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PREDICTION OF PROTECTED-PERMISSIVE LEFT-TURN PHASING CRASHES BASED ON CONFLICT ANALYSIS

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PREDICTION OF PROTECTED-PERMISSIVE LEFT-TURN PHASING CRASHES BASED ON CONFLICT ANALYSIS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the College of Engineering at the University of Kentucky

By

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ABSTRACT OF THESIS

PREDICTION OF PROTECTED-PERMISSIVE LEFT-TURN PHASING CRASHES BASED ON CONFLICT ANALYSIS

Left-turning maneuvers are considered to be the highest risk movements at intersections and two-thirds of the crashes associated with left-turns are reported at signalized intersections. Left-turning vehicles typically encounter conflicts from opposing through traffic. To separate conflicting movements, transportation agencies use a protected-only phase at signalized intersections where each movement is allowed to move alone. However, this could create delays and thus the concept of a protected-permissive phase has been introduced to balance safety and delays. However, the permissive part of this phasing scheme retains the safety concerns and could increase the possibility of conflicts resulting in crashes. This research developed a model that can predict the number of crashes for protected-permissive left-turn phasing, based on traffic volumes and calculated conflicts. A total of 103 intersections with permissive-protected left-turn phasing in Kentucky were simulated and their left-turn related conflicts were obtained from post processing vehicle trajectories through the Surrogate Safety Assessment Model (SSAM). Factors that could affect crash propensity were identified through the Principal Component Analysis in Negative Binomial Regression. Nomographs were developed from the models which can be used by traffic engineers in left-turn phasing decisions with enhanced safety considerations.

KEYWORDS: Left-Turn Phasing Decisions, Microsimulation, Surrogate Safety Measures, Conflict Points, Negative Binomial Regression & Principal Component Analysis

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Tuesday, November 28 2017

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In memories of my Brother,

Siddhartha Sagar

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1 INTRODUCTION

A left-turn is one of the most challenging movements a driver has to handle. It is considered as one of the highest risk traffic movements as the turning vehicles face several sources of conflict with opposing through traffic and pedestrians crossing the side street. These conflicts can lead to crashes and create safety problems. The Federal Highway Administration (FHWA) reports that around 27 percent of all intersection-related crashes in the US are associated with left-turns where two-thirds of them occur at signalized intersections [1]. To control the left-turning traffic at signalized intersections, the Manual on Uniform Traffic Control Devices (MUTCD) defines four design alternatives for the left-turn movements: permissive, protected-only, protected-permissive, and variable left-turn phasing [2].

The type of signal phasing used for a left-turn maneuver affects the safety and operational performance of the turning traffic [2]. The MUTCD and many state Departments of Transportation (DOTs) have developed warrants or guidelines for the selection of left-turn phasing type for an intersection. Several DOTs use a combination of criteria to determine the left-turn phase for a signalized intersection. These criteria include traffic volumes, number of crashes, geometric features, operational performance, and speed limits. The guidelines adopted by DOTs may vary from the MUTCD to reflect state policies. However, there are no nationally accepted criteria for the selection of left-turn phasing. FHWA reports that many states in the USA have a policy to use protected-only left-turn phasing always where the left-turn movement crosses three lanes, while other states allow the use of permissive phasing or protected-permissive phasing in those situations [2].

Usually, protected-only is considered safer than permissive left-turn phase as it provides a separate phasing for left-turning traffic avoiding all conflicting traffic. The increasing level of traffic demands an evolution of innovative means of traffic control such as protected-permissive left-turn (PPLT) phasing, which balances safety as well as operational efficiency. According to FHWA guidelines, a protected-permissive left-turn phasing may be considered at intersections that do not satisfy the phasing criteria for a protected-only phasing while satisfying one or more of the left-turn phase criteria listed for PPLT phase [2]. Generally, PPLT phase is used when the geometric conditions of the intersection allow permissive left-turn phase and the high volume demands an exclusive left-turn phase. The notable advantages of PPLT include reduced average delay per left-turn vehicles and a protected green arrow time which accommodates the left-turn movement. At the same time, the permissive phase of PPLT increases the potential for vehicle-vehicle and vehicle-pedestrian conflicts. The phasing of PPLT, therefore, makes a potentially dangerous scenario in traffic flow known as the yellow trap. In a permissive mode of PPLT, the left-turning traffic obeys the green display for the adjacent through maneuver. When the yellow is displayed for the adjacent through movement, the left-turning driver presumes the opposing through display to be yellow as well which may not always be true. The problem mainly occurs when a vehicle from a permissive left-turn phasing faces a vehicle from a lagging protected left-turn phase where the yellow signal for the left-turning driver does not reflect the signal display to the opposing through driver. This creates a very unsafe movement for the conflicting traffic. To eliminate such unsafe conflicts, different methods have been tried such as altering the signal display which allows the signal to display a permissive left-turn indication independent of the adjacent through movement. To allow this type of operation, signal displays such as flashing red arrow, flashing circular yellow and flashing yellow arrow have been introduced [2]. Also, NCHRP 3-54 [3] raised a question about the confusion PPLT creates among the drivers which can increase conflicts and possibility of crashes, and thus affect the safety of PPLT intersections. The main objective of this research is to develop a guideline in making decisions on protected-permissive left-turn phasing based on safety implications.

For years research has been conducted to study the observed conflicts between vehicles [4, 5] but a quantitative relationship between observed conflicts and crashes has not been developed. More recently, the conflict observations have been extended to vehicle movements using microsimulation models, and these calculated conflicts are recommended to be used for crash analysis and safety considerations [6, 7]. Therefore, in this research, microsimulation and associated calculated conflicts are used for the safety assessment of protected-permissive left-turn phasing.

This research determines a relationship between simulated conflicts and historical crashes of protected-permissive left-turn phasing installations, which can give an estimate of safety at such locations. Stamatiadis et al. [8] specified that many variables, including left-turn volumes, opposing through volumes, and their product can be used for safety analysis of left-turn phasing. Past research also shows that traffic volumes and the number of opposing lanes are used for predicting crashes [8, 9]. Amiridis et al. [10] in a recent work on permissive left-turn phasing intersections used simulated conflicts as another good predictor of crashes. This research develops a model for protected-permissive left-turn phasing that can predict the number of crashes, which can support the evaluation and decision of the traffic community to select safe and operationally efficient left-turn phasing options for intersections.

2 LITERATURE REVIEW

Generally, left-turn related crashes account for a high percentage of total crashes in a signalized intersection. Therefore, the safety of left-turn traffic been the hot topic of research and many resulting studies developed guidelines for the installation of left-turn phasing. Stamatiadis et. al [8] developed a guideline for left-turn phasing selection which recommends that some type of protection to be used for a left-turn phase when the product of left-turn and opposing through lane hourly volumes exceeds 50,000 and 100,000 vehicles per hour for approaches with one and two opposing through lanes, respectively. Rouphail [11] proposed an analytical warrant recommending protection of left-turn when the volume-to-capacity ratio for left-turning vehicles exceeds the volume-to-capacity ratio for through traffic.

As discussed in the previous section, there are no nationally accepted criteria for the selection of left-turn phasing. The commonly used criteria for the selection of phase include left-turn and opposite through volume, crash history, number of left-turn and opposing through lanes, speed limit of opposing lanes, sight distance, intersection geometry and pedestrian volume. Several state DOTs have their own guidelines for the selection of left-turn phase depending on the state policies. For example, the state of Arizona [12] uses three major criteria, including cross product of left-turn and opposite through lane volumes, delay and number of crashes, while Alabama [13] considers traffic volumes, sight distance and crash history.

A study conducted by Virginia Department of Transportation reviewed the guidelines of nine state DOTs on Left-Turn Phasing [14]. Among all the state policies reviewed, Maryland DOT has no formal statewide guidelines on selection of left-turn phasing. The most common safety components used for decision-making is the cross product of left-turn and opposing through lane volumes, however, the threshold values used vary from state to state. For example, the Minnesota DOT recommends a protected-only left-turn phase when the volume cross product is greater than 80,000 and 100,000 for one and two opposing through lanes, respectively. At the same time Oregon recommends a protected-only phase when the cross product of the volumes is greater than 150,000 or 300,000 depending on the number of lanes.

Warren [15] demonstrated that the choice of left-turn phase has an impact on the number of left-turn crashes observed. He examined the effect on changing protected-only left-turn phase to protected-permissive left-turn phase. The before and after comparison shows that such a change resulted in an increase in left-turn crashes. At the same time, Harwood et al. [16] conducted an Empirical Bayes analysis to evaluate the safety effects of adding left-turn lanes at three- and four-leg intersections with protected-only or protected-permissive signal phasing. They demonstrated that installing a left-turn lane at an urban four-leg signalized intersection results in a nine percent reduction of total intersection crashes when a protected-only phase was used and in a 10 percent reduction in the total intersection crashes when a protected-permissive signal phasing was used. However, the study did not mention the statistical significance of the result and they concluded that there is no effect of type signal phase on the safety of left-turn movements. In 1991, Upchurch [17] compared the average left-turn crash rates for different left-turn phasing and he observed that the crash rates reported for intersections with a permissive phasing are 2.5 times greater than those observed at intersections with protected-only phasing.

In 2014, Srinivasan et al. [18] conducted an Empirical Bayes study at 117 intersections in North Carolina to evaluate the safety effect of signalization in the presence and absence of left-turn lanes. The primary objective of the study was to develop Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) indicating the effect of introducing left-turn lanes. The left-turn lanes on the minor road were controlled by a stop sign before the signalization. Among the group of three-leg and four-leg intersections, 50 were signalized without adding left-turn lanes and major approaches of four of them had protected-permissive left-turn phasing while for the rest of the intersections permissive left-turn phasing was implemented. For the other 67 signalized intersections with at least one left-turn lane, 36 intersections had permissive phase and 30 had protected-permissive left-turn phasing. The before-after study demonstrated that the signalization in the absence of left-turn lane reduced the overall crashes, injury and fatal crashes and frontal impact crashes but increased the rear end crashes. However, introducing the left-turn lane decreased the rear end crashes and the CMF calculated to exhibit the effect due to left-turn lane is 0.412 and 0.555 for three-leg and four-leg intersections. Due to limited number of three-leg and four-leg intersections under the different categories, it was difficult to determine the safety effect of the phasing type. However, Srinivasan et al. [19] had previously shown that the change of a left-turn phase from permissive to protected-permissive reduces the left-turn related crashes by about 25 percent, but the possibility of rear-end crashes increases the number of overall intersection crashes.

The growing level of traffic demands in the United States led to extensive use of protected-permissive left-turn signal control which balances safety and operational efficiency. A survey conducted by Noyce et al. [20] shows that 29 percent of these signalized intersections in the US contain PPLT signal phasing. To minimize the left-turn related crashes, many cities in the USA upgraded the permissive left-turn signal control to protected-permissive mode, especially on those intersections where installation of protected-only phasing affects operational efficiency. In Detroit/Grand Rapids, Michigan, three intersections with a high incidence of injury crashes (mainly due to left-turn head on crashes) were treated by converting the permissive left-turn mode to protected-permissive phasing [1]. Installation of the protected-permissive left-turn mode reduced the total crashes overall by 32 percent per year [1]. The Traffic Signal Policy and Guidelines of Oregon DOT [21] recommends a threshold left-turn and opposing through volume combination for PPLT phases. The policy notes that a PPLT can be used at intersection that they do not satisfy the phasing criteria for a protected-only phasing and routinely exceed left-turn volume threshold of 200 vph or the product of left-turn and opposing through lane hourly volumes exceeds 50,000 and 100,000 for approaches with one and two opposing through lanes, respectively. It is therefore imperative that similar guidelines or tools which can be used to make decisions on PPLT phases with safety considerations should be developed.

Previous research shows that left-turn related crash history is one of the major criteria used for the safety assessment of left-turn phase decisions [22, 23]. But the crash data of an intersection reflect only the past and it lacks the information about the change in volume or nature of traffic flow. Therefore, a tool is required to show the effect of the changing traffic characteristics on road safety. According to Gettman and Head [7], microsimulation modeling is a suitable instrument which provides insight into such changes. Microsimulation is a common technique used to evaluate operational performances and safety assessments. Such studies generally use vehicle trajectories produced during the simulation for the analysis. The recommended safety indicator in these models is the conflict points, in which two vehicles approach each other and will crash if no action is taken [24]. Several past studies were conducted to analyze how the field measured conflicts are correlated with conflicts obtained from micro-simulation models using the Surrogate Safety Assessment Model (SSAM) [25-28]. SSAM is a tool developed by the FHWA that uses vehicle trajectories obtained through microsimulation to estimate the number of conflicts based on several surrogate measures of safety. SSAM supports the trajectory file format as an export option by four traffic micro-simulation models: VISSIM, AIMSUN, Paramics, and TEXAS and therefore it is recommended to be used with one of these software packages for easy grouping with SSAM.

Gettman and Head [7] in one of the FHWA-sponsored research projects investigated the potential surrogate safety measures that can be derived from traffic simulation models. The research proposed that time to collision, post encroachment time, deceleration rate, maximum speed, and speed differential are best surrogate measures [7]. In simulation models, surrogate measures are collected for each conflict, in which one vehicle take ambiguous action to avoid a collision. Also, Svensson made a plausible argument that crashes are the extreme form of serious conflicts [29]. Further, Sacchia et al. compared the collision-based evaluation results of an intersection with conflict based result and proposed that assessing conflicts is a recommendable substitute of evaluating crashes [30]. Therefore, for the safety assessment of protected-permissive intersections, it is possible to develop prediction models for crashes based on conflicts obtained from microsimulation models.

In general, studies on intersection safety and crash modeling investigate traffic, geometric and operational characteristics. Hauer [31] used crash data and approach specific traffic flow to build a model for the estimation of safety at signalized intersections. In a more recent study on intersections with a permissive left-turn phasing, approach specific traffic was used with left-turning volume and the opposing through volume considered as explanatory variables [10]. For geometric variables, the number of lanes, angle of intersection, terrain type and stopping sight distance have been used as independent variables in other studies [10, 19, 32]. Operational characteristics such as operating speed, intersection density, and phasing plan are suggested as explanatory variables in other safety assessments [32, 33]. Past research showed that cycle length and the effective green time percentage are correlated with conflicts obtained from microsimulation models [34, 35]. As mentioned above, simulated conflicts are good predictors of crashes and hence cycle length and the effective green time percentage are also considered to be an efficient predictive operational variable in crash modelling.

The cross product of left-turn traffic and opposing through movements is a common indicator used for determining left-turn phase in an intersection. However, Al-Khaisy and Stewart [36] have questioned the use of this cross product. Their study concluded that in protected-permissive left-turn phases, the opposing volume is not as significant as it is in other phases. Stamatiadis et al. [17] have also noted the potential implications of the cross product when both volumes are considered equally, since a cross product of 200 left-turns and 1,000 opposing traffic in current approaches is considered the same as 100 left-turns and 2,000 opposing vehicles. Taking this into account, this research also tries to determine the effect of left-turn and opposing through volumes on the number of crashes, whose product is generally considered to be a good predictor in left-turn related crash modelling.

Statistical models are mathematical functions which can be graphically presented as a two-dimensional diagram called nomograph. The advantage of nomographs is that they can be used as a tool to study the relationship between the variables in the model. On fixing the values of some of the variables in the model, the relationship between the other variables can be analyzed. This is a common practice when such statistical models are developed in order to facilitate their implementation and ease their use on day-to-day operations. In a safety related study, Stamatiadis et al. [8] developed guidelines for selecting appropriate left-turn phase for an intersection considering delay and crashes. The study developed a nomograph which can be used for selecting the left-turn phase type based on cross product of left and opposite through volumes and left-turn delays or crashes. This was one of the first studies that developed nomographs combining safety and operational criteria to establish guidelines for left-turn phase. 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.

The literature reviewed here shows an overall agreement on the factors that could affect left-turn related crashes and thus used as explanatory variables in modelling these crashes. The most common variables used as predictors of crashes are the number of opposing lanes and traffic volumes of the approaches and most research efforts are based on these variables. Most warrants that consider intersection safety have been developed utilizing historical data of converted intersections. As such, this requires long waiting periods for historical crash data collection and thus traffic conflicts could provide an alternative. Methodologically, this study utilizes the VISSIM microscopic traffic simulation tool and SSAM to determine the number of traffic conflicts and use them as a surrogate in order to examine the safety implications and develop a crash prediction model for the protected-permissive intersections. The SSAM is used to study vehicle trajectories derived from VISSIM to determine the number of conflict points.

3 METHODOLOGY

3.1 Data

The geometric and traffic details of 200 intersections in Kentucky were collected from a Kentucky Transportation Cabinet (KYTC) database which includes traffic counts of turning movements ranging from 2-hour AM and PM peak hour counts to 24-hours [37]. The information regarding the number of lanes and traffic volumes of each lane in every approach of the intersection was also included in the dataset. The crash history of each intersection was collected for 6 years (2010-2015) through the Kentucky State Police database, and the crashes related to left-turn and opposing through combination were identified for the analysis [38]. The type of left-turn phasing design was identified for each intersection based on the signal type installed. This research focuses on the protected-permissive left-turns, and therefore the information of PPLT intersections was filtered from the dataset of a total of 200. Hence the study used information of 103 intersections with a total of 2,441 protected-permissive phase approach combinations.

In the dataset, some of the hourly volumes of left and opposite through lanes are very low (e.g., one or two vehicles) and this is due to traffic counts conducted in early morning hours. Most of the approach combinations had a single opposing through lane (47 percent) or two opposing through-related lanes (52 percent). The approach combinations with three opposing through lanes were less than one percent which can be a potential noise in the modeling. Therefore, the approach combinations with three opposite through-related lanes were excluded from the data used in the final modeling.

There was a total of 397 crashes for all approach combinations with protected-permissive left-turns in the database. Most of the approach combinations had no crashes (87 percent) respective to the hourly period, only 11 percent of the combinations had one crash and the remaining two percent of the approach combinations had more than one crash reported.

3.2 Microsimulation and Conflict Analysis

The intersections used for the study were modeled using the microsimulation software, PTV VISSIM [39, 40]. The simulation for each hour of the day was completed for each intersection leaving an initial seed time of 900 seconds. For each simulation run, a trajectory file was created in which all traffic movements were recorded. These trajectory files are fed into SSAM to identify conflict events and their types. For each trajectory file loaded, SSAM calculates several surrogate safety measures such as minimum time-to-collision, type of event (lane-change, rear end or path crossing), and minimum post-encroachment. In this research, the default thresholds in SSAM were used for the conflict analysis. The maximum time-to-collision is 1.5 seconds and the maximum post-encroachment time is 5.0 seconds. The primary SSAM output used for the analysis is a table of all conflicts identified consisting of file name, time, location, type of conflict and several other measures of conflict severity. Another SSAM feature used in the analysis was a summary of conflict counts by type and file, with average values of surrogate measures and overall conflicts [41].

In modeling the intersection in VISSIM, link function was used to create lanes for each approach and all the maneuvers were created using connectors. Each link and connector thus created has a unique attribute number called link number or connector number. On performing the simulation process, trajectory files are generated which record the movement of vehicles. As mentioned above, these files are fed into SSAM to identify conflict events and their types. The SSAM output file derived from the VISSIM trajectory files addresses the conflict points based on the unique attribute number which identifies the movement of the vehicle. For example, Figure 1 shows the VISSIM model of an intersection, identified to be a protected-permissive intersection on KY 876.

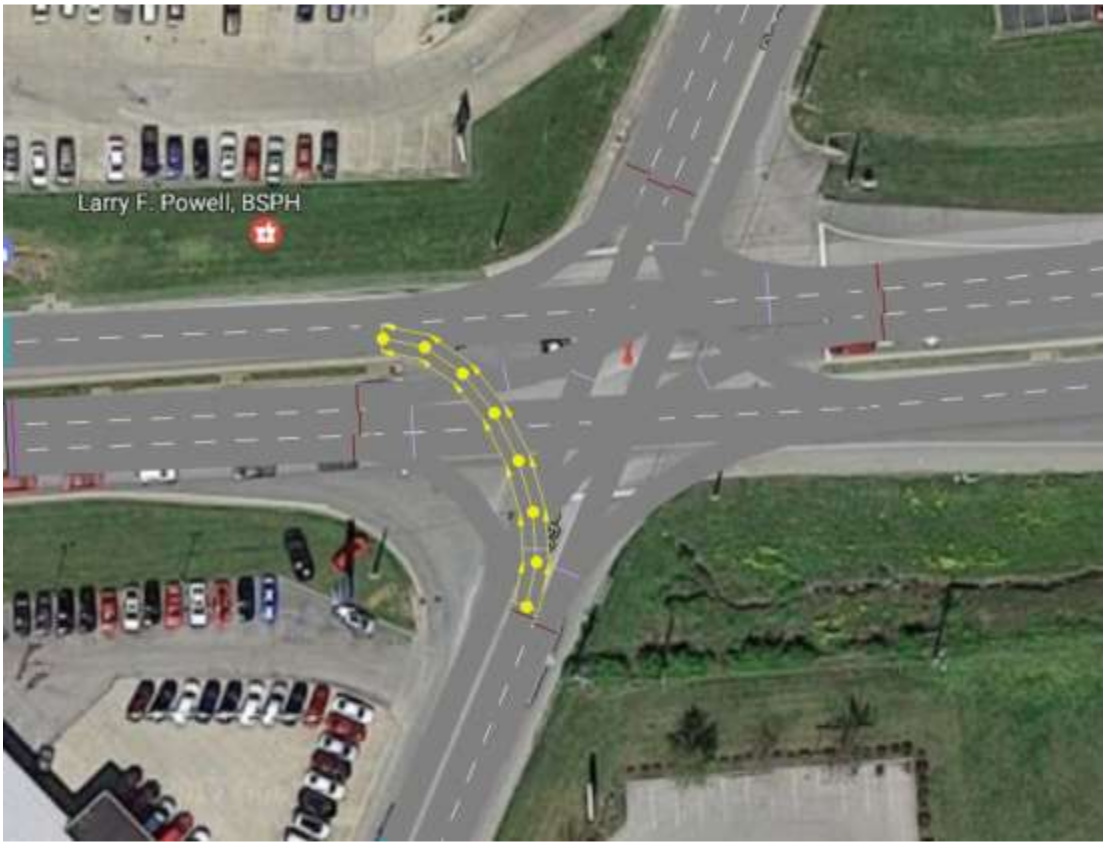

Figure 1: VISSIM model of Intersection #30

The connector shown in Figure 1 facilitates northbound left-turn and the unique attribute number for the connector is identified to be 10008. Similarly, the attribute numbers of all the left-turn and through maneuvers were identified for each intersection. Table 1 gives the attribute number of left-turn and through movement for all directions in Intersection #30.

Table 1 – Unique Attribute Number of Left-turn and Through Movement at Intersection #30

Direction	Unique Attribute Number	
	Left-turn movement	Through movement
North Bound	10008	10009
South Bound	10005	10006
East Bound	10001	10000
West Bound	10002	10003

The main interest of this research are the characteristics of left-turn and through movement of vehicles at an intersection. Therefore, the unique attribute number of left-turn and opposite through combinations were identified. From the above example, the connector number of North left and South through maneuver combination was identified to be (10005, 10009). Similarly, the combination of a unique identification number for all the four approaches was identified for all the intersections in the database. These combinations were matched with the SSAM output to identify the associated conflict points.

3.3 Variables Used

The research aims at developing a model predicting crashes of intersections with protected-permissive left-turn phase, and the number of crashes is the response variable. As noted above, past research shows that traffic counts of left-turn and opposite through, number of opposite through lanes, and number of conflicts points per combination can be chosen as explanatory variables in crash data modeling. The descriptive statistics of these variables are shown in Table 2.

Table 2 – Descriptive Statistics of Variables

Variable	Minimum	Maximum	Mean	Standard Deviation
Number of Opposite through lanes	1	2	1.47	0.50
Left-turn lane volume	1	496	83.75	80.24
Opposite Through lane volume	1	1382	33.15	351.74
Conflict points	0	133	7.02	15.41

Generally, in regression modeling, interaction terms are added to develop a better understanding of relationships among the variables thus permitting more hypotheses to be tested. Interaction variables are used in modeling when the effect of one independent variable on the dependent variable is not expected to be the same at all levels of the other independent variable. The interaction is generally introduced into the analysis by crossing two (or more) independent variables so that there are observations at every level of the two independent variables. As mentioned above, past research shows that product of left-turn and opposite through volume is a recommended interaction variable to be used for safety analysis of left-turn phasing. Amiridis et al. [10] in a study on permissive intersections, analyzed the interaction between several variables affecting crash occurrence. They demonstrated that a model with the two-way interaction term between left and opposite through volume has the lowest Bayesian Information Criterion (BIC), which is a measure of the quality of the model. Following the literature reviewed here, the cross product of left-turn and opposite through volume was included in the final model.

4 STATISTICAL ANALYSIS

For safety analysis, Poisson or Negative Binomial regression models are generally used. The Poisson distribution is a special case of the Negative Binomial Distribution that is used when the data shows less variability from the mean. The major assumptions for the application of Negative Binomial Distribution in a dataset are based on the mean and variance. Unlike Poisson distribution, the Negative Binomial Distribution has an additional parameter that adjusts the variance independently from the mean. In the database developed for this research, the range of the response variable (i.e., the number of crashes) varies from 0 to 19 with around 47 percent of the values being zero. The data of the number of crashes look over-dispersed with a mean of 1.26 and variance of 4.50. Therefore, for the statistical modeling of the Kentucky data, Negative Binomial Regression is preferred over Poisson regression. As noted above, the explanatory variables chosen by the previous studies were the number of vehicles turning left (vph), number of vehicles from the opposing through approach (vph), number of opposing through lanes, and the number of conflict points per approach combination per hour.

A Negative Binomial Distribution refers to a Generalized Linear Model (GLM), whose focus is on estimating the model parameters. The major assumptions of GLMs are: the data are independently distributed, the dependent variable assumes to have distribution from an exponential family, errors are independent and the model has an acceptable measure of Goodness of Fit [42]. The Goodness of Fit is checked for the final model to establish whether the assumption of Negative Binomial Distribution is satisfied.

An ordinary Negative Binomial Regression was conducted for the chosen explanatory variables to develop a model for the dependent (response) variable, i.e., the number of crashes. In this initial effort, the predictor variables failed to indicate statistical significance with the dependent variable which is potentially due to the multicollinearity or dependence among the variables. One of the common multivariate analysis methods used in cases where the variables are inter-correlated is the Principal Component Analysis (PCA). This technique removes the correlation among the independent variables that are to be used in the regression analysis. The IBM SPSS Statistics is used for the statistical analysis process [43, 44].

4.1 Principal Component Analysis

Principal Component Analysis is a statistical technique used to examine the interrelations among a set of variables to identify the underlying structure of those variables. It is a non-parametric analysis independent of any hypothesis about the data distribution [10, 45, 46]. It is also a common method used for explanatory data analysis and developing predictive models. To conduct regression analysis using the PCA technique, the data of the explanatory variables should be scaled such that all the variables have zero mean and unit variance. This process is known as standardizing or z-scoring. There are few assumptions made before using the PCA techniques and they were checked for the dataset using the software tool SPSS.

1. There are multiple explanatory variables used for the analysis which are continuous or ordinal in nature.
   There are four explanatory variables and one interaction term that will be analyzed in the model and these variables are continuous in nature.
2. There is an appropriate correlation between the variables.
   A correlation matrix was generated for all the variables in SPSS to check the clustering between the group of variables. The correlation coefficients for many of the variables were above 0.3 which shows a good sign of clustering [44, 46].
3. The overall dataset has acceptable sampling adequacy.
   The common method used to detect the sampling adequacy is the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy, which ranges from 0.5 to 1. The dataset gives a KMO test value of 0.5 which is considered to be an average level of sampling adequacy. However, a value greater than 0.5 is acceptable [47].
4. The overall dataset is suitable for data reduction.
   To carry out a PCA approach, the variables should have an adequate correlation between each other for them to be reduced to a smaller number of components. The method used by SPSS Statistics to detect this is Bartlett's test of sphericity. The test gives an approximate chi-square score of 512 with a degree of freedom 10

and therefore the p-value is observed to be <0.00001(i.e., the result is significant at $p < \alpha = 0.05$).

In Principal Component Analysis, the information from the variables which are possibly correlated is expressed as a set of new orthogonal variables called principal components (PC). The main goal of PCA is to eliminate multicollinearity by reducing the number of explanatory variables and therefore, the number of principal components can be less than or equal to the number of explanatory variables used for the modeling. The researcher will be able to decide how many PCs should be retained for the modeling. To make choices on PCs, Scree Plots can be used which graph the component number against the eigen values in the decreasing order and the PCs with larger eigen values are generally chosen. Another approach is to retain the PCs with eigen values greater than one [48]. Following the most common practice, this research produced all potential PCs and then considered the summation of them all as a single explanatory variable. As noted, the explanatory variables included in the final model, are:

V_L: Number of Vehicles Turning Left (vph)
V_T: Number of Vehicles from Opposing Through Approach (vph)
N: Number of Opposing Through Lanes
C: Number of Conflicts

As discussed in the previous section, the left-turn and opposite through volume have shown to have an influence on the number of crashes and generally their cross product is used as an indicator for determining phase selection. An investigation of the potential relative influence of each volume on the cross product was undertaken but the results obtained did not produce any improvement to the model and hence, the interaction term $V_L V_T$ (denoted as I) was included in the model directly.

The PCs of all the five prediction variables are summed up together to SUM PC which is the final independent variable entered in the regression model. Equation 1 shows the final explanatory variable entered in the model. Table 3 list the coefficients of the standardized variables in each principal component.

$$\text{SUM PC} = \text{PC}_1 + \text{PC}_2 + \text{PC}_3 + \text{PC}_4 + \text{PC}_5 \quad (1)$$

Table 3 – Coefficients of Principal Components (PCs)

Variable	Principal Component				
	1	2	3	4	5
Zscore(N)	-0.02	-0.06	1.14	-0.31	-0.08
Zscore(V_L)	1.12	-0.02	-0.02	0.27	-0.50
Zscore(V_T)	0.18	-0.13	-0.24	1.47	-0.64
Zscore(I)	-0.29	-0.17	-0.08	-0.51	1.61
Zscore(C)	-0.02	1.12	-0.06	-0.16	-0.24

For example, the linear combination of PC_1 is:

$$PC_1 = -0.02 \cdot Z(N) + 1.12 \cdot Z(V_L) + 0.18 \cdot Z(V_T) - 0.29 \cdot Z(I) - 0.02 \cdot Z(C) \quad (2)$$

The five PCs are combined together to develop the SUM PC as shown in Equation 3.

$$\text{SUM PC} = 0.65 \cdot Z(N) + 0.84 \cdot Z(V_L) + 0.64 \cdot Z(V_T) + 0.56 \cdot Z(I) + 0.64 \cdot Z(C) \quad (3)$$

The model developed using the SUM PC is statistically significant, but it does not imply that the five explanatory variables chosen are statistically significant as well. The combination of the variables is proven to be statistically significant but if taken individually they may not be significant. The final step of the PCA approach is to inverse standardize the formula of SUM PC into the original explanatory variable. After a series of mathematical manipulations, SUM PC took its final form shown in Equation 4.

$$\text{SUM PC} = -4.07 + 1.30 \cdot N + 0.01 \cdot V_L + 0.0018 \cdot V_T + 0.00001 \cdot V_L V_T + 0.04C \quad (4)$$

4.2 Regression Model

The final negative binomial model developed through the PCA approach has a p-value 0.046 for the intercept and a p-value of <0.0001 for SUM PC. The final model predicting the number of crashes is shown in Equation 5.

No of crashes = 0.169 + 0.153 SUM PC (5)

This study used a 6-year crash database. Therefore, an offset variable was included in the modeling which converts the data to indicate number of crashes per year. To develop the final model predicting the number of crashes per year Equation 4 and Equation 5 are combined. The final predictive regression model takes the form shown in Equation 6. All the coefficients of the variables in the final model are positive which indicates that there is a positive relationship between crashes and volumes, conflicts and number of lanes.

$$\text{Number of Crashes} = -0.50 + 0.19 \cdot N + 0.001 \cdot V_L + 0.0003 \cdot V_T + 0.000002 \cdot V_L V_T + 0.006C \qquad (6)$$

The value of Pearson's Chi-Square for the model was 392 for a degree of freedom of 310 which gives a p-value of 0.001. The Chi-Square test gives a p-value less than the level of significance (α = 0.05). This shows that there is no evidence that the residuals do not follow a negative binomial distribution.

5 APPLICATION

The model developed in this research can be used for making decisions about left-turn phasing at signalized intersections. Also, traffic engineers can simulate the concerned protected-permissive intersection to identify the number of possible conflicts and use the model to predict the number of crashes. This value can be used to analyze the safety of the intersection and take appropriate measures of improvement if required. Nomographs can be created using the model which can be used as a tool to decide whether a protected-permissive phase is adequate, or if some protection may be needed. Users can develop similar nomographs utilizing the model based on the acceptable number of crashes per intersection per approach per year and also the characteristics of the intersection approach.

Figure 2 shows an example nomograph developed from the model. The crash data used for the modeling is for six years and for the development of the nomograph number of crashes is assumed to be one over the study period, i.e., 0.16 crashes per year. The data used to develop the model includes intersections with a maximum of two opposing through lanes. Therefore, the nomograph gives the left-turn and opposite through volume combination recommended for PPLT, distinguished between intersection configurations with one and two opposing lanes when 0.16 crashes per year are anticipated. The average number of conflicts per intersection from the intersections used in the study is 7.01 which is rounded to seven to develop the example nomograph. Figure 2 shows the potential left and opposing through volume combinations that can result in a protected-permissive phase if their values are below the corresponding line for the number of lanes. In this case, volume combinations above the lines require a protected-only phase while those below the lines can be handled with a protected-permissive phase.

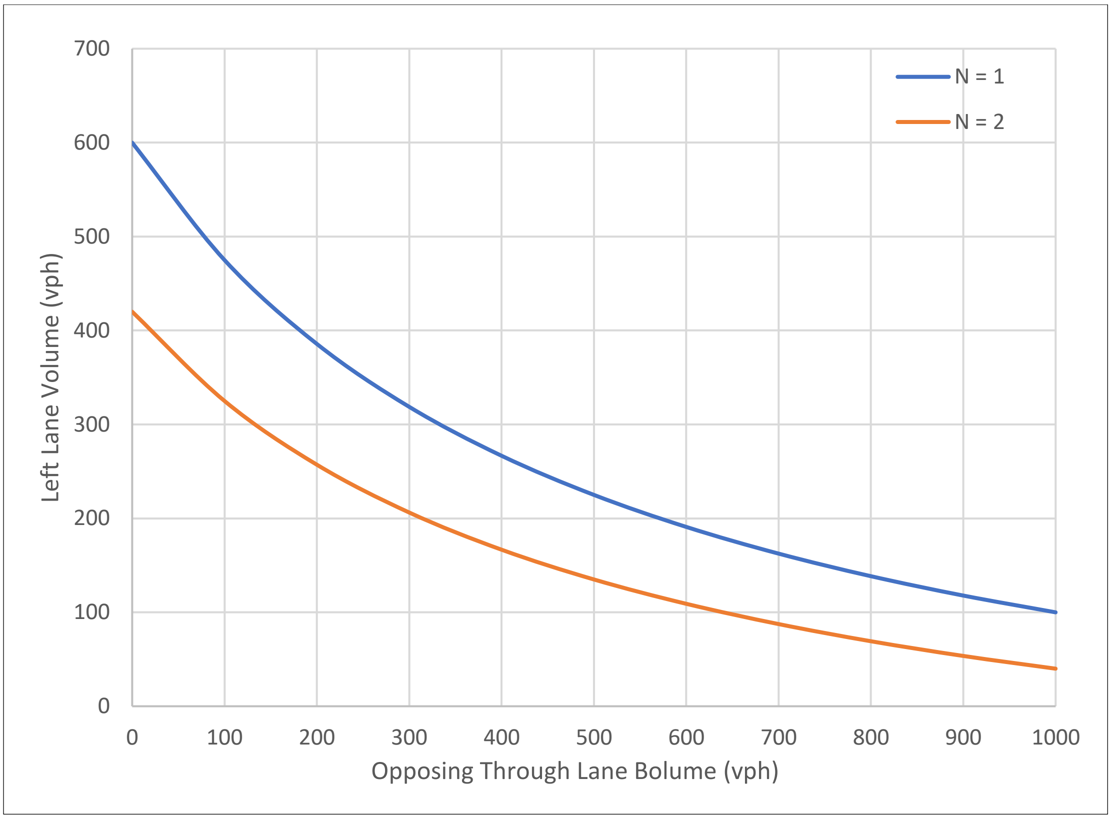

Figure 2: Example Nomograph for 0.16 crashes per year

5.1 Model Limitations

The ability of the model to predict the number of crashes in accordance with the traffic volume, number of opposing lanes and left-turn conflicts is statistically significant, but as all such models have some limitations. First, this research accommodates intersections with a protected-permissive left-turn phasing and it does not answer whether the intersection needs some type of protection. Second, the model is developed based on microsimulation analysis which does not reflect driver behavior or real-world situations, and this is one of the common concerns when using microsimulation analysis. Although the simulation of the intersection model reflects existing conditions, driver behavior is likely to be different among the models which affect the number of conflicts. Finally, the model is limited to intersections with one or two opposing through lanes. Hence the model cannot be used for the intersections which do not confirm the model characteristics.

6 DISCUSSION AND CONCLUSION

The Federal Highway Administration has developed the Traffic Signal Timing Manual, a set of guidelines for selecting left-turn phase. Many state DOTs also provide guidance for evaluating the factors informing the selecting on left-turn phase mode adopting the MUTCD. These guidelines are developed to indicate conditions where the benefits of a left-turn phase would address operational and safety concerns at a signalized intersection. These guidelines, as well as previous research, indicate that a left-turn phase can be justified based on consideration of several factors such as left-turn and opposing through volumes, number of opposing through lanes, crash history, cycle length and vehicle speed. As discussed in the literature review, conflicts are the optimal surrogate safety measure and the number of conflicts is a good predictor of crashes. This research created a predictive safety assessment model for left-turn movements at signalized intersections based on such predictor variables.

This research examined the effect of the explanatory variables - left-turn and opposing through volumes, number of opposing through lanes and number of conflicts on the number of crashes. Past research on safety analysis of left-turn phasing showed that there is an interaction between the left-turn and opposite through volumes. Therefore, an interaction term of left-turn and opposite through volumes is also included in the model. The effect of all the selected explanatory variables on the response variable was analyzed. However, the predictor variables failed to indicate statistical significance with the dependent variable which is potentially due to the multicollinearity or dependence among the variables. The Principal Component Analysis was used to eliminate the inter-correlation between the variables and thus develop a statistically significant model including all the chosen predictor variables.

The model developed in this research can be used to understand the implications and make better decisions about left-turn phasing at signalized intersections. It can be used as a guideline for making decisions on protected-permissive left-turns based on safety implications. This study does not include operational effects on left-turn phasing decisions and how these decisions will impact the intersection safety.

Additional research is needed which incorporates the left-turn operational effects as an additional factor in the model, thus balancing safety and operations.

The model developed in this research predicts the number of crashes in protected-permissive intersections and it serves as a guidance to left-turn phasing decisions. However, it does not answer whether the intersection needs some type of protection. This is one of the major limitation of the final model. Also, the model is developed based on microsimulation analysis which does not reflect driver behavior or real-life scenarios. However, incorporating human behavior in statistical modeling is still considered to be a challenge.

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