INTEGRATED SIMULATION AND SAFETY-UK

FINAL REPORT

YEAR 2

SOUTHEASTERN TRANSPORTATION CENTER

N. STAMATIADIS, K. AMIRIDIS, A. KIRK

SEPETMBER 2016

US DEPARTMENT OF TRANSPORTATION GRANT DTRT13-G-UTC34

DISCLAIMER

<table>
<tr><td>1. Report No.</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Integrated Simulation and Safety: Signalized Left Turn Evaluation Year 2 (UK)</td><td>5. Report Date
Sepetember 2016</td></tr>
<tr><td>6. Source Organization Code
Budget</td></tr>
<tr><td colspan="2">7. Author(s)
Stamatiadis, Nikiforos; Amiridis, Kiriakos and Kirk, Adam</td><td>8. Source Organization Report No.
STC-2015-##-XX</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address

Southeastern Transportation Center
UT Center for Transportation Research
309 Conference Center Building
Knoxville TN 37996-4133</td><td>10. Work Unit No. (TRAIS)</td></tr>
<tr><td>11. Contract or Grant No.
DTRT13-G-UTC34</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address

US Department of Transportation
Office of the Secretary of Transportation–Research
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td>13. Type of Report and Period Covered
Final Report: May 2014-December 2015</td></tr>
<tr><td>14. Sponsoring Agency Code
USDOT/OST-R/STC</td></tr>
<tr><td colspan="3">15. Supplementary Notes:</td></tr>
<tr><td colspan="3">16. Abstract

The efficient and safe movement of traffic at signalized intersections is the primary objective of any signal phasing and timing plan. Accommodation of left turns is more critical due to the higher need for balancing operations and safety. The objective of this study is to develop models to estimate the safety impacts of the use of left-turn phasing schemes. The models are based on data from 200 intersections in urban areas in Kentucky with several hourly volume observations for each intersection. For each intersection, approaches with a left-turn lane were isolated and considered with their opposing through approach in order to examine the left-turn related crashes. The models utilize the most common variables that are already known during the design phase and can be used to determine whether a permitted or protected-only phase will suit the intersection when considering safety performance.</td></tr>
<tr><td>17. Key Words
Left-turn phasing; Signalized intersections; Highway safety</td><td colspan="2">18. Distribution Statement

Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.</td></tr>
<tr><td>19. Security Classif. (of his report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages 32   22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A fundamental objective of traffic signals is the development of signal plans that improve efficiency of operations and reduce delays while maintaining a high level of safety. One issue of concern is the treatment of left-turn phasing, which can operate as a protected movement, a permitted movement yielding to conflicting traffic, a combination protected-permitted movement or as a split-phase intersection. While protected-only movements and split phasing can improve safety, they can also increase delays and congestion at the intersection. Permitted movements can safely serve traffic when volumes are low, such as during off-peak periods, but may experience safety or capacity problems with high volumes, such as during the AM and PM rush hour. Due to the varying traffic demands throughout the day, the choice of left-turn phasing is not always clear. The lack of any nation-wide acceptable criteria or prediction models for the installation and usage of left-turn phasing generated the need for improving existing guidelines for the use of left-turn phasing. Most the current state policies prescribe the use of protected-only phasing for certain geometric configurations, such as when three or more opposing through lanes are present, when dual left-turn lanes exist, if there is insufficient sight distance for the turning vehicle and opposing traffic, or if the intersection geometrics prevent adequate sight distance due to lane configuration and offsets.

The objectives of the study are to improve existing understanding of the safety performance of signalized intersections though the use of simulation and develop models aiming to estimate the safety impacts of the use of permitted, protected, and protected-permitted left-turn phasing.

The literature review conducted here points to the wide variety of factors considered for the selection of the left-turn phase among the various agencies. There seems to be an overall agreement on the various factors to be used in determining the appropriate left-turn phase but there is little agreement on the specific values to be used. Several agencies consider left-turn volume warrants based on the constant cross product of left-turn and opposing volumes. However, there is little agreement on the numbers to be used. Many studies also indicate that there is a need to consider a wide variety of factors in addition to the cross product. One of the issues that has been identified in the early studies, and has been addressed to a certain extent more recently, is that most of the warrants were developed based minimizing intersection delay with little consideration to intersection safety and thus minimizing potential conflicts. It should be noted here that most of the warrants and guidelines developed consider only operational efficiency or safety impacts and very few consider the combined impacts of both. In general, almost all studies that develop left-turn volume warrants consistently applied the cross product as the main warrant. However, a limitation of this approach is the inability to allow for distinctions among different intersection geometric features and has not been evaluated for three or more opposing though lanes. Furthermore, additional research is needed to understand how other factors affect and interact with each other to provide a more appropriate and balanced operational and safety performance. As it was noted above, there is very little work that has successfully combined safety and operational aspects and this should be addressed in the future.

The approach undertaken at this stage of the research was the identification of historical crash data for approximately 200 intersections in order to develop safety prediction models. For each intersection, approaches with a left-turn lane were isolated and considered with their opposing through approach in order to examine the left-turn related crashes. This combination of movements is considered one of the most dangerous in terms of intersection safety. Hourly traffic volumes and crash data were used in the modeling approach along with the geometry of the intersection. The models allow for the determination of the most effective type of left-turn signalization based on the specific characteristics of an intersection approach.

Through an iterative process, a series of powers of the individual root variables were evaluated resulting in (Eq. 1) and (Eq.2) that can predict the number of crashes:

$$Number\ of\ Crashes_{Permitted-only} = e^{-4.42452+3.73640\times 10^{-7}\times \mathrm{L\_T}^{1.5}\times \mathrm{TH}\times N^{2}+\ln(6)} \qquad (1)$$

$$Number\ of\ Crashes_{Perm/Prot} = e^{-4.02186+2.20362\times10^{-7}\times L\_T^{1.5}\times TH\times N+\ln(6)} \quad (2)$$

where: L_T: Left-turn volume (vph), TH: Through volume (vph), and N: Number of opposing through lanes

These models also supports the notion that opposing and left turn volumes may have a different impact on the potential for a conflict since the left turning movements have more of an influence (higher power) than the opposing through movements when predicting Crossing conflicts. The reason for the need of differentiating between each of these volumes is their potential effects on safety, since this cannot be accounted for in a cross product. It is therefore reasonable to assume that combinations of left turn and opposing volumes resulting in the same cross product, would have a different safety performance and this was captured in the Crossing conflict model developed here though the inclusion of the independent variables and their relative impact.

Based on the models shown in Equations 1 and 2, a series of nomographs were developed to assist in left turn phase selection representing the thresholds between phase selections. Figure 1 is such an example.

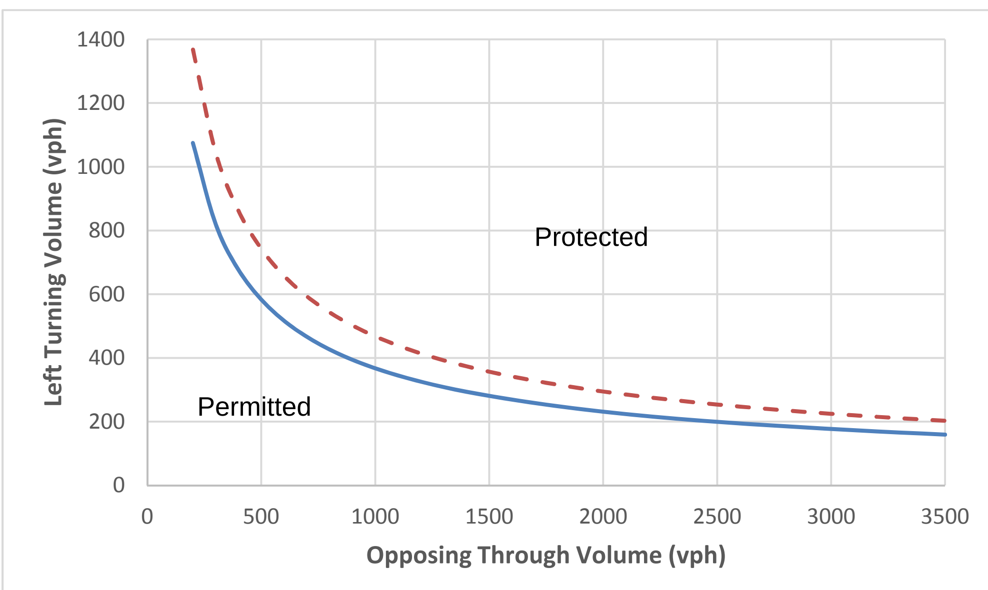

Figure 1. Left turn phasing guidance, one crash/year, one opposing lane

DESCRIPTION OF PROBLEM

A fundamental objective of traffic signals is the development of phasing and timing plans that improve efficiency of operations and reduce delays while maintaining a high level of safety. One issue of concern is the treatment of left-turn phasing, which can operate as protected-only, permitted (yielding to conflicting traffic) or a combination permitted/ protected movement. While protected-only phasing can improve safety, it can also increase delays and congestion at the intersection. Permitted movements can safely serve traffic when volumes are low, such as during off-peak periods, but may experience safety or capacity problems with high volumes, such as during the AM and PM rush hour. The recent introduction of the Flashing Yellow Arrow provides the opportunity to vary left turn phasing by time of day further complicating the selection of appropriate phasing. Current guidance has not yet evaluated the effect of hourly variations as most safety performance models focus on Average Daily Traffic Volumes, and operational models focus peak hour demand. Therefore, there is a need for improving existing guidelines for the use of left-turn phasing to provide improved selection by time of day to deliver safe and efficient operations through varying traffic demands.

Signalized intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. As an example, intersection crashes account for approximately 26 percent of all crashes in Kentucky (Kentucky State Police 2012). Left-turning maneuvers are considered as one of the most hazardous traffic movements, since turning vehicles have to cross in front of the opposing through traffic. The difficulty of completing this movement is evident in crash statistics indicating that 45 percent of all crashes that occur at intersections throughout the United States involve left-turning vehicles even though left-turning movements represent a disproportionate small percentage (10-15 percent) of all the approach traffic (Maze et al. 1994). To alleviate this problem and improve safety, protected left-turn phasing is frequently installed at traffic signals.

The issue of left-turn phasing is a two-step process. The first question is whether an exclusive left-turn phase is warranted. Major factors affecting this decision are peak hour left-turn and opposing volumes, left-turn delays, and left-turn accidents. After a decision is reached to add a left-turn phase, one of two basic phasing methods is commonly used:

1) protected-only, where the driver is allowed to turn left only during the green arrow portion of the cycle while the opposing traffic is stopped; or
2) a combination of protected and permitted left-turn phasing, where during a portion of the left-turn phase the left-turning movement is protected from opposing traffic but drivers can continue to turn left during the remaining green through phase when there are available gaps in the opposing traffic.

In addition to the factors affecting the decision for the installation of left-turn phasing, a constant trade-off between the goals of efficiency and safety is present and thus, influences the final decision.

There are no nation-wide acceptable criteria or prediction models for the installation and usage of left-turn phasing despite the fact that studies exist that have developed guidelines for the use of left-turn phasing. Most the current state policies prescribe the use of protected-only phasing for certain geometric configurations, such as when three or more opposing through lanes are present, when dual left-turn lanes exist, if there is insufficient sight distance for the turning vehicle and opposing traffic, or if the intersection geometrics prevent adequate sight distance due to lane configuration and offsets. Additionally, the common ground of the existing guidelines is the use of traffic volumes and threshold values for crashes and acceptable delays as means to make a decision. Moreover, each state has its own criteria in determining when a severe crash problem occurs and when a left-turn treatment is needed or warranted.

The potential for improving existing understanding of the safety performance of signalized intersections though the use of simulation is undeniable and has led to this study aiming to develop crash prediction models for signalized intersections estimating the impact of left-turn phasing decisions. The objective of this study is to develop models that can utilize readily available information to determine the potential safety performance of left-turn phasing schemes. This will allow for a systematic evaluation of the various schemes and provide decision-makers with a tool to evaluate options before determining the option to be used. It is expected that the findings of this research will be used to improve intersection operations and assist in creating a more appropriate left-turn phasing guidance for varying traffic demand.

LITERATURE REVIEW

This literature review briefly discusses current research findings and reviews policies of other state agencies relative to permitted left-turn guidelines. A more extended review was presented in the Year 1 Final Report of this project (Stamatiadis et al. 2016).

Guidelines

In 1979, Agent developed one of the first efforts addressing protected left-turn phasing. He proposed a set of warrants for intersections with a left-turn lane that were based on crash experience, delays, volumes, and traffic conflicts (Agent 1979). The warrants were based on a set of Kentucky intersections and state practices at the time of the research. These warrants were evaluated and augmented with guidelines for protected-permitted left turns in 1985 (Agent 1985). It should be noted that these reports introduced for the first time the cross product of peak hour left-turn and opposing through volumes to determine the need for protected phase. Agent found that a considerable increase in left-turn crashes occurred when permitted/protected phasing replaced protected-only phasing when the cross product was above 50,000 for one opposing single lane and 100,000 for two opposing lanes. In 1982, the Florida Section of the Institute of Transportation Engineers (FL-ITE) conducted a before and after crash analysis of intersections that were converted from protected-only to permitted/protected as well as those with a reverse change, i.e., from permitted/protected to protected-only (FL-ITE 1982). The study utilized this before and after crash analysis along with a survey of FL-ITE members to develop a set of guidelines for left-turn phasing selection. The guidelines developed were very similar to those developed by Agent (1985). Cottrell (1985) also developed a set of guidelines in an effort to address this issue for the Virginia DOT in 1985. These guidelines were similar to the ones developed by Agent and FL-ITE.

Several states use a combination of considerations to determine whether a left-turn phase is required. For example, Arizona (ADOT 2011) and California (CALTRANS 2002) use cross product, left-turn volume, delay of left turns, and crash history while Indiana (INDOT 2013) uses left-turn volume and delays and Virginia (VDOT 2011) uses cross product and crash history. Even though several states use similar guidelines, there is no agreement on the threshold values to be used when a left-turn phasing decision is required. For example, the use of cross product threshold value varies among the states using this criterion. In this case, Virginia uses 50,000, California 100,000, Arizona 50,000-225,000 depending on lane configuration and intersection location (urban/rural), Oregon 150,000 or 300,000 depending on the number of opposing lanes and phasing type (ODOT 2013) and Texas 130,000 or 93,000 per lane based on number of opposing lanes (Qi et al. 2008).

Stamatiadis et al. (1997) considered delays and crashes in developing guidelines and boundary conditions for selecting the appropriate left-turn phase. The study utilized micro-simulation for operational decisions and crash history for safety and developed nomographs that allow for the selection of the phase type (permitted, permitted/ protected or protected-only) based on cross product and left-turn delays or crashes. It should be noted that this was one of the first studies that developed nomographs to be used combining safety and operational criteria as well as considering the impacts of the number of opposing lanes in establishing guidelines for phase. Ozmen, Tian and Gibby (2009) developed a process that utilized a Multi-Criterion Decision Analysis in selecting appropriate left-turn phase. The approach developed considers volumes, geometry and crashes while ranking possible left-turn phasing options. Their approach provided an index-based recommendation using weights and scores resulting in a numerical scale for comparing each type of left-turn control with the others instead of an absolute type.

Safety

The safety of left-turning vehicles has been the topic of past research and few studies have resulted in developing guidelines for the installation of left-turn phasing (Agent 1979; FL-ITE 1982; Rouphail 1986; McCoy and Malone 1989; Clark and Daniel 1994; Agent, Stamatiadis and Dyer 1995). These studies use two distinct methods, empirical analysis and microsimulation.

These studies have indicated that the intersection features that affect safety and are prominent in determining the left-turn treatment include traffic volumes (opposing through, left-turning, and their product), geometry (number of opposing lanes and presence of exclusive left-turn lanes), and operational characteristics (speed limits, sight distance, and delays). Among these features, traffic volumes are more widely used by establishing upper limits for specific phasing treatment. The number of left-turn related crashes has also been used in determining the left-turn phasing (Bonneson and McCoy 1993; Stamatiadis, Agent and Bizakis 1997).

There have been a number of efforts to develop Crash Modification Factors (CMFs) in order to estimate the safety effect of left-turn phase options and changes. Hauer (2004) reviewed 14 studies conducted over a 24-year period and concluded that the CMF for converting from permitted to protected left-turn phase most likely depends on the number of opposing lanes and that most of the other evidence is insufficient and contradictory. Hauer estimated that the CMF for changing to protected only phasing from either permitted only or permitted/ protected is approximately 0.30 for left-turn crashes. However, he noted that for total crashes the CMF is 1.0, i.e., no effect. Hauer argued that a change to protected phase from a permitted/protected left-turn phasing will substantially reduce left-turn crashes but would have no difference in the total number of crashes.

Harwood et al. (2002) conducted a before-after study using the empirical Bayes (EB) approach to study the safety impact of adding left-turn lanes with protected or permitted-protected signal phasing. A total of 36 four-leg signalized intersections were included; 31 of these sites received a permitted-protected signal phasing while 5 received a protected signal phasing. The 31 sites with permitted-protected signal phasing system experienced a 9 percent reduction in crashes (CMF of 0.91); the five sites with protected signal phasing system experienced a 10 percent reduction in crashes (CMF of 0.90). The study report did not indicate if these results were statistically significant. The authors conclude that there is "essentially no effect of the type of signal phasing on the safety effectiveness of left-turn lanes", and "there are too few data to obtain definitive results".

Srinivasan et al. (2008) conducted a study to determine the safety effect of converting left-turn phasing schemes from one type to another. Their study considered changes to protected only phasing from either permitted only or permitted/protected. Their findings were very similar to those noted by Hauer (2004). The study indicated that the lack of overall crash reduction from such phase changes could be attributed to potential increase of rear end crashes. However, the authors indicate that the overall effect could be positive if one considers potential differences in severity between left-turn and rear end crashes. Even though their study examined conversions from permitted to permitted/protected phasing, there were no recommendations because the sample was very small.

In a more recent effort, Srinivasan et al. (2012) attempted to develop a CMF for left-turn phasing conversions based on a large number of intersections in North Carolina and Toronto. The study considered intersections that converted from permitted to permitted/protected and used an Empirical Bayesian approach to estimate the CMFs from such change. Safety Performance Functions (SPFs) were estimated for crash severity (injury), total number of crashes and crash type (left turn, rear end and left turn with opposing through). The study showed that target crashes, i.e., left-turn related, improve with the change and when more than one approaches is treated with the change, there is an overall crash reduction. However, the total number of crashes increases with the change and this could be attributed to the increase in rear end crashes.

Cottrell (1985) determined that safety is not affected by use of protected/permitted phasing at intersections with speed limits of 45 mph or higher. This finding could have an impact on determining the left-turn phase option. In most guidelines, the use of protected only phase is recommended for approaches with speeds greater than 45 mph. The current CMFs do not provide any distinction based on approach speeds and it is important to review this guideline in order to determine whether it is still valid.

The studies reviewed here show a general trend in decreased left-turn crashes with protected left-turn phasing. However, they do not provide the guidance necessary to identify crash performance as a function of other operational parameters and thus provide guidance as to when protected phasing should be selected. In order to develop such guidance, crash analysis must be approached differently identifying crash modification functions to determine the rate of reduction as a function of operational parameters or through direct analysis of the safety performance function to identify when predicted crashes increase to an unacceptable level.

Summary

The literature review conducted here points to the wide variety of factors considered for the selection of the left-turn phase among the various agencies. There seems to be an overall agreement on the various factors to be used in determining the appropriate left-turn phase but there is little agreement on the specific values to be used.

Several agencies consider left-turn volume warrants based on the constant cross product of left-turn and opposing volumes. However, there is little agreement on the numbers to be used showing a variety between 50,000 to 225,000 as the cross product to be considered when evaluating the shift from permitted to protected phasing. Many studies also indicate that there is a need to consider a wide variety of factors in addition to the cross product. Several studies have indicated the need of considering intersection geometry. One of the issues that has been identified in the early studies, and has been addressed to a certain extent more recently, is that most of the warrants were developed based minimizing intersection delay with little consideration to intersection safety and thus minimizing potential conflicts.

Most warrants that consider intersection safety have been developed utilizing historical data of converted intersections. The major analysis in several of these studies focused on the development of a benefit and cost analysis based on before-and-after study. However, such an approach may be difficult to be implemented, since it requires knowledge of both crash history and intersection delays for both before and after periods in order to estimate the benefits and costs accurately. It should be noted here that most of the warrants and guidelines developed consider only operational efficiency or safety impacts and very few consider the combined impacts of both.

The studies reviewed here show a general trend in decreased left-turn crashes with protected-only left-turn phasing. However, they do not provide the guidance necessary to identify crash performance as a function of other operational parameters, nor do they provide the resolution to select left turn treatments based on hourly variations in turn volume and directionality to assist in the development of time of day signal phasing. In order to develop such guidance, crash analysis must be approached differently identifying crash modification functions to determine the rate of reduction as a function of operational parameters or through direct analysis of the safety performance function to identify when predicted crashes increase to an unacceptable level.

In general, almost all studies that develop left-turn volume warrants consistently applied the cross product as the main warrant. However, a limitation of this approach is the inability to allow for distinctions among different intersection geometric features and has not been evaluated for three or more opposing though lanes. Furthermore, additional research is needed to understand how other factors affect and interact with each other to provide a more appropriate and balanced operational and safety performance. As it was noted above, there is very little work that has successfully combined safety and operational aspects and this should be addressed in the future.

APPROACH AND METHODOLOGY

In order to address the need for detailed left-turn volume in left-turn phasing selection, this research set to develop hourly left turn crash prediction models based on data typically available during signal retiming projects. This included intersection geometry and hourly turning movement counts at the intersection. Crash data was then disaggregated by hour to develop unique data points of geometry, volume, and crashes for each observed hour. Based on this dataset explanatory statistical models were developed to allow understanding of the influence of recorded factors so that necessary guidance could be developed.

Database Development

Hourly traffic volumes were obtained for a total of 200 signalized intersections mainly in the areas of Lexington and Louisville, Kentucky. Counts ranged from 2-hour AM and PM peak hour counts to full 12- or 24-hour turning movement counts collected by each agency. The type of left-turn phasing scheme, i.e., permitted, protected or permitted/protected, was identified based on the type of signal installation at the intersection. For each intersection, the geometry was collected identifying the number of lanes and the use (i.e., left, through and right or combinations) of each lane by approach. The information regarding the type of phasing scheme and intersection geometry was derived through observation from Google Earth. These two data types allow for the examination of the potential contribution of geometry and phasing scheme on the intersection crashes.

The crash history of each intersection was obtained for the 6-year period, 2010-2015, through the "Kentucky Collision Analysis for the Public" based on specific filters (KYOPS 2016). Each crash was evaluated to determine whether it was left-turn related with opposing traffic based on the crash type and directions of the vehicles involved. This was achieved by selecting the pre-collision vehicle action code as either going straight ahead or turning left and the crash type as angle collision (one vehicle turning left), rear end (one vehicle turning left), or opposing left turn. This process identified only the pertinent crashes that could be related to left-turn phasing and eliminate all others that could create noise in the dataset. For each crash, the directions of the vehicles were recorded afterwards in order to determine the left turn and opposing through combination of approaches to be used in the analysis. In general, four potential crash types were identified at an intersection relating to each of the four approaches.

1. Left turn from North with opposing through from South
2. Left turn from East with opposing through from West
3. Left turn from South with opposing through from North
4. Left turn from West with opposing through from East

The next step in the crash database development was the examination of the time the crash occurred in order to "join" them with the available hourly volumes and to ensure that the crash occurred within the specific time period provided. This process resulted in utilizing 756 crashes in 7,677 approach combinations. Among these 7,677 approach combinations, there were 3,111 with a permitted phase, 2,441 with a permitted/protected, and 2,125 with protected-only.

In order to relate the crashes with their corresponding intersections, the "Spatial Join" command was applied by using the ArcGIS software. More specifically, a 300ft buffer was created in each intersection, indicating that each crash contained in that buffer is related to that specific intersection. The results of this procedure for a sample intersection in the city of Louisville are presented in Figure 1.

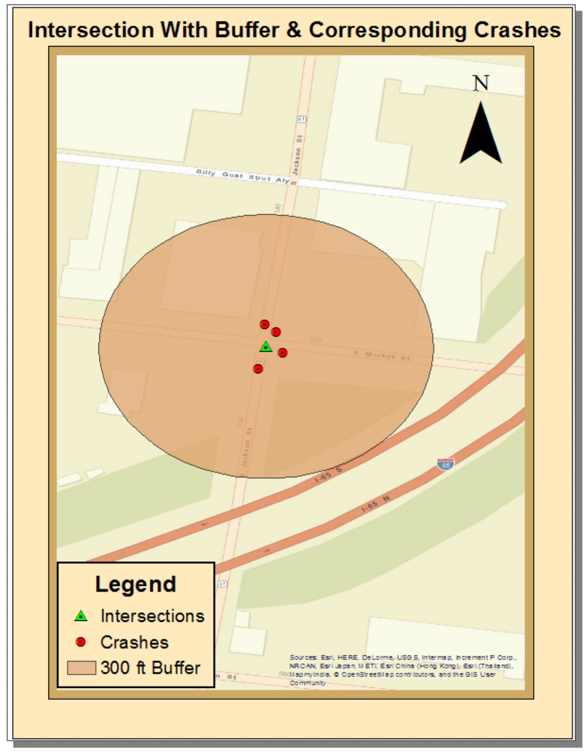

FIGURE 1 Sample intersection showing the 300 ft buffer and corresponding crashes

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

The next step involved the development of models and the identification of predictor variables that could be used in predicting the number of crashes over the 6-year period.

The first efforts in the process focused on identifying variables that could be used in the models. Table 1 shows the range of values for each of the variables available in the database. Some of the left-turn volumes are very small and this is due to traffic counts conducted in early morning hours (e.g. 2:00-5:00 am).

TABLE 1 Data Range Values

Variable	Minimum	Maximum	Mean
Left-turn volume (vph)	1	850	75
Through volume (vph)	1	2364	338
Number of opposing through lanes	1	4	1.518
Number of crashes	0	6	0.098

The presence of a large number of records with no crashes (Table 1) could require the use of the Zero Inflated Poisson (ZIP) or the Zero Inflated Negative Binomial (ZINB). However, zero inflated models should be utilized when there is an excess of zeros, not simply because there are many zeros in the dataset, but because the structure of the dataset itself produces them. For example, if there were zero left or through volumes, then it could be reasonably argued that there is no chance of having a crash simply because there are no vehicles present during that specific time period in that specific intersection approach. In that case these would be "structure zeros" that would produce excess zeros and therefore a zero inflated model would be recommended.

In order to determine the number of opposing through lanes, all lanes that serve movements (i.e., through and right turns) in conflict with the left turn were included. Most of the approach combinations had a single opposing though-related lane (53.2 percent) or two lanes

(42.0 percent). There was a small number of approach combinations with three lanes (4.6 percent) and a few with four lanes (0.2 percent).

Most of the approach combinations (91.6 percent) had no crashes within the respective hourly time period. Only 7.2 percent of the combinations had one crash there were a few approaches with more than one crash accounting for 1.2 percent of the total.

The first test to be conducted is to determine whether there is a statistically significant difference in proportions between the three phasing types. The Chi-square test is utilized here to test for this and it was performed in SPSS. The assumptions of a Chi-square test, i.e. sample size and independence, are met. In order to obtain statistically significant results in the 95% confidence interval, the absolute value of the standardized residuals must be larger than 1.96. The residuals obtained here are 2.7, 4.9, and 2.0 for the permitted, permitted/protected, and protected-only left-turn phase schemes, respectively. The results indicate that that there is a statistically significant difference between the three types of left-turn phase types. Roughly speaking, this means that the probability of a crash occurrence depends on the specific type of left-turn phasing. Therefore, the separation of the crashes based on the type of the left-turn phasing scheme is meaningful and separate models for each phase type will be developed. The next step is to examine the probability distribution that will be utilized for this specific dataset.

The dependent variable (number of crashes) corresponds to count data and therefore the most common distributions that are utilized are the Poisson distribution and the Negative Binomial Distribution which are both generalized linear models (GLM) and the log link function will be applied in both cases.

Initially, the fit of the Poisson distribution will be tested in SPSS through the One-Sample Kolmogorov-Smirnov Non-Parametric Test. The null hypothesis in this case is that it does not follow the Poisson distribution. After conducting the test, the p-values are 1.000, 0.798, and 0.882 for the permitted, permitted/protected, and protected-only left-turn phase schemes, respectively. These values indicate that all are over the significance level of 0.05 and thus the null hypothesis cannot be rejected or that there is not enough evidence to conclude that the data do not follow a Poisson distribution. Although it is not correct in statistical terms to state that the alternative hypothesis is accepted, in this case for the sake of simplicity, it can be concluded that all three datasets that correspond to the crash counts for the permitted, permitted/protected, and protected-only left-turn phase schemes, follow a Poisson distribution.

Theoretically, in a perfect Poisson distribution, the variance is equal to the mean. However, in a real dataset, this is highly unlikely to be the case; the important question is how much they differ. Depending on the measure of this difference as well as its sign (positive or negative), other distributions or techniques may be more appropriate to consider. If the variance is larger than the mean, then the dataset is characterized as overdispersed, whereas if the variance is less than the mean then the dataset is characterized as underdispersed. It is noted that overdispersion often appears when there is a large number of zeros in the dataset; this is the norm when the dataset corresponds to crash data counts as in this case. However, another distribution, the negative binomial distribution, can take into account the overdispersion in a dataset since it has an additional parameter (dispersion parameter) that is used to model the variance. In other words, an alternative strategy of modeling overdispersed data that follow a Poisson distribution is the negative binomial distribution. The mean and variance for each of the three types of phasing schemes are presented in Table 2.

TABLE 2 Mean and Variance Comparison for Each Type of Left-Turn Phasing Scheme

Type of Left-Turn Phase Scheme	Mean (1)	Variance (2)	Difference (2)-(1)	Difference %
Permitted	0.077	0.090	0.013	16.9%
Permitted/Protected	0.134	0.176	0.042	31.3%
Protected-only	0.088	0.122	0.034	38.6%

The data in Table 2 shows that for all three left-turn phasing schemes the dataset is overdispersed. Therefore, the Negative Binomial distribution fits the data and the recommended models will be assumed to follow a negative binomial distribution. However, the goodness of fit will be checked numerically in each case before finalizing the negative binomial distribution as it is compared to the Poisson distribution. The two distributions will be compared based on three numerical values: deviance AIC (Akaike's Information Criterion) and BIC (Bayesian Information Criterion). It is noted that lower values are better.

The most common distributions that are used in crash analyses are the Poisson and Negative Binomial. Throughout the crash analysis literature, these two discrete distributions are typically used in order to model the number (i.e., counts) of crashes, whereas the statistical power or goodness of fit of the regression models is typically expressed by the deviance. Moreover, the R-squared statistic does not extend generally to the Poisson or Negative Binomial regression or count data. An alternative measure of goodness of fit for count data besides the deviance is the pseudo R-squared measures. However, these R-squared measures (there are several approaches such as the Efron's, McFadden's, Cox & Snell's, Nagelkerke/Cragg & Uhler's, and McKelvey & Zavoina's among others) are rarely utilized or reported in empirical studies since it is not a common practice. Surprisingly, the pseudo R-squared residuals are not even offered in most statistical packages such as SPSS or SAS. In summary, when the dataset refers to count data and especially to crash data which are typically overdispersed due to the large number of zeros, the most common practice is to apply a negative binomial regression and finalize the optimal predictor combination through an experimental design process by checking the deviance, AIC, and BIC and also assuring that the predictors and dependent variable are statistically significant at the desired significance level (i.e., 5%).

An initial negative binomial regression model utilized the left and opposing through volumes and the number of opposing lanes and the phasing type as significant predictors. An experimental design process was conducted in order to achieve better statistical models in terms of deviance, AIC, and BIC. Through this process, it was determined that a variable combining the significant variables may be more appropriate for the model.

The first effort used the left-turn volume (L_T) and the corresponding opposing volume (TH). The model used the cross product of these variables and the phasing type was also included as a factor. It should be noted here that separate models are determined for each left-turn phasing scheme as it was determine before. Stamatiadis et al. (2016a, 2016b) in prior research had indicated that there is a difference in significance for conflict contribution between the left turn and its associated opposing through volume. The same research also indicated that the effect of the number of lanes is multiplicative and therefore a new analysis was undertaken to determine the possibility of a model where the left and opposing through volumes were used in conjunction with the number of lanes. In a similar manner various exponents were used to determine the best fit based on the deviance and the AIC score.

Separate models were developed for the permitted and permitted/protected phase types in order to determine a model that could best describe each type. This would also allow for developing decision models where the phasing type could be determined. Two models were selected based on the phase type after multiple trials mainly focused on the values of the exponential values, and are shown in Equations 1 and 2. Equation 1 corresponds to the crash prediction model for the permitted-only left-turn phasing, whereas Equation 2 corresponds to the crash prediction model for the permitted/protected left-turn phasing. It is worth mentioning that models corresponding to the protected-only phase have also been developed, but mainly for the sake of completeness and statistical evaluation. In other words, the protected-only regression line has no practical use in the warrant or nomograph development for the decision-making of the left-turn phasing type. The permitted/protected phase is actually the criterion for the establishment of the protected-only phase; if the left and through volume combination is above the permitted/protected regression line, then the specific intersection approach should automatically be operated by a protected-only left-turn phase.

At this point it also has to be noted that the crash data correspond to a 6-year period and this should be accounted for in the Negative Binomial Regression model. This is achieved by utilizing the offset variable, in the regression model, which actually normalizes the number of crashes, through a time rate, to a one-year period. The one-year period approach is desirable in order for the results to be more comparable to other existing or future studies and more flexible in terms of suggesting warrants or policies in general.

$$Number\ of\ Crashes_{Permitted-only} = e^{-4.42452+3.73640\times10^{-7}\times \mathrm{L\_T}^{1.5}\times \mathrm{TH}\times N^2+\ln(6)} \quad (1)$$

$$Number\ of\ Crashes_{Perm/Prot} = e^{-4.02186+2.20362\times10^{-7}\times \mathrm{L\_T}^{1.5}\times \mathrm{TH}\times N+\ln(6)} \quad (2)$$

where: L_T: Left-turn volume (vph), TH: Through volume (vph), and N: Number of opposing through lanes

The recommended models are compared to the statistics of the Poisson distribution in order to verify that the negative binomial distribution, that was eventually used, was indeed a better choice in terms of statistical significance. As it was noted above, there is overdispersion in the dataset, i.e., the variance is larger than the mean. Therefore, in this case, the negative binomial distribution is recommended instead of the Poisson distribution which assumes that the variance and mean are equal. Hence, it is expected that the negative binomial distribution, which was finally used, will produce better statistical results. However, the values from the Poisson distribution are also considered for the sake of completeness and verification purposes that prove that the applied statistical analysis is based on a concrete data interpretation. These values are presented in Table 3 for each type of left-turn phasing scheme. The data in Table 3 clearly indicate that the Negative Binomial distribution offers better statistical results in terms of goodness of fit when it is compared to the Poisson distribution. The model is more appropriate when lower values are observed in this comparison. In other words, the lower these statistics are, the closer the model's predictions are to the observed outcomes.

TABLE 3 Best Fit comparison Between the Poisson and Negative Binomial Distribution for Left-Turn Phasing Scheme

Statistic	Distribution	Permitted	Permitted/Protected
Deviance	Poisson	0.416	0.587
	Negative Binomial	0.322	0.428
AIC	Poisson	1743.637	2014.522
	Negative Binomial	1725.701	1967.964
BIC	Poisson	1755.719	2026.117
	Negative Binomial	1743.829	1985.355

Based on the models shown in Equations 1 and 2, a series of nomographs were developed to assist in left turn phase selection representing the thresholds between phase selections. Figures 2 and 3 are examples of such graphs. These figures show a line of equality where the combination of left turn volume, opposing volume and signal phasing equate to a single crash per year for the evaluated hour based on the explanatory model. Nomographs similar to these may be used in selection of appropriate left turn phasing by identifying a crash threshold (such as 1 crash shown in the graph below). Combinations below the solid line would result in a recommended permitted phase, combinations above the dashed line result in a protected-only phase, while combinations between the two lines will result in permitted/protected phase.

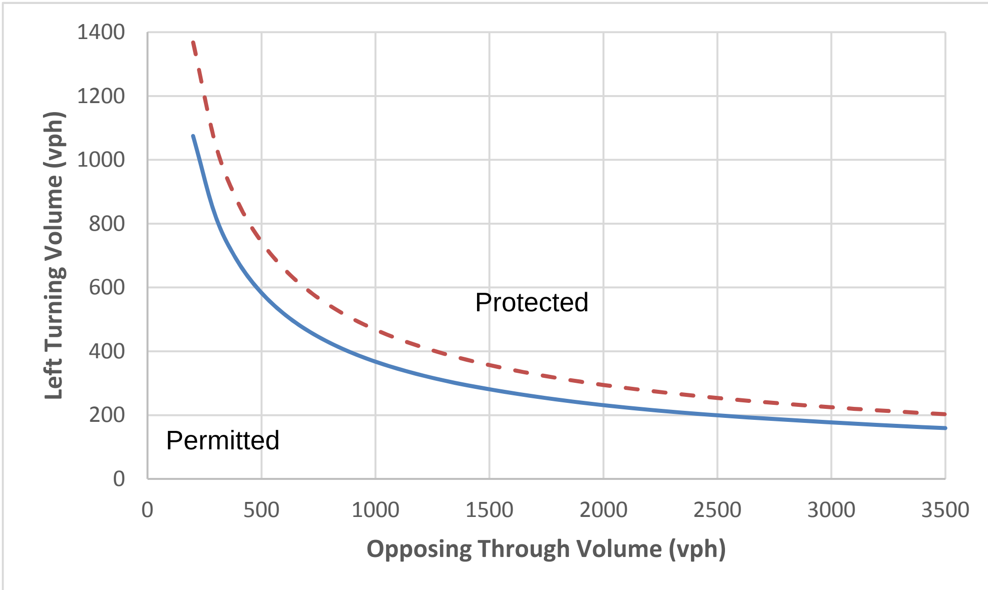

FIGURE 2 Left-turn phasing selection, one crash/year, one opposing lane

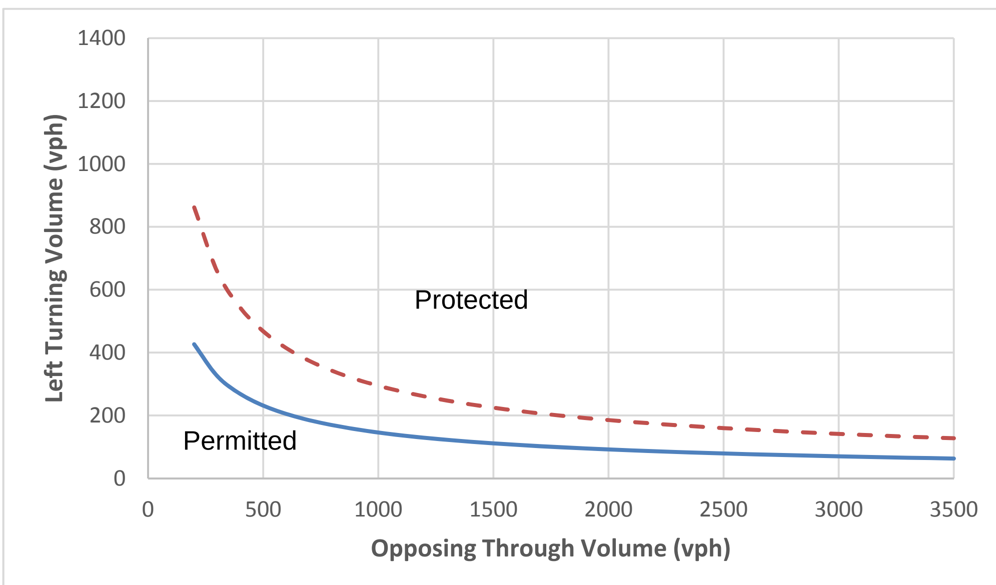

FIGURE 3 Left-turn phasing selection, one crash/year, three opposing lanes

The primary measure to control left turns, perhaps the most critical intersection movement in terms of safety, is the implementation of a variety of signal phasing schemes including permitted-only, protected-only, or a combination of permitted/protected left turns. Many state DOTs have developed warrants, or guidelines, for selecting the left turn phasing type for an intersection based on a number of explanatory factors such as the cross product between left turn movements and opposing through volumes. The purpose of this research was to create a left-turn phasing guidance at signalized intersections which determines the most appropriate left-turn phasing scheme in each case based on a combination of left and opposing volumes and the number of opposing through lanes. The number of crashes, during the 6-year period 2010-2015, was considered the dependent variable in the negative binomial regression model.

An important area of discussion is variable selection and the combination of such variables, particularly the cross product between opposing through movements and left turn maneuvers. For example, an intersection with 500 left turning vehicles and 1,000 opposing through vehicles has the same cross product as an intersection with 1,000 left turning vehicles and 500 opposing through vehicles. It is therefore reasonable to assume that each combination would have a different safety performance and this was captured in the model developed here though the inclusion of the separate values and their relative impact, i.e., left turn volume has a power of 1.5 in the model. Based on the results, it is determined that left turning movements have a higher correlated relationship with crashes than the opposing through movements.

The purpose of the research is to develop a predictive tool for left turn crashes and to be used as guidance for determining appropriate left-turn phasing based on safety. Figures 2 and 3 are references that could be used to assist in signal phasing decisions. Simply knowing the typical left turn demand, opposing through volume, and opposing number of lanes, designers are able to determine the left-turn phasing that could result in one crash per year. Based on engineering judgment, conflict thresholds would then be determined as a distinction between permissive and some form of protected phasing. These figures illustrate the differences between one and three opposing lanes indicating that a higher number of left turns can be accommodated at permitted phasing with one opposing lane than in three opposing lanes. Graphs similar to these are easily derived for any number of anticipated crashes based on agency preferences.

The findings of this study indicate that additional work is needed to improve understanding of the left-turn phasing implications. As a first step, the combination of the criteria developed here and operational efficiency nomographs need to be combined to achieve a balanced solution that could efficiently address both safety and operations. Another issue is the potential to compare these models with other surrogate safety measures, such as those produced through micro-simulation and determine the potential for utilizing these surrogate measures to understand the intersection-wide potential issues associated with left-turn phasing decisions.

REFERENCES

Agent, K.R., "An Evaluation of Permissive Left-Turn Phasing," Research Report 519, Kentucky Department of Transportation, Frankfort, KY, 1979

Agent, K.R., "Guidelines for the Use of Protected/Permissive Left-Turn Phasing," Report UKTRP-85-19, Kentucky Transportation Center, University of Kentucky, Lexington, KY, 1985

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

Arizona Department of Transportation. "ADOT Traffic Engineering Policies, Guidelines, Procedures." Phoenix, Arizona, 2011

Bonneson, J. A. and P. T. McCoy, P.T. "Evaluation of Protected/Permitted Left-Turn Traffic Signal Displays. Research Report TRP-02-27-92, Nebraska Department of Roads, Lincoln, NE, 1993

California Department of Transportation. "Traffic Manual," Sacramento, California, 2002

Clark, J. E. and Daniel, J.T. "Quantifications of the Impacts of providing Protected Left-Turns at Signalized Intersections," Report FHWA-SC-94-3. South Carolina Department of Transportation; FHWA, U.S. Department of Transportation, 1994

Cottrell, B. H. "Guidelines for Exclusive/Permissive Left-Turn Signal Phasing," Research Report VHTRC 85-R19, Virginia Highway & Transportation Research Council, Charlottesville, VA 1985

Florida Section Institute of Transportation Engineers, "Left Turn Phase Design in Florida," ITE Journal, Washington, D.C., pp 28-35, September, 1982

Harwood, D.W., Bauer, K.M., Potts, I.B., Torbic, D.J., Richard, K.R., Kohlman Rabbani, E.R., Hauer, E., and Elefteriadou, L., "Safety Effectiveness of Intersection Left- and Right-Turn Lanes", FHWA-RD-02-089, Federal Highway Administration, 2002

Hauer, E. Statistical Road Safety Modeling, Transportation Research Record 1897, pp. 81-87, Transportation Research Board, Washington, D.C., 2004.

Indiana Department of Transportation. “Design Manual,” Indianapolis, Indiana, 2013

Kentucky State Police. “Traffic Collision Facts,” KSP, Frankfort KY, 2012.

Kentucky State Police. http://crashinformationky.org/KCAP/KYOPS/SearchWizard.aspx. <May, 2016>

Maze, T.H., Henderson, J.L., and Sankar, R. “Impacts on Safety of Left-Turn Treatment at High Speed Signalized Intersections,” Iowa Highway Research Board Report Project HR-347, Iowa Transportation Center, Ames, IA, 1994

McCoy, P. T. and Malone, M.S. “Safety Effects of Left-Turn Lanes on Urban Four Lane Roadways,” Transportation Research Record 1239, Transportation Research Board, Washington, D.C., pp. 17-23, 1989

Oregon Department of Transportation “Traffic Signal Policy and Guidelines,” Salem, Oregon, 2013

Ozmen, O., Tian, Z, Gibby, R., Reed, A. “Safety of Special Time-of-Day Protected/Permitted Left-Turn Signal Control Display.” TRB 88th Annual Meeting Compendium of Papers DVD. Washington, D.C., 2009.

Rouphail, N. M. “Analytical Warrant for Separate Left-Turn Phasing,” Transportation Research Record 1069, Transportation Research Board, Washington, D.C., pp. 20-24, 1986

Srinivasan, R., Lyon, C., Persaud, B., Baek, J., Gross, F., Smith, S., and Sundstrom, C. “Crash Modification factors for Changes to Left-Turn Phasing,” Transportation Research Record 2279, Transportation Research Board, Washington, D.C., pp. 108-117, 2012

Srinivasan, R., Council, F., Lyon, C., Gross, F., Lefler, N. and Persaud, B. “Safety Effectiveness of Selected Treatments at Urban Signalized Intersections,” Transportation Research Record 2056, Transportation Research Board, Washington, D.C., pp. 70-76, 2008

Stamatiadis, N., Agent, K.R. and Bizakis, A. "Guidelines for Left-Turn Phasing Treatment, " Transportation Research Record 1605, Transportation Research Board, Washington, D.C., pp 1-7, 1997

Stamatiadis, N., Sallee, T. & Kirk, A. Conflict Analysis for Left-Turn Phasing Decisions. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, D.C., 2016

Stamatiadis, N., Kirk, A., Hedges, A. & Sallee, T. Integrated Simulation and Safety: Signalized Left Turn Evaluation (UK), Southeastern Transportation Center, Knoxville TN., 2016.

Virginia Department of Transportation. "Traffic Engineering Design Manual," Richmond, Virginia, 2011