirical Bayesian (EB) before–after study design and data from urban intersections in three cities that had

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installed the countermeasure of interest (Chicago, IL; New York City (NYC), NY; and Toronto, ON).

At signalized intersections where left turns are allowed, the traffic signal may be operated as permissive only, protected only, or protected/permissive. Permissive left-turn phasing allows left-turn movements concurrently with opposing through movements. Under permissive left-turn phasing, drivers turning left must yield to any conflicting pedestrians or opposing traffic and proceed after choosing an appropriate gap through which to complete the turn. On the other hand, protected left-turn phasing provides an exclusive phase for left turns, during which opposing through movements and pedestrian crossings are prohibited. Under protected left-turn phasing, conflicts between left-turning and opposing through vehicles and between left-turning vehicles and pedestrians are eliminated. Figure 1 shows an intersection with a flashing yellow arrow (a type of permissive left-turn phasing), and figure 2 shows an intersection with protected left-turn phasing.

Some intersections use a combination of protected and permissive left-turn phasing,

Figure 1. Photo. Intersection approach operating with permissive left-turn phasing.

known as protected/permissive left-turn phasing. With protected/permissive left-turn phasing, the left-turning traffic has a permissive phase preceded or followed by a protected phase. A majority of the treated sites assembled for the current study were converted from permissive-only to protected/permissive left-turn phasing.

Literature Review

The effects of protected left-turn phasing on pedestrian safety have not been evaluated as extensively as the effects of protected left-turn phasing on crashes between vehicles. Evidence of this dearth was provided by Bonneson et al., who conducted a literature review and concluded that research had not established a reliable (crash-based) relationship between pedestrian safety and protected/permissive signal phasing.(3) Subsequently, NYC found a 43-percent reduction in pedestrian crashes from changing the signal phasing from permissive only to protected/permissive or protected only.(4)

The majority of crash-based studies for protected left-turn phasing have focused on CMFs for crash types other than vehicle–pedestrian crashes. Hauer conducted a detailed critical review of 14 studies and concluded that, when changing from either permissive-only or protected/permissive phasing to protected-only phasing, the CMF for left-turn crashes was around 0.3 (i.e., a 70-percent reduction in left-turn crashes); for other crashes, the CMF was 1.0 (i.e., no effect). When changing from permissive-only to protected/permissive phasing, Hauer estimated that the CMF was around 1.0 for both left-turn crashes and other crashes (i.e., no effect).(5) Lyon et al. found that a leading protected left-turn followed by a permissive phase decreased left-turn crashes by up to 17 percent and left-turn, side-impact crashes by up to 25 percent.(6) In 2008, Srinivasan et al. evaluated crashes involving at least one left-turning vehicle on the treated roadway. Where fully protected phasing was added, left-turn crashes were virtually eliminated, but there

Figure 2. Photo. Intersection approach operating with protected left-turn phasing.

was very little change in total crashes.[7] In 2011, Srinivasan et al. evaluated the conversion from permissive-only to either protected/permissive or protected-only phasing for at least part of the day.[8] Separate analyses were done for the intersections as a whole and for only the treated approaches. At both levels, the results indicated substantial and highly significant benefits for left turn–opposing crashes involving a left-turning vehicle and a through vehicle from the opposing approach. For intersection-level data, a CMF of 0.862 was estimated for left turn–opposing crashes. For total and injury crashes, CMFs of 1.031 and 0.962 were estimated, neither of which was statistically significant at a 95-percent confidence level. As expected, the benefit at the intersection level was greater at intersections where more than one approach was treated. At both the intersection and approach levels, there were small increases in the percent of rear-end crashes, resulting in an estimated CMF of 1.075.[8]

Methodology

The research evaluated the impacts of the following two pedestrian-safety improvements on crash frequency: adding either protected/permissive or protected-only phasing to one or more legs of signalized intersections and implementing LPI timing on some or all pedestrian crossings at signalized intersections. The protected left-turn phasing evaluation used data from 27 treated sites in Chicago, 7 treated sites in NYC, and 114 treated sites in Toronto. The project team considered the following target crash types for the protected left-turn phasing evaluation:

- Vehicle–pedestrian crashes (all severities combined).
- Vehicle–vehicle crashes (all severities combined).
- Vehicle–vehicle injury crashes (K, A, B, and C injuries).

Another objective was to investigate ways in which safety effects might vary by site characteristics and strategy implementation details. An economic analysis was conducted to estimate a benefit–cost (B/C) ratio.

The project team used the EB methodology for observational before–after studies for this evaluation.[9] This methodology is considered rigorous in that it accounts for regression to the mean using a reference group of similar but untreated sites. In the process, the project team used safety performance functions (SPFs). SPFs are equations that serve to estimate the expected crash frequency at a site based on characteristics that influence crashes (e.g., traffic volumes). The use of SPFs in the EB methodology rationally normalizes traffic-volume differences between the before and after periods, accounts for time trends, and reduces the level of uncertainty in the esti-mates of safety effects. The methodology also provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.

The project team estimated the SPFs used in the EB methodology through generalized linear modeling assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. In specifying a negative binomial error structure, the project team iteratively estimated an overdispersion parameter, which is used in the EB calculations, from the model and the data.

The full report provides a detailed explanation of the methodology, including a description of how the project team calculated the estimate of safety effects for target crashes.[10]

Results

The results for the protected left-turn evaluation showed an increase in vehicle–pedestrian crashes in Chicago and Toronto and a decrease in NYC. However, none of these results were statistically significant at a 95-percent confidence level, and the results in NYC were based on few sites and crashes. For vehicle–vehicle crashes, increases were seen in Chicago and Toronto, but these were not statistically significant. A statistically significant decrease was seen in NYC, although this was based on only 46 after-period crashes. There are two aspects of the NYC sites that are noteworthy even though the sample size was smaller. First, of the three cities that provided data for the left-turn phasing evaluation, only NYC had a citywide prohibition on turning right on red. Second, the treatment sites from NYC were dominated by conversion to protected-only phasing, whereas Chicago and Toronto were dominated by conversion to protected/permissive phasing. For vehicle–vehicle injury crashes, decreases were seen in all three cities, but only Toronto showed a statistically significant decrease, which was less than 5 percent.

For all cities combined, nonsignificant increases were seen for vehicle–pedestrian crashes and vehicle–vehicle crashes, while a small but statistically significant decrease of less than 6 percent was seen for vehicle–vehicle injury crashes. Table 1 shows the CMFs for the protected left-turn phasing evaluation for all cities combined.

The results in table 1, which were dominated by changes from permissive-only to protected/permissive phasing, were reasonably consistent with the previous findings by Hauer, who reported a CMF of 1.0 (i.e., no effect) for changes to protected/permissive phasing, and Srinivasan, who reported nonstatistically significant CMFs of 1.031 and 0.962 for total crashes and total injury crashes, respectively.[5,8]

It is possible that more pronounced and differential effects may exist for subsets of sites with different characteristics. This possibility was explored through a univariate disaggregate analysis and the potential development of crash modification functions (CMFunctions) to relate the CMF to site characteristics. Univariate disaggregate analyses were undertaken for all crash types, considering several variables, including the number of intersection approaches, the number of treated approaches, the number of approaches with a protected left-turn phase prior to treatment, the number of through or left-turn lanes, the total annual average daily traffic (AADT), the left-turn AADT, the volume of pedestrians crossing, and the EB estimate of expected crashes per year prior to treatment.

For vehicle–vehicle crashes and vehicle–vehicle injury crashes, there were no apparent relationships found between the expected CMF and any of the candidate sites' characteristics. For vehicle–pedestrian crashes, the analysis indicated that the CMF may be smaller for higher pedestrian and vehicle volumes. Thus, in developing CMFunctions, the dependent variable—the observed number of vehicle–pedestrian crashes—was modeled as a function of pedestrian volumes and vehicle AADTs with the EB estimate of expected crashes as an offset. Vehicle AADT was not statistically significant and did not improve the fit of the model to the data and was therefore not included in the final CMFunction form.

The estimated parameters showed that the expected CMF decreases as the pedestrian volume increases. At lower pedestrian volumes, the predicted CMF was greater

Table 1. CMFs for protected left-turn phasing evaluation—all cities combined (215 treatment sites).

Crash Type	Estimate of CMF*	Standard Error
Vehicle–pedestrian crashes (all severities combined)	1.091	0.066
Vehicle–vehicle crashes (all severities combined)	1.023	0.016
Vehicle–vehicle injury (KABC)	0.942*	0.028

*CMF that is statistically significant at a 95-percent confidence level.
Note: Of 215 treated approaches, 203 were protected/permissive, and 12 were fully protected.

than 1.0; the predicted CMF was less than 1.0 for 24-h crossing volumes greater than approximately 5,500 pedestrians per day. However, the CMF estimates derived for a specific pedestrian volume should not be considered robust given the lack of statistical significance for the results overall and from the univariate disaggregate analysis.

The observed increase in vehicle–pedestrian crashes following the addition of left-turn protection at low pedestrian volumes may be due to pedestrians not complying with the "do not walk" signal during the protected left-turn phase. Alternatively, it may be that vehicles turn left at unsafe speeds immediately after their protected phase is over and pedestrians have begun to cross. When pedestrian volumes are high, this type of behavior may be less prevalent as vehicles are more conscious of the presence of pedestrians. These hypotheses are only speculative, however.

Economic Analysis

The project team conducted an economic analysis to determine the potential B/C ratio for protected or protected/permissive left-turn phasing. Since the main objective of the study was the safety evaluation of vehicle–pedestrian crashes, the economic analysis focused on such crashes. Furthermore, the analysis focused on the 16 sites with pedestrian crossing volumes at or exceeding 5,500 per day because the CMFunction developed in the disaggregate analysis indicated the treatment could be beneficial in reducing pedestrian crashes at such sites. The analysis conservatively assumed a useful service life for safety benefits of 20 yr and a real discount rate of 7 percent.[11] With this information, the capital recovery factor was determined to be 0.094 for all intersections, giving annual costs of $2,632 per intersection.

The project team calculated that the aggregate 2016 unit cost for vehicle–pedestrian crashes at urban intersections was $414,993. The number of total crashes saved per year was 2.821 for all intersections. Considering the number of treated intersections (16), this resulted in an average savings of 0.1763 pedestrian crashes per intersection per yr. By multiplying the crash reduction per site-year by the cost of a crash, the project team determined the annual dollar benefit from reduced crashes to be $73,163 per intersection.

The U.S. Department of Transportation has recommended conducting a sensitivity analysis by assuming values of a statistical life of 0.56 and 1.40 times the recommended 2016 value.[12] The resulting B/C ratio ranged from 1:15.6 to 1:38.9. These results suggest that the strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective for reducing pedestrian crashes at signalized intersections with high pedestrian volumes. However, it should be noted that this B/C ratio result is based only on a small sample of sites (the 16 sites with high pedestrian volumes).

Summary and Conclusions

This study examined, with a particular focus on pedestrian safety, the effects of protected and protected/permissive left-turn phasing and LPIs on the safety of signalized intersections. The protected left-turn phasing evaluation used data from Chicago, NYC, and Toronto. The results showed that vehicle–pedestrian crashes increased in Chicago and Toronto and decreased in NYC. However, none of these results were statistically significant at a 95-percent confidence level, and the results in NYC were based on few sites and crashes. For vehicle–vehicle crashes, increases were seen in Chicago and Toronto, but these were not statistically significant at a 95-percent confidence level. A statistically significant decrease was seen in NYC, although this was based on only 46 after-period crashes. For vehicle–vehicle injury crashes, decreases were seen in all three cities, but only Toronto showed a statistically significant decrease, which was less than 5 percent. A disaggregate analysis of the effect on vehicle–pedestrian crashes indicated that the CMF was smaller (the treatment was more beneficial) for higher pedestrian and vehicle volumes, particularly pedestrian volumes above 5,500 pedestrians per day. This was shown to lead to a potential B/C ratio ranging from 1:15.6 to 1:38.9.

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