ASSESSMENT OF VARIOUS CRASH VEHICLE TYPES, THE RELATED SURROGATE MEASURES OF SAFETY, AND THEIR CORRELATION WITH THE TRAFFIC SIGNAL SETTINGS AND LEFT TURN MANEUVERS

BY

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A dissertation submitted to the Graduate School in partial fulfillment of the requirements for the degree Doctor of Philosophy

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“Assessment of Various Crash Vehicle Types, The Related Surrogate Measures of Safety, And Their Correlation with the Traffic Signal Settings and Left Turn Maneuvers,” a thesis prepared by Dusan Jolovic in partial fulfillment of the requirements for the degree Doctor of Philosophy, has been approved and accepted by the following:

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DEDICATION

To Danijela, the one and only

To Mila and Rade, my parents
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I would like to thank my adviser Dr. Peter Martin for his guidance, enthusiasm, and lots of British humor throughout my studies. It made this journey bearable. My thanks also go to Dr. James King and Dr. Ruinian Jiang for their advice and assistance during my studies – thank you for being the part of the committee. I am very grateful to Dr. Aleksandar Stevanovic, a committee member who was my mentor during my Master Studies. His influence stimulated my research oriented thinking and formed my area of research.

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Vehicular traffic crashes and fatalities are one of the major issues in the area of traffic engineering. The traditional traffic safety analysis assumes an occurrence of a crash in the field. An alternative way to assess traffic safety, without compromising drivers’ safety is the use of computational and simulation tools and relevant surrogate measures of safety. The focus of this research is on microsimulation software Vissim, post-processor Surrogate Safety Assessment Model (SSAM), and the signal timing optimization techniques to assess traffic safety.

The three major objectives of this study are: 1) assess the applicability of traffic conflict technique using Vissim microsimulation and traffic signal optimization, 2) investigate the correlation between intersection signal parameters (phasing, timing, and sequencing) and field crashes, and 3) review left turn guidelines and recommendations and propose potential improvements.

The findings show that surrogate measures of safety could be used to estimate the expected number of field crashes for both signalized intersections and the arterial links. Signal timing optimization technique can be successfully combined with Vissim microsimulation and the SSAM software to minimize the number of conflicts at traffic arterial and signalized intersections. The implementation of optimized signal setting in the field could increase safety without severely deteriorating vehicle throughput. Computational and simulation tools should be used to revise current left turn guidelines. Present left turn guidelines on protected/permitted signal phasing...
may overprotect left turners, increasing vehicular delays up to 25% and decreasing efficiency of the traffic signals.
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1. CHAPTER 1 - INTRODUCTION

1.1. Background

In the recent years, there is an increasing trend in traffic fatalities across the US. National Highway Traffic Safety Administration reported an 8 percent increase in traffic fatalities for the first nine months of 2016, compared to the same period in 2015 (1). That could be due to the higher number of Vehicle Miles Travelled (VMT) on the US roads. In 2016, Federal Highway Administration reported a new record of 3.2 trillion miles driven on the US roads (2). The increase in number of crashes can be related to the drop in the oil prices, causing a decrease in gas prices and allowing people more affordable trips by automobiles. The increase in traffic fatalities calls for the countermeasures and constant improvements in methods and techniques to assess traffic collisions.

1.2. Surrogate Measures of Safety and the Traffic Conflict Technique

There are different methods to analyze the traffic crashes and their causes. Besides the traditional analysis of field traffic crashes (e.g., identify the location, collect field data, analyze data, identify improvements, and implement changes) the researchers developed a methodology to assess the surrogate safety measures (SSM). The SSM
technique attempts to evaluate treatment beforehand, by lowering the frequency of crashes. To be acceptable, SSM has to satisfy two conditions (3):

1. It should be based on an observable non-crash event that is physically related in a predictable and reliable way to crashes;
2. There exists a practical method for converting non-crash events into a corresponding crash frequency and crash severity

The concept of SSM relies on the traffic conflicts technique (4, 5). The traffic conflict technique recognizes potential collision between two or more vehicles. A conflict between two vehicles is expected if at least one of the vehicles has to take an evasive action (e.g., accelerate or decelerate) to avoid a collision with the oncoming vehicle. Another definition states that a conflict is defined as an observable situation in which two or more road users approach each other in time and space to such an extent that there is a risk of collision if their movements remain unchanged (6). As an example, a conflict is a situation when one driver is executing a left-turn maneuver and the oncoming opposing through traffic driver has to brake slightly to avoid a collision.

The vehicle conflict theory was first formulated in the work of Perkins and Harris (7). Since then, many studies were conducted on this matter. One of the recent studies funded by FHWA developed the Surrogate Safety Assessment Model (SSAM), software coded in Java environment (8, 9). The software analyses vehicle
trajectories from the microsimulation outputs and estimates the frequency and severity of various conflict types.

Microsimulation models are stochastic, time step, driving behavior models, based on the car following and lane change theory. The microsimulation models are used in transportation engineering as tools to evaluate existing and proposed designs of future traffic facilities. Vehicle trajectory files are one of the outputs from the microsimulation. Microsimulation models record and output the trajectories of each vehicle on a second by second basis. The trajectory files could be then imported to the post processor SSAM software, and analyzed for potential conflicts.

SSAM analyzes the trajectories of the recorded vehicles on three types of conflicts:

- Lane change conflicts
- Rear end conflicts
- Crossing (angle) conflicts

Figure 1 depicts the conflicting movements.

![Figure 1 Types of traffic conflicts in SSAM](image-url)
Evaluation of traffic conflicts in a simulated environment could estimate the number of crashes at a traffic facility (e.g., streets, signalized and unsignalized intersection).

The field crashes are rare and random events. That is one of the main reasons for the development of traffic conflict theory. To conduct the statistical analysis on field data, the researchers would have to wait for several years before obtaining an appropriate dataset to analyze the specific facility.

To prevent crash occurrence, the researchers have to assess the design of traffic facilities, supporting signalization, and proposed guidelines. Ideally, the assessment should be conducted before the field implementation. The calculated number of conflicts could estimate the expected number of crashes. It could also point out any deficiencies in the design from the safety perspective.

This research utilized the traffic conflict technique to evaluate traffic safety at signalized intersections and arterial links from several perspectives.

1.3. **Research Goal and Objectives**

The goal of this research is to examine the correlation between field traffic crashes, signal timing parameters, left-turn phasing and sequencing, and simulated conflicts. This goal can be expressed through following objectives:

1. Optimize signal timings to minimize the number of simulated conflicts using genetic algorithm and microsimulation integrated approach
2. Conduct thorough literature review on the left turn practices across the US, and propose several methods to evaluate current left turn guidelines

3. Check current guidelines on left turns, and propose potential revisions by conducting tests in a simulation environment

4. Test the correlation between signal timing settings and the number of related field crashes

5. Assess the spatial match between field crashes and simulated conflicts

6. Develop statistical conflict-based crash prediction models for different crash types for arterial links and signalized intersections

**1.4. Dissertation Organization**

This dissertation deals with the traffic safety related issues from several perspectives. The second Chapter brings to attention the importance of signal timing parameters when estimating the number of conflicts. It shows that traffic signal timings could be optimized to minimize traffic conflicts at the signalized intersection. Once implemented in the field, the signal settings could lower the number of field crashes and make the facility safer, while maintaining high efficiency of the traffic flow. The third Chapter summarizes the literature and best practices on the left-turn signal settings across the US. This Chapter also recommends various simulation and computational methods for assessment of the left turn guidelines and recommendations. In the fourth Chapter some of the current guidelines on the left
turn phasing are tested using Vissim microsimulation model and SSAM post-processor. This method is one of the recommended assessment techniques in the Chapter three. Chapter five discusses the relationship between the intersections’ signal timing and phasing parameters and the field crashes in terms of crash frequency and crash severity. It shows the correlation between signal settings and intersection related crashes. The sixth Chapter provides spatial and statistical correlation results between field crashes and simulated conflicts. Chapter seven draws conclusions to the overall work and gives directions for future studies.

1.5. References


2. CHAPTER 2 - RETIMING TRAFFIC SIGNALS TO MINIMIZE SURROGATE SAFETY MEASURES ON SIGNALIZED ROAD NETWORKS


ABSTRACT

One way to improve safety of signalized arterials is to optimize signal timings. Usually, signal retiming tools optimize signal timings to reduce traffic delay and stops and other measures of traffic efficiency. The concept of optimizing signal timings specifically to improve safety metrics, or their surrogate measures, is not common in present signal timing optimization practice. This study advocates a fresh approach to integrating VISSIM microsimulation software, SSAM, and VISGAOST for optimizing signal timings to reduce vehicular conflicts and thereby reduce risks of potential real-world crashes. In addition, a genetic algorithm is implemented in VISGAOST to identify the optimal value for an objective function developed to satisfy two competing objectives: surrogate safety and traffic efficiency. Two simplistic networks served as a pair of case studies in these experiments. The optimization processes were able to find signal timings that reduced the number of conflicts without significantly reducing overall traffic activity (throughput). Most of
the improvements came at the expense of worsening efficiency of traffic streams which shows an inevitable necessity for trade-off between efficiency and safety.

Further investigation is needed to validate the approach and perform detailed analysis of impacts of signal timings on vehicular conflicts.

*Keywords: Vissim, microsimulation, genetic algorithm, SSAM, conflicts, signal timing, optimization*
2.1. Introduction

One way to improve safety of signalized arterials is to retime traffic signals. It is known that coordinated traffic signals provide good progression for major vehicular streams thus reducing the number of necessary stops and the potential for rear-end collisions. Also, balanced splits provide more equitable green times for all traffic movements thus reducing potential for unsafe operations of ‘unfairly treated’ traffic movements. However, in spite of the common understanding that proper signal timings promote safe traffic operations, there is little evidence from the field or research to support this understanding. The Highway Safety Manual (HSM, 2010) states that several signal timing-related crash-reduction treatments (e.g. modifying cycle length and phase durations, and improving signal coordination) have unknown effects on crashes.

Why is it so difficult to investigate impacts of signal timings on traffic safety at intersections on arterial streets? There are two major reasons. First, field evaluations of safety improvements obtained by tweaking signal timings are impractical and often inconclusive. Statistical correlations between crash rates and potential causes are relatively weak even for those causes (e.g. weather, geometrical design of the roads, and presence of work zones) that have much higher impact on traffic safety than signal controllers’ timings. Second, unlike other traffic metrics which reflect efficiency of traffic operations, safety metrics have not been traditionally calculated and reported by simulation tools.
Recent research (1) on use of surrogate safety measures to assess quality of various operational alternatives through microsimulation has brought new perspectives to this field. Several microscopic simulators are currently equipped to generate vehicular trajectory data that can be post-processed by Surrogate Safety Assessment Model (SSAM) (2) to provide surrogate safety estimates. Although ability to estimate surrogate safety measures does not necessarily translate to an ability to predict crashes, the relationship between surrogate safety metrics and field crashes are similar to other conventional methods and their estimation of crashes (2).

Signal timing optimization tools are traditionally used to optimize signal timings to reduce traffic delay, stops, and other measures of traffic efficiency. The concept of optimizing signal timings to directly reduce safety metrics (or their surrogate measures) is not present in current signal timing optimization practice. Unlike metrics representing efficiency of traffic operations, commonly used signal timing optimization tools (such as Synchro, TRANSYT-7F, and PASSER) are not equipped to evaluate impacts of signal timings on surrogate safety metrics. Although a recent study investigated impacts of signal timings on surrogate safety measures (3), there are many questions which remain unanswered.

This study advocates a fresh approach to integrating the evaluation of surrogate safety measures and stochastic optimization of signal timings. VISSIM microsimulation software (4), Surrogate Safety Assessment Model (SSAM) (2), and VISSIM-based Genetic Algorithm for Optimization of Signal Timings (VISGAOST) (5) have been
integrated in a framework to minimize selected surrogate safety measures by adjusting signal timings. The optimization process generates signal timings that minimize surrogate safety measures thus representing conditions which reduce risk of potential field crashes.

2.2. Literature Review

2.2.1. Traffic Safety and Retiming of Traffic Signals

When evaluating impacts of signal timings on road safety, the main focus is often on intergreen (yellow + all-red) times, while other signal timing parameters get little attention (one should note here that signal phasing for left turn treatments is not included in the discussion about signal timing parameters). Impact of intergreen on red-light running and dilemma zones is well documented (see, for example 6). However, very few studies have estimated the direct impact due to other signal timing parameters (such as cycle length, offsets, splits and phase sequence).

One of the first such studies was conducted by Moore and Lowrie (7), who investigated the impact of traffic signal coordination on number of traffic crashes in the field. They compared frequency of crashes from areas with and without coordinated signals and estimated a 23% reduction in crashes following traffic signal coordination.

In practice, when signals are retimed, consultants usually apply a crash reduction factor to estimate safety benefits of the retiming (8). However, this
approach is not very reliable because crash reduction rates may be based on a limited number of research studies. The Highway Safety Manual (9) recognizes that there is a gap in knowledge in this field and it reports that most signal timing adjustments (including coordination of traffic signals) have unknown effects on crashes.

2.2.2. Surrogate Safety Measures and Field Crash Statistics

The historical account of correlating traffic conflicts with traffic crashes is relatively long (10, 11) but unfortunately somewhat unsuccessful. While researchers have not been able to show that traffic conflicts (either from microsimulation or from the field) are strongly correlated to traffic crashes, three major arguments are used to justify continued interest in analyzing traffic conflicts as a means to estimate traffic crashes:

- Although using traffic conflicts to estimate crashes is not significantly better than using past crash data, both approaches generally produce similar results (2, 12).
- Conflicts should be used to estimate an expected rate of crashes, as opposed to predicting the actual number, because actual numbers can significantly vary by year (12).
- Other, non-safety related variables (e.g. volume, speed or occupancy) are not reliable estimators of crash rates either (13).
2.2.3. *Surrogate Safety Measures from Microscopic Simulations*

One of the first studies using a widely-available simulation model (for earlier studies see 14-16) was conducted in 2002 by Drummond et al. (17) where the authors found a high correlation \(0.54 \leq R^2 \leq 0.89\) between traffic efficiency performance measures (e.g. delays and stops) from simulation and field crash rates.

A major breakthrough in research on surrogate safety measures based on microsimulation outputs was achieved when Gettman and Head (1) developed functional requirements and algorithms for a software tool that analyzed surrogate measures generated by a simulation model. This research led to development of publicly-available SSAM software a few years later (2).

Several other studies followed with their own developments of surrogate safety measures or proposed modifications to existing ones. Klunder et al. (18) proposed development of an advanced framework for generating safety performance measures based on the Multi-Agent Real-time Simulator (MARS) interfaced with Quadstone Paramics microsimulation software. Ozbay et al. (19) emphasized a need for well-calibrated and validated microsimulation models from which safety surrogate measures are collected. In fact, they developed a new crash index and modified an existing one, and proved that both indices match field data both temporally and spatially. Tarko et al. (20) synthesized concepts, key studies, and definitions of surrogate safety measures and identified future research directions.
A recent study has furthermore investigated the impact of signal timings on surrogate safety measures using Surrogate Safety Assessment Methodology (SSAM) to evaluate simulated scenarios (3). However, the study by Sabra et al. (3) was performed within a framework which is limited by Synchro’s inability to always find the best signal timings in VISSIM. Earlier studies (21, 22) have shown that when signal timings delivered by deterministic optimization tools (such as Synchro) are evaluated in stochastic environments (such as VISSIM’s) their performances may not be optimal or consistent. In addition, the goal of Sabra et al. (3) study was to conduct a sensitivity analysis and evaluate individual impacts of signal timings on safety surrogate measures rather than to perform an optimization as proposed in this study.

2.2.4. Summary of Past Research

Research studies do not presume that surrogate safety measures are reliable estimators of real world crashes; rather they consider them valid measures with a lot of potential for improvement. Available studies on surrogate safety measures from simulation modeling show a continued interest from the research community. No current signal optimization tool offers an estimate of surrogate safety measures in its optimization of signal timings. Furthermore, there have not yet been any attempts to conduct such optimizations. Except for a recent FHWA report (3) there are practically no studies that investigate impacts of (non-intergreen) signal timings on surrogate safety measures.
2.3. **VISSIM-SSAM-VISGAOST Framework**

The following describes the integration of VISSIM, SSAM, and VISGAOST to optimize signal timings to reduce total number of conflicts (as a surrogate safety measure obtained from SSAM).

2.3.1. **VISSIM**

VISSIM is a microscopic, time step and behavior-based model developed to simulate urban traffic and public transport operations. The program can analyze vehicle operations under different lane configurations, traffic composition, traffic signals, and public transport stops. VISSIM uses the psycho-physical driver behavior model developed by Wiedemann (4) whose basic concept is that the driver of a faster moving vehicle decelerates when approaching a slower moving vehicle according to the driver’s individual perception threshold.

2.3.2. **SSAM**

The Surrogate Safety Assessment Model (SSAM), a software application sponsored by FHWA, provides safety analysis for simulation-based comparative studies (2). The software processes vehicle trajectory data exported from microscopic traffic simulation models to estimate the frequency and severity of various types of conflicts.
By definition, a conflict represents an observable situation in which two or more motor vehicles approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged (23). To determine if a vehicle-to-vehicle interaction is classified as a conflict, the threshold values for two surrogate measures of safety are applied: time-to-collision (TTC) and post-encroachment time (PET). SSAM identifies four types of conflicts: crossing (angle), lane-changing, rear-end and unclassified. The type is determined based on the conflict angle, and link and lane information. A conflict angle for a pair of vehicles is calculated based on the angle at which these vehicles converge to a hypothetical collision point. For each conflict, SSAM computes a number of corresponding surrogate measures of safety (TTC, PET, etc.) along with their summaries (mean, max, and variance).

The SSAM approach was validated using a database of 83 four-legged urban signalized intersections (2). The intersections were modeled in VISSIM and the safety was assessed with SSAM. The research included theoretical validation, field validation and sensitivity analysis. The assessments of SSAM showed accuracy similar to that of traditional theoretical crash-prediction equations, which are based on average daily traffic volumes. Thus, the SSAM approach exhibits promise to provide significant support to evaluations of traffic engineering alternatives without expensive field crash studies (2).
2.3.3. VISGAOST

VISGAOST is an optimization program that optimizes signal timings of traffic controllers based on their performance in VISSIM microscopic simulation. VISGAOST bases its optimization on the stochastic nature of Genetic Algorithms (GAs). The general structure of VISGAOST GA optimization is well documented (24). The basic version of VISGAOST is written in C++ and relies on VISSIM’s input and output files (4). The key part of the VISGAOST program is a simple GA similar to other GAs used for signal timing optimization (25).

The first version of VISGAOST enabled the optimization of all four basic signal settings, i.e. cycle, offset, splits and phase sequence. Results from the first tests and evaluations confirmed that VISGAOST can provide a better timing plan than those from the field (5). Further, the results from VISSIM showed that the GA-optimized plan generated Performance Index which was 11-23% lower than the timing plan generated by SYNCHRO. Similar results were found for delays (5-15% lower delays) and stops. All of the differences were statistically significant and based on 100 randomly-seeded simulation runs.

2.3.4. VISSIM-SSAM-VISGAOST Integration

Figure 2 shows the integration of VISSIM, SSAM, and VISGAOST to find signal timings which reduce surrogate safety measures. The program previously used for similar optimizations was modified to accommodate a new SSAM interface. The
optimization process starts with VISGAOST generating an initial population of signal timings, which is seeded by the existing set of signal timings from field. Each generated signal timing plan is evaluated in VISSIM, which generates both network-wide measures of effectiveness and trajectory data for each vehicle (where outputs are required for subsequent optimization steps).

The trajectory data file (*.trj) is processed by SSAM to identify the frequency, severity and types of conflicts (2). In the next step the number of conflicts from SSAM is manipulated with some VISSIM performance measures to produce a meaningful objective function for VISGAOST optimization (more about development of the objective function is provided later). This objective function is then minimized through the Genetic Algorithm iterative procedure by evaluating various combinations of signal timings from intersection controllers (24). The whole process is then repeated until the predefined termination criterion is met (using a number of repetitions or convergence of the solutions).
2.4. Optimizing Signal Timings to Reduce Surrogate Safety Measures

When optimizing signal timings (in stochastic platforms, such as VISSIM) with a goal to reduce some of the unconventional performance measures (e.g. fuel consumption and number of conflicts) it is necessary to combine these unconventional performance measures with conventional ones (e.g. delay, stops, and throughput) to get meaningful objective functions. Unlike delay, stops and throughput, metrics such as fuel consumed or total number of conflicts are not directly proportional to efficiency of traffic. For example, less fuel is consumed by
standing traffic than by traffic flowing at a speed of 45 mph. Similarly, the number of conflicts in jammed traffic is minimal because vehicles cannot move freely. An attempt to minimize fuel consumption or number of conflicts when these are used as sole objective functions in an evolutionary optimization process would inevitably lead to solutions (or a set of signal timing parameters) that would block at least a portion of (if not all) traffic and decrease overall traffic activity (and efficiency). So, to get meaningful results metrics such as fuel consumption and number of conflicts, which are indirectly proportional to traffic efficiency, need to be combined with metrics directly proportional to traffic activity. For this reason fuel consumption and crash rates (as an example of safety metrics) are usually expressed per mile of travel.

For the purpose of optimizations conducted in this study authors used vehicular throughput as a measure of traffic activity. Vehicular throughput in VISSIM is referred as “number of vehicles that have left the network”); it is highly correlated with total miles traveled (R2~0.9) and as such it is a good representative of traffic activity/efficiency.

At first, number of conflicts computed by SSAM was divided by the throughput to form the optimization objective function. However, after observing initial optimization experiments (26) authors noted that a simple conflict/throughput ratio is not going to lead to meaningful results. This conclusion comes from the fact that every vehicle can create multiple conflicts. So, if such a vehicle is blocked and does not finish the trip (e.g., due to an odd combination of signal timings) the
throughput is reduced for one car whereas multiple conflicts are avoided/reduced. This situation evidently leads into an optimization process that favors signal timings which block vehicles (either in the entire network or at conflict-prone intersection approaches) and thus reduces conflicts. Since blocking the traffic is undesirable outcome it was concluded that a simple conflict/throughput ratio is not a good objective function (26).

Instead, it was decided to impose a penalty (within GA optimization procedures) to any signal timing plan that reduces throughput. A GA procedure which explains imposition of penalties to signal timings which significantly reduce throughput has been presented elsewhere (26). Here, authors just want to note that the adopted approach limits the reduction of throughput to a maximum of 2% with respect to the initial throughput based on field signal timings. Although this limit is user configurable it should be noted that even small reduction in overall throughput may represent unnecessary blockage of certain traffic movements.

In addition to optimization to reduce vehicular conflicts authors performed optimizations to reduce traditional Performance Index (PI), which mainly served to establish base-case scenarios for conflict optimizations. PI is a linear combination of stops and delays and it is one of the most common (used by Synchro and TRANSYT-7F) objective functions, when optimizing signal timings for efficiency. By optimizing with PI and comparing results of such optimizations to others, authors sought to
investigate how much (surrogate) traffic safety is ‘lost’ due to excellent traffic efficiency, and vice versa.

2.5. Case Study Networks

As case studies authors decided to use two simple networks (shown in Figure 3) which were analyzed in the recent study funded by FHWA (3). Details about networks’ geometries, traffic conditions, signal timings, etc. can be found elsewhere (3). The main reason for this decision was to concentrate our research efforts on simple (synthetic) case studies in order to reconfirm findings from other studies and/or to bring new perspectives into existing knowledge.

Authors of the FHWA (3) provided the networks for this study. Authors of this study replicated few simulation runs to confirm consistency of the results with those reported by the previous study (3). The original comparisons generated identical
results but results from later comparisons were slightly different (not significantly) due to a newer version of VISSIM.

2.6. VISGAOST Optimizations and VISSIM Simulations

All of the signal timings were coded in VISSIM’s Ring-Barrier Controllers. Two groups of optimizations were conducted: for a single intersection and for three coordinated intersections. All of the optimizations started from the initial signal timings which were optimized by Synchro and used for basic experiments in the study reported by Sabra et al. (3).

Table 1 shows what types of optimizations were performed, which signal timing parameters were modified during the optimizations, and what were the optimizations’ sequences.

<table>
<thead>
<tr>
<th></th>
<th>Single Intersection (v/c = 0.85)</th>
<th>Three Intersections (v/c = 0.85)</th>
<th>Three Intersections (v/c = 1.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PI</td>
<td>Conflicts</td>
<td>PI</td>
</tr>
<tr>
<td>Splits</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cycle length</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Offsets</td>
<td>NA</td>
<td>NA</td>
<td>-</td>
</tr>
<tr>
<td>Multiple</td>
<td>3(^\wedge)</td>
<td>2(^\wedge)</td>
<td>2*, 3(^\wedge)</td>
</tr>
</tbody>
</table>

\(^\wedge\) - splits and cycle length
* - cycle length and offsets
“ - cycle length, offsets, and splits
First, PI and conflicts were minimized for single intersection for undersaturated traffic conditions ($v/c$ ratio = 0.85). The PI optimization was performed to check quality of Synchro’s signal timings and find out how much of surrogate safety is given for improvement in efficiency of traffic signals. Within this optimization splits were optimized first, then cycle length, and then both splits and cycle length. In the next optimization on the same network, the total number of conflicts is minimized through optimization of cycle length, followed by an optimization of both cycle length and splits.

For the three-intersection network two cases were investigated – undersaturated ($v/c=0.85$) and saturated traffic conditions ($v/c=1.0$). For undersaturated traffic, first PI was optimized through adjustments of cycle length, followed by adjustments of cycle length and offsets, and finally all three parameters (cycle length, offsets, and splits). Second, the three intersection network was optimized for conflicts. In this case there were two optimizations with separate adjustments (cycle length and separately offsets) followed by two optimizations with combined adjustments – cycle length and offsets and cycle length, splits, and offsets. Finally, for saturated network only one optimization was performed, with all three parameters adjusted simultaneously.

One should also note that all of the subsequent optimizations were building upon solutions achieved in previous optimizations, which is indicated by numbers 1, 2, and 3 in the Table 1. The only exception is optimization of conflicts when cycle
length was adjusted for three-intersection network (denoted with ‘0’ in Table 1). This optimization was performed to investigate relationship between conflicts and cycle lengths and it did not have subsequent optimizations. Similarly, two other optimizations were performed to investigate relationship between conflicts and signal timings: optimization of cycle length to reduce conflicts in single intersection network and optimization of offsets for conflicts in the three-intersection network.

Each optimization was based on evaluations of performance and safety measures accumulated during 60 minutes of simulation time. Each optimization had 20 signal timing plans which were operated through GA procedures for multiple generations. Number of generations significantly varied with complexity of the experiments – PI optimizations were performed for several hundred generations while the conflict optimizations (which were much more computationally intensive) were in range of dozens.

All VISSIM evaluations within VISGAOST optimizations were executed for a single random seed (for the purpose of computing efficiency). Once the final (near-optimal) solutions were achieved these were tested through the same 6 random seeds used in the study by Sabra et al. (3). Other GA parameters were default VISGAOST parameters which were justified in previous studies (5). In total, optimization experiments took several weeks to complete.
2.7. Results and Discussion

Figure 4, parts A) through F), show results of the optimization processes. Most of the charts in Figure 4 show how total conflicts and performance indices, as the two conflicting measures, varied during the course of optimizations. The exceptions are parts A) and C) which do not track the conflicts but they show how delays and stops contribute to changes in PI during the optimizations. It can be observed from Figure 4 that most of the time PI and total conflicts behave in opposite way – when PI increases conflict decrease and vice versa. However, it should be noted that sometimes PI’s trends follow trends of conflicts. This type of inconsistent behavior can be attributed to the mixed nature of the total conflicts which include various types of conflicts that may have different relationships with signal timings. Such an analysis, of relationships between various types of conflicts and signal timings, is out of scope of this study.

Table 2 shows the final results of optimization processes after they were tested in VISSIM and SSAM for multiple random seeds. Each column labeled ‘Initial’ shows performance measures (of efficiency and safety) that were delivered by original models (3). The results are only slightly different because of changes in new version of VISSIM software. Other columns correspond to optimization experiments which were performed (PI or Conflicts) and they all correspond to a particular chart from Figure 4. Few major points, from Table 2, that warrant discussion are:
• Experiments show that the original ‘best’ signal timings from Synchro (optimized for PI) are not the best signal timings in VISSIM. VISGAOST was able to further reduce VISSIM’s PI by at least 17%.

• Throughputs remained very consistent for all corresponding experiments showing that there were no solutions that prevented significant amount of traffic to enter the network.

• For most of the experiments total conflicts were significantly reduced, when compared to the results from the FHWA study (3), but at the expense of increased delay and PI. For example, when optimizing signal timings to reduce total number of conflicts one could save 35%, 51%, and 15% for single intersection, three intersections with 0.85 v/c ratio, and three intersections with 1.0 v/c ratio, respectively. In order to achieve these benefits one would need to give up 30%, 28%, and 17% of delay, respectively; with no sacrifices in the number of stops. All of these changes can be mainly attributed to increase in cycle length (~190sec).

• It is obvious that the rear-end conflicts dominate the total number of conflicts. Other two conflict types (crossing and lane-changing) are not as numerous as rear-end conflicts although they may be even more sensitive to changes in signal timings than the rear-end conflicts.
Figure 4 Various performance measures during the optimizations
When analyzing how individual signal timings may impact traffic conflicts it is difficult to show the relationships between multiple signal timings of the same type (such as splits) and the traffic conflicts. While it is possible to track down exact impact of a particular intersection’s split time on a particular type of conflict on the corresponding intersection approach, such an analysis would be too detailed for the scope of this study. Instead, authors investigated relationship between global signal timings (e.g. cycle length and offsets) and the number of conflicts. Figure 4 shows such relationships for one-intersection and three-intersection networks. Parts A) and
B) of Figure 5 show that total conflicts decline as cycle length increases. These findings confirm findings from the FHWA study (3). The trend seems to level off at cycle lengths above 180 seconds but such a conclusion cannot be strongly supported because the study did not investigate cycle lengths above 200 seconds (considered to be impractical).

When the total conflicts were decomposed to individual conflict types it was found that the overall trend (of reducing conflicts with increasing cycle length) remains valid for rear-end conflicts and to certain extent for crossing conflicts, too. The lane-changing conflicts are the ones which have the weakest correlations with the changes in cycle length, either on the intersection or on the network level. One should also note somewhat erratic behavior of any conflicts at higher cycle lengths. It seems that sometimes a one-second increase in cycle length can increase number of conflicts by 10-15%. Further investigation is needed to determine validity of the reported conflicts. Both VISSIM and SSAM may be too sensitive when generating outputs that contribute to the estimated conflicts.
Figure 5 Impacts of signal timings on various types of vehicular conflicts

The last two parts of Figure 5 (part E and part F) show how traffic conflicts vary with changes in intersection offsets. Two offsets from the two outer intersections
(the one in the middle has offset zero) were combined in two different ways: in part E) they were summed; in part F) their differences were plotted. Similarly to the findings from the FHWA study (3), no strong correlation between offsets and total number of conflicts was observed. However, this may be a consequence of a ‘poor’ cycle length for which the offsets were adjusted. Table 2 shows that the offset optimizations started for a cycle length of 50 seconds. For such a small cycle length there simple may not be good offsets which could significantly reduce the number of conflicts. Further experiments are needed to document relationship between offsets and conflicts (for those cycle lengths which are proven to reduce number of conflicts).

Nonetheless, Figure 4 E) (and also part D)) show that, in general, the cycle length contributes more to the reduction of total conflicts than the offsets. When cycle length is optimized simultaneously with offsets there were further decreases in total conflicts but these were relatively moderate improvements (middle of Part E) of Figure 3).

Regarding the splits, which were not optimized individually in these experiments, results from authors’ earlier experiments confirm results of Sabra et al. (3). It has been shown that an increase in green time for particular movement reduces number of conflicts for that movement, regardless whether the increase in green time comes from increase of split or increase of the cycle length.
In general, the results presented in this study show that all of the conflict types are very sensitive with respect to many simulation factors; and that there should be a trade-off approach when optimizing signal timings to reduce conflicts so that the optimization can be put in a context of particular interest and not merely executed to reduce overall number of conflicts.

2.8. Conclusions

The goal of the study was to present a new integration of traffic simulation, surrogate safety assessment, and signal timing optimization tools. The study describes integration of VISSIM, SSAM, and VISGAOST to optimize signal timings in such a way as to achieve minimal estimated number of conflicts while maintaining efficiency of traffic signals. The case studies served two simplistic networks which were recently analyzed in another major report (3). The optimization processes were able to find signal timings which reduced number of conflicts without significantly reducing overall traffic activity (throughput). Based on the described integration process and observed findings, it can be concluded that:

- The single-objective optimization that used a ratio of number of conflicts to throughput, with penalties for lowering throughput, significantly decreased the number of conflicts.
• This study proved that the concept of optimizing signal timings to reduce vehicular conflicts and thus improve safety conditions on a road network is a viable option. The overall conclusion from the experiments is that increasing the cycle length is the most significant contributor of the decrease in the total number of conflicts.

• Results of the optimizations showed that the overall number of conflicts can be significantly reduced if a methodology similar to one presented in this paper is used. However, benefits from reducing the total number of conflicts come at the expense of worsening efficiency of the traffic streams. These findings showed an inevitable necessity for trading off between efficiency and safety.

• Results mainly confirmed findings from Sabra et al. (3). Further investigation is needed to validate quality of VISSIM and SSAM outputs which are used to generate individual types of vehicular conflicts, which is a prerequisite for the analysis presented here.

Further research is needed to test this approach on a variety of networks and traffic conditions and to find a good composite measure (of surrogate safety measures and traditional traffic metrics) for use in single-objective optimizations. Also, it is necessary to execute more experiments to find out partial and combined impacts of various signal timings on various types of traffic conflicts. Finally, further validation of surrogate safety measures and higher fidelity of micro-simulation outputs will
increase meaningfulness of practically incorporating safety aspects into design of traffic signal timings.
2.9. References


3. CHAPTER 3 - LEFT-TURN PHASING – STATE OF THE ART REVIEW AND THE OUTLOOK FOR FUTURE IMPROVEMENTS

Authors: Dusan Jolovic, Peter T Martin, Aleksandar Stevanovic. ASCE Library, 16th COTA International Conference of Transportation, 2016

ABSTRACT

Left-turns are one of the most critical maneuvers at signalized intersections. There are several types of left turn signal phasing in use: protected-only, permitted/protected, permitted-only, and prohibited. If the protected part of a left turn phase is assigned before the through phase starts, a left-turn sequence is called lead. If the opposite is true, it is called lag. Currently there are no uniform guidelines on left-turn installations. Furthermore, the practice on left-turns is not consistent.

This paper summarizes a literature on left turn phasing, sequencing and left-turn signal displays (e.g., flashing yellow arrows) and points out the key findings and shortcomings. The authors propose computational and simulation tools—driving simulators, microsimulation, surrogate safety models and augmented reality for future research which could lead toward the unification of left-turn set of guidelines.

Keywords: left turns, augmented reality, microsimulation, surrogate safety, driving simulator
3.1. Introduction

Left turns (LT) are one of the most dangerous maneuvers at signalized intersections (FHWA, 2009). About 18% of all crashes are attributed to LT vehicles crossing the opposing through lanes (Chan, Ragland, Shladover, Misener, & Marco, 2005). The safety concern of LT vehicles is an ongoing debate that started more than 50 years ago (Ray, 1964), (Mckay, 1968), (Granger & Quy, 1971), (University of Berlin, 1974).

There are several types of LT phasing in use: permissive-only, protected only, protected/permitted, split phasing and, prohibited LT (Chandler, et al., 2013). Various phasing designs can improve signal efficiency, increase capacity and improve vehicular and pedestrian safety. Generally, the protected-only phase emphasizes safety. Permitted turns promote efficiency and protected/permitted phasing is a tradeoff between safety and efficiency.

For phase sequencing, LT can operate as: lead-lead, lag-lag and the combination of lead-lag sequence. Various sequencing allows better arterial progression, reduces protected green arrow time, and can decrease LT delay (Chandler, et al., 2013).

To assess performance, capacity, efficiency, and safety of LT, research in the past was mostly based on LT field assessment and analysis. However, field tests can be costly and dangerous. As technology progresses, it becomes more affordable, and the new ways of evaluating specific traffic phenomena emerge. In the last two
decades, researchers used driving simulators, microsimulation software, augmented reality (AR), various statistical methods, and surrogate measures of safety to assess LT operations at intersections. However, some of these techniques are underutilized (e.g., augmented reality).

There literature on LT is extensive (Fambro, Messer, & Woods, 1981), (Upchurch, Guidelines for Selecting Type of Left-Turn Phasing, 1986), (Asante, Ardekani, & Williams, 1993), (Agent, Stamatiadis, & Dyer, Guidelines for the Installation of Left-Turn Phasing, 1995), (Chang, Zhuang, & Carter, 1996), (Stamatiadis, Agent, & Bizakis, 1997), (Hauer, 2004), (Lei, Qi, Yu, Guo, & Chen, 2008), (Schattler & Lund, 2013). However, most of these reviews need updating. Many have been based on one particular topic, (e.g., signal displays, type of phasing). Further, previous reviews do not propose any direction for further research on LT issues.

This paper summarizes the research on LT movements. It includes literature on LT signal control mode types (protected, permitted, protected/permitted), LT signal display (e.g., flashing yellow arrows), and phase sequencing (lead, lag, lead/lag). The paper discusses the key literature findings and gaps and proposes opportunities and techniques for future research on LT movements.
3.2. Signal Control Mode

One of the first LT guidelines, still used today, are based on studies conducted by Agent (Agent K. R., 1979), (Agent K. R., Guidelines for the Use of Protected/Permissive Left-Turn Phasing, 1985), (Agent K. R., Guidelines for the Use of Protected/Permissive Phasing, 1987). The author showed delay reduction for LT vehicles, when protected-only LT phases are replaced with protected/permitted phases. The findings also pointed increment in number of conflicts when switching to protected/permitted phases, which compromised safety standards. The author developed a set of guidelines for protected/permitted phase use. He summarized that the protected/permissive phasing should not be used when:

- The speed limit is over 45mph;
- The protected only phasing is currently operating and the speed limit over 35mph;
- The LT movement must cross three or more opposing through lanes;
- Intersection geometrics force the LT lane to have a separate signal head;
- There are double LT lanes on the approach;
- There are LT accident problems;
- A traffic study documents a potential LT problem.

(Fambro, Messer, & Woods, 1981) discussed a pros and cons of various LT signal phasing plans and proposed initial LT guidelines for practitioners. (Machemehl &
Mechler, 1983) used the TEXAS simulation model (University of Texas, Austin & TxDOT, 1991) to evaluate the effects of LT sequence patterns. The experiments included pretimed and actuated signal control, dual leading and dual lagging LT sequencing, split, composite sequencing, and sampling of the traffic demands. All the experiments were based on a single intersection. Vehicular delay only was a basis for the experiments, with no safety studies. The following year Lin et al. (Lin, Machemehl, Lee, & Herman, 1984) developed warrants for installation of protected LT signal and bays. Various capacity models for the LT were examined and checked for inconsistencies. The TEXAS simulation model estimated the LT capacity and enabled the development of a new capacity warrant based on the relation between the critical LT volumes and capacities. They found that the average LT delay is the key indication of its performance.

Cohen et al. (Cohen & Mekemson, 1985) optimized LT sequence by delay-based programs such as TRANSYT-7F (University of Florida), SIGOP-III (Liebermann, 1983), SSTOP (Ontario Ministry of Transportation and Communications. Transportation Technology and Energy Division. Control and Communications Systems, 1983) and surrogate-based programs such as MAXBAND (Cohen & Little, MAXBAND Program for Arterial Signal Timing Plans, 1982). Experiments on seven arterials across the US showed that optimizing phase sequence can improve the performance of a corridor in terms of increased
bandwidth and decreased delay and stops. There was no consideration of the number of conflicts/accidents in this study.

LT guidelines, still in use today with slight modifications, were developed by several efforts of Upchurch (Upchurch, Guidelines for Selecting Type of Left-Turn Phasing, 1986), (Upchurch, Comparison of Left-Turn Accident Rates for Different Types of Left-Turn Phasing, 1991), (Wright & Upchurch, 1992). The authors based implementation of LT type on: LT volume, opposing volume, cycle length, speed limit, sight distance, number of opposing through lanes, and accident history. Due to the reluctance of the drivers to make a turn, protected-only LT phase is recommended by the researchers when there are three opposing through lanes present. These studies supported findings by Agent that protected LT will reduce crashes, but the LT delay will be higher. Another finding was that the opposing traffic would experience less through delay if protected-only LT were installed.

In 1991, Fambro et al. (Fambro, Gaston, & Hoff, 1991) evaluated the operational characteristics on Dallas Phasing (Kittelson and Associates) with field and simulation data using PASSER-II (Texas Transportation Institute (TTI)). Testing was done using the data from four sites, with stopped delay as the main operational measure for evaluation applied to four sites. It was concluded that the Dallas phasing reduces delay over the standard MUTCD phasing (Federal Highway Administration, 2009).
The study of Asante et al. (Asante, Ardekani, & Williams, 1993) on left turns is based on a three level decision process: first, whether the protection is needed, second, if the protection is needed the engineer needs to select protected only or protected/permissive and third, to select the sequence between lead and lag. This research resulted in several charts as a selection guide for the choice between ‘permissive only’ and ‘some protection’ for LT. These charts can be summarized as the following recommendations:

- For one opposing through lane, opposing speed limit higher than 55mph and LT volume of 130veh/h: some protection;
- For two opposing through lanes, opposing speed limit of 54mph and LT volume of 100veh/h: some protection;
- For three opposing through lanes, opposing speed limit of 45mph and LT flow of 75veh/h: some protection;

It also resulted in recommendations on when protected only phasing should be used. These, and guidelines set by research conducted by Agent and Upchurch are adopted for the Chapter 12 of the Traffic Engineering Handbook issued by the ITE (Pusey & Butzer, 1999).

In 1995, Agent et al. (Agent, Stamatiadis, & Dyer, Guidelines for the Installation of Left-Turn Phasing, 1995) updated guidelines on appropriate usage of the LT phasing type. Traffic accidents and characteristics of the intersection data from 500 approaches were used. Delays were estimated using the TRAF-NETSIM
simulation model (Federal Highway Administration, 1989). The research resulted in three guidelines for the protected/permissive phasing: 1) Regulatory signs are not typically necessary, only if there is a potential accident problem; 2) For safety, leading phase is preferred for protected/permissive phasing. Lagging can be used to increase intersection efficiency when there are no accident concerns; 3) If protected/permitted phase is used, the signal head for the LT movement should be located on the line separating the LT lane and the near through lane.

Stamatiadis et al. (Stamatiadis, Agent, & Bizakis, 1997) proposed safety guidelines for LT based on 408 approaches in Kentucky. In making the recommendations, the authors considered LT volumes, accident rates, the cross product of opposing through and LT lanes and delays. TRAF-NETSIM simulated the traffic conditions and provided delay estimates. In recognizing the complexity of a problem, the findings showed that the volumes, lane configuration, accidents and delays are important for determination of LT treatments.

Hardwood et al. (Harwood, et al., 2002), addressed a LT study on safety and effectiveness with ‘before and after’ data from 580 intersections. The ‘after’ analysis included intersection improvements in terms of added lanes or lane extensions. The researchers used three approaches to compare ‘before and after’ conditions: the matched pair approach, the comparison group approach and the Empirical Bayes method. Empirical Bayes method turned the most fit for this research in terms of accuracy and reliability of outputs. The outcomes of the research are safety and
effectiveness measures for left and right turn installation design improvements, which comply and supplement previous research findings.

Davis and Aul (Davis & Aul, 2007) simulated the LT phasing effects on crash frequency. The authors showed a statistical model capable of providing drivers’ description of gaps acceptance and rejection.

(Lei, Qi, Yu, Guo, & Chen, 2008) introduced new LT guidelines for TxDOT. They investigated LT signal control, phase sequences and signal displays. In the operational impact analysis, the authors based criteria for selecting the LT signal mode on the cross product of LT and opposing through volume. For the safety analysis, different types of LT signal phasing were ranked based on the historical accident data from about 100 intersections. The operational impact analysis was done by VISSIM. The authors calibrated and validated the models and manually adjusted the critical gap to match the field conditions. However, they did not consider the number of conflicts for each scenario developed, which VISSIM can export.

Sabra Wang (Sabra, Wang & Associates, Inc., 2011) effort was focused on LT guidance on for Maryland State Highway Administration. They found that for the LT phase order, safety, platoon progression and bandwidth, and queuing should be considered. Changing the phase sequence by time-of-day does not have any negative safety implications.
Navaro (Navaro, 2012) compares operations and parameters that affect LT at intersections with large and small intersections. The large intersection is defined with three opposing through lanes and the small as two or less opposing lanes.

Synchro (Trafficware, 1978) and Mitsim (MIT Intelligent Transportation System Lab, 1990) gave significant parameters affecting the number of permitted LT. On seven intersections studied, the author showed that there is a statistically significant difference between the large and small intersection geometry. He developed regression models for each. The models cannot predict the number of permitted LT. They just show significant parameters that influence the number of permitted LT. Safety problems and overall delay were not considered.

(Radwan, Abou-Senna, Navarro, & Chalise, 2014) coded a tool in Visual Basic to help traffic engineers determine the LT mode operation for a particular intersection for various time of day. The downside of this approach is that changing the LT mode throughout the day can confuse drivers. Confusion in traffic is unsafe.

3.3. Signal Displays

Drakopoulos et al. (Drakopoulos & Lyles, 2000) aimed at testing various LT signal displays and picking ones that are understood best by the drivers. The experiment consisted of 191 persons taking the survey on various LT sign configuration. Four practical measures that should improve driver comprehension
were found: use of permitted displays with discordant LT and through indications instead doghouse, and stacked three/five section permitted displays; elimination of simultaneous red ball and green arrow on the same signal face during protected phase; use of ‘LT Must Yield on Green Ball’ sign with doghouse displays only when sign message is visible while green ball illuminated; use of the permitted display without the supplemental sign ‘LT Yield on Yellow Arrow’.

Several research efforts revealed that red or yellow flashing indicators for permitted LT have better drivers’ understanding than circular green, especially for older drivers (Noyce, Fambro, & Kacir, Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays, 2000), (Knodler Jr, Noyce, Kacir, & Brehmer, 2003), (Noyce & Kacir, Drivers’ Understanding of Simultaneous Traffic Signal Indications in Protected Left-Turns, 2002), (Noyce & Smith, 2003), (Kacir, Brehmer, & Noyce, 2003), (Noyce, Fambro, & Kacir, Traffic Characteristics of Protected/Permitted Left-Turn Signal Displays, 2000), (Noyce D. A., Improving Left-Turn Safety Using Flashing Yellow Arrow Permissive Indications, 2003). This work led to the NCHRP 493 Report (Brehmer, Kacir, Noyce, & Manser, 2003), which findings are incorporated into MUTCD (Federal Highway Organization, 2009). The report evaluated safety and operational guidelines of the different LT indicators across the US. The authors tested the effectiveness of various permissive/protected displays and indicators in terms of: driver confusion, yellow trap, minimum signage,
allowance for exclusive only, and permitted only operation by time of the day, etc.

The findings recommended:

- The flashing yellow displays should be a part of MUTCD as an alternative control;
- The four sections all-arrow display in an exclusive signal arrangement should be used for protected/permitted control with flashing yellows;
- The flashing red indicators should be applied only to certain situations.

This research is later extended and supplemented by another NCHRP Study (Noyce, Bill, & Knodler Jr, NCHRP Web-Only Document 207: Evaluation of the Flashing Yellow Arrow (FYA) Permissive Left-Turn in Shared Yellow Signal Sections, 2014).

Knodler et al. (Knodler, Noyce, & Fisher, 2007) reached a conclusion that what a driver says he will do while driving, and what he actually does while driving is inconsistent.

(Qureshi, Spring, Malkayigari, & Rathod, 2003), in survey of the state DOTs finds that the capacity analysis should be conducted to decide when to upgrade the number of LT lanes, protected only phasing to be used for multiple LT lanes, and Dallas Phasing to be used for single LT lanes.

In 2012, Srinivasan (Srinivasan, et al., 2012) assessed the change from permissive to protected/permitted phasing and use of FYA for permitted LT. The authors estimated CMF for both scenarios. Generally, findings reveal that if the
protected phase is replaced with FYA permissive phase, crashes tend to increase; while the opposite is true when traditional permissive (green ball) is replaced with FYA phasing. This is confirmed by a later study on 222 signalized intersections in North Carolina (Simpson & Troy, 2015).

(Qi, et al., 2012) compared the LT approaches with initially protected only and traditional protected/permissive phases to installation of protected/permitted FYA. The study showed that the solid-yellow to solid-red change interval should not be used to distinguish between protective and permissive phases. Additionally, the study does not recommend FYA to be installed on high volume intersections. Similar findings are obtained by research of Pulugurtha (Pulugurtha & Khader, 2014). The authors added that intersections with high histories of crashes and at ramp intersections have only marginal benefits of FYA installation.

Recent literature review (Schattler & Lund, 2013) summarizes permissive protected LT control. The effectiveness and safety of flashing yellow arrow (FYA) indicators was documented. Studies on driver comprehension, driving simulator studies, crash based evaluations and operational effects of various protected/permitted studies are summarized. It concludes that FYA is generally a safe indicator for permitted LT and that should be adopted as an alternative protected/permitted LT control. This review is based on the NCHRP 493 Report. It summarizes LT indicators, without considering comprehensive literature review on LT phasing and sequencing.
(Appiah & Cottrell Jr, 2014) investigated whether the protected part of protected/permitted phase should be separated by a red arrow indicator (FYA delay) when FYA is in place. The authors used VISSIM to simulate hypothetical scenarios with varying approach speeds, volumes and duration of FYA delay. They showed that conflicts decreased as the duration of FYA delay increased. No significant impact on the delay was observed.

Davis et al. did two recent studies on LT indicators (Davis & Mudgal, Field Study of Driver Behavior at Permitted Left-Turn Indications, 2013), (Davis, Hourdos, & Moshtagh, Development of Guidelines for Permitted Left-Turn Phasing Using Flashing Yellow Arrows, 2015). The goal of these studies was to develop a spreadsheet-based tool to support a time-of-day switch between protected and permissive phase and to deliver appropriate gap acceptance models for LT. The models developed are specific for the Twin Cities area intersection types.

Although FYA shows very promising results, there are still some gaps in the literature. Most obvious issues are with high volume intersections, high opposing through and LT volumes, switching from protected only to FYA protected/permitted phase, and sites with previously high crash history.
3.4. Lead Lag Phase Sequencing

Indiana DOT (Hummer, Montgomery, & Sinha, 1989) looked at guidelines for lead/lag sequences. The relationship between LT sequences, delay and safety variables was tested within NETSIM simulation. Several guidelines were developed, which are supported by the flowchart for the decisions on the phasing sequence. The conclusion is that the lagging sequence can provide safety and delay advantages over the leading sequences.

In 2002, Li et al. (Li, Wang, & Han, 2002) did a theoretical study on lead/lag designs. The findings show that lagging designs on both intersections investigated produced less delay than leading design, but they do not affect through traffic delays. There was no effort of field or microsimulation testing of the results. Sheffer et al. (Sheffer & Janson, 1999) focused on protected LT only. Saturation flow rates, lost time, and accident rates are compared to reach the optimal results in terms of safety and capacity. The findings showed that there is no final conclusion whether to adopt lead or lag phasing. A mix of lead/lag protected only phasing is recommended for coordination advantages. This conclusion may be attributed to the field data, because the drivers from the area where the study was conducted were familiar with the regular timings, set up as lead/lag. Lee at al. (Lee, Wortman, Hook, & Poppe, 1991) showed that the lag design would always result in more delay than the lead one for actuated signals. The authors explained this by phase overlapping in actuated leading design. That can reduce delay of the through traffic when no opposing LT traffic is
present. The lagging design cannot overlap phases under this condition. It can only reduce delay by skipping the protected phase if no LT traffic present. The study from Nandam (Nandam & Hess, 2000) showed that lead/lag installation should not be a default decision and that dynamic change of a lead/lag phase by time-of-day can improve progression.

Li et al. (Li, Wang, & Han, 2002) researched two coordinated intersections in terms of LT signal phases, traffic patterns, and delays. Their findings show that a lagging upstream and downstream design when coupled, leads to minimum delay for the intersections in terms of coordination.

Liu (Liu, 2014) focused on the efficient start for lagging LT phases for fully actuated isolated intersection and a seven-intersection coordinated actuated arterial. The author simulated five different LT control schemes in VISSIM. There were two types of LT control tested: standard (lead-lead, lead-lag, lag-lag) and intelligent, which is an algorithm programmed for efficient start and end of lagging LT phasing. This algorithm addresses the issue of phase transition and termination according to the prediction based logic.

In terms of isolated intersections, the intelligent lagging LT phasing resulted in shorter cycle lengths, less delay, shorter average green duration, and higher average delay for non-critical LT phase, when compared to the standard control. For the arterial, intelligent LT phasing was better than standard control in terms of overall network delay and average intersection delay. The tests were not based on actual field
volumes. The study did not consider protected/permitted LT phasing, only protected ones.

From these studies, there is no clear consensus on whether to use lead or lag LT. There are no clear findings that will show that a particular design is better than the other in terms of both safety and efficiency.

3.5. Summary of Literature Review

As the literature review reveals, there is a substantial body of research on LT phasing and sequencing at signalized intersections. The gaps found in current guidelines and recommendations are summarized:

- The guidelines on signal phasing operations are mostly based on the research from the 1980’s on limited numbers of intersections evaluated;
- Previous studies are mostly focused solely on safety or efficiency analyses, without considering mutual impacts;
- Proposed guidelines do not clearly define what type of protection is needed: protected/permitted or protected only? (Asante, Ardekani, & Williams, 1993);
- There is no definitive guidelines on whether to adopt lead or lag sequencing and what can be safer or efficient
- There is no consensus on FYA and what is the ultimate display outline that should be followed. There are challenges associated with how to address

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change from protected-only to protected/permitted and do high volume
intersections benefit from FYA installation?

Evaluation of these guidelines can be beneficial in terms of lower LT delays,
decreased queues and higher vehicle throughput, while keeping the safety standards
high. It will also be an additional step toward unified LT guidelines, which are
currently ambiguous. Testing various scenarios with the computational tools such as
traffic signal optimization, traffic microsimulation and safety surrogate software may
help toward the development of lead/lag sequencing guidelines.

3.6. Research Needs and Opportunities

The authors propose several ways to assess, critique and enhance current guidelines
and recommendations for LT at signalized intersections. These are: driving simulators
and driving simulators linked to microsimulation software, microsimulation coupled
with SSAM and augmented reality approach.

3.6.1. Driving Simulators

Driving simulators can be used to test various field conditions (Godley, Triggs, &
Fields, 2002), (Van der Horst & Hogema, 2011). High integrity simulator has to have
appropriate fidelity and validity (Riener, 2010). Fidelity shows the degree of realism
in simulation, while the validity refers to the match of the behavior in the real world
and in simulation. In other words, fidelity shows how simulator’s visual components replicate the real world layout, while the validity measures the reality of driving in the simulator. Left turns can be assessed with:

- Driving simulators only, with created virtual backgrounds
- Driving simulators linked to microsimulation software (e.g., VISSIM, Aimsun, Corsim, etc.)

Recent studies confirmed that driving simulators could be used to assess traditional and innovative LT designs (Marnell, Tuss, Hurwitz, Paulsen, & Monsre, 2013), (Muttart, Fisher, & Pollatsek, 2014), (Zhao, Yun, Zhang, & Yang, 2015), (Ogle, Ladue, Sarasua, Davis, Mammadrahimli, & Zhao, 2015). Simulators also can be used to test gap acceptance and driving behavior of licensed and unlicensed drivers (de Winter, Spek, de Groot, & Wieringa, 2009).

As the technology progresses, driving simulators are becoming more reliable. Integration of driving simulators to microsimulation can have many benefits. Microsimulation can control traffic volumes, driving behavior, vehicular speeds, routing of vehicles and traffic signal controls. With enough field data, proper calibration and validation, microsimulation can represent real world traffic condition (Suda, et al., 2005), (Punzo & Ciuffo, 2011).

Upgrade of traffic conditions into 3D road environment can allow the driver to see 3D scenes in real time (Martin, Zlatkovic, & Tasic, 2012). Software such as
ARCHSIM (Rhino/Grasshopper, 2015), NADS model (University of Iowa, 2015), and VTI simulator (The Swedish National Road and Transport Research Institute (VTI), 2015) can incorporate the driving simulator in microsimulation-based traffic conditions. The person running the driving simulator linked to microsimulation will be represented by one vehicle in the microsimulation. In this way, the driver gets the impression of real traffic movements.

These approaches can be used to model intersections with specific LT geometry, turning and opposite volumes and various signal control plans. Outputs can point out which of the tested guidelines are valid and which ones should be reconsidered. This can be done by evaluating various signal displays configuration, signal control, phasing and sequencing, etc. Testing can also reveal what is the difference in reaction time between older and younger drivers. This approach also gives an opportunity to assess both safety and efficiency of various LT designs.

The driving simulators experiments involve human subjects and should be rigorously designed. For example, Dixit et al. (Dixit, Harrison, & Rutstrom, 2014) showed variability across the results when people are given financial incentives to perform the tasks in the simulators. However, in the real world, people do not get the incentives.
3.6.2. Microsimulation and SSAM software

Recent studies proved that microsimulation could be matched to existing traffic conditions in terms of vehicular conflicts (Huang, Liu, Yu, & Wang, 2013), (Fan, Yu, Liu, & Wang, 2013), (Vasconcelos, Neto, Silva, & Seco, 2014), (Essa & Sayed, 2015). Thus, microsimulation models have to be properly calibrated and validated. These models should be used in conjunction with SSAM tool (Gettman, Pu, Sayed, & Shelby, 2008) that can assess various LT signal phasing and sequencing alternatives for different lane geometry in terms of both safety and efficiency.

In this way, debatable LT guidelines and recommendation could be evaluated. The results can reveal if protected/permitted phase can be installed instead of protected only, reducing delay time, queue formations and air pollution. This approach already shows promising results (Stevanovic, Stevanovic, Jolovic, & Nallamothu, 2012), (Jolovic, Stevanovic, & Martin, 2015). However, it needs further evaluation, especially in the severity of the LT conflicts.

The disadvantage of this approach is that it cannot evaluate various signal display configurations, as it is the case with driving simulators. Also, driver’s perception and behavior may not be accurately presented, as it requires highly skilled modeler in order to calibrate and validate the model. In some cases, even with the proper setup of the model, there are additional constraints as the VISSIM is the computational model with limited capabilities in mimicking drivers’ perception.
3.6.3. Augmented Reality (AR)

Augmented reality is a combination of real and virtual objects in real time, in which the user cannot distinguish the difference between the real and augmented world (Hussain & Kaptan, 2004). AR is a promising approach because it can offer realistic environments for driving enhancement with virtual objects.

AR has been tested for two-way stop controlled intersection in two studies (Moussa G. S., 2006), (Moussa, Radwan, & Hussain, 2012), which showed that augmented reality could be used to evaluate various traffic scenarios. Further, the AR approach can successfully assess driver behavior (Hussain, Radwan, & Moussa, 2013) and help older drivers execute LT (Rusch, Schall Jr, Lee, Dawson, & Rizzo, 2014). The extension of such research to signalized intersections with the emphasis on LT movements would be highly beneficial.

Projection paths as an augmented aid in terms of dynamic driver vehicle interface (e.g., green arrow projected on the windshield when there is sufficient gap to make a turn, or a red bar when not so) can be used to extend research on LT (Tran, Bark, & Ng-Throw-Hing, 2013), (Misener, et al., 2010). Findings show that AR could be successfully implemented to support evaluation and redefining of left turn guidelines. LT displays and driver perception of new display types such as FYA can be also evaluated using the AR technique.

When designing augmented experiments, one has to pay attention to the registration of the virtual objects (alignment and scaling), non-rigid objects and their
proper positioning (e.g., trees change shape with the wind), and different terrain elevations. Also, when designing an AR environment, the following has to be taken into consideration: scene visibility, scene realism, scenario realism, driving comfort, equipment comfort, level of risk, and the whole system fidelity. These factors can affect the accuracy of the results significantly (Moussa G. S., 2006). Motion sickness can play an important role in these experiments (Tran, Bark, & Ng-Throw-Hing, 2013).

3.7. Conclusions

Left turn guidelines are primarily based on the research that considers safety alone. Instead, efficiency (or throughput maximization), LT and overall delay reduction, should be coupled with safety and mutually considered.

Testing some of these guidelines in the field can be dangerous and infeasible in some cases. For example, it is not safe to switch phase from protected-only to protected/permitted signal at the intersection and assess the impact of change; which could lead to serious consequences. Also, switching phases could lead to inaccurate demonstration of the driver perception, because regular drivers are used to wholly different signal plans. Other guidelines would be hard to test in the field due to their specific nature (specific proportion of heavy vehicles turning left, LT volume,
opposing traffic flow, etc.). From that standpoint, the authors propose that the following computational and simulation tools be used:

1. Driving Simulators and Driving Simulators Linked with Microsimulation

Tools should be deployed to:

- Evaluate and propose guidelines on LT sight distances;
- Assess gender and age effects on LT maneuver execution under various traffic conditions;
- Measure LT delays for combination of various signal phase designs and intersection volume flows;

2. Microsimulation coupled with surrogate safety models such as SSAM should be deployed to:

- Evaluate effectiveness of signal phasing and sequencing designs for various types of intersections in terms of delay and vehicular conflicts;
- Point the optimal signal designs for various intersection types;
- Measure the impact of various heavy vehicle percentages on LT. With the development of more accurate surrogate models, pedestrian safety under different LT designs can be also evaluated;

3. Augmented (enhanced) reality should be deployed to evaluate:

- The LT gap acceptance for various intersection types;
- The drivers’ perception and execution of LT maneuvers under stressful situations and drivers’ fatigue;
• The distraction from the field and also from electronic devices;
• The safety of LT maneuvers under condition of reduced visibility (e.g., sunrise and sunset, fog, smog, etc.)

As technology progresses, researchers have more opportunities to evaluate traffic guidelines using computational and tech tools, such as microsimulation software and driving simulator boxes. Augmented reality, which has high potential as a research tool, is an underutilized approach in traffic applications. Utilizing these tools in a proper way can boost research on left turns and open new views on how to approach everyday traffic problems.
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CHAPTER 4 - REVISION OF LEFT-TURN GUIDELINES
USING OPTIMAL DESIGN OF TRAFFIC SIGNAL PHASING
IN A MICROSIMULATION ENVIRONMENT

Authors: Dusan Jolovic, Peter T Martin, and Aleksandar Stevanovic. Advances in Transportation Studies, An International Journal, 2016 Special Issue Vol. 2

ABSTRACT
Several factors are usually considered when recommending left-turn phasing at signalized intersections: the volume of through traffic opposing the left-turn maneuvers, the volume of left-turn traffic, the speed of the opposing traffic, sight distance, crash history, and cycle length. The goal of this paper is to find the optimal signal phasing designs that can improve efficiency and safety of the particular signal design in the field in order to test current recommendations and guidelines on left-turn treatments. The researchers assess the impact of the number of rings in a phasing structure, the number of phases and whether to adopt lead or lag phasing on the safety and efficiency of a four-legged signalized intersection. A comprehensive set of 338 signal phasing designs is developed and the impacts are modeled using VISSIM microsimulation. The efficiency of signal phasing sets is evaluated in VISSIM, while the safety aspect is assessed using SSAM software. Optimal scenarios are tested using sensitivity analysis for various traffic flows. The findings show that the current left-
turn guidelines may over-protect left-turners which results in reduced efficiency and left-turn delays that can be increased by up to 25%. Revised guidelines should contribute to the decreased delays for left turning vehicles, while keeping the safety standards high.

*Keywords*: left turns, microsimulation, SSAM, conflicts, safety, signal optimization
4.1. Introduction

Optimization of traffic signal operations has been actively researched since the first automatic traffic signals were deployed in the field. The history of developing optimal signal phasing designs, for safe and efficient signal operations is long. In traffic flows dominated by passenger vehicles, optimal signal designs are inherently achieved in the process of developing left-turn phasing treatments for main-street and side-street intersection approaches. Several factors are usually considered when recommending left-turn phasing at signalized intersections including the volume of through traffic opposite to the left-turn maneuvers, the volume of the left-turn traffic, the speed of the opposing traffic, sight distance, crash history, and cycle length [1].

Turning vehicular traffic crossing the intersection usually diminish intersection capacity. Left-turns may conflict with opposing through traffic’s right of way, contributing to more near misses and crashes. Protected turns improve safety at left-turn approaches with high-volume left-turn traffic or high speed of the opposite traffic. Permitted turns promote efficiency, while protected/permitted phasing addresses both safety and efficiency. The last holds true for undersaturated conditions.

Optimal signal phasing for a 4-leg signalized intersection means deciding on the optimal number of phases, the proper number of rings to be used, whether to adopt lead or lag left turn phasing and the proper left turn operation setup. To assess these factors, the authors developed and tested 338 different signal phasing designs
(full iterative design) in microsimulation. Evaluation of these phase designs was used to determine the best signal designs in terms of safety and efficiency. Once the best signal designs are found, the current guidelines and recommendations for left turn treatments are tested. Most of the guidelines are based on Traffic Engineering Handbook (TEH) [2]. Specifically, the authors tested the following TEH recommendations:

1. Protected only phasing for left turns should be implemented if the opposing flow rate is greater than 1,100veh/h and the opposing speed limit is 45mph,
2. Protected only phasing for left turns should be implemented if there are three opposing traffic lanes and the opposing speed limit is 45mph or greater,
3. Protected only phasing for left turns should be implemented if the opposing flow rate exceeds 1,100veh/h and the percentage of left turns exceeds 2.5%, and,
4. For three opposing through lanes, opposing speed limit of 45mph and left turn flow of 75veh/h, some protection is recommended – but exact type of protection is not specified [3].

Current left turn guidelines are mostly based on the research conducted in the 1970’s and 1980’s [4]. Advancement in the field of electronics and vehicle technology should be followed by guidelines revisions on a regular basis. This paper aims at making the first step toward the revision of the current guidelines.
The test bed is a four-leg signalized intersection in Boca Raton, FL. The authors develop a compressive set of 338 signal phasing designs, whose impacts are modelled using VISSIM microsimulation [5]. A high-fidelity microsimulation model closely matches measured field conditions. The phasing designs follow best engineering practices. The model generates efficiency performance measures and exports trajectory data to a Surrogate Safety Assessment Model (SSAM), an industry standard for surrogate safety assessments. Sensitivity analysis is conducted for the optimal scenarios found to test performance of left-turn designs. The goal of the paper is to find the optimal signal phasing designs that can improve efficiency and safety of the particular signal design in the field and test safety guidelines on left-turn treatment at signalized intersections.

4.2. Literature Review

Optimization of signal phasing to improve safety and efficiency of signalized intersection has been addressed by a number of previous studies [6] although not as much as for example optimization of signal timings [7, 8]. Some possible explanation for the lack of signal phasing optimization studies: the inability of optimization software to account for safety measures (of their surrogates), the simplicity and quantity of possible phasing designs (measured in hundreds versus thousands of signal timing designs), a need to integrate signal head/display indications with signal...
controller features in the optimization scheme, etc. In spite of all of these difficulties several studies addressed this issue. Lam et al. found that the integrated design of lane allocation pattern and signal timing plan can increase the capacity and significantly minimize the overall delay, stop and fuel consumption at a signalized intersections [9]. The authors showed that the minimization of flow ratio might not lead to an optimal solution in terms of delay and number of stops.

Wong et al. [6] developed a lane-based signal optimization model to maximize intersection capacity and minimize cycle length. The model is formulated as Binary-Mix-Integer-Linear-Programs and solved by standard branch-and-bound routine. Wong et al. [10] addressed the reserve capacity maximization of isolated signal controlled junctions. Their algorithm is formulated as BMILP and solved by branch and bound technique for a global optimum solution. However, intersection safety was not considered. Yin [11] deployed three models to determine robust optimal timing plans on a fixed time signalized intersection. These models can solve for local optimization but not for global optimum. Safety aspects were not addressed.

Ma [12] developed an integral optimization model for signal timing plans and lane allocation pattern. Their GA algorithm coupled with ArcGIS evaluated their model. Xuan et al. [13] optimized a pre-signal system for oversaturated intersections. However, the concept is not suitable for undersaturated conditions and safety was not addressed. Stevanovic et al. [8] applied genetic algorithm and microsimulation to optimize signal timings for surrogate safety measures and network efficiency. They
reached a balance between safety and efficiency but signal phasing design was not part of the optimization process.

Signal phasing optimization studies are scarce and mainly private-car-environment based. The signal phasing process can often be substituted by the design of left turn phasing. At the intersections where little or no transit vehicles or pedestrians, optimizing signal phasing reduces to simply determining the best left-turn phase design. Several studies addressed this issue in the past both from efficiency and safety perspectives.

Agent et al. [14] developed four types of warrants for providing a protected left-turn (LT) phase. Asante et al. [3] found that protected LT have minimum accidents and conflict rates but high delays. The protected permissive mode has lower delay but high accident and conflict rates, while the permissive mode has lowest delays but very high conflict rates. Lakkundi et al. [15] developed guidelines for LT at signalized intersections using in-house developed simulation software. Minimum LT volume of either 85% LT capacity or LOS E delay was used. The safety impact was not considered.

Zhan et al. [16] proposed a framework for the development of guidelines of LT operations at signalized intersections in Texas. Yu et al. [17] investigated LT operations thoroughly, considering operational and safety impacts offering a detailed guideline on how to implement specific LT phasing treatment. Zhao et al. [18] showed that intersection spacing and phase had no significant impact on traffic
progression and that if the number of signals was more than sixteen, two-way progression cannot be achieved. Kurfees [19] presented a technique where all through movements are served twice per cycle and each LT phase is served once. This paper confirmed that serving the LT twice within each cycle has a negative impact on arterial progression.

To summarize, the optimization of signal phasing fails to address both safety and efficiency in a holistic way. Similarly, although several studies addressed LT phasing treatments, many failed to consider the impact of various phasing designs on intersection performance and the number of conflicts. This paper bridges the gap in the existing body of knowledge by comprehensively evaluating how various signal phasing designs impact efficiency and safety of signalized intersections.

4.3. Methodology

The methodology is presented in the Figure 6.
4.3.1. Development of Signal Phasing Design Scenarios

The authors developed 338 different signal phasing design scenarios for a standard 4-leg intersection. A combination of one-ring and two-ring phasing structures, lead-lag phases, and protected, permitted and protected/permitted phasing was considered. Non-standard phasing (e.g., East-Bound Left (EBL) is in protected plus permitted mode, while West-Bound Left (WBL) is in protected only mode) was also considered. The phasing scenarios are grouped into eight distinctive groups,
categorized from the simplest toward more complex designs. Table 3 summarizes the scenarios developed.

<table>
<thead>
<tr>
<th>Groups</th>
<th># Rings</th>
<th>Number of Phases</th>
<th>Scenarios in group</th>
<th>Total Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1</td>
<td>2</td>
<td>1_1</td>
<td>1</td>
</tr>
<tr>
<td>Group 2</td>
<td>1</td>
<td>3</td>
<td>2_1 to 2_8</td>
<td>8</td>
</tr>
<tr>
<td>Group 3</td>
<td>1</td>
<td>3</td>
<td>3_1 to 3_8</td>
<td>8</td>
</tr>
<tr>
<td>Group 4</td>
<td>1</td>
<td>4</td>
<td>4_1 to 4_32</td>
<td>32</td>
</tr>
<tr>
<td>Group 5*</td>
<td>1</td>
<td>4</td>
<td>5_1</td>
<td>1</td>
</tr>
<tr>
<td>Group 6</td>
<td>2</td>
<td>6</td>
<td>6_1 to 6_16</td>
<td>16</td>
</tr>
<tr>
<td>Group 7</td>
<td>2</td>
<td>6</td>
<td>7_1 to 7_16</td>
<td>16</td>
</tr>
<tr>
<td>Group 8</td>
<td>2</td>
<td>8</td>
<td>8_1 to 8_256</td>
<td>256</td>
</tr>
</tbody>
</table>

* split phasing

Total:338

4.3.2. Data Collection

The test bed consists of three intersections located on Glades Road, Boca Raton, FL. The key intersection is Glades Rd & NW 4th Ave, in the middle of the segment. Figure 7 shows intersection geometry and other necessary detailed information (e.g., movement volumes, speed limits, number of lanes and pocket lengths, etc.). The simulation model also incorporates two nearby intersections (Glades Rd & NW 13th ST and Glades Rd & NW 2nd Ave) to account for proper main-road progression, as recommended by the literature [17]. The site is chosen because of access to the field data (e.g., close circuit television - CCTV cameras, travel times) and the appropriate left-turn geometry (each approach consists of one exclusive lane). A significant factor in selecting the test-bed intersection was number of left-turn lanes/pockets as it is
common knowledge that left turns with multiple lanes cannot have permitted left-turn signal displays.

The main data source were video recordings from a CCTV camera, mounted at the test-bed intersection. They were used to extract turning movement counts (TMCs), queue lengths, and headways between vehicles. Travel time data were available for several consecutive days around the time when the video footage was recorded. Travel time data came from continuous trajectories “QStarz” GPS data and point-to-point “ACYCLICA” travel time measurements. Boca Raton Traffic Division
provided signal timings and phase sequence data. Google Maps were used to obtain speed limits, places for stop/yield signs, and to ensure accurate geometry of the simulation model.

The CCTV footage was manually processed to extract TMCs, vehicle headways and queue lengths. It was not possible to record complete queue lengths for the NB approach due to the camera’s view restrictions. This process was performed for the main intersection only.

To measure vehicular headways (saturation flow rate) the authors used the traffic engineering method presented in Highway Capacity Manual [20]. Note that the headways were not collected for the WBL/SBL movements, due to insufficient number of vehicles in the queue to perform computations. The main purpose of collecting headways was to ensure proper queue discharge in the simulation model and mimic vehicular behavior in the absence of better measures for vehicular conflicts.

4.3.3. Development of VISSIM Model

The VISSIM model was developed, calibrated and validated for the PM peak, from 4:30PM to 5:30PM, with 15-min of warm-up time. Two reasons contributed the decision to use VISSIM (version 5.3) software: it is one of the few traffic simulators that can output trajectory data necessary for post-processing in SSAM; the partial VISSIM geometry of the testing site was available.
Calibration of the model is done for TMCs, queue lengths, and vehicle headways. To calibrate TMCs, VISSIM model’s traffic inputs and routing decisions are developed in a way to correspond to the TMCs from the CCTV. The queues in VISSIM were manually observed and noted down during the simulation runs due to inaccurate results from VISSIM’s queue counters.

Two steps were necessary to calibrate the headways: enable a special evaluation in VISSIM and modify driving behavior to match the field headways. The special evaluation option was enabled in VISSIM to obtain the discharge rates, which are measured at intersection’s stop lines in the model. Once the headway data are retrieved from the simulation output the common headway-computation method was applied [21]. The driving behavior parameters were modified until the simulation headways matched field ones. The parameters ‘Additive part of safety distance’ was reduced from value of 2.0 to 0.8; parameter ‘Multiplicative part of safety distance’ was reduced from 3.0 to 1.8, increasing saturation flow rate from 1300veh/h to 1550veh/h.

The TMCs and queue lengths were checked again to ensure that they did not significantly change during the headway calibration process. The model was validated based on travel times between NW13th St and NW4th Ave and NW4th Ave and NW2nd Ave, bi-directionally. Five simulation runs were averaged and compared to the field data to account for the stochastic nature of the microsimulation. The results of the calibration and validation process are shown in Figure 8.
4.3.4. Incorporating Signal Phasing Designs in VISSIM

Synchro software is used to develop and fully optimize all the phasing scenarios developed. Each scenario was optimized in terms of cycle lengths, green splits and offsets. The reference point for all offset optimizations was the start of the green time for coordinated phases.

Once the scenarios were optimized, they were incorporated into the calibrated and validated VISSIM model resulting in 338 distinctive VISSIM models loaded with
different signal phasing scenarios. VISSIM models were run 5 times each. Five replications have been shown to create enough variability in VISSIM’s outputs [22]. An external program built in Visual Studio automatically executed 1690 VISSIM runs (338 files x 5 random seeds). The VISSIM outputs were network and intersection delays, left-turn delays, throughput, and stops.

4.3.5. Post-processing of VISSIM Data in SSAM

SSAM software developed by FHWA can deliver surrogate safety metrics for trajectory data from various simulation tools [23]. The software processes trajectory data from the microsimulation models to estimate various types of conflicts. A conflict represents an observable situation in which two or more vehicles approach each other in the time and space to such extent that there is a risk of collision were their movements to remain unchanged [24]. SSAM identifies four types of conflicts: crossing, rear-end, lane change, and conflicts with no classification [25]. Trajectory data files were exported from VISSIM and post-processed in SSAM to get the number of conflicts from the model. Outputs from SSAM were then further processed and compared with network performance measures to assess safety-related performance of various signal phasing scenarios.
4.3.6. Determination of Best Scenarios and Sensitivity Analysis

Once the data from VISSIM were post processed, the best scenarios were chosen in terms of safety and efficiency. In other words, the authors searched for scenarios that produced minimum conflicts, minimum overall network delay and number of stops, while maximizing throughput. Those scenarios were then tested for increased traffic volumes. Traffic volumes were increased by 20% and 40% to reflect future growth in traffic demand, based on engineering judgment.

4.4. Results

When considering efficiency and safety in signal phasing designs, the traffic signal practitioners are likely to opt for designs which improve safety. However, the safety surrogates, such as conflicts, are not always strongly correlated with the potential number of field crashes or similar metrics [8]. This leaves researchers an opportunity to search for signal phasing solutions that balance safety and efficiency. Such a balance is easiest to find by developing Pareto Fronts of potential solutions. Figures 9, 10 & 11 show the entire set of signal phasing scenarios in the Pareto safety-efficiency search space. A number of conflicts, from SSAM, is used as a proxy for safety, whereas efficiency is represented by delay, number of stops, or throughput (number of vehicles that completed the trips).
Figures 9-11 reveal two observations. First, many signal designs are similar in terms of both efficiency and safety – those designs form clusters of solutions located in lower-left corners of the charts for delays and stops (Figures 9&11) and the upper-left corner for the charts for throughput (Figure 10). Second, the Pareto Fronts are not always prominent (sometimes consisting of only 2-3 solutions), which suggests that many efficient solutions are also safe too, and vice versa. Each of the Figures 9-11 is accompanied with a table listing all of the solutions that belong to a Pareto Front.
Figure 9e) shows which signal phasing designs belong to a Pareto Front in terms of the Total Conflicts and Total Delay. If searching for a signal phasing design to reduce the overall number of conflicts, while keeping delay close to minimum, the choice is between those two solutions. Similarly, Figures 10 & 11 show a Pareto Front in the
search space of conflicts and throughput, and conflicts and number of stops, respectively.

Results from the Figures 9-11 are logical and expected. With smoother traffic flows, resulting in lower delays, fewer stops and an increased number of completed trips, conflicts between vehicles decrease for all the types (but not at the same rate). And
vice versa – as traffic performance becomes less efficient, the number of conflicts increases.

From the Figures 9-11, it can be observed that the same five scenarios constitute most of the Pareto fronts. All of these scenarios have cycle lengths of 160 seconds and fewer than eight phases. Only one scenario has a ring-barrier design with only one
ring (scenario 3_5). The scenarios follow similar trends in terms of intersection splits: EBL splits are between 25sec and 30sec, WBL splits are between 21sec and 25sec, West-bound through split is 65 seconds and East-bound through splits are between 65 and 74 seconds for all the scenarios. The scenarios are presented in Figure 12.

Figure 12 Optimal Signal Phasing Scenarios with Corresponding Legend

4.4.1. Sensitivity analysis for left-turn operations

To test the TEH recommendations on the left-turn treatments, the authors conducted sensitivity analyses, where selected best scenarios were evaluated, in terms of safety and efficiency, for a range of traffic volumes. Scenarios that constituted most of the Pareto Fronts were tested for 20% and 40% higher traffic flows than measured in the field. Figure 8 shows the results.

Figure 13A shows the number of conflicts between EBL and the opposing through movement. EBL is a heavy turn movement currently handling 170 veh/h,
while the opposing through traffic is about 1,150 veh/h. For the current (field) conditions, the number of conflicts is below 1 for all the scenarios tested (both protected-only and protected/permitted mode).

When the traffic volume increases by 20%, the number of conflicts remains low: less than three conflicts per hour for all of the scenarios tested. It is only when the traffic volume is increased by ~40% of its original value (EBL=240veh/h and WBT=1610veh/h), that the permitted phasing becomes more prone to conflicts.

Figure 13B shows the number of conflicts between WBL turn traffic and the opposing through movement. WBL handles fewer vehicles than EBL, around 60 veh/h, while the opposing traffic is around 1,150 veh/h. Increasing the traffic on main approaches (E-W) by 20% does not increase the number of conflicts for any of the tested scenarios. In contrast, 40% increase in traffic on main approaches (E-W) reveals a higher number of conflicts for all of the ‘optimal’ signal phasing scenarios. It should be noted here that the increase in the number of conflicts is the highest for scenarios 7_7 and 7_15, both of which represent protected/permitted modes.

Figure 13C presents delay (in seconds) for EB left turns. For all the traffic volumes tested, the lowest delay is experienced in the scenarios where left turns operate under protected/permissive mode (scenarios 3_5 and 7_7). Similar results were obtained for WB left turns, as shown on Figure 13D. In average, the drivers will spend 25% less time waiting to turn left when a protected/permissive mode is in operation.
4.5. Discussion

From the best scenarios found, the following observations can be made:

- Lower versus higher number of phases - all the optimal designs have fewer than eight phases. Four out of five optimal designs have six phases. The authors suggest that these results are due to low volumes of traffic on side street (N-S) direction, where a single phase can accommodate all the vehicles on that approach. For low left-turn volumes (less than 50veh/h) and one
opposing lane, when the speed limit is 30 mph or less, permitted-only phasing is suggested.

- Lead versus lag left turns - the optimal scenarios do not show any consistency on whether to adopt lead or lag left-turn mode. Thus, no clear recommendations can be made based on the executed experiments.

- Phase design with single ring versus double ring - only one out of five optimal designs is a single-ring design. Thus, it seems that double-ring designs provide more safety and efficiency benefits than the others do. Additionally, Figure 13A shows increased number of conflicts for single-ring scenario, for a high number of left turns (more than 200 veh/h).

- Intersection splits follow the similar trends for all the movements on main approaches (E-W). This means that the optimal signal designs consistently utilize similar green splits to provide best safety and efficiency.

Sensitivity analysis reveal that the current guidelines and recommendations for left turn treatment should be considered for revision. Specifically, the authors found that:

- Protected/permitted left turns should be considered even when the opposing amount of traffic is higher than 1100 veh/h (as recommended by TEH) on a facility with 3 opposing through lanes and 45mph speed limit. The results from our experiments did not show that protected/permitted designs are less safe or more efficient than the others.
• Preliminary findings show that the boundary of 1,100 veh/h should be raised to about 1,400 veh/h. This increment of 300 veh/h needs to be comprehensively tested in the future studies.

• Very low number of conflicts (less than 3 per hour) is observed for both protected and protected/ permitted phasing designs, when the opposing traffic is less than 1,400 veh/h and left turn flow is less than 200 veh/h. This is valid for 45mph speed limit on a tested facility. Current TEH guidelines recommend protected only mode when the opposing traffic is higher than 1,100 veh/h and the speed limit is 45mph.

• Preliminary findings also show that protected-only phasing should be implemented when left-turn traffic volume exceeds 200 veh/h and opposing traffic is 1,400 veh/h or higher for a 45mph speed limit on a the corridor. This is valid for the facility with 3 opposing lanes. Current standards [3] recommend some protection but do not specify exactly what type of protection for left turns is required.

• Delay for left-turn vehicles can be reduced by approximately 25% if protected/ permitted left turns are instituted instead of protected-only left-turns, keeping the safety standards high. Current standards for protected/ permitted mode implementation lead to increased delay for left turns.
4.6. Conclusions and Limitations

The goal of the paper is to evaluate various signal phasing designs to understand which of those can improve efficiency and safety of signalized intersections. Particular attention is given to replicate field conditions and compare results to the guidelines/recommendations from industry standards on left-turn treatments at signalized intersections. Partially, motivation of this paper was to test if there is a need for revision of the left-turn design industry guidelines that were mostly developed in the 1970’s and 1980’s. Since then, the technology has advanced and acceleration/braking systems have been improved, requiring revision of related guidelines on a regular basis. The most important conclusions reached in this study are:

1. Safety and efficiency align very well along with each other. The experiments have shown that some of the safest signal phasing designs are at the same time the most efficient, and vice versa.

2. Design plans with double-rings seem to outperform single-ring designs, which agree with current practice. Only one out of five best scenarios had a single ring design (3_5).

3. If any of the intersection approaches have moderate traffic flows, one phase instead of two should be considered, thereby reducing lost time and increasing the efficiency of the intersection. Four out of the five optimal signal designs in
this study have six phases in total. That is due to moderate volume on N-S approach, where one phase per approach accommodates the traffic flow.

4. The findings are mixed on lead versus lag left-turn modes. No definite conclusion can be reached based on the experiments of this study. Lead and lag left-turns are often provided for efficiency and in conjunction with signal timing optimization, especially when offset and cycle lengths are considered to provide the best progression between intersections.

Preliminary conclusions are reached regarding tested left-turn guidelines. All of the recommendations tested from TEH [2] should be considered for revision. Our results show that current guidelines may over-protect left-turners which results in reduced efficiency and left-turn delays that can be increased by up to 25%. At the time when vehicles start to be better equipped with various sensors to recognize potential conflicts and warn drivers, experiments with vehicle-to-vehicle and vehicle-to-infrastructure technologies (a trend that will only increase in future) it might be the time to consider new (preliminary) recommendations:

1. Protected/permitted phasing should be implemented if the opposing flow rate is greater than 1,100 veh/h but less than 1,400 veh/h, while the opposing speed limit is 45 mph.

2. Protected/permitted phasing should be implemented if there are three opposing traffic lanes and the opposing speed limit is 45 mph.
3. Protected/permitted phasing for left turns should be implemented if the opposing flow rate is greater than 1,100 veh/h, but less than 1,400 veh/h and the percentage of left turns is less than 10%.

4. For three opposing through lanes, an opposing speed limit of 45mph, an opposing flow rate higher than 1,400 veh/h and left-turn flow that exceeds 200 veh/h, protected-only mode should be implemented.

All the recommendations above are valid for a facility with three opposing lanes.

As a computer model, VISSIM cannot account for drivers’ perception for various phasing option designs. Additionally, these findings are based on one signalized intersection. The difference in intersection configuration, geometric parameters, driver behaviors and operational parameters might affect safety measures differently. Conflict severity and frequency, maximum speed of conflicting vehicles should be also considered. Future research should address additional scenarios with various: ratios of main vs. side street volumes, speed limits, driving behaviors, and proportions of left-turn volumes.

4.7. Acknowledgments

The authors express their sincere gratitude to the City of Boca Raton Traffic Division for the data access provided and all the necessary hardware and software support.
4.8. References


5. CHAPTER 5 - THE IMPACT OF TRAFFIC SIGNAL CONTROL PARAMETERS ON FREQUENCY AND SEVERITY OF INTERSECTION-RELATED CRASHES


ABSTRACT

While previous research in the area of intersection crash modeling mostly distinguishes between signalized and unsignalized intersections, this paper provides a detailed insight into the association of signal timing parameters with intersection-related crashes. Crash data were collected for 148 urban signalized intersections in Fort Lauderdale, Florida, for the period of 11 years. Crash frequency is modeled by using negative binomial regression, while distinguishing between the crashes that occur upstream and downstream of the intersection. Crash severity is modeled by using multinomial logit model for three crash categories: no injury, possible injury, and severe injury or fatality. The results obtained from the crash frequency models show that crashes occurring upstream of the intersection are more influenced by signal timing parameters than those occurring downstream. The average annual daily traffic (AADT) volume, cycle
length, offset, number of phases and all-red clearance time significantly impacted intersection crash frequency. Crash severity was influenced by the speed limit, AADT, all-red clearance time, left turn phase setup, number of signal phases, number of approach lanes, split time, and cycle length. Crash frequency models obtained and presented in this paper show the potential for future exploration of developing separate models for crashes that occur upstream and downstream of the intersection. Crash severity models developed show the need for future consideration of signal timing parameters when modeling intersection-related crashes.

*Keywords: traffic crashes, crash frequency, crash severity, signal control parameters, negative binomial, multinomial logit*
5.1. Introduction

After a multiple-year decline in traffic fatalities, crash rates increased in 2014 and 2015. Almost 30% of those fatalities occurred at intersections (1, 2). The quality of traffic control at signalized intersections plays a key role in keeping the traffic flowing with minimum disruptions while keeping safety standards high and avoiding potential conflicts. Signal timing parameters which drive the controller’s logic, are hypothesized to have considerable influence on traffic crashes. This study addresses intersection safety by investigating the impact of traffic signal parameters (i.e., signal timing, signal phasing, and phase sequencing) on crashes which occurred in the middle of intersections and the approaches within the intersection vicinity.

Previous studies that focused on intersection crashes explore the effects of various features of an intersection on crash frequency and severity: geometric design (3), traffic control (4), operational characteristics, the capacity of the approaches (5), speed (6) and intersection sight distance (7, 8, 9). One study examined the effects of traffic signals, by going beyond simple differentiation between signalized and stop-controlled intersections, and analyzing the traffic signal timing parameters in depth to determine how they contribute to crash frequency and severity (10). Previous research emphasizes the need to develop safety performance-based standards for determining the duration of signal timing intervals (11). While few research efforts explore the
relationship between signal timing and intersection crashes, it is acknowledged by Hughes et al. that safety impacts of signal timing should be separated from the impacts of intersection design (3).

The goal of this paper is to explore the association between signal timing, phasing, and sequencing parameters and the intersection-related crashes. Signal timing parameters considered in this study are: all red time, yellow clearance, split time (i.e., the sum of green time, yellow clearance, and all red), cycle length, and offset. Signal phasing and phase sequencing parameters encompass: the number of phases at the intersection, protected left turns, permitted left turns, protected/permitted left turns, lead left turns, and lag left turns. Description of these parameters and their detailed definitions can be found elsewhere (12).

The following section summarizes past studies that attempted to link intersection crashes to signal timing parameters. The third section of this paper explains the data collection and presents methods used to model crash frequency and severity of intersection-related crashes. The results of the statistical modeling process are presented in the fourth section, and discussed in the following section of the paper. The final section provides the summary of findings and recommendations for future research steps.
5.2. Review of Previous Research

The current edition of the Highway Safety Manual states that signal timing related crash reduction treatments have unclear effects on crashes (7). The influence and the impact of individual signal timings on traffic conflicts was previously assessed by Stevanovic et al. (13). Zador et al. (1985) analyzed traffic flow and crash data at 91 signalized intersections. The authors assessed the effects caused by shifts from the recommended signal timing practice on the rate of intersection crashes. The interpretation of the overall pattern of association between intersection characteristics, clearance intervals, traffic flow and crash rates was reducing clearance interval timing, increasing the proportion of drivers who entered the intersection failing to clear during the clearance interval (10).

Studies that consider signal timing and phasing parameters as a factor contributing to intersection crashes focus on the duration of signal change and yellow intervals, and their influence on crash risk in the intersection vicinity (14, 15). The duration of signal timing intervals is known to be related to stop-and-go decisions in the so-called dilemma zone, or aggressive driving behavior such as red light running (15, 16). Potential solutions for reducing crash frequency through modification of signal change intervals or warning flashers are also briefly addressed in previous research (17). The inclusion of all-red intervals is discussed as a potential countermeasure for red light crashes (18). Methodologies used to explore safety
effects of signal timing parameters in the reviewed group of studies include multiple
regression (19), binary logit regression (15), and before and after studies (17).

Hauer (1988) found that if the traffic flow for signalized intersections is
known, one can predict how many and the type of collisions that should be expected
(20). Lau et al. (1988) found that the following factors were significant for property
damage crashes occurring at signalized intersections: traffic intensity, proportion of
cross street traffic, intersection type, number of lanes and LT arrangement. For fatal
crashes, the traffic intensity, intersection type and design speed were relevant (21).

Bhesania (1991) documented that all red clearance intervals could reduce right
angle crashes at signalized intersections (22). Bonneson and Patrick (1993) used a
Generalized Linear Model approach to develop a model that links intersection traffic
demands to crash frequency. Variables were time period, average daily traffic,
environmental, traffic control and intersection geometry. Crash frequency for similar
intersections is gamma distributed, and that negative binomial distribution can assess
-crash counts (23).

Wolverton and Mounce (1996) found that high traffic volume and population
were contributing crash factors (24). Al-Turk and Moussavi (1996) developed
regression equations to predict the effects of changes in v/c ratio and traffic volumes
on the average number of crashes. They used a negative binomial probability
distribution because crash variance was greater than crash mean (25). Ogden et al.
(1997) studied signalized intersections in Melbourne. The majority of the variation in
crashes between intersections was not explained by traffic volumes, but rather by other factors (26).

In general, signalized intersections have higher crash rates but lower severity.

Stamatiadis et al. (1997) developed guidelines for the installation of left-turn phasing. Their recommendations took into account left-turn volumes, crash rates, the product of opposing, left-turn volumes and left-turn delays (27).

Chin and Abdul-Quddus (2003) examined the relationship between crash frequencies, geometry, traffic flows and regulatory characteristics on signalized intersections. A random effect negative binomial model was used to examine explanatory variables. The following variables were found to affect safety at intersections significantly: 1) Highly significant: total approach volume, number of phases per cycle, uncontrolled left-turn lane, presence of surveillance cameras; and 2) Less significant: presence of acceleration section, provision of bus bays, use of adaptive control (28).

Abdel-Aty et al. (2006) pointed out that standard tools for modeling crash rates or crash frequencies are regression analyses, negative binomial and Poisson models (29).

Li and Tarko (2008) summarized the statistical models of crashes from previous studies. They showed that the most frequent crashes that are most susceptible to poor signal timing at signalized intersections are rear end and right angle crashes (30).
The literature shows which statistical analysis and tools should be used to evaluate and correlate traffic crashes. It emphasizes the importance of AADT, number of lanes, geometry layout and signal parameters on intensity of traffic crashes. While the literature addresses the relationship between crash frequency and the traffic volume, geometry, and partial signal timings, it lacks in-depth research on the relationship between crash frequency and crash severity with signal settings (e.g., phasing, sequencing and timing). This study aims to bridge the gap in the current body of knowledge by addressing the relationship between signal parameters and crashes, and their severity, at signalized intersections.

5.3. Methodology and Data

An important step in intersection crash analysis is to distinguish crashes that have occurred in the intersection vicinity. Crashes upstream and downstream from the intersection may be intersection-related, but the factors contributing to these crashes may be different. For this reason, the authors distinguished between ‘upstream’ and ‘downstream’ crashes. Upstream crashes are defined as the crashes which occurred at intersections (within the curb limits) plus crashes on the approaching leg of the signalized intersection. Downstream crashes assumed vehicles which were involved in a crash just as they exit the intersection’s curb area (i.e., on a departing leg of the intersection). The authors analyzed both upstream and downstream crash datasets to explore the association between signal parameters and traffic crashes. Only crashes
within 250ft radius were considered as Florida Department of Transportation (FDOT) guidance recommends (29). The authors hypothesize that upstream crashes are more likely to be influenced by signal control and associated parameters than downstream crashes.

5.3.1. Study Site

The study site is located in Fort Lauderdale, Broward County, FL. It consists of four-leg signalized intersections on six major arterials: Oakland Blvd, Sunrise Blvd, Broward Blvd, Davie Blvd, in the East-West direction, State Road 7 and US 1, in the North-South direction. Signalized intersections on minor roads within this area were also considered. A total of 148 signalized intersections were analyzed. The map provided in Figure 14 gives an overview of the analysis area with the intersections for which the data were collected. Figure 14 shows how 250-foot buffer zones were created around every intersection. Related crashes are shown as red dots. Buffer zones were created to extract the intersection-related crashes only.
5.3.2. Data Collection

The FDOT Safety Office provided crash data in the form of geographic information system (GIS) shape files for 11 years, from 2003 to 2013. The Broward County Traffic Engineering Division (BCTED) provided signal timing and phasing plans for the 148 signalized intersections in electronic format for the study area. Google Maps provided data on intersection geometric design and traffic control features. The Average Annual Daily Traffic (AADT) volume data for the analyzed intersections are available through an open source Florida Traffic Interactive Map (31).

After obtaining crash data for the analysis area, we aggregated crash data by extracting only those crashes that are considered intersection-related. In agreement with the current Highway Safety Manual (7) methodology, intersection area boundary
within the curb limits was used to aggregate the crash data, and crashes outside of this area characterized as “intersection-related” were also included in the dataset. This method was appropriate, as the considered intersections are similar in terms of their footprint size, decreasing the likelihood that the number of crashes joined per intersections would be overestimated or underestimated. In the case of high variation in intersection size, more complex methods for crash data merging are recommended, and this issue has been a subject of multiple recent studies (32, 33). According to FDOT guidelines, an intersection-related crash only occurs within a radius of 250 feet around the intersection (29).

Crashes that occurred during weekends and nights were excluded from the analysis since the signal timings operate differently at those days and times. Work zone related crashes were also excluded from the analysis along with the crashes that involved work zones. The data cleaning procedure reduced the dataset with 20,098 crashes to 5,627 intersection-related crashes.

Table 4 shows the descriptive statistics for variables collected and aggregated for each one of the 148 intersections in the dataset, over the 11-year period. It shows how the number of upstream and downstream crashes was comparable with about 52% of all crashes were recorded upstream and 48% downstream. The cycle lengths span from 60 to 180 seconds, and the number of signal phases from two to eight. This provided a good range of intersection operation characteristics for the proposed crash analysis. Additionally, all-red also provides a beneficial variation, along with speed
and AADTs on major and minor approaches. Yellow clearance is four seconds at all intersections, which prevent authors from drawing valuable conclusions on crash association with the amber interval.

The timing of traffic signals uses traffic volumes as one of the main inputs for allocating the cycle length among signal phases. Correlation analysis should be conducted to determine whether correlation exists between the AADT on major and minor intersection approaches, and selected signal timing parameters. Figure 15 provides the results of correlation analysis done using the R statistical software. The values of the Pearson correlation coefficients show the existence of a moderate correlation between the cycle length and AADT on the major approach. Moderate correlation is also detected among the signal timing parameters, but this was not the major concern and it was expected. A strong correlation between traffic volumes and signal timing parameters would represent a concern from the statistical modeling.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Observation</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Crash</td>
<td>Total no. of intersection crashes</td>
<td>148</td>
<td>38.68</td>
<td>47.87</td>
<td>0</td>
<td>250</td>
</tr>
<tr>
<td>Crash Ups</td>
<td>Total no. of crashes upstream of the intersection</td>
<td>148</td>
<td>20.65</td>
<td>25.89</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>Crash Downs</td>
<td>Total no. of crashes downstream of the intersection</td>
<td>148</td>
<td>17.99</td>
<td>23.20</td>
<td>0</td>
<td>121</td>
</tr>
<tr>
<td>Cycle Length</td>
<td>Signal cycle length</td>
<td>148</td>
<td>136.4</td>
<td>34.97</td>
<td>60</td>
<td>180</td>
</tr>
<tr>
<td>Offset</td>
<td>Signal timing offset</td>
<td>148</td>
<td>62.70</td>
<td>44.63</td>
<td>0</td>
<td>153</td>
</tr>
<tr>
<td>Phases</td>
<td>Number of signal phases at the intersection</td>
<td>148</td>
<td>5.41</td>
<td>2.02</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Yellow CLR</td>
<td>Yellow clearance time duration</td>
<td>148</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>All Red</td>
<td>All red time duration</td>
<td>148</td>
<td>1.52</td>
<td>0.40</td>
<td>0.75</td>
<td>3</td>
</tr>
<tr>
<td>Speed Major</td>
<td>Speed limit on the major approach</td>
<td>148</td>
<td>38.55</td>
<td>5.03</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Speed Minor</td>
<td>Speed limit on the minor approach</td>
<td>148</td>
<td>25</td>
<td>0</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>AADT Major</td>
<td>AADT on the major approach (in thousands)</td>
<td>148</td>
<td>18.45</td>
<td>8.73</td>
<td>1.8</td>
<td>35</td>
</tr>
<tr>
<td>AADT Minor</td>
<td>AADT on the minor approach (in thousands)</td>
<td>148</td>
<td>3.56</td>
<td>3.90</td>
<td>0</td>
<td>25</td>
</tr>
</tbody>
</table>
standpoint, as it would cause the authors to question the significance of signal timing parameters in terms of their association with crash frequencies and severities. Since no strong correlation with traffic volumes on the major and minor approach was detected among the most relevant signal timing parameters, the statistical modeling process continued as described in the following subsection of the paper.

Figure 15 Pearson Correlation coefficients for selected traffic volume and signal timing variables
5.3.3. Statistical modeling methods

Statistical crash modeling was conducted for the crash data aggregated for each intersection, followed by the models developed for separate intersection movements. This study uses Negative Binomial (NB) and Multinomial Logit (ML) distributions to explore the relationship between intersection-related crash frequency and crash severity, and variables that represent traffic signal timing parameters and intersection geometry. Several previous studies point out the advantages of using NB distribution in analyzing traffic crashes (34, 35, 36, 37).

The NB regression model is based on the Poisson regression model. Poisson and the NB model differ in variance, which is in case of the NB model different from the mean. That is important in capturing overdispersion in the model. The NB model is estimated as follows:

$$\lambda_i = \exp (x_{ij}\beta_j + \xi_i)$$

Where:

- $\lambda_i$ – expected number of crashes on a section $i$
- $x_{ij}$ – explanatory variables
- $\beta_j$ – parameters that quantify the relationship between $x_{ij}$ and $\lambda_i$
- $\xi_i$ - disturbance term

The Multinomial Logit (ML) model is a traditional discrete model used to predict crash severity (38). It assumes that the unobserved factors do not have any correlation in outcomes of the experiment (39). This model assumes that the probability of
deciding between alternatives is independent from all other alternatives. The parameter estimation is by the maximum likelihood method. The log likelihood function is defined as (40):

$$LL(\beta) = \sum_{n=1}^{N} \sum_{i} Y_{ni} \ln (P_{ni})$$

Where:

- $n$ – number of persons (observations)
- $Y_{ni}$ – equal to 1 if person $n$ is affected by severity level $i$
- $P_{ni}$ – probability that person $n$ experienced severity $i$
- $\beta$ – vector containing model parameters, which maximizes the function

All the experiments were done using R statistical package.

5.4. Results and Discussion

Table 5 provides the results of the NB regression model executed with the aggregated intersection data (i.e., total intersection-related crashes within a radius of 250ft). The final model specification was obtained through an iterative process of considering the variables available for the data aggregated in this manner. The variables were kept in the model specification based on their statistical significance, previous literature findings, the existing knowledge about the logical relationships between the signal timing parameters, and the total number of intersection crashes. The variables that
remained in the final model specification include the logarithm of AADT on the major road and the minor road, the length of signal timing cycle, the length of offset time, the total number of signal phases at the intersection and the length of “all red” time.

Table 5 Results of the NB Regression Model for Total Number of Crashes

| Total Crash    | Coef. | Std. Err. | z     | P>|z|  | 95%      | Conf. Interval |
|----------------|-------|-----------|-------|------|---------|--------------|
| ln_AADTmaj     | 1.880 | 0.288     | 6.530 | 0.000| 1.316   | 2.444        |
| ln_AADTmin     | 0.406 | 0.129     | 3.140 | 0.002| 0.152   | 0.660        |
| Cycle Length   | 0.023 | 0.006     | 3.870 | 0.000| 0.011   | 0.034        |
| Offset         | -0.006| 0.002     | -2.270| 0.023| -0.010  | -0.001       |
| Phases         | 0.193 | 0.069     | 2.820 | 0.005| 0.059   | 0.328        |
| All Red        | -0.292| 0.278     | -1.050| 0.294| -0.837  | 0.253        |
| c_cons         | -6.433| 0.696     | -9.240| 0.000| -7.797  | -5.068       |
| /lnalpha       | 0.010 | 0.181     |      |      | -0.344  | 0.365        |
| alpha          | 1.010 | 0.183     |      |      | 0.709   | 1.440        |

Log likelihood = -454.19751
LR chi2(6) = 108.00
Prob > chi2 = 0.0000
Pseudo R2 = 0.1063

5.4.1. Crash Frequency Analysis

The NB regression model for model specification shown in Table 5 was also run for the crashes upstream and downstream of the intersection separately. It was expected that the signal timing parameters would have a stronger influence on the crashes upstream of the intersection, so both upstream and downstream models were tested to verify this expectation. The signs of the variables included in the final model
specification shown in the model for total crashes (Table 5) and upstream/downstream crashes (Table 6) can be logically interpreted, and indicate the expected direction of impact on the estimated number of crashes. The exposure variables represented through AADT on the major and minor intersection approaches are associated with the increase of total crashes and upstream/downstream intersection crashes. The volume of this impact is significantly higher for the AADT on the major approach (coefficient $> 1$) than for the AADT on the minor approach (coefficient $< 1$). That is also expected, as the major approach with higher traffic volumes is expected to contribute to a higher number of crashes. The negative sign in front of the coefficient shows that the particular parameter decreases frequency of crashes and vice versa.

Intersections with longer cycle length are associated with higher number of crashes, and the estimated parameter for this variable has strong statistical significance in total and upstream/downstream crash models. The length of a signal timing cycle can also serve as a proxy for exposure, as longer cycles represent higher volumes on all approaches, and more time is needed to clear the intersection. This is why more detailed signal timing parameters are also explored in order to determine the significance of their effect on intersection crashes. The length of signal timing offset is associated with the decrease of total and upstream/downstream crashes. Similar to this association is the finding for “all red” time duration, where fewer crashes were expected in intersections where the proportion of “all red” time is
higher, as vehicles spend less time being exposed to crashes. Both of these variables, offset and “all red” time has a stronger significance and slightly higher impact on upstream crashes then on downstream crashes and even total intersection crashes. Also, good offsets should contribute to better intersection coordination, thus reducing the number of stops. The number of stops is highly correlated with rear end crashes (13). This finding serves as the first indicator for the potential need to observe intersection crashes in two separate directions. The number of signal phases at the intersection is usually correlated with the number of conflicts that need to be separated, meaning that intersections with fewer phases and conflicts would be associated with fewer crashes, as the models in Tables 5-6 demonstrated. Additional efforts will be made in further studies to include more signal related variables in the NB model.
### Table 6 Results of the NB Regression Model for Crashes Upstream/Downstream of the Intersection

<table>
<thead>
<tr>
<th>Crash Upstream</th>
<th>Coef.</th>
<th>Std. Err.</th>
<th>z</th>
<th>P&gt;z</th>
<th>95% Conf. Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln_AADTmaj</td>
<td>2.043</td>
<td>0.255</td>
<td>8.020</td>
<td>0.000</td>
<td>1.544 – 2.542</td>
</tr>
<tr>
<td>ln_AADTmin</td>
<td>0.437</td>
<td>0.113</td>
<td>3.860</td>
<td>0.000</td>
<td>0.215 – 0.658</td>
</tr>
<tr>
<td>Cycle Length</td>
<td>0.021</td>
<td>0.005</td>
<td>4.030</td>
<td>0.000</td>
<td>0.011 – 0.031</td>
</tr>
<tr>
<td>Offset</td>
<td>-0.005</td>
<td>0.002</td>
<td>-2.410</td>
<td>0.016</td>
<td>-0.009 – 0.001</td>
</tr>
<tr>
<td>Phases</td>
<td>0.135</td>
<td>0.062</td>
<td>2.180</td>
<td>0.029</td>
<td>0.014 – 0.256</td>
</tr>
<tr>
<td>All Red</td>
<td>-0.379</td>
<td>0.235</td>
<td>-1.620</td>
<td>0.106</td>
<td>-0.839 – 0.081</td>
</tr>
<tr>
<td><em>cons</em></td>
<td>-6.780</td>
<td>0.653</td>
<td>-10.390</td>
<td>0.000</td>
<td>-8.060 – -5.501</td>
</tr>
<tr>
<td>lnalpha</td>
<td>-0.410</td>
<td>0.198</td>
<td></td>
<td></td>
<td>-0.798 – -0.022</td>
</tr>
<tr>
<td>alpha</td>
<td>0.664</td>
<td>0.131</td>
<td></td>
<td></td>
<td>0.450 – 0.979</td>
</tr>
</tbody>
</table>

Log likelihood = -387.76479  
LR chi²(6) = 127.20  
Prob > chi² = 0.0000  
Pseudo R² = 0.1409

<table>
<thead>
<tr>
<th>Crash Downstream</th>
<th>Coef.</th>
<th>Std. Err.</th>
<th>z</th>
<th>P&gt;z</th>
<th>95% Conf. Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln_AADTmaj</td>
<td>1.684</td>
<td>0.273</td>
<td>6.180</td>
<td>0.000</td>
<td>1.150 – 2.218</td>
</tr>
<tr>
<td>ln_AADTmin</td>
<td>0.375</td>
<td>0.115</td>
<td>3.260</td>
<td>0.001</td>
<td>0.150 – 0.600</td>
</tr>
<tr>
<td>Cycle Length</td>
<td>0.021</td>
<td>0.006</td>
<td>3.660</td>
<td>0.000</td>
<td>0.010 – 0.032</td>
</tr>
<tr>
<td>Offset</td>
<td>-0.004</td>
<td>0.002</td>
<td>-1.980</td>
<td>0.048</td>
<td>-0.009 – 0.000</td>
</tr>
<tr>
<td>Phases</td>
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<td>0.065</td>
<td>3.360</td>
<td>0.001</td>
<td>0.090 – 0.344</td>
</tr>
<tr>
<td>All Red</td>
<td>-0.259</td>
<td>0.245</td>
<td>-1.060</td>
<td>0.289</td>
<td>-0.739 – 0.220</td>
</tr>
<tr>
<td><em>cons</em></td>
<td>-6.583</td>
<td>0.681</td>
<td>-9.670</td>
<td>0.000</td>
<td>-7.917 – -5.249</td>
</tr>
<tr>
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<td>0.199</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>alpha</td>
<td>0.742</td>
<td>0.147</td>
<td></td>
<td></td>
<td>0.503 – 1.096</td>
</tr>
</tbody>
</table>

Log likelihood = -376.21052  
LR chi²(6) = 116.32  
Prob > chi² = 0.0000  
Pseudo R² = 0.1339
5.4.2. Crash severity analyses

The multinomial model used for capturing crash severity was estimated on the condition that there was a crash within 250ft upstream of the intersection. Some of the approaches had zero crashes, which were counted toward NB crash frequency model, but not toward the crash severity model, since no-crash was considered as an outcome in the crash severity model. This resulted in a dataset of 88 intersections, which is less than those used in the NB model. The data collected distinguished several crash severity types: 1) no injury, 2) possible injury, 3) non-incapacitating injury, 4) incapacitating injury and 5) fatality, which includes fatalities occurred within 30 days of crash.

For estimating the multinomial model, the authors grouped crashes as follows: ‘no injury,’ ‘medium’ and ‘severe injury’ crashes. ‘No injury’ included only crash type 1), the ‘medium’ group included crash types 2) and 3), and ‘severe injury’ included types 4) and 5). The results estimated with the ML model assume the ‘medium’ group as the base case (i.e., reference case) for the model. The other two groups were considered as lower and upper extreme cases. If the coefficient has a negative sign, the probability that the severity was ‘medium’ was higher than the probability that the severity was a ‘no injury’. The results are presented in Table 7.
5.4.3. *Findings on the impact of speed limit, AADT and number of lanes*

The speed limit parameter is highly significant (p<0.05), and it shows that as the speed limit increases there is a higher probability of crashes or non-incapacitating injuries. This finding follows the general findings on speed in the transportation field.

AADT follows the findings from the previous studies, showing that the higher AADT is, the more severe crashes are expected to occur. Regarding the no-injury crashes, the estimated coefficient is negative, pointing out that the higher AADT is, the lower number of expected no-injury crashes. The all-red interval is highly significant for severe crashes, which confirms the literature findings (10) that all-red time has a strong influence on vehicle crashes. The estimated coefficient for no-injury crashes (0.44667) implies that during longer all-red intervals, lower severity crashes are more probable.

A greater number of approach lanes is more likely to decrease crash severity. More lanes at the intersection approach create more separation between the various movements, thus decreasing the chance of severe vehicular conflicts. One can argue that more lanes indicate more corridor traffic, which can increase crash frequency. However, this model is developed for crash severity, and only for the intersection vicinity. It does not necessarily mean that a higher number of lanes will lead toward lower crash frequency as well.
5.4.4. Findings on the impact of signal parameters

Lag left turns show a higher probability of contribution to the medium-severity crashes (e.g., possible injury and non-incapacitating injury) than for no-injury or high-severity crashes. Lead left turns did not significantly (p>0.05 for the null hypothesis) affect crash severity. The findings from the literature also showed mixed results on the effect of lead/lag settings on crash/conflict frequency. This observation requires more investigation in the future work.

When investigating left-turn phasing influence (e.g., protected/permited, protected only) on severity, protected left turns are more likely to contribute to no-injury crashes than to severe injury crashes. The estimated coefficient for protected/permited setup is higher than the coefficient for protected-only phasing. That means the protected/permited setup is more likely to contribute to severe crashes than protected only. Although the protected/permited setup addresses both safety and efficiency, it can confuse drivers. Some drivers will think that they have the right-of-way when they actually should yield to oncoming traffic. One of the possible ways to address this is the installation of flashing yellow arrows (FYA), and educating drivers on FYA operations and meaning. No FYA were installed in the area for the investigated period.

Protected-only left turns in heavy left-turn volume can decrease the efficiency of the intersection. This paper does not deal with operational performances of an intersection; it addresses it from the safety perspective only.
The data indicate that the number of phases has the highest impact on possible and non-incapacitating injuries. The findings on severity impact show that as the number of phases increases, crash severity has a decreasing trend. This is reasonable, since more phases offer more protected time for various movements (e.g., protected left turns), which should decrease the severity of crashes.

Split time, which includes green time, yellow clearance and all red time for a specific movement, does not show any particular trend in affecting crash severity. While there is a slightly higher probability that higher split time will lead to more ‘no injury’ crashes (i.e., the estimated coefficient is higher for ‘no injury’ than ‘severe’ crashes), additional experiments, possibly with larger datasets, are necessary to investigate this question.

Higher cycle length is expected to reduce crash severity. As noted in a previous study (13), longer cycle lengths give more flexibility for intersection coordination, improving progression and reducing the number of vehicular stops at intersections. A lower number of stops is related to a lower number of rear end collisions, which dominate the number of conflicts. However, our NB model shows that the signal timing cycle can also serve as a proxy for exposure, which leads to the conclusion that the longer cycle may imply higher volumes on all approaches, thus more time is required to clear the intersection. As the study (13) and this study have fundamentally different approaches (e.g., microsimulation model vs. NB statistical model), it may be beneficial to investigate the differences between them.
5.5. Conclusions

The goal of this paper was to examine the relationship between the frequency and severity of vehicular crashes, with signal parameters (i.e., signal timing, phasing and sequencing) at signalized urban intersections in Fort Lauderdale, FL. The authors used data from 148 intersections to develop a NB crash frequency model and data from 88 intersections to develop an ML crash severity model. The authors used NB and ML models to assess the parameters’ impact on the crash frequency and severity,
respectively. Based on the results discussed in the previous sections, the authors conclude that:

- Signal parameters (i.e., timing, phasing, and sequencing) have statistically significant impact on the intersection-related crashes. Additional research is necessary to validate these findings and confirm causal relationships between various signal parameters and crash frequencies and severities.
- Upstream, intersection-related crashes have a slightly higher correlation with signal parameters than downstream crashes. This is expected, because the vehicles which successfully clear an intersection have a lower chance of being affected by the operations of an upstream signal. However, this may not be the case if the crash occurs very close to downstream of the intersection. This conclusion calls for further investigation, but current guidelines which assume that intersection-related crashes occur within a 250ft radius from the intersection center, seem to overestimate impact of the (signalized) intersections on downstream crashes.
- AADT has a significantly higher influence on major approaches than on minor streets, and it has a significant impact on crash frequency. Higher AADT is also correlated with higher crash severity, which confirms findings from previous studies (34).
- The NB model shows that longer cycle length leads to a higher crash frequency, but the ML model points out a lower crash severity. This may be
attributed to the fact that longer cycles are implemented at corridors with heavy traffic in order to provide greater capacity (and sometimes better progression). Longer cycle lengths do not imply non-congested conditions. The speeds are more consistent on high-capacity and high-speed facilities.

- According to the results, longer all-red times contribute to both lower crash frequency and lower crash severity, which aligns with previous findings (10).

- Fewer signal phases lead to lower crash frequency. Fewer phases could mean the traffic volume is low and thus specifically protecting certain movements is not justified. Fewer phases may also imply that the traffic volume is too high and the intersection capacity is sought to be improved by reducing number of phases. Thus, the findings are inconclusive and debatable, as some previous studies (36) concluded that two-phase intersections tend to increase crash frequency. On the other hand, crash severity should decrease with more phases, as more protection is being provided for specific movements (e.g., protected left turns).

- The findings on left-turn phasing (e.g., protected, protected/permitted) and sequencing (e.g., lead and lag setup) are inconclusive. There are some indications that more left-turn protection means less severe crashes, but further investigation is necessary to confirm the significance of these results.
Our results show that the number of lanes per approach reduces crash severity due to the provision of dedicated lanes for each intersection movement. This does not necessarily mean that crash frequency on the corridor will decrease.

This study has several limitations which should be addressed in the future research. The dataset provided by FDOT Safety Office did not include type of the crashes; thus, the authors could not distinguish if the crash was a rear-ending, lane-change or path crossing crash. The study investigates crashes aggregated per each intersection and approach, not per movement. This study also aggregated crashes for all years in consideration. A study which would consider crashes per each movement, and account for the specific years in the analysis, accompanied with turning movement counts, could produce more reliable results.

Considering that this is one of the first studies which assesses the correlation of detailed signal parameters and crashes, it is not clear if the dataset is large enough to account for all the parameters thoroughly. Also, diversification of the study area (i.e., including data from the other States) could provide valuable insights. The authors assume that the signal parameters, especially offsets and cycle lengths deployed in the field are optimal for all the intersections investigated. The authors also argue that there were no major changes regarding traffic signal settings and no major construction updates in the study area for the analysis period.
5.6. References


6. CHAPTER 6 - SPATIAL AND STATISTICAL CORRELATION TECHNIQUES TO ASSESS VARIOUS TYPES OF FIELD TRAFFIC CRASHES AND THE MICROSIMULATION SURROGATE MEASURES OF SAFETY

Authors: Dusan Jolovic, Aleksandar Stevanovic, Peter T Martin. Submitted to the 2017 Road Safety and Simulation International Conference for presentation and potential publication.

ABSTRACT

Traffic crashes are one of the major issues in traffic engineering. A crash is basically a deficiency of the system. It usually occurs due to human factor. In this paper, we present the approach on the spatial and statistical correlation of field crashes and simulated conflicts. The authors used Vissim microsimulation and SSAM post processor to obtain the simulated conflicts. Vissim model is developed, calibrated, and validated for a corridor of 18 signalized intersections in Fort Lauderdale, FL. The field crash counts were collected for a 11-year period (2003-2013), for the same area. The spatial matching technique was developed in MATLAB. Vissim has an internal coordinate system which cannot easily be translated to any standard geographic system. That makes it challenging to perform the spatial match. The prediction of
traffic crashes was statistically modeled in SAS software using a general linear regression modeling approach. We developed regression models for three types of crashes: rear-end, lane change, and crossing (angle) crashes. In addition, we assessed total number of crashes. The models are developed for signalized intersections and for the arterial links separately. The results showed that our technique for spatial matching of conflicts and crashes has a promising potential. The results on the crash prediction models showed very good model fits. The models for the arterial links showed a better fit when explanatory variable was number of simulated conflicts only.

*Keywords: Vehicle Crashes; Vissim; SSAM; Vehicle Conflicts; Road Safety;*
6.1. Introduction

Traffic crashes are the issue humankind is facing for more than hundred years now (Bailey, 1960). Even with all the technological advances in the last fifty years, we still do not have an effective way to eliminate crashes. What is more concerning is that after several years of decline in traffic casualties, the traffic fatalities are again showing an increasing trend (National Highway Traffic Safety Administration, 2016), (National Highway Traffic Safety Administration, 2017).

Although the concept of traffic conflicts as a surrogate safety measures was introduced in the 1960’s, using simulation models and corresponding conflicts to assess safety took off in the 90’s and early 2000’s (Sayed, Brown, & Navin, Simulation of traffic conflicts at unsignalized intersection with TSC-Sim, 1994), (Huang & Pant, 1994), (Persaud & Mucsi, 1995), (Trinadha Rao & Rengaraju, 1998), (Mehmood, Saccomanno, & Hellinga, 2001), (Archer, 2001).

One of the popular post processors for vehicular conflict analysis is the Surrogate Safety Assessment Model (SSAM) developed by Gettman et al. (Gettman, Pu, Sayed, & Shelby, 2008). This software uses vehicle trajectories from the microsimulation models and outputs the vehicular conflicting situations in a spreadsheet form. Other approaches on the safety simulation are summarized in the study conducted by Young et al. (Young, Sobhani, Lenne, & Sarvi, 2014).

The goal of this paper is to analyze and find the correlation between field crashes and simulated conflicts from the two perspectives – spatial and statistical. The
first part of the paper focuses on the technique to spatially match simulated conflicts and the field crashes. To the best of authors’ knowledge, there are no research efforts to spatially match field crashes and simulated conflicts. Since Vissim has internal coordinate system it is not possible to easily transfer the conflict points from Vissim/SSAM to the GIS map and examine the spatial match. This research effort could bring a benefit because it will allow examining the shortcomings in the microsimulation (e.g., many conflicts occur on a particular spot, while in the field there are no crashes in that area). It can also point out the spots in the simulation which may be prone to the higher number of crashes.

The second part of this paper focuses on the statistical correlation between simulated conflicts and the field crash data. The authors performed analysis on three types of crashes: rear-end, lane change (sideswipe), and crossing (angle) ones. We also analyzed and developed regression models for the total number of crashes. This part of the analysis is subdivided in the two parts: one part focuses on signalized intersections, while the other deals with the links between the intersections. The statistical analysis on total number of crashes was also conducted in previous studies but for intersections only (Dijkstra, Marchesini, Bijeveld, Kars, Drolenga, & van Maarseveen, 2010), (Caliendo & Guida, 2012).

An innovative approach of this paper consists of: a technique to spatially match simulated conflicts and field crashes, and the effort to develop crash prediction models for arterial links for various crash types.
6.2. Literature Review

The conflict simulation models gained popularity in the last few years. Using S-Paramics simulation and crash data from 2002 to 2007, Dijkstra et al. examined the relation between crashes and conflicts at 569 signalized intersections. Using generalized linear models in SAS software they found significant relationship between the field crashes and simulated conflicts. More research is needed to determine combination of variables to best assess the observed crash frequency (Dijkstra, Marchesini, Bijeveld, Kars, Drolenga, & van Maarseveen, 2010).

Ariza explored the correlation between conflicts obtained from Paramics and SSAM and the field crashes. He found that the conflict based prediction models work well for intersections but not for arterials. A possible reason for that is the imperfection of lane changing models. Additionally, SSAM is developed to assess conflicts at the intersections. Volume-based prediction models are better fit for arterials, while conflict-based models are better for intersections (Ariza, 2011).

Caliendo and Guida investigated the relationship between field crashes and the vehicular conflicts obtained from Aimsun and post processed in SSAM (Caliendo & Guida, 2012). The authors developed both conflict based and volume based crash prediction models for unsignalized intersections. The study conducted was based on 5-year period and for peak hours only. They found a significant correlation between
simulated conflicts and field crashes. Also, the conflict based model for crash prediction fitted the crash data better that the volume based one. One possible drawback of this study is that the crashes were aggregated, i.e., the authors did not investigate relationships between different conflict types (e.g., rear-end, lane change, crossing).

Huang et al. measured field conflicts using traditional techniques and compared them with the simulated conflict outputs from VISSIM and SSAM (Huang, Liu, Yu, & Wang, 2013). The test bed consisted of 10 signalized intersections. VISSIM model was calibrated in two stages. First, the authors calibrated volumes, speed and headways. The second stage focused on adjusting parameters in VISSIM in order to replicate observed field safety measures. The authors showed good match between rear end and crossing conflicts. Lane change conflicts did not show good consistency. They also pointed out the inability of the model to replicate illegal lane change maneuvers.

Based on two case studies in VISSIM and Paramics, Saleem et al. developed crash prediction models for 4-leg signalized intersections (Saleem, Persaud, Shalaby, & Ariza, 2014). The obtained crash conflict relationships were different from SSAM recommended ones. When authors changed the left turn settings from permissive to protected-permissive within microsimulation, results indicated reduction in angle and turning crashes. These results were similar to the ones obtained from empirical Bayes
crash based evaluation. This approach showed that traffic conflicts could be used to measure safety effects.

Bahrololoom et al. stressed that the simulation models are able to explain most crash types. The only concern is in the area of single vehicle crashes and when more than two vehicles are involved (Bahrololoom, Tay, & Young, 2014). These crash types should be excluded from crash and conflict studies, as simulation models may not be able to assess them.

A study conducted for Czech Republic conditions by Ambros et al. showed that there were four times more simulated conflicts than the observed ones (Ambros, Turek, & Paukrt, 2014). The authors used Paramics model and SSAM to calculate simulated conflicts. The shortcomings of this study are: 1) only one hour of simulation, 2) calibration of Paramics is done only by comparing field and simulated queue lengths.

Shahdah et al. developed statistical relationship between simulated conflicts and field observed crashes using 53 signalized intersections (Shahdah, Saccomanno, & Persaud, 2015). The authors used only left-turn opposing crashes in the AM peak period to show how the number of simulation runs affects the calibrated crash-conflict relationship. While calibrating the crash-conflict model, the authors pointed out that the number of simulations would have an effect on the model. The calibrated coefficients in the generalized linear negative binomial model are sensitive to the number of simulations and the TTC threshold.
The literature shows a great potential for surrogate measures of safety and their ability to estimate actual number of crashes in the field. This paper will complement the current body of knowledge by examining all the three crash types for both signalized intersections and arterial links. Contrary to some of the previous studies, this will not be done for isolated links or intersections but for a busy arterial, which model is accurately developed, calibrated and validated.

6.3. Methodology

The test bed for this study was Broward Blvd, a 4-mile long arterial in Fort Lauderdale, FL. It consists of 18 signalized intersection (from SR7 to US1), one freeway interchange, and dozens of links between intersections. The corridor consists of six lanes, three in each direction. The posted speed limits vary between 35mph and 40mph. There is one railroad crossing and one I-95 freeway interchange. The corridor was modeled, calibrated and validated in Vissim 7 (PTV Group, 2016), for weekday, from 6AM to Midnight, using data from 2012. We gathered the field crashes for Broward Blvd for years 2003 to 2013 from the FDOT Safety Office. Since we modeled only vehicular traffic from 6AM to Midnight, we excluded 1) the pedestrian, bike and single vehicle crashes; 2) crashes which occurred during the weekends; 3) crashes from Midnight to 6AM. We also excluded the interchange from the study.
The corridor is heavily congested from 7 am-10 am in the eastbound direction and from 4 pm-7 pm in the westbound direction.

This model was previously built in Vissim’s version 5.4 which did not have interactive background maps. Instead, the modelers had to crop figures from Google/Bing maps, to scale them and import as a background. Once we exported the model to the newer version of Vissim, which had the interactive map, we observed several errors in the geometry of the model. Some of the links were shorter than the actual streets in the field. The authors recreated the model, shifting the links and the connectors to accurately match the field geometry. The model was then recalibrated and revalidated to make sure it mimics the field conditions well. We performed calibration by matching traffic counts from the field and the model output, and the validation by matching travel times from the field and the model between intersections. The results are shown in the Figure 16.

To obtain vehicular conflicts from Vissim, we run Vissim simulation and exported vehicle trajectories for five different random seed runs. This was done to account for the stochastic nature of the microsimulation. The trajectories were then post processed in the Surrogate Safety Assessment Model (SSAM). Since there were five runs, the authors averaged the number of conflicts across all runs. The rear end, lane change, and crossing conflicts were extracted for each intersection and for each link pair (e.g., east-west).
We used the default parameters in SSAM for time-to-collision (TTC) and post-encroachment time (PET). TTC was set to 1.5 seconds, and PET to 5 seconds. Since microsimulation cannot model the crash, only the conflict between two vehicles, the authors excluded SSAM conflicts with TTC=0, which was recommended by the previous study (Caliendo & Guida, 2012).

To develop a technique to project Vissim internal coordinate points into the standard lat-long system, we assumed a linear relationship between the field crashes and simulated conflicts. Vissim model is used to approximate eighteen coordinates (i.e., x, y) of the points placed at the centers of 18 investigated intersections along the corridor. We refer to this matrix as a matrix A18x2. For the approximately same spots, we estimated the lat-long coordinates of the sample data points using Google Maps (Google, Inc., 2017). This is referred to as a matrix B18x2. Then we assumed a linear relationship between A and B matrices as:

\[ B \approx AX + C \]

where X and C are empirically estimated parameters.

In the similar fashion, we projected the field coordinates data into Vissim’s coordinate system. The matrices are coded in MATLAB (The MathWorks Inc., 2016).

For the statistical analysis, we used generalized linear regression model – a GENMOD procedure in SAS software to develop the regression models (SAS...
Institute, 2016). The assumption was that the observed field crash counts were occurring randomly following the negative binomial distribution. The form of negative binomial distribution is given as:

\[ \lambda_i = \exp(x_i^T \beta) \]

where \( \lambda_i \) is the expected (predicted) number of crashes, \( x_i \) is the vector of \( k \) covariates, and \( \beta \) is the vector of \( k \) unknown parameters.

The dependent variable was the observed number of field crashes, while the explanatory variables were the average number of conflicts, the number of passing vehicles (for the intersection analysis) and the AADTs for the link analysis. The number of passing vehicles was obtained from the Vissim microsimulation using node evaluation. Other variables such as maximum and minimum number of conflicts and link AADTs were also tested in regression analysis.
Figure 16 Calibration and Validation Sample for AM and PM Peak Hours
6.4. Results and Discussion

6.4.1. Spatial match between Vissim and field coordinates

It is possible to set a Bing interactive map (Microsoft, Inc., 2017) as a background in Vissim. However, there is no option to choose the preferred coordinate system. Vissim has an internal coordinate system which does not translate to any other standard geographic (projected) coordinate system. The discussion with PTV team revealed that the PTV is working on resolving this issue but is not known when the fix will be implemented. Currently, there is no straightforward way of presenting the data from Vissim on a GIS map. Exported conflict points, which we tried to plot on a map, had a significant shift from the area where they were supposed to appear on a map. After several unsuccessful attempts to translate simulated conflicts to a standard map, we decided to pick 18 independent points, each one representing a center of the signalized intersection. Based on the position of each pair of Vissim coordinates, we estimated the field coordinates pair from Google Maps. In that way we obtained 18 coordinate pairs from Vissim and from the field. Note that the Vissim model is developed with high geometrical precision, as the Bing Maps served as a background for traffic geometry building.

Figure 17 shows the performance of the projections: (i) from Vissim to field (black bars and primary Y-axis) and (ii) from field to Vissim (white bars and the secondary Y-axis). Most of the data points are projected within 5 meters radius (approximately 16ft). In the future, we aim to use this method on a large conflict
dataset to investigate the spatial distribution of the conflict points in both field and simulated environment. This finding is important because it can reveal deficiencies in the model (e.g., a spot where unusual amount of conflicts occur) and also point out the areas which could be prone to the higher number of crashes. It would also help understand the difference between the spatial distribution of the simulated conflicts and the field crashes. As the technique has shown a promising potential, the method could be also applied to other traffic simulation software as well.

Figure 17 Spatially Projected coordinates form Vissim to Field and vice versa
6.4.2. Correlation between simulated conflicts and the field traffic crashes

The objective of the statistical modeling performed in this paper was to find a relationship between the field crashes and simulated conflicts and to estimate the number of crashes in the field using simulated conflicts and vehicular volumes. We developed several conflict-only and conflict-volume based crash prediction models for different crash types (e.g., rear end, lane change, crossing). The models were developed for signalized intersections and for the arterial links between intersections. We used 18 signalized intersections and 19 link pairs. The distribution summary of various conflict types for the signalized intersections and link pairs is given in Table 8.

As expected, rear ends have the most frequent occurrence. Observe that SSAM underestimates crossing (angle) number of conflicts in both cases. This may be due to the heavy congestion at the corridor during peak hours as the heavy congestion could affect the simulation model to produce higher number of rear ends. Figure 18 shows the correlation between the mean number of crashes, conflicts, and the amount of passing vehicles. The higher the volume, it is expected more that more field crashes and simulated conflicts will occur.

| Table 8 Frequency distribution of field crashes and simulated conflicts |
|--------------------------|----------|----------|----------|----------|
|                         | Rear End | Lane Change | Crossing (Angle) |
|                         | Crash    | Conflict  | Crash    | Conflict  | Crash    | Conflict  |
| Intersections           | 0.53     | 0.83      | 0.11     | 0.13      | 0.36     | 0.04      |
| Link Pairs              | 0.63     | 0.86      | 0.13     | 0.13      | 0.24     | 0.1       |
For the statistical estimation of crash frequency, we used the general linear regression modeling technique. All models were developed using SAS GENMOD procedure. The class of generalized linear models is an extension of traditional linear models that allows the mean of a population to depend on a linear predictor through a nonlinear link function and allows the response probability distribution to be any member of an exponential family of distributions (SAS Institute, 2016).

It was assumed that the number of field crashes is a dependent variable, negative binomially distributed. Three goodness-of-fit measures were estimated to assess the relationship between modeled variables – Scaled Deviance, Pearson Chi-
Square and the Scaled Person Chi-Square. To obtain estimates, we maximized log-likelihood function.

Table 9 shows the crash models for three types of crashes and also for the total number of crashes. The conflict estimates showed significance for all crash types. The tested goodness-of-fit shows a good fit of the models. The deviance over the degrees of freedom (i.e., overdispersion) is close to the value of 1, which indicates a good model fit. All models are given in the second row in a table. As expected, the rear end crashes have the highest estimated coefficient, which indicated that we expect most of rear ends in the field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Rear End</th>
<th>Lane Change</th>
<th>Crossing (Angle)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( e^{-1.918} \cdot \text{conf}^{0.744} )</td>
<td>( e^{-0.991} \cdot \text{conf}^{0.557} )</td>
<td>( e^{2.058} \cdot \text{conf}^{0.304} )</td>
<td>( e^{-1.078} \cdot \text{conf}^{0.6999} )</td>
</tr>
<tr>
<td>Constant</td>
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<td>-0.9912</td>
<td>2.058</td>
<td>-1.0784</td>
<td></td>
</tr>
<tr>
<td>lnconf (std)</td>
<td>0.7442 (1E-04)</td>
<td>0.5574 (1.6E-03)</td>
<td>0.3038 (2.5E-03)</td>
<td>0.6999 (1E-04)</td>
<td></td>
</tr>
<tr>
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<td>234.12</td>
<td>1276.39</td>
<td>5126.16</td>
<td></td>
</tr>
<tr>
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<td>18.29</td>
<td>18.68</td>
<td>18.58</td>
<td></td>
</tr>
<tr>
<td>Pearson Chi-Square</td>
<td>18.50</td>
<td>21.55</td>
<td>19.64</td>
<td>19.66</td>
<td></td>
</tr>
<tr>
<td>Scaled Pearson X2</td>
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<td>19.64</td>
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<tr>
<td>Degrees of Freedom</td>
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<td>16</td>
<td>16</td>
<td>16</td>
<td></td>
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<tr>
<td>Scaled Deviance/DF</td>
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<td>1.14</td>
<td>1.17</td>
<td>1.16</td>
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<tr>
<td>AIC</td>
<td>151.80</td>
<td>112.89</td>
<td>143.67</td>
<td>174.59</td>
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</tr>
</tbody>
</table>

Table 10 represents regression models for signalized intersections, which includes passing volumes and simulated conflicts as explanatory variables. Passing volumes were collected from Vissim using ‘node evaluation’ output option. We encircled each intersection with a node and recorded passing volumes. The authors performed 5 simulation runs with different random seeds (i.e., to account for stochastic nature of
the model), and averaged passing volumes for each intersection. Since the model was calibrated and validated with the high accuracy, this approach is considered reasonable. Goodness-of-fit statistics confirms a good fit of the model. However, for the rear ends and total crashes, the estimates are not significant on a 95% confidence level. For lane change and crossing conflicts we found high statistical significance, meaning that the models developed for these two types of crashes are valid. The models also show that the number of crashes increases as the amount of passing vehicles and the number of conflicts increase. However, the number of passing vehicles has a steeper slope, thus being more influential on the amount of field crashes.

Table 10 A regression model for various types of traffic crashes at signalized intersections (conflicts + volumes)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rear End</th>
<th>Lane Change</th>
<th>Crossing (Angle)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>$e^{-23.78 \cdot \text{conf}^{0.156}} \cdot \text{vol}^{2.392}$</td>
<td>$e^{-23.81 \cdot \text{conf}^{0.495}} \cdot \text{vol}^{2.102}$</td>
<td>$e^{-15.8 \cdot \text{conf}^{0.281}} \cdot \text{vol}^{1.631}$</td>
<td>$e^{-15.89 \cdot \text{conf}^{0.349}} \cdot \text{vol}^{1.59}$</td>
</tr>
<tr>
<td>lnconf (std)</td>
<td>0.1561 (0.45)*</td>
<td>0.495 (2.7E-03)</td>
<td>0.2817 (7E-04)</td>
<td>0.3491 (0.1)*</td>
</tr>
<tr>
<td>lnVolume</td>
<td>2.3924 (2E-04)</td>
<td>2.1025 (1.7E-02)</td>
<td>1.6316 (1.8E-03)</td>
<td>1.5951 (2.9E-02)</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>2240.22</td>
<td>236.62</td>
<td>1280.48</td>
<td>5128.29</td>
</tr>
<tr>
<td>Scaled Deviance</td>
<td>18.78</td>
<td>18.80</td>
<td>18.40</td>
<td>18.73</td>
</tr>
<tr>
<td>Pearson Chi-Square</td>
<td>18.46</td>
<td>24.29</td>
<td>18.30</td>
<td>19.21</td>
</tr>
<tr>
<td>Scaled Pearson X2</td>
<td>18.46</td>
<td>24.29</td>
<td>18.30</td>
<td>19.21</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Scaled Deviance/DF</td>
<td>1.25</td>
<td>1.25</td>
<td>1.23</td>
<td>1.25</td>
</tr>
<tr>
<td>AIC</td>
<td>143.70</td>
<td>110.5</td>
<td>143.4</td>
<td>172.3</td>
</tr>
</tbody>
</table>

* not statistically significant on a 95% confidence level; + significant on a 90% confidence level

Table 11 shows a regression model which aims at estimating the expected number of crashes at the arterial links. The explanatory variable was simulated number of conflicts. The tabular values show a good fit and a significant correlation for all types
of crashes but the crossing (angle) ones. The crossing path crashes are mostly associated with intersections (left-turn crashes) so this may be the reason why the statistical model is not able to properly estimate this crash type.

Table 11 A regression model for various types of traffic crashes at arterial links (conflicts only)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rear End</th>
<th>Lane Change</th>
<th>Crossing (Angle)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>$e^{-4.318} \cdot \text{conf}^{0.848}$</td>
<td>$e^{-5.627} \cdot \text{conf}^{1.034}$</td>
<td>$e^{1.962} \cdot \text{conf}^{0.365}$</td>
<td>$e^{-5.203} \cdot \text{conf}^{0.981}$</td>
</tr>
<tr>
<td>Constant</td>
<td>-4.318</td>
<td>-5.627</td>
<td>1.9617</td>
<td>-5.2026</td>
</tr>
<tr>
<td>lnconf (std)</td>
<td>0.8481 (2E-04)</td>
<td>1.0346 (3.2E-02)</td>
<td>0.3647(0.16)*</td>
<td>0.9807(4E-04)</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>1374.11</td>
<td>114.47</td>
<td>351.25</td>
<td>2621.42</td>
</tr>
<tr>
<td>Scaled Deviance</td>
<td>19.66</td>
<td>22.13</td>
<td>21.29</td>
<td>19.50</td>
</tr>
<tr>
<td>Pearson Chi-Square</td>
<td>20.22</td>
<td>15.51</td>
<td>20.93</td>
<td>22.71</td>
</tr>
<tr>
<td>Scaled Pearson X2</td>
<td>20.22</td>
<td>15.51</td>
<td>20.93</td>
<td>22.71</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Scaled Deviance/DF</td>
<td>1.16</td>
<td>1.30</td>
<td>1.25</td>
<td>1.15</td>
</tr>
<tr>
<td>AIC</td>
<td>152.92</td>
<td>110.66</td>
<td>134.60</td>
<td>173.62</td>
</tr>
</tbody>
</table>

* - not statistically significant on a 95% confidence level

Table 12 presents the crash prediction models which include conflicts and AADTs as explanatory variables. In these models, AADT variable is significant for rear ends only. This may be due to the correlation between simulated conflicts and AADT variable. The correlation reduces the probability that the traffic volumes will have an additional explanatory effect in the model. Even for the rear end crashes, the estimated coefficient for the number of conflicts is greater than the value for AADT (e.g., 0.7333>0.5951) showing that the number of conflicts has a higher impact on the expected number of crashes. This is somewhat expected because as the facility approaches congested conditions the risk of occurring crash may decrease. Regarding the crossing (angle) crashes, we can observe that the estimates are not significant for
both conflicts and AADTs variables. This may be related to the SSAM’s underestimation of angle crashes and also to the relation of this crashes to the intersections.

### Table 12 A regression model for various types of traffic crashes at arterial links (conflicts + volumes)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Rear End</th>
<th>Lane Change</th>
<th>Crossing (Angle)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$e^{-23.78} \cdot \text{conf}^{0.156} \cdot \text{vol}^{2.392}$</td>
<td>$e^{-23.81} \cdot \text{conf}^{0.495} \cdot \text{vol}^{2.102}$</td>
<td>$e^{-15.8} \cdot \text{conf}^{0.281} \cdot \text{vol}^{1.631}$</td>
<td>$e^{-15.89} \cdot \text{conf}^{0.349} \cdot \text{vol}^{1.59}$</td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td>-9.7577</td>
<td>-12.3192</td>
<td>-2.8195</td>
<td>-8.3848</td>
</tr>
<tr>
<td>lnconf (std)</td>
<td>0.7333 (9E-04)</td>
<td>1.0144(2.8E-02)</td>
<td>0.3649 (0.16)*</td>
<td>0.9241(1E-03)</td>
<td></td>
</tr>
<tr>
<td>lnAADT</td>
<td>0.5951 (8E-02)</td>
<td>0.6285(0.33)*</td>
<td>-0.0791(0.91)*</td>
<td>0.3404(0.39)*</td>
<td></td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>1375.54</td>
<td>114.93</td>
<td>351.25</td>
<td>2621.78</td>
<td></td>
</tr>
<tr>
<td>Scaled Deviance</td>
<td>19.71</td>
<td>22.41</td>
<td>21.29</td>
<td>19.48</td>
<td></td>
</tr>
<tr>
<td>Pearson Chi-Square</td>
<td>19.54</td>
<td>15.84</td>
<td>20.66</td>
<td>21.79</td>
<td></td>
</tr>
<tr>
<td>Scaled Pearson X2</td>
<td>19.54</td>
<td>15.84</td>
<td>20.66</td>
<td>21.79</td>
<td></td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Scaled Deviance/DF</td>
<td>1.23</td>
<td>1.40</td>
<td>1.33</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>AIC</td>
<td>152.07</td>
<td>111.74</td>
<td>136.59</td>
<td>174.89</td>
<td></td>
</tr>
</tbody>
</table>

* - not statistically significant on a 95% confidence level

### 6.5. Conclusions and Future Research

This paper deals with vehicular crashes and simulated conflicts from the spatial and statistical standpoint. The authors developed a technique on how to translate conflict points coordinates from the microsimulation and plot them in a traditional coordinate system. Due to Vissim’s specific internal coordinate system this was a challenging task. In a second part of this paper, we developed regression models for intersections and arterial link pairs. This was performed for three crash types and also for the total crashes. The following conclusions are drawn from this research:
Simulated conflicts can be accurately plotted on a GIS map and spatially matched with the field crashes. This can point on the spatial frequency distribution differences between the field and simulated values. The technique can reveal the weak spots in the model or point out that a specific area in the field has some shortcomings and should be examined carefully to minimize crashes in the future.

Vissim microsimulation underestimates the number of crossing (angle) conflicts. This may be due to the heavy congestions on the modeled corridor in the peak periods.

Conflict based crash prediction models are able to accurately predict the expected number of crashes in the field for all crash types.

For a model with both conflicts and traffic as explanatory variables, the conflicts were not significant on a 95% confidence level. This may be due to presence of traffic in the model as conflicts and traffic are correlated variables. This aligns with the research findings of (Caliendo & Guida, 2012).

The regression models developed for signalized intersections showed better fit and more significance than the model for the arterial links. The estimates for links showed more statistical significance for conflict-only based crash models. The findings do not align with previous research of (Ariza, 2011). To validate these finding, additional research is required.

These findings can serve to evaluate different design projects from both safety and the operational perspective.
This research has several shortcomings which should be addressed in the future. The authors developed a technique to transfer the conflict points from simulation to the GIS map and match them with high accuracy with the field crashes. However, this should be tested on a larger dataset to prove the validity of the approach. Since the number of conflict points is much higher than the number of crashes, additional techniques would be necessary to accurately match and link conflicts and crashes from the spatial perspective. The analysis could also include various levels of crash severity.

The crash prediction models developed in this paper should be tested on a different dataset to prove their transferability and ability to accurately estimate the number of crashes on a facility. Also, additional explanatory variables can be included such as the length of the links, number of lanes, speed limit, and major and minor volumes. In this paper, the TTC parameter was held constant – instead the models should be tested for different TTC values (e.g., test 0.1 increments) as the models could achieve even better fit.

**6.6. Acknowledgments**

The authors want to express their sincere gratitude to Dr. KwangSoo Yang from Florida Atlantic University for the crash data sorting and to the FDOT Safety Office for providing the crash data.
6.7. References


7. CHAPTER 7- OVERALL CONCLUSIONS

This research focuses on the relation between traffic crashes, traffic conflicts, intersections’ signal timing parameters, and the left turn field settings. It offers thorough evaluation of traffic conflict technique from several standpoints: (i) optimization of traffic signals to minimize the number of conflicts at the arterial, while maintaining efficiency of traffic signals; (ii) evaluation of current left turn guidelines on protected/permitted signal settings in terms of safety and efficiency; (iii) ability to estimate the expected number of crashes at signalized intersections and connecting arterial links. The research covered in dissertation also establishes a relationship between the signal timing parameters and the field crash frequency and crash severity. This research also provides a detailed literature review on the left turn signal phasing practices across the US.

The major conclusions reached in this study are as follows:

- The concept of optimizing signal timings to reduce the vehicle conflicts, improve safety, and keep the efficient vehicle throughput is a viable option
- Computational and simulation tools such as (i) standalone driving simulators and Simulators linked with microsimulation tools, (ii) microsimulations coupled with surrogate safety models, and (iii) Augmented Reality, could be utilized to evaluate current left-turn signal phasing guidelines and recommendations without compromising the safety of the drivers
• Current guidelines on protected/permitted left-turn signal phasings should be revised. The results show that left turn delays for drivers can be increased by up to 25% due to overprotection of left turners

• Traffic signal parameters (e.g., timing, phasing, and sequencing) have statistically significant impact on the intersection related crashes frequency and crash severity

• Traffic conflicts can be spatially matched with the field crashes, revealing model deficiencies or problematic spots in the field

• Conflict-based crash prediction models are viable option to accurately predict the expected number of crashes in the field for all crash types (e.g., crossing, rear end, lane change)

7.1. Research contribution

The first contribution of this research is successful assessment of the integration between microsimulation, optimization of signal timings and the SSAM post processor. It showed that the idea of optimizing signal timings could reduce the number of conflicts, thus positively affecting safety. This could be achieved without severely impacting the efficiency of traffic operations. Second, this research provides a state-of-the-art literature review on the left turn operations and best practices across the US. It also proposes various simulation and computational tools to assess the
current left turn signal phasing guidelines. One of these techniques is evaluated in Chapter 4. It showed a lot of potential in revising some of the present guidelines on protected/permitted left turn phasing. Chapter 5 showed that cycle length, traffic volume, all-red time, the number of signal phases, and the number of lanes, have significant impact on crash frequency and crash severity. Chapter 6 presents the spatial matching technique which can map and match simulated conflicts and the field crashes using lat-long coordinate system. It also shows that expected number of field crashes can be estimated using simulated conflicts from microsimulation models.

7.2. Future research

The traffic conflict technique is a powerful tool to assess the traffic safety related issues. The advantage of this technique is a controlled environment which excludes the possibility of field injuries while testing the different scenarios. However, there is a lot of potential space for enhancements. The biggest possibilities for improvements are in the further investigation of crash prediction models for both arterial links and the signalized intersections, as discussed in Chapter 6. With the advance in computational power, it is expected that the simulation models will be able to perform faster and handle very large networks on a micro level. This could cover larger areas and provide more general applicability and findings. Currently, many of the crash prediction models (including ones in this research) are developed for limited areas.
Using more advanced techniques of augmented reality and sophisticated driving simulators, all current left turn guidelines should be tested. The findings could be then implemented in the field and potentially reduce unnecessary delays due to the overprotection of left turners.

The signal timing parameters should be collected for a larger and more diverse area (e.g., one thousand signalized intersections across the US) and correlated with the related field crashes. The outcomes could provide more general findings on the correlation between field crashes and signal parameters. This should be done for all different crash types.