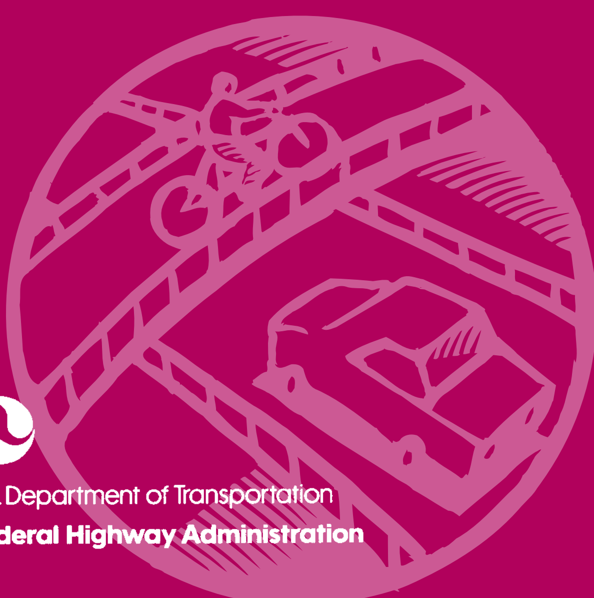
Surrogate Safety Assessment Model and Validation: Final Report

PUBLICATION NO. FHWA-HRT-08-051 JUNE 2008



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Federal Highway Administration

Research, Development, and Technology
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McLean, VA 22101-2296

FOREWORD

The safety of intersections, interchanges, and other traffic facilities is most often assessed by tracking and analyzing police-reported motor vehicle crashes over time. Given the infrequent and random nature of crashes, this process is slow to reveal the need for remediation of either the roadway design or the flow-control strategy. This process is also not applicable to assess new designs that have yet to be built, or to assess new flow-control strategies before they are employed on-site.

This document is a final report on research and development of an alternative safety-assessment approach utilizing conflict analysis—analyzing the frequency and character of narrowly averted vehicle-to-vehicle collisions in traffic—as a surrogate measure of actual crash data. A software prototype has been developed to automate conflict analysis of vehicle trajectory data, which can now be exported from the traffic simulation software of four vendors who collaborated on the project. The majority of the report describes validation testing conducted to evaluate the efficacy of this approach. The findings may be of interest to transportation engineers, safety engineers, researchers, simulation designers, and firms providing simulation or intersection design services.

Michael Trentacoste
Director, Office of Safety
Research and Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-08-051	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Surrogate Safety Assessment Model and Validation: Final Report		5. Report Date June 2008 6. Performing Organization Code:
7. Author(s) Douglas Gettman, Lili Pu, Tarek Sayed, and Steve Shelby		8. Performing Organization Report No.
9. Performing Organization Name and Address Siemens Energy & Automation, Inc. Business Unit Intelligent Transportation Systems 6375 E. Tanque Verde, Suite 170 Tucson, AZ 85715		10. Work Unit No. 11. Contract or Grant No. DTFH61-03-C-00129
12. Sponsoring Agency Name and Address Office of Safety RD&T Turner Fairbank Highway Research Center Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report: September 2003–November 2007 14. Sponsoring Agency Code HRDS-05

15. Supplementary Notes

FHWA Contracting Officer's Technical Representative (COTR): Joe Bared

16. Abstract

Safety of traffic facilities is most often measured by counting the number (and severity) of crashes that occur. It is not possible to apply such a measurement technique to traffic facility designs that have not yet been built or deployed in the real world. This project has resulted in the development of a software tool for deriving surrogate safety measures for traffic facilities from data output by traffic simulation models. This software is referred to as SSAM—an acronym for the Surrogate Safety Assessment Model. The surrogate measures developed in this project are based on the identification, classification, and evaluation of traffic conflicts that occur in the simulation model. By comparing one simulated design case with another, this software allows an analyst to make statistical judgments about the relative safety of the two designs. An open-standard vehicle trajectory data format was designed, and support for this format has been added as an output option by four simulation model vendors/developers— PTV (VISSIM), TSS (AIMSUN), Quadstone (Paramics), and Rioux Engineering (TEXAS).

Eleven "theoretical" validation tests were performed to compare the surrogate safety assessment results of pairs of simulated design alternatives. In addition, a field validation exercise was completed to compare the output from SSAM with real-world crash records. Eighty-three intersections from British Columbia, Canada were modeled in VISSM and simulated under AM-peak traffic conditions. The processed conflict results were then compared with the crash records in a number of different statistical validation tests. Last, sensitivity analysis was performed to identify differences between the SSAM-related outputs of each simulation model vendor's system on the same traffic facility designs. These comparative analyses provide some guidance to the relative use of surrogate measures data from each simulation system. The SSAM software tool and user manual (FHWA-HRT-08-050) are available to the public at no cost from FHWA.

17. Key Words Surrogate measures, safety, traffic simulation, validation, traffic conflicts, conflicts, crashes, accidents, prediction	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	322	

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ACRONYMS AND SYMBOLS

Acronym	Definition
AADT	annual average daily traffic
ADT	average daily traffic
AMF	accident modification factor
CSV	comma separated values
EB	Empirical Bayes
FHWA	Federal Highway Administration
GUI	graphical user interface
ICBC	Insurance Corporation of British Columbia
PET	post-encroachment time
SPUI	Single-Point Urban Interchange
SSAM	Surrogate Safety Assessment Model
TRJ	The filename extension for vehicle trajectory files.
TTC	time to collision

Symbol	Definition
α	Greek letter Alpha
β	Greek letter Beta
Δ	Greek letter Delta
λ	Greek letter Lamda
π	Greek letter Pi
θ	Greek letter Theta

CHAPTER 1. INTRODUCTION

Motor vehicle crashes are the leading cause of death in the United States for people between the ages of 3- and 33-years old.[(1)] Crashes are complex events, often resulting from multiple contributing factors. Human behavior, the roadway environment, and vehicle failures are factors found to contribute in approximately 94 percent, 34 percent, and 12 percent of crashes, respectively.[(2)] Transportation agencies focused on the safety of their respective roadways generally use statistical analysis of historical crash records as the primary yardstick to measure the safety of intersections, interchanges, and other traffic facilities. As it becomes evident that a specific location is experiencing an unusually high frequency of crashes, this location is subjected to investigation and possible remediation. Unfortunately, this process of remediating roadways presents the considerable drawback of actually realizing an excess of crashes. Thus, motivated by the need to assess and manage the safety of traffic facilities more effectively, this report presents new research on the use of surrogate safety measures—that is, measures of safety not based on a series of actual crashes.

This report develops and evaluates a method for the surrogate safety assessment of traffic facilities that has been codified into a software utility referred to as the Surrogate Safety Assessment Model (SSAM). The following sections briefly present additional background information, a synopsis of the technique, and a summary of the chapters in this report.

BACKGROUND

Throughout the United States, there are over 6 million police-reported motor vehicle crashes each year, resulting in 43,000 deaths, 2.7 million injuries, and $230 billion in economic losses.[(3)] However, at one specific location, it may take years of infrequent and sporadically occurring crashes (and injuries) to reveal the need for remediation of the roadway layout or traffic control strategy. This section briefly reviews current crash analysis techniques to establish a basic perspective of their capabilities and limitations.

Safety Prediction Models

A safety prediction model is most commonly designed to estimate the expected number of crashes per year for a given traffic facility, based on traffic factors (e.g., average daily traffic), geometric layout, and traffic control features. The reported accuracy of representative crash prediction models—specifically looking at intersections—can be fairly capable at times but is also fairly variable. For example, in a study of 205 rural California and Michigan intersections of various types (e.g., three-legged, four-legged, stop-controlled, and signalized), Vogt found that the correlation between predicted crash rates and actual crash rates—expressed in terms of coefficient of determination (R-squared (R^2))—ranged between 0.31 and 0.51 depending on the intersection type, averaging about 0.41 across all intersections.[(4)] Thus, there remains a considerable degree of unexplained variation in the prediction of a “normal” rate of crashes for a given facility.

However, it is not specifically the accuracy of estimated “normal” crash rates that presents the greatest challenge. Rather, it is most perplexing that the nature of motor vehicle crashes—being so infrequent and exhibiting such variable yearly crash counts—is such that it may take years of crash data to reasonably narrow down the actual underlying crash rate of a location.

Statistical Challenges

The statistical challenges posed by the nature of motor vehicle crashes can be appreciated by considering the examples in the next few paragraphs.

Yearly crash counts, similarly to hourly traffic volume, can be approximated fairly well by a Poisson distribution, which exhibits variance (σ^2) as high as the mean (μ).[1] Thus, the standard deviation (σ) is equal to the root of the mean (i.e., $\sigma = \mu^{1/2}$). With a mean greater than 6, the Poisson distribution can be approximated by a normal distribution, and, in a normal distribution, approximately 95 percent of all outcomes fall within two standard deviations of the mean. Applying these assumptions to intersections with a mean rate of 100 crashes in a given timeframe, it could be said that most of these intersections (about 95 percent of them) would have crash counts during this timeframe that would fall within two standard deviations of the mean. With one standard deviation being 10 crashes, most crash counts would fall within 20 crashes of the mean (i.e., within the range of 80 to 120 crashes). Thus, in the timeframe necessary to generate 100 crashes, one could expect that all but 5 percent of intersections to exhibit crash counts within plus or minus 20 percent of the mean (100).

Crash rates are generally discussed as yearly rates, and intersections generally have far fewer than 100 crashes per year. In the aforementioned study by Vogt, a group of 49 intersections exhibited a mean crash rate of approximately 20 crashes per year. Thus, it would take about 5 years, on average, for each of these intersections to accumulate 100 crashes. However, Vogt’s study was based on 3 years of crash data for each intersection, which would result in an average of 60 crashes per intersection. Assuming, for the sake of illustration, that all 49 intersections had an identical mean rate of 20 crashes per year, then most of these intersections would have 3-year crash counts between 45 and 75 (i.e., within 25 percent of the mean). Vogt also studied a group of 84 unsignalized intersections with a mean of about 4 crashes per year. Intersections in this group would take 25 years to accumulate enough crashes—100 crashes—such that most intersections (even with identical crash rates) would be within 20 percent of the mean rate. However, with only a 3-year crash history, resulting in a mean of 12 crashes per intersection, it could only be said (assuming all intersections had an identical crash rate of 4 crashes per year) that most intersections would have crash counts between 5 and 19 (within 58 percent of the mean). Thus, the infrequent and variable nature of crashes presents a significant challenge in accurately pinpointing an underlying crash rate. The

[1] On closer examination, both crash counts and traffic counts actually exhibit somewhat higher variance than the mean, which further strengthens the point being made.

problem is increasingly difficult for areas with lower (more infrequent) crash rates, such as rural intersections.

Collecting 25 years of crash data is clearly impractical, and it is unlikely that underlying traffic conditions will remain static for even a few years. Thus, for lack of being able to pinpoint crash rates of intersections quickly and accurately, an agency might select the intersections with the most crashes for remediation. Consider, for example, that an agency was managing a set of 84 unsignalized intersections that all exhibited Poisson-distributed crashes at a rate of 4.0 crashes per year. Having collected three years of data, it could be expected that 10 percent of these signals (about 8 signals) would have accumulated 16 or more crashes, exhibiting a crash rate of 5.3 crashes per year. This agency could then contract a consultant to sprinkle a few drops of "safety water" on these intersections. After three more years, with no relevant change to the intersections and their underlying crash rate, one would expect these 8 signals to then exhibit a mean crash rate of 4.0 crashes per year. Thus, the consultant could update his sales brochure to claim a reduction in crashes of 33 percent on average, including perhaps one signal that did not respond to the treatment. This artificial before-and-after benefit is well known as regression-to-the-mean bias. Hauer and Persaud have shown a significant bias can exist even with 6 years of data, and they recommend using Empirical Bayes (EB) techniques to correct for this bias.(5) However, correcting for the bias does not recover the resources spent (in this example on "safety water") to treat intersections that were not as unsafe as they seemed to be with only 3 years of crash data.

Surrogate Safety Measures

The notion of surrogate safety measures—that is, measures other than actual crash frequency—is of interest to address the following needs:

- There is a need for the capability to assess the safety of traffic facilities without waiting for a statistically significant "abnormal" or "relatively greater" number of crashes to actually occur.
- There is a need for the capability to assess the safety of experimental roadway designs and/or operational strategies before they are actually built or employed in the field.

Several surrogate safety measures have been proposed in the literature and have been reviewed by Gettman and Head in a preceding report, FHWA-RD-03-050, *Surrogate Safety Measures from Traffic Simulation.*[6] The following list provides several examples:

- Vehicle delay or travel time.
- Approach speed.
- Percentage of stopped vehicles.
- Queue lengths.
- Stop-bar encroachments.
- Red-light violations.
- Percentage of left turns.
- Speed distribution.
- Deceleration distribution.

The most prevalent literature in surrogate measures is related to the traffic conflicts technique, which is focused on observing traffic conflicts.

Traffic Conflicts

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 risk of collision if their movements remain unchanged.[7]

The traffic conflicts technique utilizes field observers to identify conflict events at intersections by watching for strong braking and evasive maneuvers.[8] The method has a long history of development, formally beginning with studies at General Motors (GM) Research Laboratories in the late 1960s.[9] The method has been shown to have some correlation to crashes. There is, however, still some debate regarding the connection between conflict measures and crash predictions. The main criticism of the technique is that the subjectivity of field observers induces additional uncertainty into the collection of accurate data on conflicts.

Nonetheless, conflict studies are still used to rank locations with respect to safety and a corresponding need for construction upgrades. There is general consensus that higher rates of traffic conflicts can indicate lower levels of safety for a particular facility. Aside from using total conflict counts, conflict events can also be categorized based on the type of driving maneuver (crossing, rear-end, and lane-change events) and by several measures of severity of the event.

In this study, it was found that the ratio of traffic conflicts to actual crashes was approximately 20,000 to 1. Thus, traffic conflicts occur with adequate frequency to overcome the statistical challenges posed by infrequent crashes. Also, since adequate conflict data can be collected in a relatively short time, conflict analysis is not subject to the problem of changing underlying conditions (e.g., traffic volumes and pavement conditions) that affect long-term crash records.

SURROGATE SAFETY ASSESSMENT MODEL

To analyze new and innovative traffic facility designs, microscopic traffic simulation models are often used to predict the performance of those facilities before they are deployed in the real world. Simulation tools are extremely valuable in assessing the relative performance of one design versus another. In terms of measures of safety, existing simulation systems provide no guidance to analysts. This project is intended to evaluate the ability of simulation models to output meaningful measures of safety based on the occurrence of conflicts during the simulation. Relative differences in the frequency and severity of conflicts recorded from distinct traffic facility designs for the same underlying traffic demand would indicate that one facility design was safer than another. Thus, the purpose of this project is to test this hypothesis and provide guidance to the traffic engineering community in this regard.

The high-level scope of this study is twofold:

- To develop a software application to automate the task of conflict analysis.[2]
- To conduct validation testing to gauge the efficacy of this approach.

The use of surrogate safety assessment methods is grounded in the discussion of the methodology and recommendations outlined in report FHWA-RD-03-050. That study recommended the combination of traffic simulation and automated traffic conflict analysis, which in this project has been realized by the development a software utility referred to as SSAM. The software development effort included the following tasks:

- To determine data requirements and develop a “universal” data format—trajectory file format—that could be easily supported by all major simulation vendors and also be used for real-world datasets.
- To develop an algorithmic approach while concurrently defining data requirements to efficiently identify and classify conflict events and compute a series of desired surrogate safety measures for such events.
- To provide basic visualization and statistical features to facilitate analysis and report generation.
- To team with simulation vendors to add SSAM support to their software via support of the trajectory file format.

[2] Although this project focuses on simulated vehicle trajectory data, it would seem entirely applicable to the analysis of real-world vehicle trajectory data as well.

SSAM is compatible with the following traffic simulation software from four vendors who participated in the project:

- AIMSUN.
- Paramics.
- TEXAS.
- VISSIM.

The validation of the SSAM includes three distinct efforts:

- Theoretical validation.
- Field validation.
- Sensitivity analysis.

Each of these efforts are documented in a corresponding chapter and summarized in the next section.

REPORT ORGANIZATION

The chapters of the report are summarized as follows:

- Chapter 1 has provided an introduction to SSAM and provided motivational background information.
- Chapter 2 provides an overview of SSAM, including a brief description of how the vehicle trajectory data are processed to identify conflict events. Chapter 2 includes a listing and definitions of various surrogate safety measures calculated by the software. A user manual for the software is also available separately from FHWA.
- Chapter 3 presents "theoretical" validation, which consists of relative safety comparisons of 11 design pairs. These comparison tests included assessment of basic roadway improvements with well-established incremental safety benefits, such as intersections with and without exclusive turn lanes. Tests were also performed for facilities without established safety assessments, including a comparison of three- and four-phase interchange control strategies, and a comparison of a traditional interchange to a double-roundabout.
- Chapter 4 discusses a field validation study based on 83 intersections in British Columbia, Canada. These intersections were modeled and simulated in VISSIM and then assessed with SSAM. Actual crash records were obtained from the Insurance Corporation of British Columbia (ICBC), and several validation tests were performed to compare simulation-based conflict data with the real-world crash records.
- Chapter 5 presents a sensitivity analysis (of the choice of simulation software) that parallels the field validation study on a smaller scale, comparing the results of SSAM assessment conducted with each of the four simulation systems

(AIMSUN, Paramics, TEXAS, and VISSIM) on 5 of the 83 intersections from field validation study.

- Chapter 6 summarizes the overall effort under this project, recounting the salient findings and providing recommendations for future work.

CHAPTER 2. SSAM SOFTWARE

This chapter provides a brief overview of the SSAM software, developed to automate the process of identifying conflicts and calculating surrogate safety measures.[3] The software overview is organized into the following sections:

- SSAM workflow.
- Conflict identification algorithms.
- Terms and definitions.

The SSAM software and corresponding user manual are available upon request from the Federal Highway Administration (FHWA).[4]

SSAM WORKFLOW

This section provides an overview of the typical workflow of using the SSAM software, tracing the flow of information through various input data, tasks or operations, and resulting outputs. In doing so, many of the screens of SSAM's graphic user interface (GUI) are introduced.

SSAM operates by processing data describing the trajectories of vehicles driving through a traffic facility (e.g., a signalized intersection) and identifying conflicts. The vehicle trajectory input data for SSAM are generated by traffic simulation software in a trajectory file format (where files are labeled with a .trj file extension), specially designed for SSAM. SSAM calculates surrogate measures of safety corresponding to each vehicle-to-vehicle interaction and determines whether or not each interaction satisfies the criteria to be deemed an official conflict. A table of all identified conflicts and their corresponding surrogate safety measures is then presented to the user. Figure 1 illustrates the workflow for using SSAM.

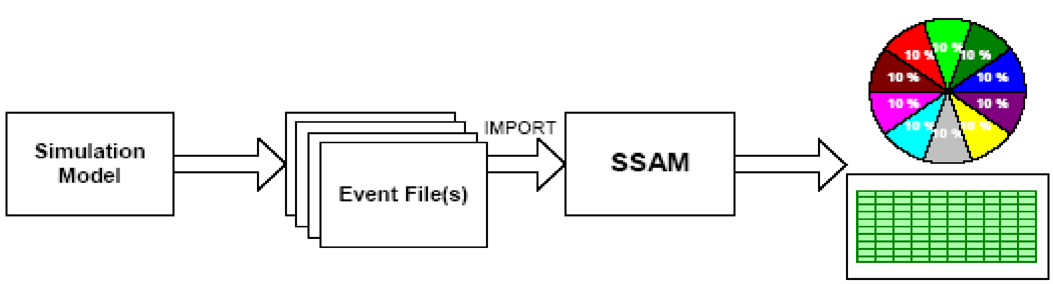


Figure 1. Illustration. SSAM Operational Concept.

[3] The SSAM acronym may be used in the sense "the software," as in SSAM identifies conflicts.
[4] Inquiries for the SSAM software and documentation should be directed to the FHWA Office of Safety R&D.

The traffic engineer begins the analysis by first enabling output of vehicle interaction (or trajectory) data in the simulation model of his or her choice. The traffic engineer then runs the simulation model for a number of iterations (replications with alternate random number seeds) to obtain a statistically sufficient set of simulation output data. The traffic engineer then launches the stand-alone SSAM application. The user interface of SSAM is shown in figure 2.

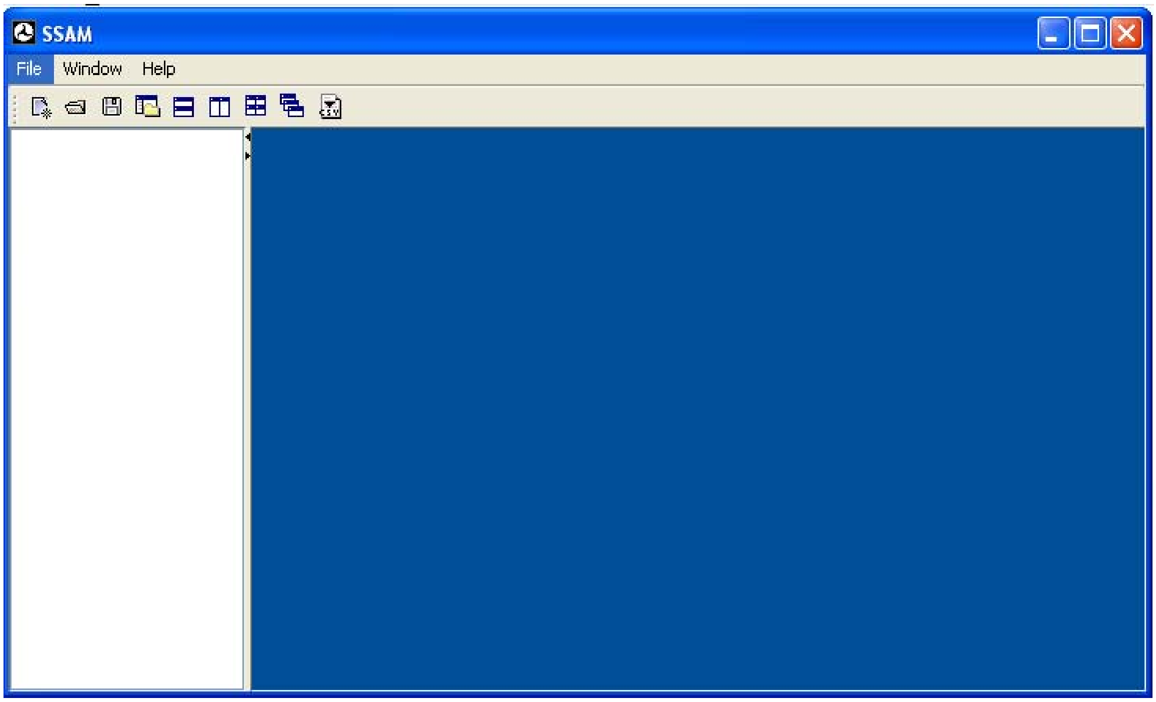


Figure 2. Screen Capture. SSAM User Interface after Launching.

The user begins by defining a new conflict analysis *case* by using the Menus to create a new case file (or alternatively to open an existing case file). The user interface provides a tree-view listing of all existing case documents in the left-hand pane of the display, as shown in figure 3 (with a single existing case document). One or more case documents may be viewed in the workspace in the right-hand pane. Figure 3 shows a case document where various views of its corresponding input and output data are organized in a multi-tabbed format. In particular, the Configuration tab (or panel), shown in figure 3, allows the user to browse the file system and select one or more trajectory files to be processed for the current case. The software uses two threshold values for surrogate measures of safety to delineate which vehicle-to-vehicle interactions are classified as conflicts. These two thresholds are applied to the value of

- Time-to-collision (TTC).
- Post-encroachment time (PET).

The software provides default threshold values for these measures, which the analyst may optionally override with his or her preferred alternate values. SSAM utilizes a default

TTC value of 1.5 seconds, as suggested in previous research.(10, 11) Use of a PET threshold is attributed to research by Hyden.(12)

Once the conflict identification thresholds are determined, the user presses the Analyze button, and simulation (trajectory) data are processed to identify vehicle-to-vehicle interactions which satisfy the conflict classification criteria.

Each conflict identified during analysis (including data from the trajectory files of all corresponding replications of the simulation) is listed in a table (the conflict table) under the Conflicts tab, which is shown in the right-hand pane in figure 4. The conflict table shows all conflict details, including the time, location, and all surrogate measures of safety for that conflict.

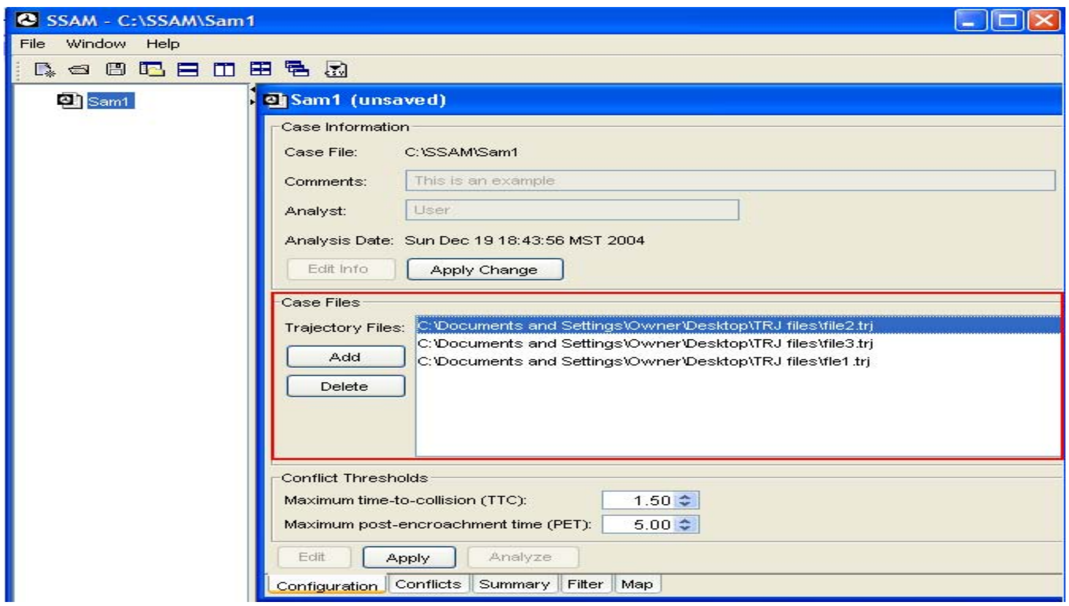


Figure 3. Screen Capture. SSAM User Interface with Case File Defined.

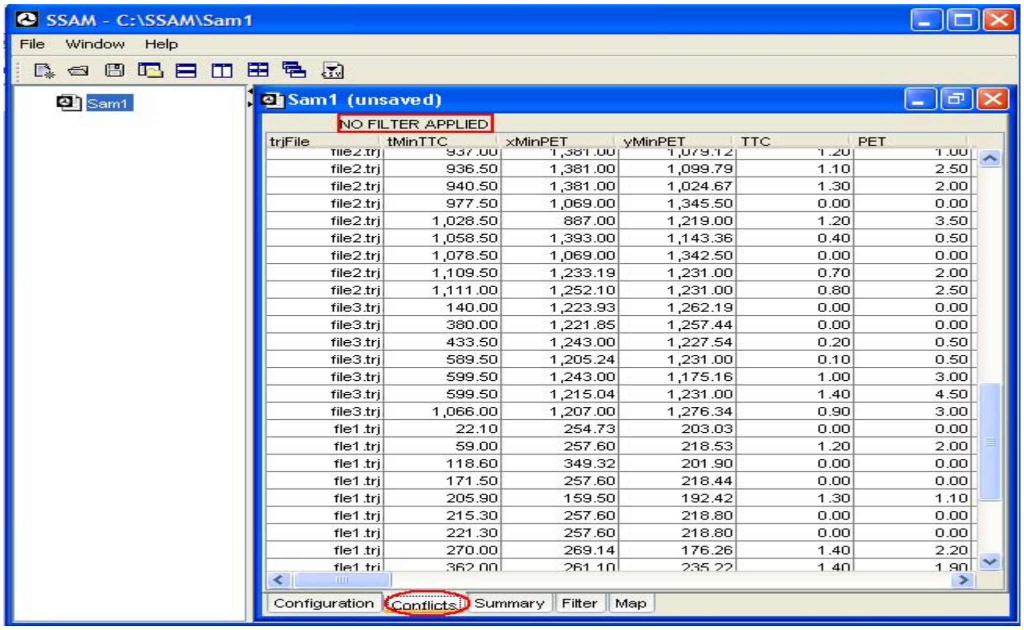


Figure 4. Screen Capture. SSAM User Interface with Conflicts Tab Selected.

SSAM also provides a Summary screen for each case, as shown in figure 5. Users click the summary tab to switch from the conflict table to a view of summary statistics. Summary statistics include the number of different conflict types for each simulation replication, as well as the average and total values over all replications. Additionally, average values of each proposed surrogate measure are presented in the summary.

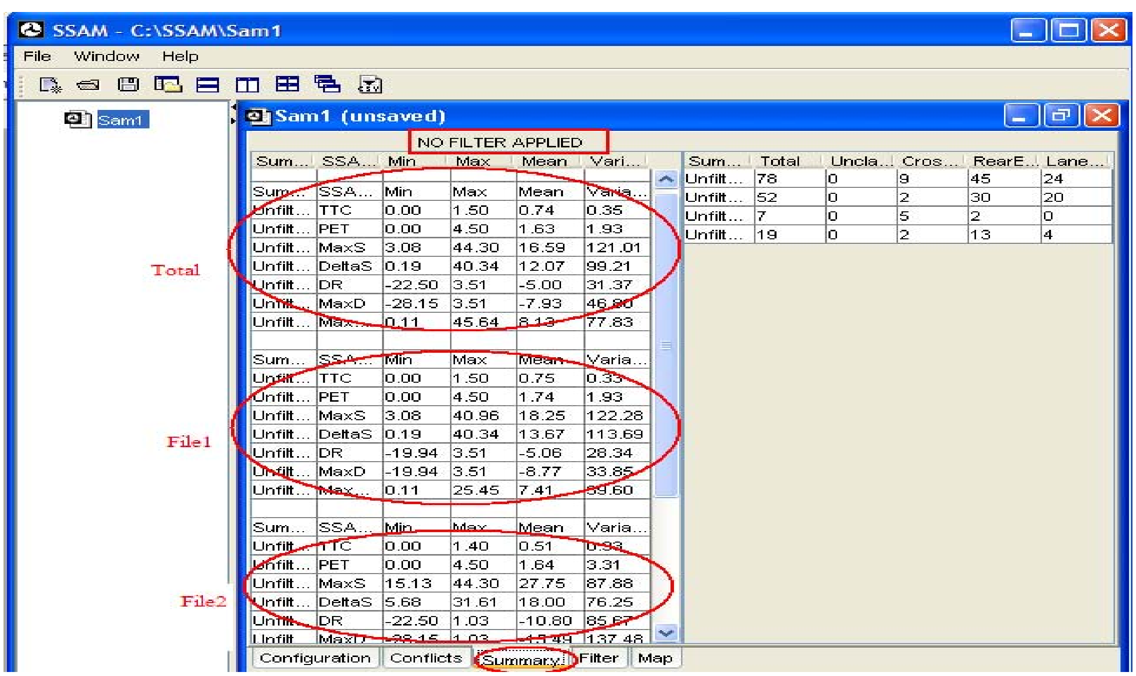


Figure 5. Screen Capture. SSAM User Interface with Summary Tab Selected.

SSAM also includes a Filter tool, shown in figure 6, which can be accessed via the Filter tab of the case display. By configuring filter parameters, the user can effectively instruct the software, “Show me all rear-end conflict events where the speed differential was greater than 40.25 km/h (25 mi/h) occurring in lane 5 of link 12.” Once the filter is applied, only those conflicts satisfying the filter criteria appear in the conflict table, and the summary statistics are recomputed for this subset of the conflicts.

SSAM also supports analysis and report generation by providing copy and paste features so that data from the filtered conflict table may be transferred to a spreadsheet application such as Microsoft Excel®. Alternatively, the table can be exported (i.e., saved to a file) in comma separated values (CSV) format, which is a universal format that can be imported into other applications for statistical analysis, charting, and report generation. Figure 7 shows an exported CSV file as it appears when opened with the Microsoft Excel® spreadsheet application.

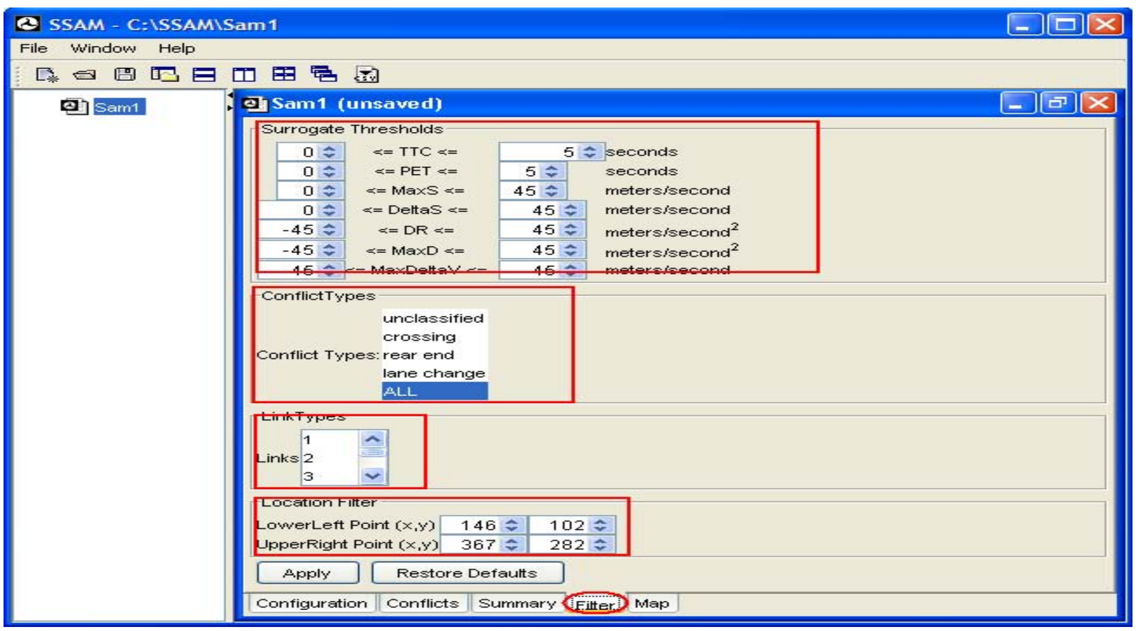
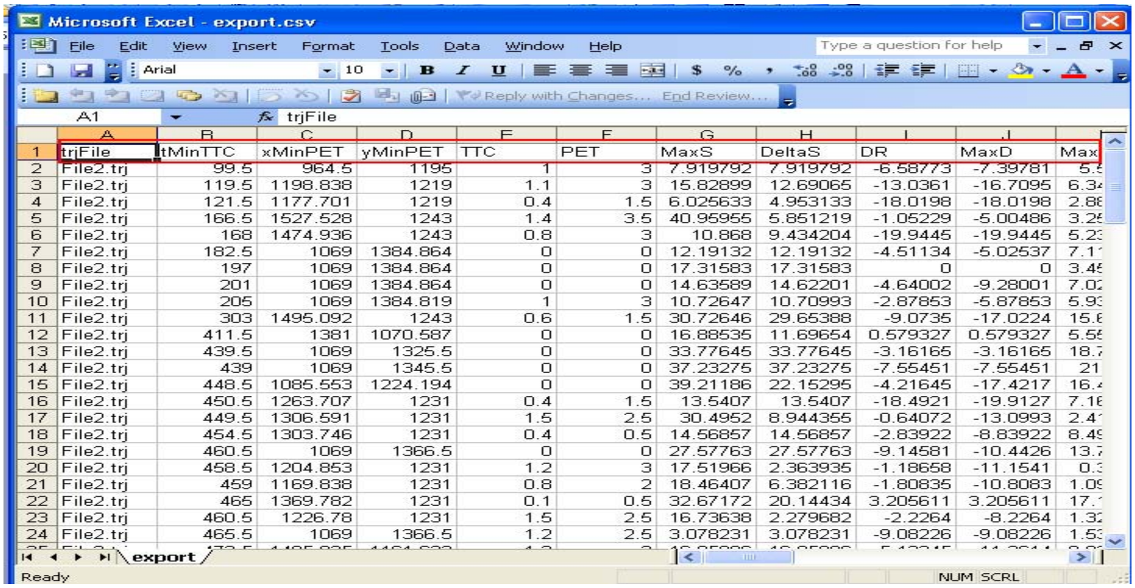


Figure 6. Screen Capture. SSAM User Interface with Filter Tab Selected.



	A	B	C	D	E	F	G	H	I	J	
1	trjFile	tMinTTC	xMinPET	yMinPET	TTC	PET	MaxS	DeltaS	DR	MaxD	Max
2	File2.trj	99.5	964.5	1195	1	3	7.919792	7.919792	-6.58773	-7.39781	5.5
3	File2.trj	119.5	1198.838	1219	1.1	3	15.82899	12.69065	-13.0361	-16.7095	6.34
4	File2.trj	121.5	1177.701	1219	0.4	1.5	6.025633	4.953133	-18.0198	-18.0198	2.88
5	File2.trj	166.5	1527.528	1243	1.4	3.5	40.95955	5.851219	-1.05229	-5.00486	3.25
6	File2.trj	168	1474.936	1243	0.8	3	10.868	9.434204	-19.9445	-19.9445	5.23
7	File2.trj	182.5	1069	1384.864	0	0	12.19132	12.19132	-4.51134	-5.02537	7.1
8	File2.trj	197	1069	1384.864	0	0	17.31583	17.31583	0	0	3.45
9	File2.trj	201	1069	1384.864	0	0	14.63589	14.62201	-4.64002	-9.28001	7.02
10	File2.trj	205	1069	1384.819	1	3	10.72647	10.70993	-2.87853	-5.87853	5.93
11	File2.trj	303	1495.092	1243	0.6	1.5	30.72646	29.65388	-9.0735	-17.0224	15.6
12	File2.trj	411.5	1381	1070.587	0	0	16.88535	11.69654	0.579327	0.579327	5.55
13	File2.trj	439.5	1069	1325.5	0	0	33.77645	33.77645	-3.16165	-3.16165	18.7
14	File2.trj	439	1069	1345.5	0	0	37.23275	37.23275	-7.55451	-7.55451	21
15	File2.trj	448.5	1085.553	1224.194	0	0	39.21186	22.15295	-4.21645	-17.4217	16.4
16	File2.trj	450.5	1263.707	1231	0.4	1.5	13.5407	13.5407	-18.4921	-19.9127	7.16
17	File2.trj	449.5	1306.591	1231	1.5	2.5	30.4952	8.944355	-0.64072	-13.0993	2.4
18	File2.trj	454.5	1303.746	1231	0.4	0.5	14.56857	14.56857	-2.83922	-8.83922	8.49
19	File2.trj	460.5	1069	1366.5	0	0	27.57763	27.57763	-9.14581	-10.4426	13.7
20	File2.trj	458.5	1204.853	1231	1.2	3	17.51966	2.363935	-1.18658	-11.1541	0.3
21	File2.trj	459	1169.838	1231	0.8	2	18.46407	6.382116	-1.80835	-10.8083	1.09
22	File2.trj	465	1369.782	1231	0.1	0.5	32.67172	20.14434	3.205611	3.205611	17.
23	File2.trj	460.5	1226.78	1231	1.5	2.5	16.73638	2.279682	-2.2264	-8.2264	1.32
24	File2.trj	465.5	1069	1366.5	1.2	2.5	3.078231	3.078231	-9.08226	-9.08226	1.53

Figure 7. Screen Capture. CSV File from SSAM.

In addition, the SSAM software also features two additional screens which also appear as tabs on the user-interface. These additional screens are a Map panel and a *t*-test panel. The Map panel allows a user to display a map or image of the underlying roadway network and overlay conflicts on that map. The map display can be exported to an image file to facilitate report generation. In additional, the *t*-test panel can be used to calculate statistical property of the conflict data to facilitate comparisons.

More information about SSAM is available in a corresponding user manual.

CONFLICT IDENTIFICATION ALGORITHMS

This section summarizes the algorithms used by SSAM to identify conflicts from the vehicle trajectory files (TRJ files) to be processed. This can be a computationally intensive task depending on the size of the TRJ file, which is a function of the number of vehicles in the network model and the amount of time simulated. A high-end computer might require more than 10 minutes to process data from 5 hours of traffic for a single intersection model. Large multi-intersection networks might require hours of processing time. The following steps summarize the technique to identify conflicts:

Step 1

Determine the dimensions of the analysis area based on the header name in the TRJ file. These dimensions define the width and height of a rectangular analysis area and indicate if trajectory data are provided in English or metric units. SSAM constructs a zone grid to cover the entire rectangular analysis area, as shown in figure 8. Individual square zones cover 15.25-m by 15.25-m (50-ft by 50-ft) areas depending on the units specified in the

TRJ file. By dividing the region into these zones, the number of vehicle-to-vehicle comparisons necessary to identify potential conflicts is reduced considerably.

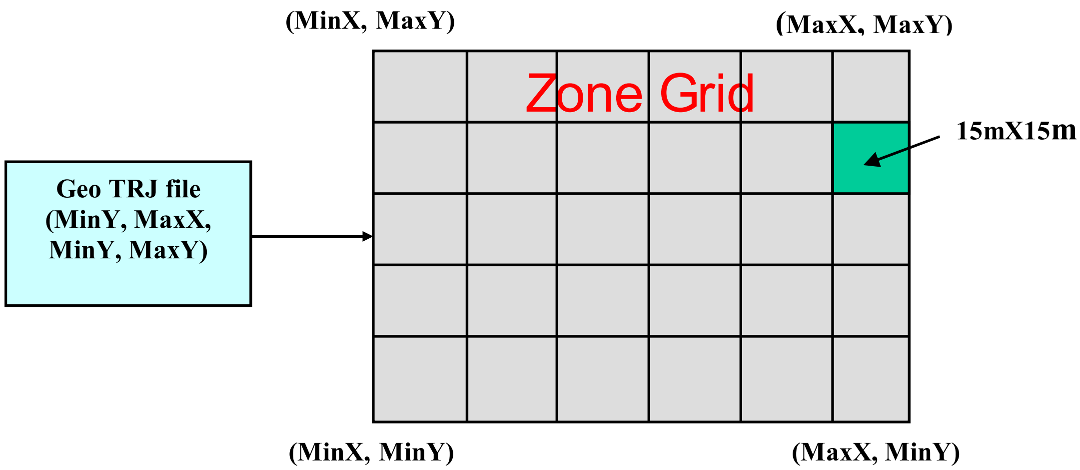


Figure 8. Illustration. Illustration of Zone Grid.

Step 2

Analyze a single time step of a trajectory file. For each vehicle in the analysis region, SSAM projects that vehicle's expected location as a function of its current speed, if it were to continue traveling along its (future) path for up to the duration of the configured time-to-collision (TTC) value. A vehicle's projected path is based on a look ahead over the next 10 seconds of trajectory data. The path, as shown in figure 9, is a set of straight line segments (labeled *S*) connecting the vehicle's future downstream locations (labeled *X*). The threshold TTC value is configured by the user of SSAM, typically with a threshold value of order of 1.5 seconds. Conflicts with TTC values larger than 1.5 seconds are not generally considered in the safety community to be "severe" enough events for recording in a traditional field conflict study.

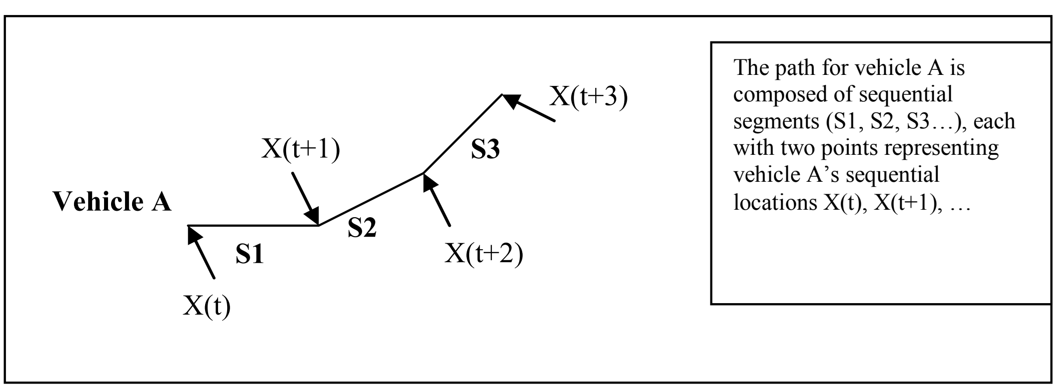


Figure 9. Illustration. Illustration of Vehicle Path.

The process of projecting the distance that a vehicle may progress forward during the specified look-ahead time interval and the calculation of the exact coordinates of that projected vehicle position occurs as follows, assuming SSAM is going to analyze the conflicts for vehicle *A* at time t_1. First, SSAM extracts all data related with vehicle *A* from the trajectory file, such as vehicle *A*'s location, speed, acceleration, etc., at time t_1 and several time steps after t_1. Each location is denoted as (x_1,y_1), (x_2,y_2), etc. Then SSAM projects vehicle *A*'s distance forward along its trajectory defined by those locations:

1. Each vehicle is defined as a polygon (rectangle) with four corner points (shown in figure 10).

2. The forward distance that the vehicle will travel is calculated in the MaxTTC interval, denoted as $DIS_1 = V_1$ * MaxTTC (shown in figure 10).

3. The vehicle's next time step location (x_2,y_2) is calculated based on the distance from current location to that location, denoted as DIS_2=|Location (t+1)-Location (t)| (shown in figure 10).

4. If DIS_2 is less than DIS_1, then DIS_2 is subtracted from DIS_1 and the previous two calculations are repeated, updating $DIS_1=DIS_1-DIS_2$ and DIS_2=|Location (t+2)-Location (t+1)| and comparing the new DIS_1 and DIS_2 (shown in figure 11).

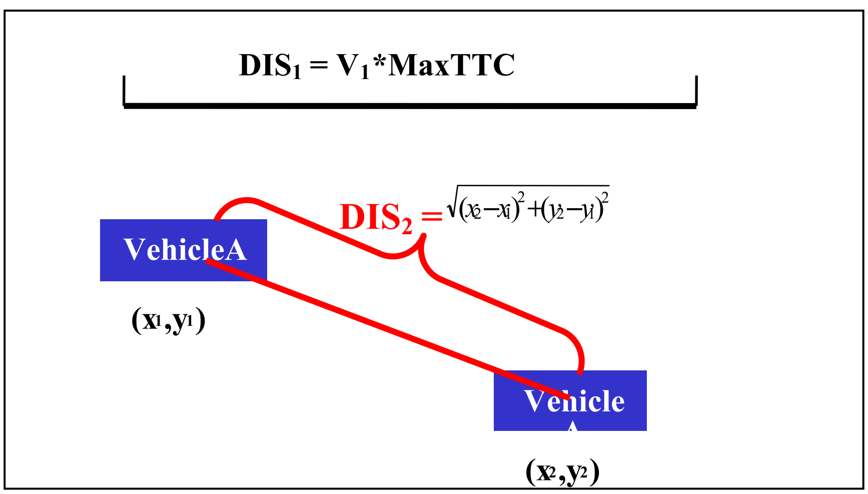


Figure 10. Illustration. DIS_1 and DIS_2.

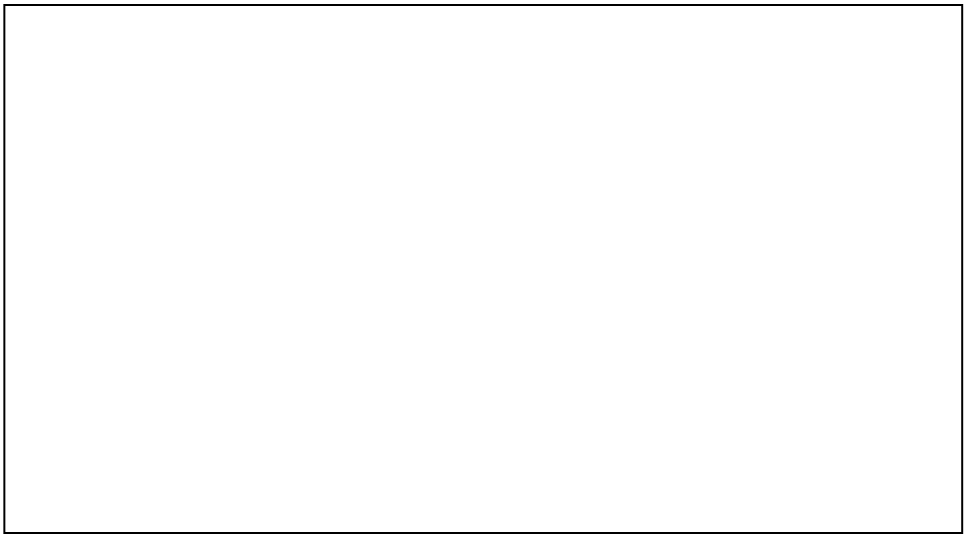


Figure 11. Illustration. Updated DIS_1 and DIS_2 when Old $DIS_1 > DIS_2$.

5. If DIS_2 is more than DIS_1, then the x-y position is calculated to locate the projection point within the segment of DIS_2 (shown in figure 12).

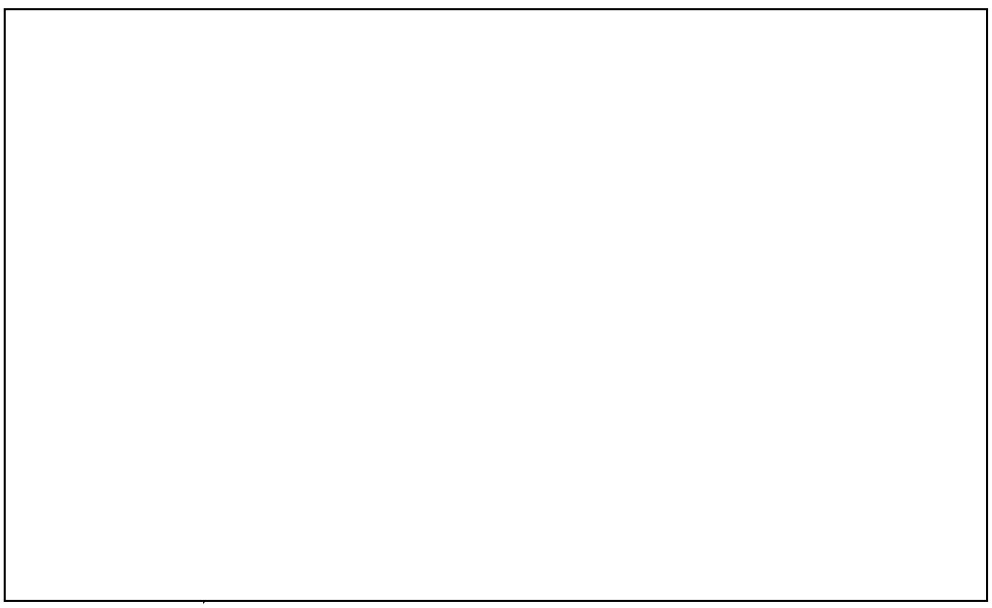


Figure 12. Illustration. Projection Point when $DIS_1 < DIS_2$.

Step 3

For each vehicle, calculate the rectangular perimeter delineating the location and orientation of that vehicle at its projected future position. Overlay that rectangle on the zone grid, calculating which (rectangular) zones in the grid will contain at least some portion of that vehicle. For each zone the vehicle will occupy, "add" the vehicle to that zone, or rather, add that vehicle to a list of "occupants" maintained for each zone. Any time a vehicle is added into a zone that currently contains one or more other vehicles, check for overlap of the new vehicle (rectangle) with each of the other vehicles (rectangles) in that zone. It is possible that two vehicles may partially occupy the same zone without overlapping. However, two overlapping rectangles indicate that a future collision is projected for this pair of vehicles, and therefore, a potential conflict has been identified, as portrayed in figure 13. SSAM maintains a list of all conflicting vehicle-pairs (all conflict events) for the current time-step. Each time-step, the list is prepopulated with all conflicting vehicle-pairs from the prior time-step. If the current vehicle being added to the zone grid overlaps with any other vehicle, that vehicle-pair is added to the conflict list for the current time-step (if not already in the list).

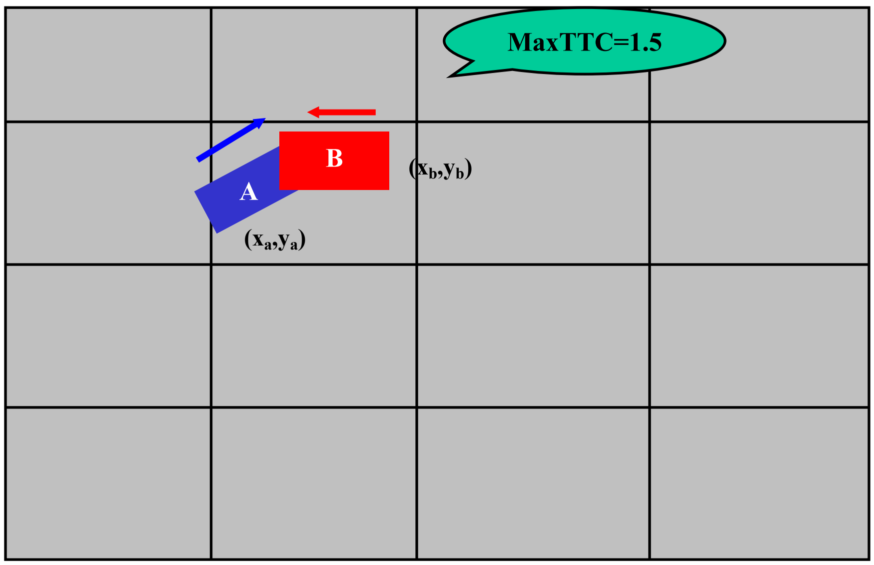


Figure 13. Illustration. Checking Conflict Between Two Vehicles at MaxTTC.

Step 4

Continue so that SSAM can perform more detailed processing of each conflicting vehicle-pair in the list for the current time-step as follows:

1. First, update the TTC of the vehicle-pair. This is done by iteratively shortening the future projection timeline by a tenth of second and reprojecting both vehicles as before over successively short distances until the pair of vehicles no longer overlaps in their projected locations. In this way, a more accurate TTC value is established for this time-step. This is portrayed in figure 14, where the TTC values have reduced from the maxTTC value of 1.5 seconds (illustrated previously in figure 13) to a TTC value of 1.3 seconds. Instead of the large overlap in figure 13, the vehicles in figure 14 have just barely come into contact. Note that if the projection timeline reduces to 0 seconds and the vehicles still overlap, then this is a crash.

2. At this point, various surrogate safety measures, such as the minTTC (taking the minimum of the current TTC value and that of the prior time-step, if applicable), are calculated and updated. Also, the current (actual) positions of both vehicles are recorded for post-encroachment analysis.

3. If it was found that the vehicle-pair does not overlap over any projection time between 0 and maxTTC, then this vehicle-pair has made its way into the conflict event list by virtue of being in the list during the prior time-step. In this case, the event remains in the list, watching for the one vehicle (the trailing vehicle) to eventually occupy (or encroach on) on a position formerly held by the other vehicle (the leading vehicle). The time differential between when the leading vehicle occupied this location and the trailing vehicle arrived is the post-encroachment time (PET). If a post-encroachment was observed, then the minimum PET is updated, and this conflict event remains in the list, as the post-encroachment could potentially reduce as the vehicle trajectories progress over time.

4. If a vehicle-pair in the conflict event list is no longer on an imminent collision course, and it is clear that PET to any prior positions could not further reduce the minimum PET, or the maximum PET has elapsed, then this vehicle-pair is identified for removal from the conflict event list. Prior to removal, all final surrogate measures are computed, including conflict starting and end points, conflict angles, and DeltaV. Also, the conflict is classified at this time as a crossing conflict, rear-end conflict, or lane-change conflict. The next section defines all surrogate measures and provides the conflict type classification logic. If this conflict event has ended, then the conflict and all surrogate measures are added to the conflict table, and the event is removed from the tracking list.

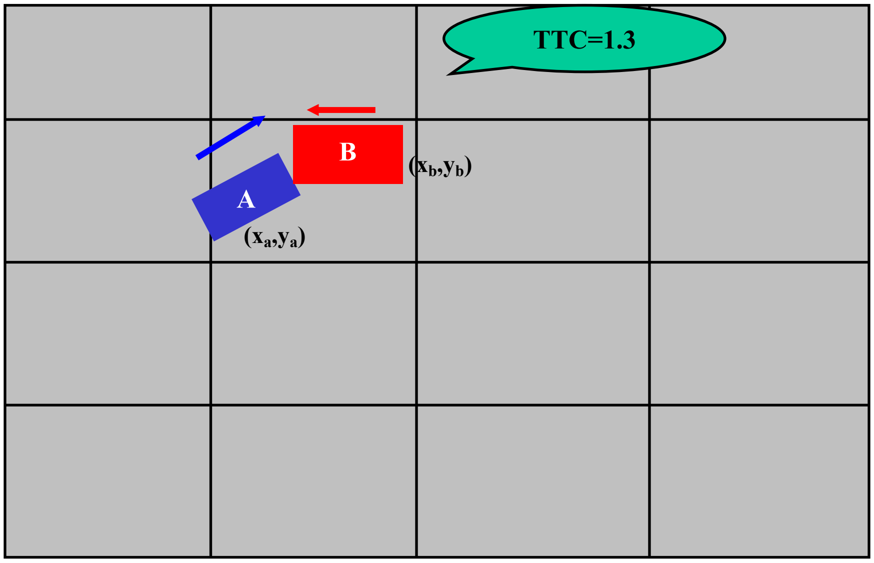


Figure 14. Illustration. Checking Conflict Between Two Vehicles at TTC = 1.3 (Vehicles No Longer in Conflict).

TERMS AND DEFINITIONS

SSAM computes and records the following data or measures for each conflict identified in the vehicle-trajectory input data. This information is provided in the Conflicts table on the Conflicts panel. It is possible to filter out several of the conflicts based on specified ranges of these values, using the Filter tool. This data may also be exported for use in other third-party processing software, such as Microsoft Excel®, where more complicated analysis options may be available.

tMinTTC is the simulation time when the minimum TTC (time-to-collision) value for this conflict was observed.

xMinPET is the x-coordinate specifying the approximate location of the conflict at the time when the minimum PET was observed. More specifically, this location corresponds to the center of the (first) vehicle where the subsequent arrival of the second vehicle to the same location was the shortest encroachment observed.

yMinPET is the y-coordinate specifying the approximate location of the conflict at the time when the minimum PET was observed. More specifically, this location corresponds to the center of the (first) vehicle where the subsequent arrival of the second vehicle to the same location was the shortest encroachment observed.

ConflictAngle is an approximate angle of hypothetical collision between conflicting vehicles based on the estimated heading of the each vehicle (see explanation of **FirstHeading**). The angle, expressed in the perspective of the first vehicle to arrive at the conflict point, conveys the direction from which the second vehicle is approaching the first vehicle. The angle ranges from -180 ° to +180 °, where a *negative* angle indicates approach from the left and a positive angle indicates approach from the right. An angle of

180 ° (or -180 °) indicates a direct head-on approach, and an angle of 0 ° (or -0 °) indicates a direct rear approach, as illustrated in figure 15.

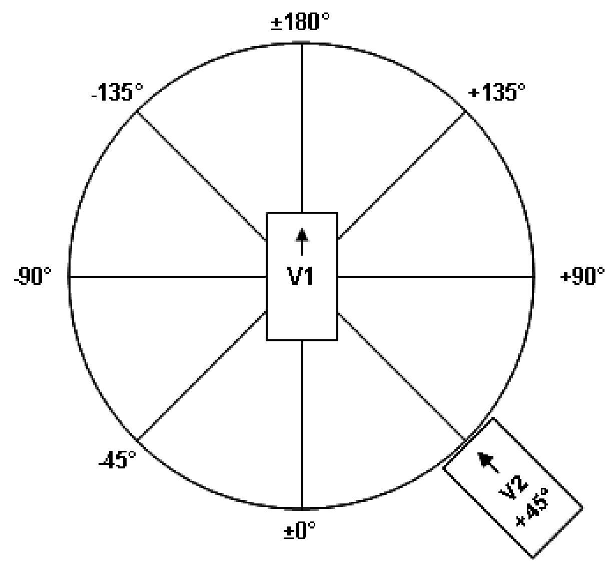


Figure 15. Illustration. Conflict Angle.

ClockAngle is an alternative expression of the conflict angle in terms of more familiar clock-hand positions. Again, the angle is expressed in the perspective of the first vehicle, with the clock time indicating the angle from which the second vehicle is approaching. The 12:00 position is directly ahead of the first vehicle, 3:00 is to the right, 6:00 is directly behind, and 9:00 is to the left, as illustrated in figure 16.

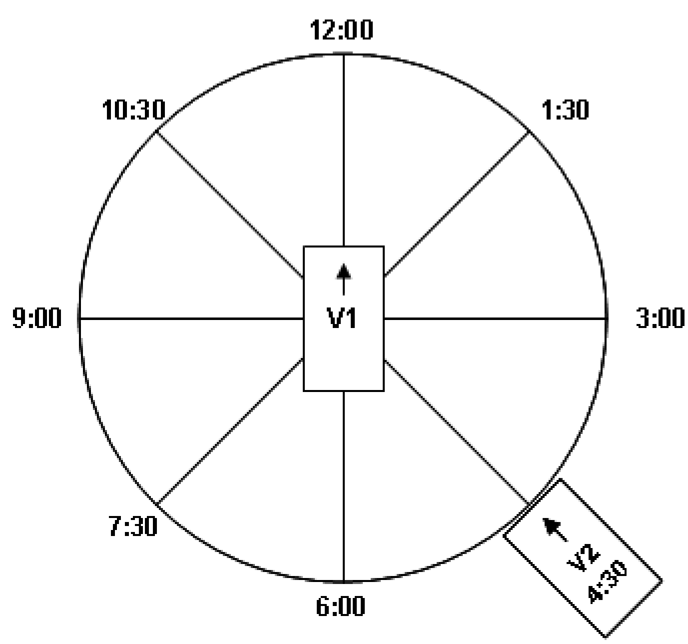


Figure 16. Illustration. Clock Angle.

PostCrashV is an estimate of the post collision velocity of both vehicles. This estimate assumes that the vehicles did crash at the estimated **ConflictAngle**, at velocities observed at the **tMinTTC**. It also assumes an inelastic collision between the center of mass of both vehicles, where both vehicles subsequently deflect in the same direction and at the same velocity.

PostCrashHeading is the estimated heading of both vehicles following a hypothetical collision (as discussed in **PostCrashV**). This heading is expressed as the angle measured counterclockwise from the x-axis (which is assumed to point right), such that 0 ° is right, 90 ° is up, 180 ° is left, and 270 ° is down. The angle ranges from 0 ° to 360 °.

FirstVID (SecondVID) is the vehicle identification number of the first (second) vehicle. The first vehicle is the vehicle that arrives to the conflict point first. The second vehicle subsequently arrives to the same location. In rare cases (actually collisions), both vehicles arrive to a location simultaneously, in which case the tie between first and second vehicle in broken arbitrarily.

FirstLink (SecondLink) is a number indicating which link the first (second) vehicle is traveling on at **tMinTTC**.

FirstLane (SecondLane) is a number indicating in which lane the first (second) vehicle is traveling on at **tMinTTC**.

FirstLength (SecondLength) is the length of the first (second) vehicle in feet or meters.

FirstWidth (SecondWidth) is the width of the first (second) vehicle in feet or meters.
FirstHeading (SecondHeading) is the heading of the first (second) vehicle during the conflict. This heading is approximated by the change in position from the start of the conflict to the end of the conflict. Note that in most non-rear-end conflicts, at least one vehicle is turning throughout the conflict. Its actually heading would vary accordingly throughout the conflict. If the vehicle does not move during the conflict, then the direction in which it is facing is taken as the heading. This heading is expressed as the angle measured counterclockwise from the x-axis (which is assumed to point right), such that 0 ° is right, 90 ° is up, 180 ° is left, and 270 ° is down. The angle ranges from 0 ° to 360 °.

FirstVMinTTC (SecondVMinTTC) is the velocity (speed) of the first (second) vehicle at **tMinTTC**.

xFirstCSP (xSecondCSP) is the x-coordinate of the first (second) vehicle at the conflict starting point (CSP). The CSP is the location of the vehicle at **tMinTTC**.

yFirstCSP (ySecondCSP) is the y-coordinate of the first (second) vehicle at the CSP. The CSP is the location of the vehicle at **tMinTTC**.

xFirstCEP (xSecondCEP) is the x-coordinate of the first (second) vehicle at the conflict ending point (CEP). The CEP is the location of the vehicle at either the last time step where the TTC value is below the specified threshold or where the last post-encroachment value was observed, whichever occurs later in the conflict timeline.

yFirstCEP (ySecondCEP) is the y-coordinate of the first (second) vehicle at the CEP. The CEP is the location of the vehicle at either the last time step where the TTC value is below the specified threshold or where the last post-encroachment value was observed, whichever occurs later in the conflict timeline.

Definitions of Surrogate Measures Computed by SSAM

TTC is the minimum time-to-collision value observed during the conflict. This estimate is based on the current location, speed, and future trajectory of two vehicles at a given instant. A TTC value is defined for each time step during the conflict event. A conflict event is concluded after the TTC value rises back above the critical threshold value. This value is recorded in seconds.

PET is the minimum post-encroachment time observed during the conflict. Post-encroachment time is the time between when the first vehicle last occupied a position and the time when the second vehicle subsequently arrived to the same position. A value of zero indicates a collision. A post-encroachment time is associated with each time step during a conflict. A conflict event is concluded when the final PET value is recorded at the last location where a time-to-collision value was still below the critical threshold value. This value is recorded in seconds.

MaxS is the maximum speed of either vehicle throughout the conflict (i.e., while the TTC is less than the specified threshold). This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

DeltaS is the difference in vehicle speeds as observed at **tMinTTC**. More precisely, this value is mathematically defined as the magnitude of the difference in vehicle velocities (or trajectories), such that if v_1 and v_2 are the velocity vectors of the first and second vehicles respectively, then **DeltaS =** $\| v_1 - v_2 \|$. For context, consider an example where both vehicles are traveling at the same speed, v. If they are traveling in the same direction, **DeltaS** = 0. If they have a perpendicular crossing path, **DeltaS** = $(\sqrt{2})v$. If they are approaching each other head on, **DeltaS** = $2v$.

DR is the initial deceleration rate of the second vehicle, recorded as the instantaneous acceleration rate. If the vehicle brakes (i.e., reacts), this is the first negative acceleration value observed during the conflict. If the vehicle does not brake, this is the lowest acceleration value observed during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

MaxD is the maximum deceleration of the second vehicle, recorded as the minimum instantaneous acceleration rate observed during the conflict. A negative value indicates deceleration (braking or release of gas pedal). A positive value indicates that the vehicle did not decelerate during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

ConflictType describes whether the conflict is the result of a rear end, lane change, or crossing movement. If link and lane information is not available for both vehicles then the event type is classified based solely on the absolute value of the **ConflictAngle** as follows. The type is classified as a rear-end conflict if ||**ConflictAngle||** < 30 °, a crossing conflict if ||**ConflictAngle||** > 85 °, or otherwise a lane-changing conflict. However, the simulation model that produced the vehicle trajectory data can generally provide link and lane information for both vehicles—though the coding of these values may vary significantly from one simulation vendor to the next. If link and lane information is available, that information is utilized for classification in the case that the vehicles both occupy the same lane (of the same link) at either the start or end of the conflict event. If the vehicles both occupy the same lane at the start and end of the event, then it is classified as a rear-end event. If either vehicle ends the conflict event in a different lane than it started (while having not changed links), then the event is classified as a lane-change. If either of the vehicles changes links over the course of the event, then the conflict angle determines the classification as previously described, with the following possible exception). For two vehicles that begin the conflict event in the same lane but change links over the course of the event, the classification logic considers only rear-end or lane-change types, based on the conflict angle (using the threshold value previously mentioned). Note that vehicle maneuvers such as changing lanes into an adjacent turn bay lane or entering into an intersection area may be consider changing links, depending on the underlying simulation model. In some cases, vehicles which appear to be traveling in the same lane may actually by considered by the simulation model as traveling on different links that happen to overlap.

MaxDeltaV is the maximum **DeltaV** value of either vehicle in the conflict (see **FirstDeltaV** or **SecondDeltaV** for more information).

FirstDeltaV (SecondDeltaV) is the change between conflict velocity (given by speed **FirstVMinTTC** and heading **FirstHeading**) and the postcollision velocity (given by speed **PostCrashV** and heading **PostCrashHeading**). This is a surrogate for the severity of the conflict, calculated assuming a hypothetical collision of the two vehicles in the conflict.

CHAPTER 3. THEORETICAL VALIDATION

The validation effort for SSAM consists of a theoretical validation, field validation, and sensitivity analysis. This chapter presents the theoretical validation effort.

PURPOSE

The main purpose of theoretical validation of SSAM is to determine if the surrogate measures computed with the SSAM approach can discriminate between intersection designs in a simulation model. The secondary purpose of the theoretical validation effort is to identify any correlation between the surrogate measures produced by the SSAM approach and existing crash prediction models available from the literature.

METHODOLOGY

The hypothesis for the utility of surrogate measures of safety is that they will discriminate between two design alternatives implemented in a simulation. This involves the following steps:

- Model several intersection designs in a traffic simulation system.
- Run the simulation for various traffic scenarios and collect trajectory data.
- Process the trajectory data with SSAM to identify conflict events and derive surrogate measures of safety.
- Statistically compare the results from each design to identify statistical significant differences.

In addition, this effort also includes analysis of the following:

- Identify of the sensitivity of surrogate measures to simulation input variables (e.g., volumes).
- Identify the sensitivity of the results to severity thresholds for TTC

Implement Alternative Intersection Designs

As discussed in chapter 1, the resulting frequency and severity distributions of the conflict events that occur in the simulation are hypothesized to represent the surrogate measures of the safety of a particular intersection design. To evaluate the viability of using these measures for assessing safety, alternative intersection designs have been implemented in microscopic simulation systems and the corresponding output surrogate measures of safety for each conflict event or aggregation of the conflict events among alternative designs have been compared.

The intersection designs studied include many of the intersection types that are used in the real world. For each set (or pair) of alternative designs, traffic conditions (e.g. volumes for each approach, vehicle class, speed limit, driver's aggressive distributions, gap acceptance threshold, etc.) have been configured identically in order to make the alternatives comparable. Where alternative traffic flow scenarios were investigated, with a range of volumes and/or turning probabilities, the same conditions were applied to both intersection designs in the design-pair to maintain a reasonable basis for comparison. To ensure statistically representative measures for comparison, each situation was replicated 10 times for each design alternative.

Measures of Discrimination Between Designs

After running the simulation for each design, the corresponding surrogate measures were collected with SSAM, and statistical distributions of various aggregations were compared by the following:

- Total number of conflict events.
- Number of conflicts of a particular type.
- Mean and variance of surrogate measures of safety (TTC, PET, etc.).

The analysis of design alternatives has been conducted in a comparative manner because the essential information is more likely found in the differences between the results for two scenarios rather than from the absolute results for a particular scenario.

Data from One Simulation Run

After each simulation run, the vehicle trajectory data were processed by SSAM to compute the surrogate measures. For each conflict event identified by SSAM, the following has been recorded:

- Conflict type.
- Starting and ending points.
- Values of surrogate measures of safety.

An example of the data collected is shown in table 1. More data are collected on each event than is shown in the table below. Refer to the SSAM user manual for detail of all measures collected by SSAM.

SSAM classifies each conflict event as one of three conflict types: crossing, lane-change, or rear-end. Conflict type classification is based on the **ConflictAngle**, as defined in chapter 2. During the theoretical validation study, the conflict type was classified as a rear-end conflict if ||**ConflictAngle**|| < 2 °, a crossing conflict if ||**ConflictAngle**|| > 45 °, or a lane-changing conflict if 2 ° ≤ ||**ConflictAngle**|| ≤ 45 °. However, it is important to note that the classifications logic of SSAM changed subsequent to the theoretical validation in this chapter to achieve more accurate classification. (The revised logic appears in its entirety in the definition of **ConflictType** in chapter 2.) Revising the classification logic allowed recognition that many of the lane-change conflicts in a particular AIMSUN round-about model were actually events between pairs of vehicles on the same link and in the same lane. These events were clearly rear-end events, but due to the curvature of the roadway, the difference in vehicle headings (i.e., the conflict angle) exceeded the 2 ° threshold for a rear-end event. The revised logic improved classification, though there are still “gray area” cases (e.g., a vehicle entering into a roundabout collides with a vehicle within the roundabout) where classification of an event as crossing, lane-changing, or rear-end is arguably a subjective judgment. Indeed, it could be argued that some conflicts are simultaneously of two or three types (e.g., lane-change and rear-end).

Table 1. Conflict Events Data for Each Replication.

Time/ Index	TTC	PET	MaxS	DeltaS	DR	Max D	MaxDeltaV	Conflict type[1]		
								I	II	III
1	0.2	0.5	29	9.3	1	1	7.6	✓		
2	0.1	0.5	44	31.6	-0.6	-1.45	20.5		✓	
3	1.4	4.5	27	5.7	-21.2	-21.2	25			✓
…	0.9	3	15.1	15.1	-11.2	-16.3	13		✓	
Total	Total conflict events: 177							55	65	57

[1] I—Crossing conflict event.
II—Lane-changing conflict event.
III— Rear-end conflict event.

Table 1 is an example of the data available for each conflict event. Aggregated values or summary measures have also been collected, such as the total number of conflict events with TTC values in different severity ranges (e.g. 0 < TTC ≤ 0.5, 0 < TTC ≤ 1.0). This down-selection of the data is done by using the Filter function of SSAM. An example aggregation by conflict type is shown in table 2.

Table 2. Mean Safety Measures for Each Conflict Type.

Conflict Type	# of Conflict Events	$\overline{TTC}$	$\overline{PET}$	$\overline{DR}$	$\overline{MaxS}$	$\overline{DeltaS}$
I	55	1.2	1.1	-4.5	20.5	17.3
II	65	1.5	1.3	-1.68	19.5	16
III	57	1.33	1.12	-5.73	22.6	21.3

Note: The bar over the variable indicates the average value of that surrogate safety measure over all the conflict events of each conflict type.

Statistical Results from Multiple Replications

Each intersection design is simulated with multiple replications, each using different random number seeds, and statistical distributions of the results were collected and analyzed. For the intersection design alternatives, a sample size of 10 replications was used throughout this study.

Comparison of Alternative Designs

For each set (pair) of alternative designs, the output measures have been compared statistically to identify the significance of the difference between the designs. An example of this comparison is shown in table 3. The student's *t*-test was used to compare each type of surrogate safety measures and the frequency of conflicts for alternative designs. The *t*-test calculates the probability of the difference of the two means. In this test, the null hypothesis (H0) indicates that the difference between the means of two samples is 0. Based on the difference level of the two sample variances, *t*-ratios and degree of freedom are calculated in different ways. Whether or not the sample variances are significantly different is verified by using the *F*-test before the *t*-test is performed. When the average number of events in a conflict type category and/or total conflicts is less than 0.5 (meaning that out of the 10 replications, an event occurs approximately every other simulation run), the data are marked as N/A, and no test outcome is recorded.

Table 3. Example of *T*-Test Results for Number of Conflict Events.

Designs	# of Lane Changing Events	# of Rear-End Events	# of Crossing Events	Total # of Conflict Events
A	215	199	58	582
B	106	176	24	353
t-Value	2.98	1.56	2.06	2.39
Significant?	YES	NO	YES	YES

Table 4. Example of *T*-Test Results for Average TTC Value.

Designs	TTC Threshold 1.5s	TTC Threshold 1.0s	TTC Threshold 0.5s	TTC Total
A	1.2	0.9	0.5	1.0
B	0.8	0.78	0.45	1.25
t-Value	2.21	1.35	1.23	1.28
Significant?	YES	NO	NO	NO

Table 3 and table 4 are examples of the statistical analyses that were performed in the theoretical validation study.

Comparison to Predicted Crash Frequency

In addition to the comparison analysis for each set (pair) of the alternative designs, the theoretical validation study also compared the relative values of surrogate measures of safety to predictions of safety from regression-based models of crash prediction developed and calibrated by others.

Regression models were used to calculate the expected crash frequency for each simulated scenario. Lognormal regression models have been applied in this study. Specific models are used for each of the following for classes of intersections:

- Urban, four-leg, signalized/stop-controlled intersection.
- Urban, three-leg, signalized/stop-controlled intersection (T-intersection).
- Diamond interchange.
- Roundabout.

Many of the models presented in this chapter use the term *accident* instead of the term *crash*. *Crash* is the preferred term used in this document; however, these terms may be considered interchangeable. The term *accident* is retained at times due to the historical use of variables or acronyms, such as AMF, which stands for accident modification factor.

Accident prediction models for urban, four-leg, signalized intersection are established by Harwood and Council:[(13)]

$$A = AMF_1 * AMF_2 * \exp(-5.73 + 0.6 \ln ADT_1 + 0.2 \ln ADT_2)$$

Figure 17. Equation. Accident Prediction Model for an Urban, Four-Leg, Signalized Intersection.

Where:

A	is the predicted number of total intersection-related accidents per year.
AMF_1	is the accident modification factor for the presence of left- turn lane: 0.82 for one major-road approach. 0.67 for both major-road approaches.
AMF_2	is the accident modification factor for the presence of right-turn lane: 0.975 for a right-turn lane on one major-road approach. 0.95 for right-turn lanes on both major-road approaches.
ADT_1	is the average daily traffic (ADT) volume (veh/day) on the major road.
ADT_2	is the ADT volume (veh/day) on the minor road.

Accident prediction for urban, four-leg, stop-controlled intersection are also given by Harwood and Council:(13)

$$A = AMF_1 * AMF_2 * AMF_3 * AMF_4 \exp(0.0054 SKEW) \exp(-9.34 + 0.6 \ln ADT_1 + 0.61 \ln ADT_2)$$

Figure 18. Equation. Accident Prediction Model for an Urban, Four-Leg, Stop-Controlled Intersection.

Where:

A	is the predicted number of total intersection-related accidents per year .
AMF_1	is the accident modification factor for the presence of left-turn lane on major road: 0.76 for one major-road approach. 0.58 for both major-road approaches.
AMF_2	is the accident modification factor for the presence of right-turn lane: 0.95 for a right-turn lane on one major-road approach. 0.90 for right-turn lanes on both major-road approaches.
AMF_3	is the accident modification factor for the sight restrictions: 1.05 if sight distance is limited in one quadrant of the intersection. 1.10 if sight distance is limited in two quadrants of the intersection. 1.15 if sight distance is limited in three quadrants of the intersection. 1.20 if sight distance is limited in four quadrants of the intersection
AMF_4	is 0.53, the accident modification factor for the conversion from minor road to all-way stop-control.
SKEW	is the intersection skew angle (degrees), expressed as the absolute value of the difference between 90 ° and the actual intersection angle.
ADT_1	is the ADT volume (veh/day) on the major road.
ADT_2	is the ADT volume (veh/day) on the minor road.

Accident prediction models for urban, three-leg, signalized intersection (T-intersection) are given by Bared and Kaiser:(14)

$$A = (ADT_{main})^{0.3008} (ADT_{cross})^{0.2867} \exp(-4.9666)$$

Figure 19. Equation. Accident Prediction Model for a Three-Leg, Signalized Intersection.

Where:

A	is the predicted number of total intersection-related accidents per year.
ADT_{main}	is the entering ADT on the main road.
ADT_{cross}	is the entering ADT on the crossroad.

An accident model for urban, three-leg, stop-controlled intersection (T-intersection) is provided by Harwood and Council:[13]

$$A = AMF_1 * AMF_2 * AMF_3 * AMF_4 \exp(0.005 SKEW) \exp(-10.9 + 0.79 \ln ADT_1 + 0.49 \ln ADT_2)$$

Figure 20. Equation. Accident Prediction Model for an Urban, Three-Leg, Stop-Controlled Intersection.

Where:

A	is the predicted number of total intersection-related accidents per year
AMF_1	is the accident modification factor for the presence of left-turn lane on major road: 0.78 for one major-road approach.
AMF_2	is the accident modification factor for the presence of right-turn lane: 0.95 for a right-turn lane on one major-road approach.
AMF_3	is the accident modification factor for the sight restrictions: 1.05 if sight distance is limited in one quadrant of the intersection. 1.10 if sight distance is limited in two quadrants of the intersection. 1.15 if sight distance is limited in three quadrants of the intersection. 1.20 if sight distance is limited in four quadrants of the intersection.
AMF_4	is 0.53, accident modification factor for the conversion from minor road to all-way stop-control.
SKEW	is the intersection skew angle (degrees), expressed as the absolute value of the difference between 90 ° and the actual intersection angle.
ADT_1	is the ADT volume (veh/day) on the major road.
ADT_2	is the ADT volume (veh/day) on the minor road.

An accident prediction at a diamond interchange is given by Wolshon:[15]

$$A = (ADT_{cross} * ADT_{off-ramps})^{0.5499} \exp(-8.6706)$$

Figure 21. Equation. Accident Prediction Model for a Diamond Interchange.

Where:

A	is the predicted number of intersection related accidents at the cross-road of a diamond interchange.
ADT_{cross}	is the ADT volume (veh/day) on the cross-road.
$ADT_{off-ramps}$	is the ADT volume (veh/day) on the off-ramps.

Roundabout

Crash prediction models have been developed for four-leg, signalized intersections in the United States, as discussed previously. However, no crash prediction models exist for U.S. roundabouts and driver behavior. Given the relatively recent introduction of roundabouts to the United States and driver unfamiliarity with them, crash prediction models from other countries have been used.

Crash models relating crash frequency to roundabout characteristics are available from the United Kingdom. The British crash prediction equations for each type of crash are listed in figure 22 through figure 26. Note that these equations are only valid for roundabouts with four legs. However, the use of these models for relative comparisons may still be reasonable.[16]

1. Entry-Circulating:

$$A = 0.052 Q_e^{0.7} Q_c^{0.4} \exp(-40C_e + 0.14e - 0.007ev - \frac{1}{1+\exp(4R-7)} + 0.2P_m - 0.01\theta)$$

Figure 22. Equation. Entry-Circulating Roundabout Accident Prediction Model.

Where:

A	are personal injury accidents (including fatalities) per year per roundabout approach.
Q_e	is entering flow (1,000s of vehicles/day).
Q_c	is circulating flow (1,000s of vehicles/day).
C_e	is entry curvature ($C_e = 1/R_e$).
R_e	is entry path radius for the shortest vehicle path (m).
e	is entry width (m).
v	is approach width (m).
R	is ratio of inscribed circle diameter/central island diameter.
P_m	is proportion of motorcycles (percent, %).
θ	is the angle to next leg measured centerline to centerline (degrees, °).

2. Approaching:

$$A = 0.057 Q_e^{1.7} \exp(20C_e - 0.1\theta)$$

Figure 23. Equation. Accident Prediction Model for Roundabout Approaches.

Where:

A	are personal injury crashes (including fatalities) per year at roundabout approach or leg.
Q_e	is entering flow (1,000s of vehicles/day).
C_e	is entry curvature $=1/R_e$.
R_e	is entry path radius for the shortest vehicle path (m).
e	is entry width (m).

3. Single vehicle:[5]

$$A = 0.0064 Q_e^{0.8} \exp(25C_e + 0.2v - 45C_a)$$

Figure 24. Equation. Single-Vehicle Accident Model for Roundabouts.

Where:

A	are personal injury crashes (including fatalities) per year at roundabout approach or leg.
Q_e	is entering flow (1,000s of vehicles/day).
C_e	is entry curvature $=1/R_e$.
R_e	is entry path radius for the shortest vehicle path (m).
V	is approach width (m).
C_a	is approach curvature $= 1/R_a$.
R_a	is approach radius (m). Defined as the radius of a curve between 50m (164 ft) and 500 m (1,640 ft) of the yield line.

4. Other (vehicle):

$$A = 0.0026 Q_e^{0.8} Q_c^{0.8} \exp(0.2P_m)$$

Figure 25. Equation. Other Vehicle Accident Prediction Model for Roundabouts.

Where:

A	are personal injury crashes (including fatalities) per year per roundabout approach.
Q_e	is entering flow (1,000s of vehicles/day).
Q_c	is circulating flow (1,000s of vehicles/day).
P_m	is proportion motorcycles (percent, %).

5. Pedestrian:

$$A = 0.029 Q_{ep}^{0.6}$$

Figure 26. Equation. Pedestrian Accident Prediction Model for Roundabouts.

Where:

A	are personal injury crashes (including fatalities) per year at roundabout approach or leg.
Q_{ep}	is the product $(Q_e + Q_{ex})Q_p$.
Q_e	is entering flow (1,000s of vehicles/day).

[5] Not used in the study because no data were collected in the simulation on single-vehicle events.

Q_{ex}	is exiting flow (1,000s of vehicles/day).
Q_p	is pedestrian crossing flow (1,000s of pedestrians/day).

Since the current method only defines conflict events for pairs of vehicles, crash types 3, 4, and 5 (single, other, and pedestrian, respectively) have been ignored in using the prediction models for roundabouts.

Comparison of Intersection Rankings by Conflict and Crash Frequencies

Another important indicator that would validate SSAM would be a correlation of surrogate measures with predicted crash frequencies. Such a comparison has been performed for each comparison scenario in the theoretical validation study. To do this, first the simulation for each intersection design was run with different traffic volumes (low, medium, high annual average daily traffic (AADT)) and the corresponding conflicts (total conflicts and total number of conflicts of each event type) were analyzed. The results were then ranked from highest to lowest. Summary measures with the same values were assigned equal rank.

For each design scenario, the predicted number of crashes using an existing crash prediction model was also calculated. This prediction is repeated for each level of traffic volume (i.e., AADT). A rank of the number of crashes was then established and compared to the ranking of number of conflicts of each type. Table 5 gives an example of the data needed for the correlation calculation. Table 6 shows an example of the paired rank data.

The Spearman rank correlation coefficient was then computed to determine the level of agreement between each pair of rankings. The Spearman rank correlation coefficient is defined by

$$R_S = 1 - 6\sum \frac{d^2}{N(N^2 - 1)}$$

Figure 27. Equation. Spearman Rank Correlation Coefficient.

Where:

d	is difference between ranks.
N	is number of paired ranks.

Then the resulting correlation coefficient is compared with the critical coefficient value with the appropriate sample size and the significance level. If the absolute value of the coefficient is greater than the critical value, then it can be concluded that there is a rank order relationship between these samples. If the R_s value is -1, then there is a perfect negative correlation between the two sets of data. If the R_s value is 1, then there is a perfect positive correlation between the two sets of data. Table 8 provides a numeric example of this. In this example, we would find that the conflict data have a positive, but weak, correlation with the predicted crash frequency.

Table 5. Example of Rank Order Data Sets.

AADT	Crossing Conflict		Rear-End Conflict		Lane Change Conflict		Conflict Number		Crash Frequency	
	M	Rank	*M*	Rank	*M*	Rank	*M*	Rank	*M*	Rank
AADT1	5	9	25	5	20	3	50	8	6	8
AADT2	7	11	30	7	7	1	44	6	5.5	7
AADT3	2	1	5	3	18	2	25	3	3	3
AADT4	3	5	2	2	20	3	25	3	4	5
…	5	9	1	1	30	4	36	5	5	6

Note: *M* = average value of the measure.

Table 6. Example for the Spearman Rank Correlation Calculation.

AADT	AADT1	AADT2	AADT3	AADT4	AADT5	AADT6
Conflict Rate Ranking	5	3	1	6	6	8
Crash Frequency Ranking	5	3	3	7	9	9
Rank Diff. (*d*)	0	0	-2	-1	-3	-1
Rs	0.57					

Issues with Validation Metrics

Reconciliation of ADT with Hourly Volumes

In crash prediction models, traffic volumes are in the unit of ADT while traffic volumes used in all of the simulation systems are in the unit of vehicles per hour. To ensure the consistency of the comparison, converting rules need to be applied to reconcile these two terms. By using *K* factors, we have converted *ADT* to vehicles per hour and vice versa as shown in figure 28:(17)

$$ADT = \frac{HV}{K}$$

Figure 28. Equation. Using *K*-Factors to Scale Hourly Volume to Daily Volume.

Where:

ADT is the average daily traffic volume.
HV is the hourly volume.
K is the conversion factor.

The *K* value should vary with different area types. For the general purpose of this study, values from the *Highway Capacity Manual* (2000) were used as shown in table 7:(17)

Table 7. Typical *K*-Factors.

Area Type	*K*-Factor
Urbanized	0.091
Urban	0.093
Transitioning/Urban	0.093
Rural Developed	0.095
Rural Undeveloped	0.100

Where:

- Urbanized areas are those designated by the U.S. Census Bureau.
- Urban areas are places with a population of at least 5,000 not already included in an urbanized area.
- Transitioning areas are the areas outside of, or urbanized areas expected to be included in, an urbanized area within 20 years.
- Rural areas are whatever is not urbanized, urban, or transitioning.

Overlapping Vehicles in TRJ Output ("Crashes")

In each of the simulation models, some situations result in "virtual" crashes. These are situations where the logic in the simulation model does not accurately and completely represent the physical possibility of a particular maneuver.

This does not happen frequently relative to the total number of traffic maneuvers being performed in a simulation; however, because the data are being analyzed at an extremely "nanoscopic" scale, SSAM identifies these modeling inaccuracies as conflicts with TTC = 0 ("crashes"). In this report, all crashes have been removed before the statistical calculations are performed. In some cases during the analysis of the theoretical validation data, it was observed that including the virtual-crashes in the analysis results in a different statistical determination. As many crashes as possible have been removed by appropriate modeling of the design case. For all the models tested, it is imperative that the analyst implement the design appropriately.

CASE STUDIES

Various types of intersections have been implemented and evaluated in three simulation systems: VISSIM, TEXAS, and AIMSUN.

The goal of this portion of the validation effort was not to compare the results of the simulation model with traffic at a comparable real-world location. Hence, no calibration effort was necessary or performed in this study. Reasonable driver behavior was verified, and appropriate control measures were used to avoid gridlock during high-volume test cases. As such, for all the intersection designs, default driving behavior models and parameters were applied for each simulation model. The same underlying simulation parameters were used for each comparison case to maintain comparability.

Eleven comparison cases were executed among the three simulation systems as follows:

TEXAS Cases

- Case 1: Signalized, four-leg intersection with permitted left turn versus protected left turn.
- Case 2: Signalized, four-leg intersection with and without left turn bay.
- Case 3: Signalized, four-leg intersection with and without right turn bay.

VISSIM Cases

- Case 4: Signalized, four-leg intersection with leading left turns versus lagging left turns.
- Case 5: Signalized, four-leg intersection versus offset T-intersection;
- Case 6: Diamond interchange with three-phase timing versus four-phase timing.
- Case 7: Single point urban interchange (SPUI) versus diamond interchange.

AIMSUN Cases

- Case 8: Signalized, four-leg intersection with left turns versus signalized intersection with median U-turns.
- Case 9: Signalized, four-leg intersection versus single roundabout.
- Case 10: Signalized, three-leg, T-intersection versus single roundabout with three legs.
- Case 11: Diamond interchange versus double roundabout.

Three sets of traffic volumes (low, medium, and high) were applied for each intersection design, and timing plans were designed to ensure no over-saturation would occur.

Case 1: Conventional Four-Leg Intersection with Permitted Left Turn Versus Protected Left Turn (TEXAS)

There are two basic alternative designs for left turns: protected and permitted. Protected left-turn design allocates an exclusive phase for left turn only, which will make the left-turn maneuvers have fewer conflict events with the opposing through traffic. Permitted left-turn design allows vehicles to make a left turn during the through traffic green phase and provides no specific green phase for left-turn only. This logic applies mostly to traffic conditions with low left-turn volumes. When the left-turn volumes become higher, there have been more conflict events when drivers begin accepting smaller gaps to cross the intersection.

According to the crash prediction models for four-leg signalized intersection, the existence of left-turn phase will result in lower crash frequency. Thus, it is hypothesized that protected left turn should have lower predicted conflict frequency than permitted left turn when other network parameters remain the same. Also, it would be reasonable to expect that severity values of the surrogate measures would be less critical for protected left turns versus permitted left turns.

Intersection Description for Case Study

The intersection used to test the alternative traffic control logic for left turns is four-legged intersections with three through lanes in the main travel directions and two through lanes on the side-street approaches to the intersection, as shown in figure 29. All left-turn bays are 76.25 m (250 ft) long.

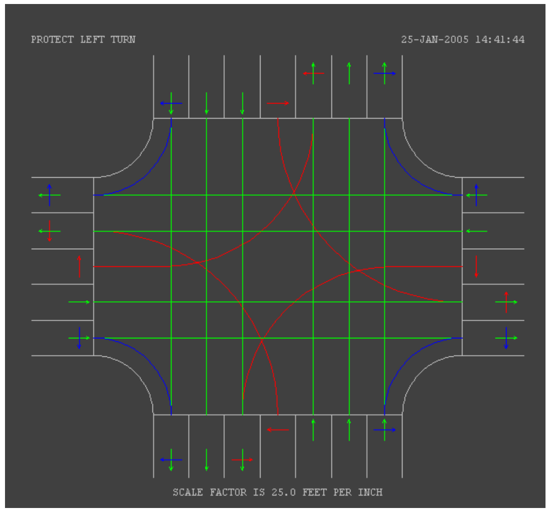


Figure 29. Screen Capture. Intersection Geometry for Testing Control Logic.

Table 8 lists the traffic volumes applied for each approach of the intersection. Fixed time traffic control is applied in this test. Figure 30 through figure 35 provide the key timing plan parameters for each testing scenario.

Table 8. Case 1 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase# (Permitted)	4	4		8	8		2	2		6	6	
Phase# (Protected)	7	4		3	8		5	2		1	6	
Low Volume	100	350	50	100	350	50	60	210	30	60	210	30
Medium Volume	240	400	160	240	400	160	180	240	180	180	240	180
High Volume	300	1050	150	300	1,050	150	240	840	120	240	840	120

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

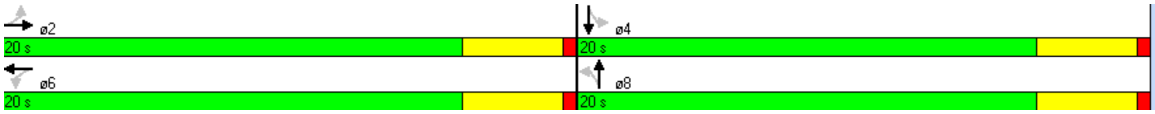


Figure 30. Illustration. Timing Plan for Permitted Left Turn in Low Volumes.

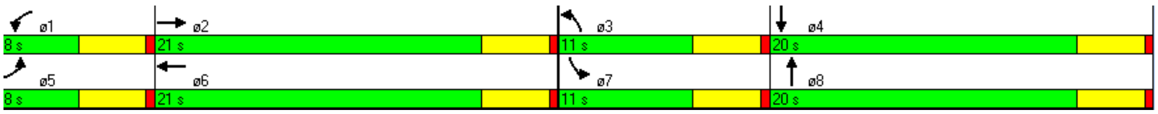


Figure 31. Illustration. Timing Plan for Protected Left Turn in Low Volumes.

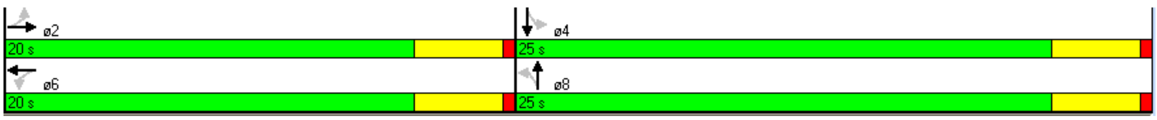


Figure 32. Illustration. Timing Plan for Permitted Left Turn in Medium Volumes.

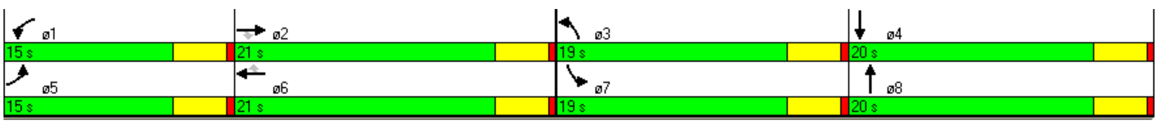


Figure 33. Illustration. Timing Plan for Protected Left Turn in Medium Volumes.

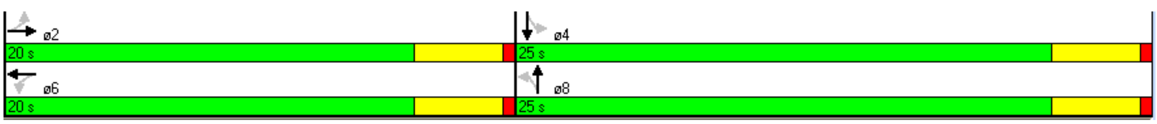


Figure 34. Illustration. Timing Plan for Permitted Left Turn in High Volumes.

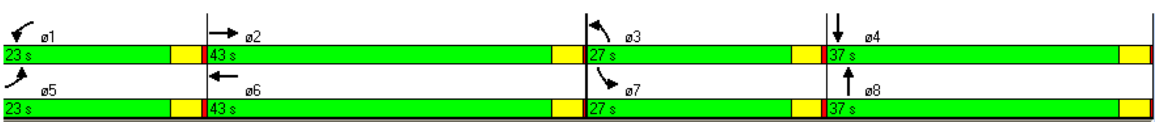


Figure 35. Illustration. Timing Plan for Protected Left Turn in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each design case and the resulting output trajectory data were analyzed by SSAM. *F*-test and *t*-tests were applied to compare surrogate measures of safety and the aggregations of those measures.

Table 9 through Table 13 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 9. Case 1 Comparison Results for Total Conflicts.

Total	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	PER	PRO	PER	PRO	PER	PRO
Low volume Mean	4.7	4.7	16.1	14	25.7	22.4
Variance	6.2	5.3	11.2	11.3	12.0	17.2
***t*-value(95%), difference (%)**	0		1.399		1.932	
Medium volume Mean	13.7	12.8	33.1	32.6	53.7	63.3
Variance	21.6	8.2	21.4	24.7	39.8	113.8
***t*-value(95%), difference (%)**	-0.522		0.233		**-2.45, -17.88%**	
High volume Mean	108.3	174.2	184.1	489.1	309.5	1208.6
Variance	138.7	183.1	332.8	189.2	408.1	1344.5
***t*-value(95%), difference (%)**	**-11.618 , -60.85%**		**-42.216, -165.67%**		**-67.916, -290.5%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table illustrates a counterintuitive result. The design with the protected left turn has, on average, more total conflicts than the case with the permitted left turn for medium- and high-traffic volumes. The following tables explain this result by breaking the total results into a result for each conflict type.

Table 10. Case 1 Comparison Results for Only Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	PER	PRO	PER	PRO	PER	PRO
Low volume Mean	3.1	0.3	5.2	0.4	6.3	1
Variance	3.4	0.5	4.4	0.5	4.2	1.1
***t*-value(95%), difference (%)**	**4.490, 90.32%**		**6.865, 92.31%**		**7.250, 84.13%**	
Medium volume Mean	5.2	0.6	8.1	0.8	10.1	1.8
Variance	7.3	0.7	5.0	0.8	10.1	0.8
***t*-value(95%), difference (%)**	**5.143, 88.46%**		**9.558, 90.12%**		**8.89, 92.808**	
High volume Mean	23.3	6.4	27.5	9.2	33.8	15
Variance	46.9	6.7	67.2	11.1	71.5	16.0
***t*-value(95%), difference (%)**	**7.299, 72.53%**		**6.543, 66.75%**		**6.355, 55.62%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates what is expected to happen from adding a protected left-turn phase; that the total crossing conflicts are reduced for all levels of traffic volume. This indicates that SSAM, in its most basic form, is a valid indicator of safety.

Table 11. Case 1 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	PER	PRO	PER	PRO	PER	PRO
Low volume Mean	1.3	3.9	8.6	11.4	15.4	17.7
Variance	0.7	2.3	12.5	7.6	21.2	10.0
t-value(95%), difference (%)	**-4.747, -200.00%**		-1.976		-1.303	
Medium volume Mean	5.3	5.2	17.2	19.5	29.7	42.9
Variance	7.6	7.7	13.7	10.9	32.0	83.9
t-value(95%), difference (%)	0.081		-1.464		**-3.878, -44.44%**	
High volume Mean	19.3	84.5	56.3	309.1	122.9	848.4
Variance	34.7	174.1	125.8	109.9	202.8	957.4
t-value(95%), difference (%)	**-14.271 , -337.82%**		**-52.075, -449.02%**		**-67.357 , -590.32%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates the large increase in rear-end conflicts for high and medium volumes that is generated by adding the protected left-turn phase. This large increase in rear-end events is the primary cause of the total conflicts being counter-indicative. Thus, it should be important to analyze all types of conflicts rather than just examining the total number of events when comparing designs.

Table 12. Case 1 Comparison Results for Lane Change Conflicts.

LC	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	PER	PRO	PER	PRO	PER	PRO
Low volume Mean	0.3	0.5	2.3	2.2	4	3.7
Variance	0.5	0.9	2.0	4.0	2.4	4.5
t-value(95%), difference (%)	-0.535		0.129		0.361	
Medium volume Mean	3.2	7	7.8	12.3	13.9	19.6
Variance	1.5	7.6	8.0	24.7	9.2	40.7
t-value(95%), difference (%)	**-3.991 , -118.75%**		**-2.491 , -57.69%**		**-2.551, -41.01%**	
High volume Mean	65.7	83.3	100.3	170.8	152.8	345.2
Variance	101.1	26.2	142.0	148.0	93.3	381.1
t-value(95%), difference (%)	**-4.932,-26.79%**		**-13.092,-70.29%**		**-27.935,-125.92%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates a 40-percent increase in lane change events at medium volumes and a 125-percent increase at high volumes. These results are likely due to longer queues in the left-turn bay because there is no permitted portion of the phase.

Table 13. Case 1 Comparison Results for Average Surrogate Measures of Safety.

	TPER	TPRO	CPER	CPRO	REPER	REPRO	LPER	LPRO
TTC (low)	0.92	0.91	0.6	0.99	1.03	0.9	1.01	0.92
t-value, diff(%)	0.299		**-2.547, -65.00%**		**3.849, 12.62%**		1.112	
TTC (med)	0.89	0.97	0.59	0.29	0.97	1.06	0.94	0.81
t-value, diff(%)	**-3.167, -8.99%**		1.776		**-3.256, -9.28%**		**2.639, 13.83%**	
TTC (high)	0.8	1.05	0.46	0.74	1.01	1.11	0.71	0.92
t-value, diff(%)	**-25.245, -31.25%**		**-5.922, -60.87%**		**-8.067, -9.90%**		**-13.285, -29.58%**	
PET(low)	2.21	1.83	0.92	1.75	2.63	1.86	2.64	1.71
t-value, diff(%)	**3.796, 17.19%**		-1.991		**7.580, 29.28%**		**3.912, 35.23%**	
PET(med)	1.81	1.85	0.92	0.15	2.13	2.2	1.75	1.17
t-value, diff(%)	-0.532		**8.840, 83.70%**		-0.769		**4.046, 33.14%**	
PET(high)	1.42	2.08	0.58	0.73	2.07	2.41	1.08	1.33
t-value, diff(%)	**-26.886, -46.48%**		**-2.218, -25.86%**		**-8.598, -16.43%**		**-8.445, -23.15%**	
MaxS(low)	26.7	33.22	34.5	38.64	24.29	33.3	23.69	31.35
t-value, diff(%)	**-7.947, -24.42%**		**-3.091, -12.00%**		**-9.521, -37.09%**		**-3.601, -32.33%**	
MaxS(med)	32.4	27.94	37.41	37.73	30.56	26.37	32.68	30.98
t-value, diff(%)	**8.321, 13.77%**		-0.159		**5.916, 13.71%**		1.831	
MaxS(high)	28.27	25.11	32.2	23.42	26.32	24.85	28.97	25.82
t-value, diff(%)	**20.782, 11.18%**		**14.825, 27.27%**		**6.757, 5.59%**		**13.492, 10.87%**	
DeltaS(low)	29.16	31.83	47.48	37.92	23.66	32.44	21.51	27.25
t-value, diff(%)	**-2.524, -9.16%**		**5.886, 20.13%**		**-8.739, -37.11%**		**-2.838, -26.69%**	
DeltaS(med)	31.07	19.54	48.5	37.26	27.06	18.46	27	21.2
t-value, diff(%)	**13.651, 37.11%**		**3.089, 23.18%**		**8.425, 31.78%**		**4.461, 21.48%**	
DeltaS(high)	22.22	16.12	34.98	21.3	20.44	16.97	20.83	13.79
t-value, diff(%)	**27.963, 27.45%**		**16.672, 39.11%**		**11.610, 16.98%**		**23.063, 33.80%**	
DR(low)	-5.54	-6.91	-0.91	-7.22	-7.12	-6.96	-6.73	-6.57
t-value, diff(%)	**4.632, -24.73%**		**6.826, -693.41%**		-0.555		-0.245	
DR(med)	-5.12	-3.72	-1.7	-1.43	-6.15	-4.21	-5.4	-2.73
t-value, diff(%)	**-6.947, 27.34%**		-0.235		**-8.651, 31.54%**		**-6.712, 49.44%**	
DR(high)	-2.97	-4.77	-0.88	-0.56	-4.93	-5.61	-1.85	-2.88
t-value, diff(%)	**23.945, -60.61%**		-1.309		**5.818, -13.79%**		**10.026, -55.68%**	
MaxD(low)	-11	-15.98	-2.09	-17.26	-14.03	-16.45	-13.37	-13.39
t-value, diff(%)	**9.844, -45.27%**		**16.899, -725.84%**		**5.388, -17.25%**		0.019	
MaxD(med)	-13.04	-11.43	-4.28	-1.62	-15.25	-13.11	-14.7	-8.14
t-value, diff(%)	**-4.499, 12.35%**		**-2.490, 62.15%**		**-7.662, 14.03%**		**-9.440 44.63%**	
MaxD(high)	-7.97	-12.06	-2.02	-3.44	-12.97	-13.96	-5.27	-7.76
t-value, diff(%)	**31.265, -51.32%**		**2.918, -70.30%**		**7.012, -7.63%**		**13.251, -47.25%**	
MaxDeltaV(low)	16.91	18	28.86	20.85	13.21	18.35	12.36	15.56
t-value, diff(%)	-1.594		**5.112, 27.75%**		**-8.851, -38.91%**		**-2.636, -25.89%**	
MaxDeltaV(med)	18.02	11.2	29.22	21.68	15.5	10.47	15.24	12.38
t-value, diff(%)	**12.935, 37.85%**		**2.312, 25.80%**		**8.262, 32.45%**		**3.647, 18.77%**	
MaxDeltaV(high)	12.67	9	20.35	11.82	11.67	9.44	11.78	7.79
t-value, diff(%)	**27.676, 28.97%**		**15.233, 41.92%**		**12.307, 19.11%**		**22.270, 33.87%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Correlations with Predicted Crash Frequency

The predicted crash rates (crashes per year) for all scenarios in this test are listed in table 14 with the corresponding surrogate measures of safety (conflicts per hour). Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test.

Table 14. Case 1 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		*R*s
		PER	PRO	PER	PRO	PER	PRO	
Crash Frequency	M	5	3.3	7.5	5	12.6	8.4	**1**
	R	2	1	4	2	6	5	
Total Conflict	M	25.7	22.4	53.7	63.3	309.5	1,208.6	**0.77**
	R	1	1	3	4	5	6	
Crossing Conflict	M	6.3	1	10.1	1.8	33.8	15	**0.89**
	R	3	1	4	2	6	5	
Rear-End Conflict	M	15.4	17.7	29.7	42.9	122.9	848.4	**0.74**
	R	1	1	3	4	5	6	
LC Conflict	M	4	3.7	13.9	19.6	152.8	345.2	**0.74**
	R	1	1	3	4	5	5	

Note: Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the observation of the safety surrogate test data, the following conclusions can be drawn:

- Total number of conflicts for protected left turn is significantly more than that of permitted left turn.
- Protected left turn has less crossing conflicts but more rear-end and lane-change conflicts than permitted left turn.
- The comparison results for all other safety measures show no distinct safety preference between protected left turn and permitted left turn.

In general, the surrogate measures present mixed results; however, an appropriate conclusion can be drawn with consideration of the differing severities of different conflict types. The addition of a protected left-turn phase tended to increase the total number of conflicts while the protected phase substantially decreased crossing conflicts, as expected. The increase in conflicts came primarily from rear ends and, under higher flows, from lane-changing maneuvers. This result is elucidated by considering that, in adding a protected left-turn phase, the cycle time was increased and the proportion of green time for through phases was decreased. This change in the timing has the effect of increasing the number of vehicle stops for through traffic. The number of vehicle stops is known to correlate with the number of rear-end crashes and thus with higher rear-end conflicts. It is also possible that with a greater proportion of vehicles arriving to a standing or dispersing queue, there is an increased tendency of drivers to change to a lane with a shorter queue, despite all lanes having stopped traffic. Drivers in free-flowing lanes may be relatively content to stay in their lane when all lanes are flowing at the same (nonzero) speed. Thus, the conflict frequency results appear reasonable and have provoked consideration of the effect of timing changes and driver behavior. However, the severity-related surrogate measures indicate that the protected left-turn case has improved average values (increased TTC and PET and decreased DeltaV, especially at high volumes), indicating that the protected left-turn phasing is safer than the permitted left-turn case, as would be expected.

The Spearman-rank correlation coefficients from all tests show a strong positive relationship between the rank orders of the surrogate measures of safety and the rank orders of the predicted crash rates. The relationships between the rank order of the totals of all conflict types and crossing conflict types are stronger than the relationship of rear-end and lane-change crossing conflicts. This, again, would be expected because it has been validated in the field that protected left turns reduce crossing crashes. TEXAS, however, shows a very high rate of rear-end and lane-change events per hour, indicating that the default driver behavior parameters may allow vehicles to perform maneuvers that allow closer proximity than the "rule of thumb" threshold of TTC = 1.5 would preclude in the real world.

Case 2: Left-Turn Bay Versus No Left-Turn Bay (TEXAS)

A left-turn bay on an approach to an intersection provides an independent lane for the storage and movement of the left-turn vehicles. With the left-turn bay, the conflict events between through movement vehicles (primarily traveling in the same direction as the turn vehicles) and left-turn vehicles is hypothesized to be significantly reduced. This has been tested over a range of traffic volume scenarios from light traffic to heavy traffic.

According to the crash prediction models for all conventional intersections, the existence of a left-turn bay will reduce the crash frequency under the same traffic conditions.[13]

Intersection Description

The intersection used to test the left-turns bay versus no left-turn bay is a four-legged intersection with two through lanes with shared right turn for all approaches to the intersection, as shown in figure 36 and figure 37. All left-turn bays are 76.25 m (250 ft) long. Table 15 indicates the traffic volumes arriving to each approach of the intersection. Fixed-time traffic control is applied in this test. The ring-diagrams from figure 38 through figure 43 show the timing plans for each testing scenario.

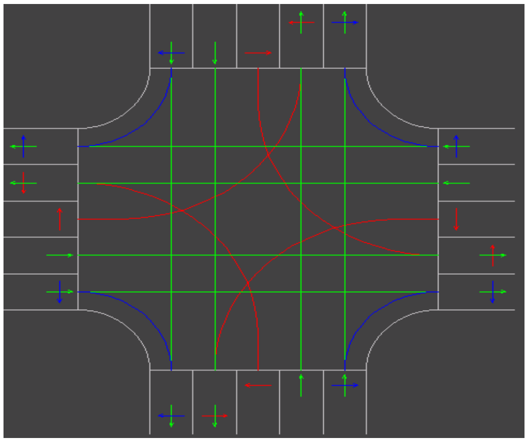


Figure 36. Screen Capture. Exclusive Left-Turn Lane.

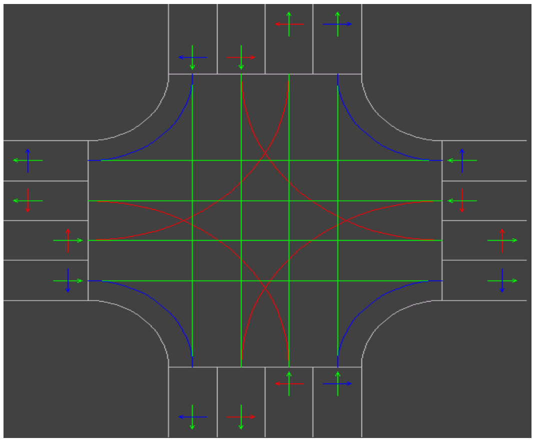


Figure 37. Screen Capture. Shared Use Left-Turn and Through Lane.

Table 15. Case 2 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase# (Permitted)	4	4		8	8		2	2		6	6	
Low Volumes	125	250	125	125	250	125	125	250	125	125	250	125
Medium Volumes	200	400	200	200	400	200	200	400	200	200	400	200
High Volumes	300	600	300	300	600	300	300	600	300	300	600	300

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

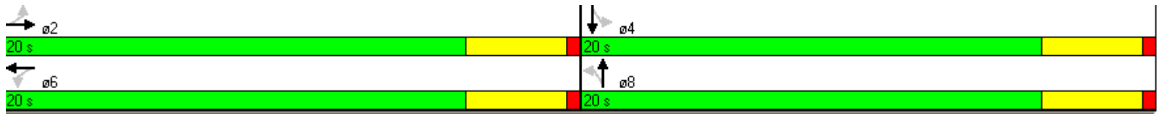


Figure 38. Illustration. Timing Plan for Intersection with Left-Turn Bay in Low Volumes.

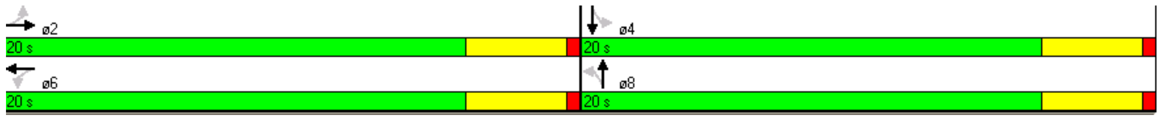


Figure 39. Illustration. Timing Plan for Intersection without Left-Turn Bay in Low Volumes.

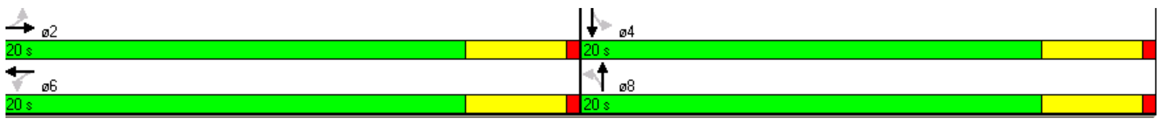


Figure 40. Illustration. Timing Plan for Intersection with Left-Turn Bay in Medium Volumes.

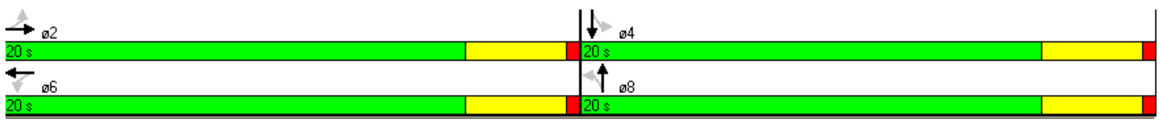


Figure 41. Illustration. Timing Plan for Intersection without Left-Turn Bay in Medium Volumes.

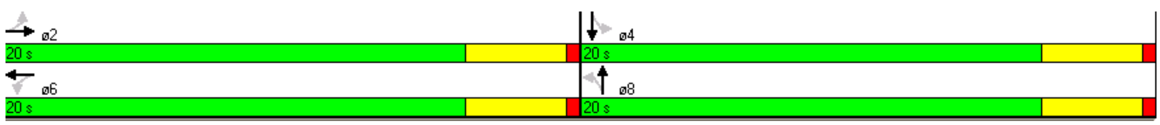


Figure 42. Illustration. Timing Plan for Intersection with Left-Turn Bay in High Volumes.

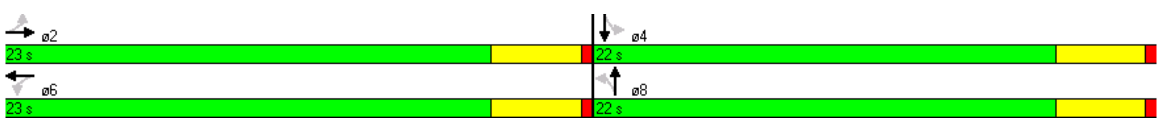


Figure 43. Illustration. Timing Plan for Intersection without Left-Turn Bay in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. *F*-test and *t*-tests were applied to identify statistical significance. Table 16 through table 20 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 16. Case 2 Comparison Results for Total Conflicts.

Total	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NLB	WLB	NLB	WLB	NLB	WLB
Low volume Mean	9.6	11.3	9.6	26.3	54	42.6
Variance	7.2	26.9	7.2	45.8	68.7	63.8
***t*value(95%), difference (%)**	-0.921		**-7.258, 173.96%**		**3.132, 21.11%**	
Medium volume Mean	15.8	19.7	58.2	47.6	210.7	98.5
Variance	18.8	19.3	166.2	32.3	704.5	53.6
***t*-value(95%), difference (%)**	-1.996		**2.38, 18.21%**		**12.887, 53.25%**	
High volume Mean	140.8	150.1	506.8	279.1	985.9	487
Variance	156.4	78.5	250.4	81.4	467.9	293.6
***t*-value(95%), difference (%)**	-1.919		**39.528, 44.93%**		**57.174, 50.6%**	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay. Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Table 17. Case 2 Comparison Results for Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NLB	WLB	NLB	WLB	NLB	WLB
Low volume Mean	5.3	8.5	5.3	12.3	11.9	15.3
Variance	2.7	12.5	2.7	15.3	6.3	17.3
***t*-value(95%), difference (%)**	**-2.597, -60.38%**		**-5.214, -132.08%**		**-2.210, -28.57%**	
Medium volume Mean	6.1	13.4	9	18.6	11	27.1
Variance	5.9	6.9	7.8	13.4	7.1	23.2
***t*-value(95%), difference (%)**	**-6.45, -119.67%**		**-6.6, -106.67%**		**-9.246, -146.36%**	
High volume Mean	9.1	34	15	45.6	19.4	60.8
Variance	11.7	52.7	10.7	62.9	15.6	69.5
***t*-value(95%), difference (%)**	**-9.818, -273.63%**		**-11.279, -204.00%**		**-14.191, -213.4%**	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay. Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates that, for all traffic volumes, the number of severe-crossing conflicts is increased when the left-turn bay is added. This result likely reflects the increase in the number of available left-turn maneuvers due to the bay.

Table 18. Case 2 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NLB	WLB	NLB	WLB	NLB	WLB
Low volume Mean	2.7	2.3	2.7	11.6	31.8	21.3
Variance	3.1	3.8	3.1	18.3	40.2	42.7
t-value(95%), difference (%)	0.481		**-6.085, -329.60%**		**3.648, 33%**	
Medium volume Mean	5.6	4	38.4	22.2	175.5	54.8
Variance	10.933	6.222	129.378	17.956	637.611	23.067
t-value(95%), difference (%)	1.222		**4.221, 42.19%**		**14.85, 68.77%**	
High volume Mean	110.4	24.2	434.1	94.8	855.8	223
Variance	131.8	44.6	209.0	183.7	377.3	194.7
t-value(95%), difference (%)	**20.521, 78.08%**		**54.143, 78.16%**		**83.673, 73.97%**	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay. Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates a definite decrease in the number of rear-end conflicts when a left- turn bay is added to the intersection, as expected from field experience.

Table 19. Case 2 Comparison Results for Lane-Change Conflicts.

Lane Change	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NLB	WLB	NLB	WLB	NLB	WLB
Low volume Mean	1.6	0.5	1.6	2.4	10.3	6
Variance	1.4	0.3	1.4	3.6	6.0	6.4
t-value(95%), difference (%)	**2.703, 68.80%**		-1.134		**3.853, 41.75%**	
Medium volume Mean	4.1	2.3	10.8	6.8	24.2	16.6
Variance	1.878	3.567	4.844	8.622	31.289	27.156
t-value(95%), difference (%)	**2.439, 43.9%**		**3.447, 37.04%**		**3.144, 31.4%**	
High volume Mean	21.3	91.9	57.7	138.7	110.7	203.2
Variance	21.6	93.7	53.3	177.3	113.1	242.6
t-value(95%), difference (%)	**-20.799, -331.46%**		**-16.864, -140.38%**		**-15.509, -83.56%**	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay. Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Table 20. Case 2 Comparison Results for Average Surrogate Measures of Safety.

	TNLB	TWLB	CNLB	CWLB	RENLB	REWLB	LCNLB	LCWLB
TTC (low)	0.97	0.86	0.67	0.56	1.08	1.01	1.01	1.09
t-value, diff(%)	**3.928, 11.34%**		1.804		**2.428, 6.48%**		1.339	
TTC (med)	1.17	0.97	0.54	0.66	1.23	1.11	1.02	1.04
t-value, diff(%)	**12.404, 17.09%**		**-2.048, -22.22%**		**7.646, 9.76%**		-0.506	
TTC (high)	0.99	0.84	0.64	0.58	1	1.07	0.96	0.68
t-value, diff(%)	**18.245, 15.15%**		1.484		**-7.507, -7.00%**		**16.155, 29.17%**	
PET(low)	2.22	2.07	1.44	1.29	2.56	2.5	2.07	2.51
t-value, diff(%)	1.732		0.880		0.670		-1.866	
PET(med)	2.75	2.27	1.26	1.47	3.03	2.71	1.45	2.11
t-value, diff(%)	**9.464, 17.45%**		-1.364		**5.996, 10.56%**		**-5.236, -45.52%**	
PET(high)	1.77	1.64	1.16	0.95	1.82	2.38	1.49	1.02
t-value, diff(%)	**5.860, 7.34%**		**2.252, 18.10%**		**-18.904, -30.77%**		**12.073, 31.54%**	
MaxS(low)	30.75	29.65	33.6	34.07	29.54	27.06	31.18	27.6
t-value, diff(%)	1.833		-0.518		**2.933, 8.40%**		**2.353, 11.48%**	
MaxS(med)	27.01	29.95	34.33	34.77	26.16	27.11	29.88	31.45
t-value, diff(%)	**-8.429, -10.88%**		-0.499		**-2.248, -3.63%**		-1.623	
MaxS(high)	24.38	28.78	28.44	31.78	24.12	27.38	25.64	29.42
t-value, diff(%)	**-31.808, -18.05%**		**-5.551, -11.74%**		**-17.846, -13.52%**		**-12.115, -14.74%**	
DeltaS(low)	28.57	30.05	38.86	39.96	25.03	24.93	27.59	22.95
t-value, diff(%)	-1.788		-0.732		0.104		**2.848, 16.82%**	
DeltaS(med)	19.23	28.28	38.02	41.46	18.05	23.46	19.21	22.69
t-value, diff(%)	**-18.607, -47.06%**		**-2.558, -9.05%**		**-11.112, -29.97%**		**-3.351, -18.12%**	
DeltaS(high)	18.97	23.24	32.31	34.25	18.74	21.36	18.45	22.02
t-value, diff(%)	**-23.467, -22.51%**		**-2.555, -6.00%**		**-11.461, -13.98%**		**-10.732, -19.35%**	
DR(low)	-6.3	-5.32	-2.48	-1.47	-7.48	-7.49	-7.08	-7.43
t-value, diff(%)	**-3.323, 15.56%**		**-2.022, 40.73%**		0.032		0.476	
DR(med)	-6.1	-5.65	-0.49	-1.57	-6.6	-7.55	-5.04	-6.02
t-value, diff(%)	**-2.539, 7.38%**		**3.233, -220.41%**		**4.818, -14.39%**		**2.373, -19.44%**	
DR(high)	-4.79	-3.83	-0.03	-1.2	-5.1	-6.19	-3.27	-2.02
t-value, diff(%)	**-13.525, 20.04%**		**8.067, -3900.00%**		**11.276, -21.37%**		**-9.530, 38.23%**	
MaxD(low)	-12.86	-11.36	-5.63	-5.52	-15.11	-14.95	-14.26	-13.52
t-value, diff(%)	**-3.487, 11.66%**		-0.135		-0.419		-0.838	
MaxD(med)	-13.64	-11.91	-2.09	-5.21	-14.62	-14.86	-11.78	-13.13
t-value, diff(%)	**-7.813, 12.68%**		**5.299, -149.28%**		1.371		**2.427, -11.46%**	
MaxD(high)	-13.56	-9.09	-1.98	-2.72	-14.11	-14.15	-11.34	-5.45
t-value, diff(%)	**-41.995, 32.96%**		**2.288, -37.37%**		0.398		**-30.409, 51.94%**	
MaxDeltaV(low)	16.35	17.23	22.74	23.05	14.27	14.21	15.39	13.08
t-value, diff(%)	-1.706		-0.309		0.103		**2.448, 15.01%**	
MaxDeltaV(med)	10.87	16.14	23.86	24.42	10.06	13.09	10.84	12.72
t-value, diff(%)	**-17.353, -48.48%**		-0.586		**-10.731, -30.12%**		**-3.140, -17.34%**	
MaxDeltaV(high)	10.62	13.23	19.46	19.61	10.44	12.05	10.44	12.61
t-value, diff(%)	**-24.135, -24.58%**		-0.286		**-11.999, -15.42%**		**-10.832, -20.79%**	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay, and these abbreviations are prepended with T-, C-, RE-, and LC- to indicate data based on total, crossing, rear-end, and lane-change conflicts respectively.

Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

In general, the data in the table 20 have some counter-indicative results. Some of the average surrogate measures of safety are better with the left-turn bay, and others are worse.

Correlations with Predicted Crash Frequency

The predicted crash rates (crashes per year) for all scenarios in this test are listed in table 21 with the corresponding average conflicts per hour. Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test.

Table 21. Case 2 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		***R*s**
		NLB	**WLB**	**NLB**	**WLB**	**NLB**	**WLB**	
Crash Frequency	**M**	5.5	3.7	8	5.3	8.7	5.8	**1**
	R	3	1	5	2	6	4	
Total Conflict	**M**	54	42.6	210.7	98.5	985.9	487	**0.8**
	R	1	1	4	3	6	5	
Crossing Conflict	**M**	11.9	15.3	11	27.1	19.4	60.8	**0**
	R	2	3	1	5	4	6	
Rear-End Conflict	**M**	31.8	21.3	175.5	54.8	855.8	223	**0.8**
	R	1	1	4	3	6	5	
LC Conflict	**M**	10.3	6	24.2	16.6	110.7	203.2	**0.6**
	R	2	1	3	4	5	6	

Note: NLB indicates no left-turn bay and WLB indicates with left-turn bay. Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the observation on the total number of conflicts of various types and the average values of the surrogate measures obtained from the test, the following conclusions can be drawn:

- The average number of total and rear-end conflicts for intersection with left-turn bay is less than that of intersection without left-turn bay. This is an intuitive result.
- An intersection with a left-turn bay has more crossing and lane change (in high volumes) conflicts than an intersection without a left-turn bay. With an extra lane to change to, and increase in lane-change conflicts seems reasonable. Also, with exclusive left-turn bays on both sides of the street, drivers making left turns then face opposing vehicles traveling through the intersection at higher speeds since they are no longer periodically blocked by left-turning vehicles. It seems possible that the increased speed of opposing traffic increases the likelihood of conflicts. It is also possible that left-turning "blockers" in

opposing traffic also created episodes of relatively safe crossing opportunities because there is one less oncoming lane of traffic to contend with.

- Some average values of surrogate measures of safety indicate that adding the bay increases the severity of the conflicts that do occur, primarily by increasing speeds at the intersection. This fact makes it difficult to definitively determine the superiority of one design over the other.

In general, an intersection with a left-turn bay experiences fewer total and rear-end conflicts but more crossing and lane-change conflicts than an intersection without a left- turn bay. Rear-end conflicts constitute a major part of total conflicts (ranging from 60 to 80 percent) and have larger TTC and PET values (≥ 1.0).

The Spearman rank correlation coefficients resulted from all tests show a strong positive relationship between the rank orders of the surrogate measures of safety and the rank orders of the predicted crash rates, except for crossing conflicts, which shows no correlation with total crash rates. Perhaps a more normative comparison could be made by using rates of conflict occurrence by maneuver rather than total number of conflicts without relation to the number of other maneuvers that were executed by drivers without a conflict occurring.

TEXAS shows a very high rate of rear-end and lane-change events per hour, indicating that the default driver behavior parameters may allow vehicles to perform maneuvers that allow closer proximity than the "rule of thumb" threshold of TTC = 1.5 would preclude in the real world. Also, the existence of the turn bay requires more lane-changing maneuvers and thus a higher frequency of conflict events related to those necessary lane changes.

Case 3: Right-Turn Bay Versus No Right-Turn Bay (TEXAS)

A right-turn bay near the intersection provides an independent lane for the storage and movement of right-turn vehicles. With a right-turn bay near an intersection, the conflict events between through-movement vehicles (primarily traveling in the same direction as the turn vehicles) and right-turn vehicles is hypothesized to be reduced significantly. This reduction has been tested over a range of traffic volume scenarios, from light traffic to heavy traffic.

According to the crash prediction models for all conventional intersections, the existence of a right-turn bay will definitely reduce the crash frequency when all other roadway network factors remain the same.[13]

Intersection Description

The intersection used to test the right-turn bay versus no right-turn bay is a four-legged intersection with two through lanes and one left-turn lane for all approaches to the intersection, as shown in figure 44 and figure 45. All left-turn bays have are 76.25-meters (250-feet) long. Table 22 shows the traffic volumes applied for each approach of the intersection. Fixed time traffic control is applied in this test. Figure 46 through figure 51 provide the timing plans for each testing scenario.

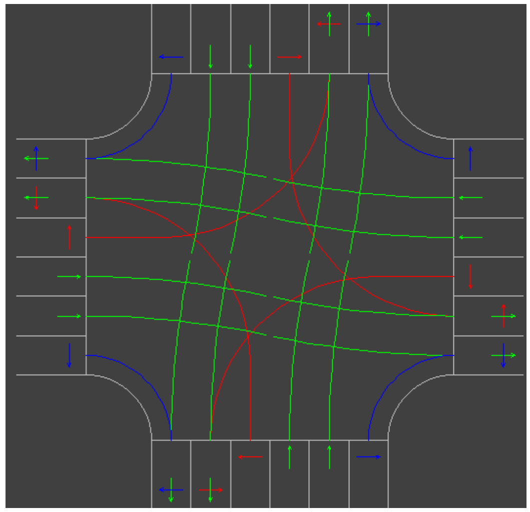


Figure 44. Screen Capture. Intersection with Right-Turn Bay.

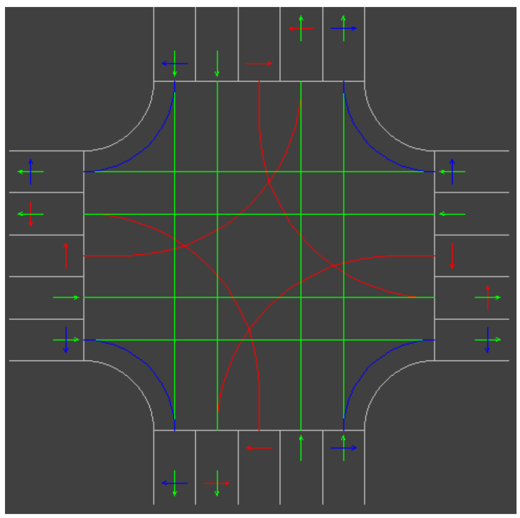


Figure 45. Screen Capture. Intersection without Right-Turn Bay.

Table 22. Case 3 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID	7	4		3	8		5	2		1	6	
Low Volumes	125	250	125	125	250	125	125	250	125	125	250	125
Medium Volumes	200	400	200	200	400	200	200	400	200	200	400	200
High Volumes	300	600	300	300	600	300	300	600	300	300	600	300

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

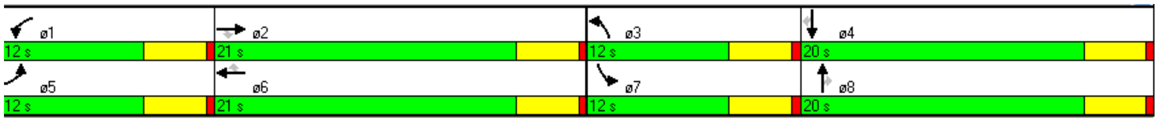


Figure 46. Illustration. Timing Plan for Intersection with Right-Turn Bay in Low Volumes.

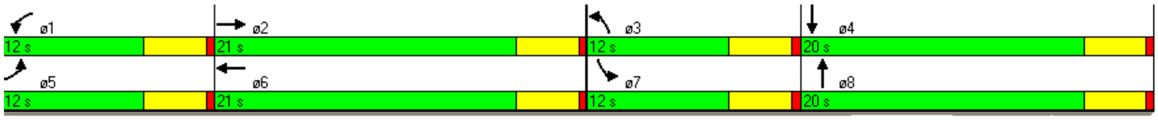


Figure 47. Illustration. Timing Plan for Intersection without Right-Turn Bay in Low Volumes.

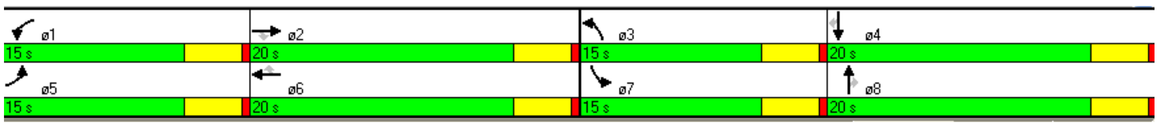


Figure 48. Illustration. Timing Plan for Intersection with Right-Turn Bay in Medium Volumes.

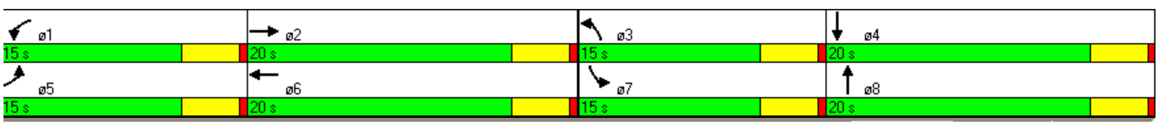


Figure 49. Illustration. Timing Plan for Intersection without Right-Turn Bay in Medium Volumes.

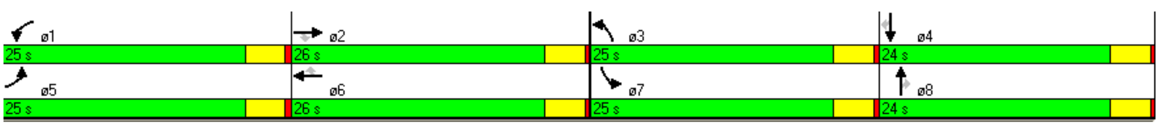


Figure 50. Illustration. Timing Plan for Intersection with Right-Turn Bay in High Volumes.

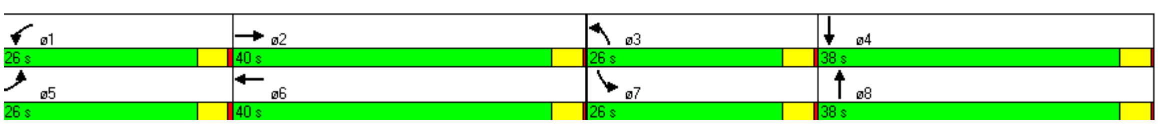


Figure 51. Illustration. Timing Plan for Intersection without Right-Turn Bay in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data was analyzed by SSAM. The *F*-test and *t*-test were applied to compare surrogate measures of safety and the aggregations of those measures. Table 23 through table 27 provide the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 23. Case 3 Comparison Results for Total Conflicts.

Total	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NRB	WRB	NRB	WRB	NRB	WRB
Low volume Mean	5.8	3.5	16.4	14.7	35.9	24.2
Variance	7.067	3.611	17.822	9.122	38.544	18.844
***t*-value(95%), difference (%)**	**2.226, 39.66%**		1.036		**4.884, 32.59%**	
Medium volume Mean	12	10.1	43.4	31.2	119	67.3
Variance	16.444	14.322	132.711	66.400	361.556	256.900
***t*-value(95%), difference (%)**	1.083		**2.734, 28.11%**		**6.574, 43.45%**	
High volume Mean	163	113.7	532.3	372.1	1259.5	883.8
Variance	207.333	86.233	1108.456	485.433	623.167	1494.622
***t*-value(95%), difference (%)**	**9.099, 30.25%**		**12.689, 30.1%**		**25.817, 29.83%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that the right-turn bay reduces the total number of conflict events for most levels of traffic volume and threshold for the TTC value.

Table 24. Case 3 Comparison Results for Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NRB	WRB	NRB	WRB	NRB	WRB
Medium volume Mean	0.5	0.6	0.7	0.8	1.3	0.8
Variance	0.944	0.933	1.122	1.511	1.567	1.511
***t*-value(95%), difference (%)**	-0.231		-0.195		0.901	
High volume Mean	6.5	7.3	9	10.8	14.3	15.3
Variance	6.278	3.122	7.778	7.067	11.789	11.789
***t*-value(95%), difference (%)**	-0.825		-1.477		-0.651	

As expected this table indicates that a right-turn bay would not reduce the number of crossing-conflict events.

Table 25. Case 3 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NRB	WRB	NRB	WRB	NRB	WRB
Low volume Mean	3.3	2.1	11.6	7.7	25.8	12.6
Variance	3.344	1.656	14.044	9.789	23.733	13.156
***t*-value(95%), difference (%)**	1.697		**2.526, 33.62%**		**6.873, 51.16%**	
Medium volume Mean	5	3.3	29.6	18.7	92.1	44.4
Variance	5.556	4.678	76.044	22.011	252.544	99.600
***t*-value(95%), difference (%)**	1.681		**3.481, 36.82%**		**8.038, 51.79%**	
High volume Mean	97.6	60	409.9	262.9	1024.9	675.6
Variance	108.044	81.111	922.322	360.322	468.767	1380.711
***t*-value(95%), difference (%)**	**8.645, 38.52%**		**12.98, 35.86%**		**25.685, 34.08%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that adding a right-turn bay will statistically reduce the number of rear-end conflicts for all traffic volumes, as expected from field experience.

Table 26. Case 3 Comparison Results for Lane-Change Conflicts.

Lane Change	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	NRB	WRB	NRB	WRB	NRB	WRB
Low volume Mean	2.5	1.4	4.7	7	9.6	11.4
Variance	2.056	1.600	2.233	5.556	5.156	13.156
***t*-value(95%), difference (%)**	1.819		**-2.606, -48.94%**		-1.330	
Medium volume Mean	6.5	6.2	13.1	11.7	25.6	22.1
Variance	6.722	8.622	15.656	28.456	30.044	66.544
***t*-value(95%), difference (%)**	0.242		0.667		1.126	
High volume Mean	58.9	46.4	113.4	98.4	220.3	192.9
Variance	82.322	4.711	170.044	20.267	235.122	169.656
***t*-value(95%), difference (%)**	**4.237, 21.22%**		**3.438, 13.23%**		**4.307, 12.44%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates that adding a right-turn bay will statistically reduce the number of lane change conflicts for some traffic volumes. Notably, at high volumes, the number of high-severity (indicated by considering only TTC values less than 0.5s and 1.0s) lane-change events is reduced, as expected from field experience.

Table 27. Case 3 Comparison Results for Average Surrogate Measures of Safety.

	TNRB	TWRB	CNRB	CWRB	RENRB	REWRB	LCNRB	LCWRB
TTC (low)	1.03	0.97	N/A	N/A	1.05	0.96	0.94	0.97
t-value, diff(%)	1.887		N/A		**2.213, 8.57%**		-0.504	
TTC (med)	1.11	1.02	0.82	0.49	1.17	1.09	0.92	0.9
t-value, diff(%)	**4.625, 8.11%**		1.378		**4.115, 6.84%**		0.445	
TTC (high)	1.05	1.05	0.71	0.65	1.08	1.09	0.9	0.92
t-value, diff(%)	0.000		1.012		-1.842		-1.339	
PET(low)	2.16	1.88	N/A	N/A	2.28	2.09	1.78	1.62
t-value, diff(%)	**2.569, 12.96%**		N/A		1.362		0.884	
PET(med)	2.49	2.22	1.68	0.26	2.77	2.53	1.52	1.69
t-value, diff(%)	**4.315, 10.84%**		**2.687, 84.52%**		**3.545, 8.66%**		-1.462	
PET(high)	2.12	2.14	0.85	0.75	2.3	2.4	1.35	1.32
t-value, diff(%)	-1.165		1.042		**-5.378, -4.35%**		0.918	
MaxS(low)	30.74	32.3	N/A	N/A	31.1	31.34	29.99	33.61
t-value, diff(%)	-1.925		N/A		-0.212		**-2.676, -12.07%**	
MaxS(med)	27.07	26.33	25.48	27.73	25.83	24.3	31.59	30.37
t-value, diff(%)	1.616		-0.553		**2.946, 5.92%**		1.380	
MaxS(high)	24.67	25.15	21.32	23.43	24.75	25.28	24.55	24.84
t-value, diff(%)	**-4.347, -1.95%**		**-3.162, -9.90%**		**-4.218, -2.14%**		-1.181	
DeltaS(low)	26.28	29.12	N/A	N/A	27.84	29.01	22.13	29.45
t-value, diff(%)	**-3.004, -10.81%**		N/A		-0.907		**-4.854, -33.08%**	
DeltaS(med)	17.9	17.84	23.98	26.08	17.24	16.46	19.96	20.31
t-value, diff(%)	0.101		-0.515		1.054		-0.348	
DeltaS(high)	18.29	18.58	19.35	21.89	18.95	19.44	15.14	15.29
t-value, diff(%)	**-2.165, -1.59%**		**-3.382, -13.13%**		**-3.253, -2.59%**		-0.515	
DR(low)	-6.96	-6.48	N/A	N/A	-7.29	-6.59	-5.71	-6.22
t-value, diff(%)	-1.662		N/A		-1.925		1.010	
DR(med)	-5.66	-4.69	-7.27	-3.97	-5.9	-4.99	-4.7	-4.12
t-value, diff(%)	**-4.732, 17.14%**		-1.052		**-3.670, 15.42%**		-1.489	
DR(high)	-5.17	-5.16	-0.83	-0.93	-5.75	-5.96	-2.78	-2.7
t-value, diff(%)	-0.176		0.320		**3.440, -3.65%**		-0.667	
MaxD(low)	-14.54	-15.33	N/A	N/A	-15.54	-16.13	-11.66	-14.39
t-value, diff(%)	**1.980, 5.43%**		N/A		1.164		**3.866, -23.41%**	
MaxD(med)	-13.19	-12.28	-9.69	-4.48	-13.95	-13.41	-10.62	-10.29
t-value, diff(%)	**-3.977, 6.90%**		-1.558		**-2.852, 3.87%**		-0.558	
MaxD(high)	-13.03	-12.72	-3.82	-3.14	-14.23	-14.33	-8.09	-7.86
t-value, diff(%)	**-4.475, 2.38%**		-1.158		1.924		-1.150	
MaxDeltaV(low)	14.83	16.75	N/A	N/A	15.8	16.7	12.21	16.92
t-value, diff(%)	**-3.278, -12.95%**		N/A		-1.128		**-5.199, -38.57%**	
MaxDeltaV(med)	10.11	10.07	13.59	14.13	9.72	9.28	11.32	11.52
t-value, diff(%)	0.115		-0.227		1.024		-0.342	
MaxDeltaV(high)	10.19	10.37	10.89	12.52	10.54	10.82	8.54	8.62
t-value, diff(%)	**-2.357, -1.77%**		**-3.428, -14.97%**		**-3.263, -2.66%**		-0.478	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Similar to the average value results for the left-turn bay, the existence of the right-turn bay tends to make the severity of conflicts worse for measures other than the primary measure TTC.

Correlations with Predicted Crash Frequency

The predicted crash rates for all scenarios in this test are listed in table 28 with the corresponding surrogate measures of safety. Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test.

Table 28. Case 3 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		***R*s**
		NRB	**WRB**	**NRB**	**WRB**	**NRB**	**WRB**	
Crash Frequency	**M**	5.5	5.2	8	7.5	8.7	8.3	**1**
	R	2	1	4	3	6	5	
Total Conflict	**M**	35.9	24.2	119	67.3	1,259.5	883.8	**0.97**
	R	2	1	4	3	5	5	
Crossing Conflict	**M**	0.5	0.2	1.3	0.8	14.3	15.3	**0.91**
	R	1	1	3	3	5	5	
Rear-End Conflict	**M**	25.8	12.6	92.1	44.4	1,024.9	675.6	**0.97**
	R	2	1	4	3	5	5	
LC Conflict	**M**	9.6	11.4	25.6	22.1	220.3	192.9	**0.80**
	R	1	1	3	3	5	5	

Note: Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

As seen in the table above, the correlation between the number of conflicts and the crash prediction model is very high.

Findings and Conclusions

Based on the observation on the safety surrogate data obtained from the test, the following conclusions can be drawn:

- The number of total, rear-end, and lane-change conflicts for an intersection with a right-turn bay are less than that of an intersection without a right-turn bay. This is an intuitive result.
- There is no significant difference for the number of crossing conflicts between an intersection with a right-turn bay and an intersection without a right-turn bay. This is an intuitive result.
- There is no distinct difference for the average values of the surrogate measures of safety between an intersection with a right-turn bay and an intersection without a right-turn bay.

In general, an intersection with a right-turn bay experiences less total, rear-end, and lane-change conflicts than an intersection without a right-turn bay. Rear-end conflicts constitute the major part of the total conflicts (ranging from 50 to 80 percent) and have larger TTC and PET values (≥ 1.0) than other types of conflicts. There is no significant difference for the number of crossing conflicts between these two intersection designs. These results match what would generally be expected from field experience.

The Spearman-rank correlation coefficients resulted from all tests show a strong positive relationship between the rank orders of the surrogate measures of safety and the rank orders of the predicted crash rates, with only slight differences between the correlation coefficients for the various individual conflict types.

Case 4: Leading Left Turn Versus Lagging Left Turn (VISSIM)

Leading left turn and lagging left turn are two different control logics for protected left turns. A leading left turn allows the green phase of left-turn movements ahead of the green phase of through movements, while a lagging left turn places the green phase of the left turn after the green phase of through movements. At the beginning of the study, there is no determinate evidence that either type of left-turn operation has an appreciable effect on the safety of the intersection. Several combinations of the left-turn to through-volume ratio have been evaluated for each design alternative (leading versus lagging).

Until now, no considerations of control logic for protected left turn have been included in crash prediction models for conventional intersections, so no rank order comparison can be performed.

Intersection Description

The intersection used to test leading left turn versus lagging left turn is a four-legged intersection with one through lane having left- and right-turn bays in the main travel directions and one though lane on the side street, as shown in figure 52 and figure 53. All left- turn bays are 76.25 m (250 ft) long.

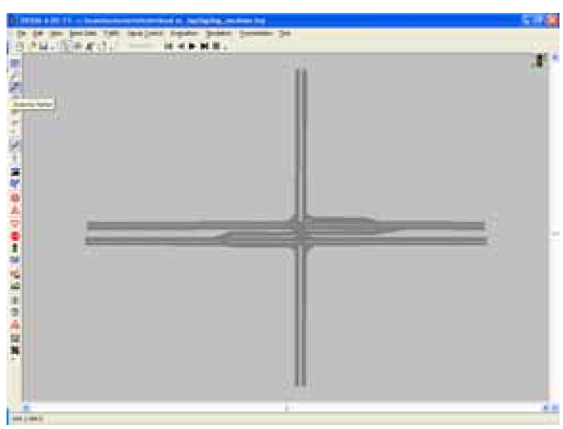


Figure 52. Screen Capture. Intersection with Leading Left Turn.

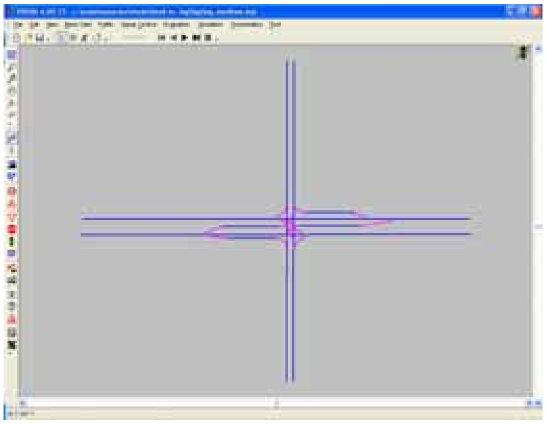


Figure 53. Screen Capture. Intersection with Lagging Left Turn.

Table 29 shows the traffic volumes applied for each approach of the intersection. Fixed time traffic control is applied in this test. Figure 54 through figure 59 provide the timing plans used for each testing scenario (low to high volumes).

Table 29. Case 4 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID	3	3		4	4		1	2		1	2	
Low Volumes	25	75	25	50	100	50	150	400	50	150	400	50
Medium Volumes	25	75	25	50	100	50	125	650	75	125	650	75
High Volumes	100	250	50	100	250	50	150	700	150	150	700	150

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

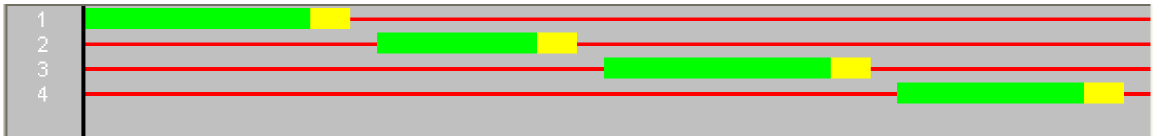


Figure 54. Illustration. Timing Plan for Intersection with Lag Left Turn in Low Volumes (Cycle: 80; Split: 22, 17, 22, and 19).

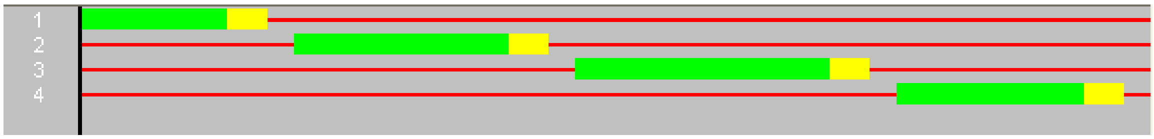


Figure 55. Illustration. Timing Plan for Intersection with Lead Left Turn in Low Volumes (Cycle: 80; Split: 17, 22, 22, and 19).

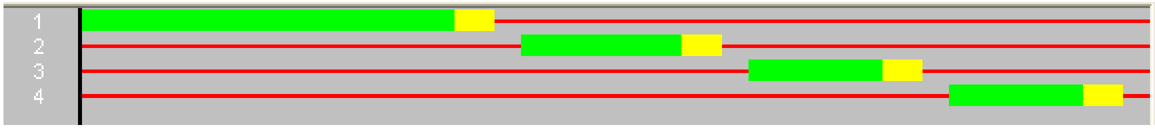


Figure 56. Illustration. Timing Plan for Intersection with Lag Left Turn in Medium Volumes (Cycle: 80; Split: 33, 17, 15, and 15).

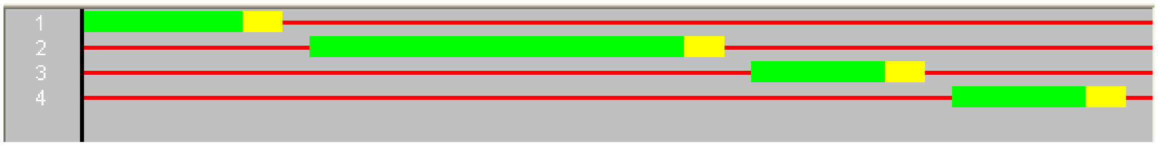


Figure 57. Illustration. Timing Plan for Intersection with Lead Left Turn in Medium Volumes (Cycle: 80; Split: 17, 33, 15, and 15).

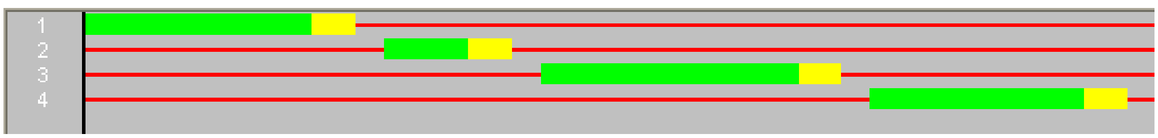


Figure 58. Illustration. Timing Plan for Intersection with Lag Left Turn in High Volumes (Cycle: 75; Split: 20, 11, 23, and 21).

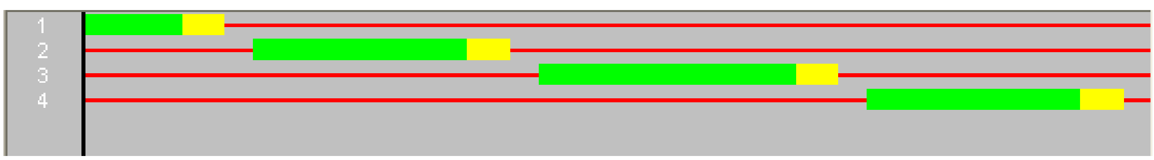


Figure 59. Illustration. Timing Plan for Intersection with Lead Left Turn in High Volumes (Cycle: 75; Split: 11, 20, 23, and 21).

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data was analyzed by SSAM. The *F*-test and *t*-test were applied to compare the average number of conflict events and surrogate measures of safety from one scenario to the other.

Table 30 through table 33 provide the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 30. Case 4 Comparison Results for All Conflict Event Types.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	Lead	**Lag**	**Lead**	**Lag**	**Lead**	**Lag**
Low volume Mean	N/A	N/A	N/A	N/A	9.90	8.80
Variance	N/A	N/A	N/A	N/A	5.43	14.84
***t*-value(95%), difference (%)**	N/A		N/A		0.772	
Medium volume Mean	N/A	N/A	N/A	N/A	16.30	13.40
Variance	N/A	N/A	N/A	N/A	12.23	23.60
***t*-value(95%), difference (%)**	N/A		N/A		1.532	
High volume Mean	N/A	N/A	8.10	8.10	35.60	32.30
Variance	N/A	N/A	5.88	11.88	78.27	33.34
***t*-value(95%), difference (%)**	N/A		0		0.988	

Table 31. Case 4 Comparison Results for Rear-End Conflicts.

Rear End	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	Lead	**Lag**	**Lead**	**Lag**	**Lead**	**Lag**
Low volume Mean	N/A	N/A	N/A	N/A	5.70	5.70
Variance	N/A	N/A	N/A	N/A	3.57	8.90
***t*-value(95%), difference (%)**	N/A		N/A		0	
Medium volume Mean	N/A	N/A	N/A	N/A	10.00	8.60
Variance	N/A	N/A	N/A	N/A	7.78	13.60
***t*-value(95%), difference (%)**	N/A		N/A		0.958	
High volume Mean	N/A	N/A	5.80	5.80	24.30	22.10
Variance	N/A	N/A	3.96	6.18	42.01	21.21
***t*-value(95%), difference (%)**	N/A		0		0.875	

Table 32. Case 4 Comparison Results for Lane-Change Conflicts.

Lane Change	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	Lead	**Lag**	**Lead**	**Lag**	**Lead**	**Lag**
Low volume Mean	N/A	N/A	N/A	N/A	4.10	3.10
Variance	N/A	N/A	N/A	N/A	5.21	2.54
***t*-value(95%), difference (%)**	N/A		N/A		1.136	
Medium volume Mean	N/A	N/A	N/A	N/A	6.20	4.50
Variance	N/A	N/A	N/A	N/A	6.40	3.17
***t*-value(95%), difference (%)**	N/A		N/A		1.738	
High volume Mean	N/A	N/A	2.20	2.30	11.20	9.90
Variance	N/A	N/A	2.84	3.12	15.29	6.99
***t*-value(95%), difference (%)**	N/A		-0.129		0.871	

Table 33. Case 4 Comparison Results for Average Surrogate Measures of Safety.

	TLead	TLag	CLead	CLag	RELead	RELag	LCLead	LCLag
TTC (low)	1.28	1.28	N/A	N/A	1.32	1.3	1.23	1.25
t-value, diff(%)	0.000		N/A		0.571		-0.305	
TTC (med)	1.27	1.29	N/A	N/A	1.31	1.28	1.2	1.28
t-value, diff(%)	-0.868		N/A		1.281		-1.533	
TTC (high)	1.2	1.2	N/A	N/A	1.2	1.19	1.2	1.24
t-value, diff(%)	0.000		N/A		0.46		-1.240	
PET(low)	2.1	2.02	N/A	N/A	2.27	2.13	1.89	1.83
t-value, diff(%)	0.695		N/A		1.102		0.272	
PET(med)	2.3	2.35	N/A	N/A	2.42	2.52	2.1	1.99
t-value, diff(%)	-0.497		N/A		-0.860		0.607	
PET(high)	2.47	2.47	N/A	N/A	2.48	2.58	2.48	2.23
t-value, diff(%)	0.000		N/A		-1.467		**2.154, 10.08%**	
MaxS(low)	6.69	6.78	N/A	N/A	6.37	6.72	7.16	6.9
t-value, diff(%)	-0.242		N/A		-0.763		0.405	
MaxS(med)	7.52	7.19	N/A	N/A	6.94	7.53	8.47	6.6
t-value, diff(%)	0.964		N/A		-1.331		**3.834, 22.1%**	
MaxS(high)	7.76	7.94	N/A	N/A	7.78	7.8	7.78	8.24
t-value, diff(%)	-0.734		N/A		-0.064		-1.036	
DeltaS(low)	5.35	5.25	N/A	N/A	5.28	5.25	5.45	5.26
t-value, diff(%)	0.576		N/A		0.195		0.481	
DeltaS(med)	5.37	5.35	N/A	N/A	5.24	5.21	5.56	5.59
t-value, diff(%)	0.135		N/A		0.184		-0.1015	
DeltaS(high)	4.47	4.61	N/A	N/A	4.22	4.3	4.22	5.23
t-value, diff(%)	-0.986		N/A		-0.462		**-4.079, -23.93%**	
DR(low)	-2.48	-2.24	N/A	N/A	-2.62	-2.23	-2.28	-2.25
t-value, diff(%)	-1.781		N/A		**-2.357, 14.89%**		-0.129	
DR(med)	-2.28	-2.44	N/A	N/A	-2.31	-2.34	-2.22	-2.51
t-value, diff(%)	1.095		N/A		0.230		0.871	
DR(high)	-1.9	-1.97	N/A	N/A	-1.72	-1.85	-1.72	-2.21
t-value, diff(%)	0.624		N/A		1.057		**2.371, -28.49%**	
MaxD(low)	-3.42	-3.05	N/A	N/A	-3.2	-2.9	-3.65	-3.32
t-value, diff(%)	-1.573		N/A		-1.177		-0.743	
MaxD(med)	-3.54	-3.79	N/A	N/A	-3.26	-3.83	-3.94	-3.61
t-value, diff(%)	1.117		N/A		**2.379, -17.48%**		-0.737	
MaxD(high)	-4.13	-4.02	N/A	N/A	-4.02	-4.02	-4.02	-4
t-value, diff(%)	-0.805		N/A		0.000		-0.077	
MaxDeltaV(low)	2.78	2.68	N/A	N/A	2.78	2.62	2.79	2.77
t-value, diff(%)	1.027		N/A		1.801		0.094	
MaxDeltaV(med)	2.74	2.7	N/A	N/A	2.66	2.6	2.87	2.86
t-value, diff(%)	0.452		N/A		0.675		0.051	
MaxDeltaV(high)	2.28	2.36	N/A	N/A	2.15	2.2	2.15	2.68
t-value, diff(%)	-1.089		N/A		-0.559		**-4.107, -24.65%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

These tables indicate no significant differences between either the number or severity of conflict events for leading and lagging protected left turns, as expected from field experience.

Correlations with Predicted Crash Frequency

Since no consideration for leading or lagging left turns has been incorporated into a crash prediction model to date, any comparisons do not have meaning. Results for crossing conflicts have been excluded from the table below because there were not enough events to analyze (left turns were protected only).

Table 34. Case 4 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		***R*s**
		Lead	**Lag**	**Lead**	**Lag**	**Lead**	**Lag**	
Crash Frequency	**M**	3.9	3.9	4.8	4.8	6.3	6.3	**1**
	R	1	1	3	3	5	5	
Total Conflict	**M**	9.90	8.80	16.3	13.4	35.60	32.30	**1**
	R	1	1	3	3	5	5	
Crossing Conflict	**M**							N/A
	R							
Rear-End Conflict	**M**	5.7	5.7	10	8.6	24.30	22.10	**1**
	R	1	1	3	3	5	5	
LC Conflict	**M**	4.1	3.1	6.20	4.50	11.20	9.90	**1**
	R	1	1	3	3	5	5	

Note: Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The Rs column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the observation on the safety surrogate data obtained from the test, the following conclusions can be drawn:

- There is no significant difference for any of the surrogate measures of safety between leading left turns and lagging left turns. Note that in both cases the left turns were protected only.

In general, there is no significant difference for any of the surrogate measures of safety between leading protected left turns and lagging protected left turns. This result matches the intuitive expectation. There may, however, be some difference between the two if a permitted-protected operation was considered instead of a protected-only operation.

Case 5: Three-Phase Interchange Versus Four-Phase Interchange (VISSIM)

This case study compares the safety performance of the two primary types of traffic control logic for diamond interchanges. A diamond interchange, as shown in figure 60, is composed of two closely spaced signalized intersections that connect the surface street system to the freeway system. One controller is most often used to control both intersections of a diamond interchange. Because of this, both intersections of the interchange are dealt with together as a single entity.

Two alternatives for interchange traffic control are typically used: three-phase signal control and four-phase signal control.

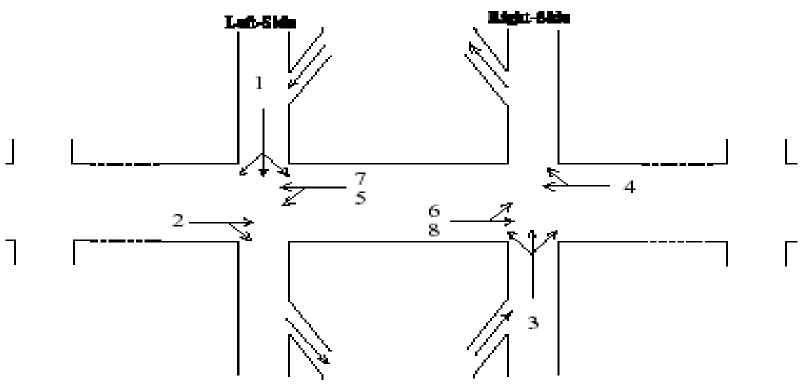


Figure 60. Illustration. Diamond Interchange.

Three-phase is a legacy term that implies the concurrent service of the two cross-road movements, the two left-turn movements, and the two frontage-road movements during common phases as well as a cross-road left-turn phase that lags (or follows) that of the conflicting cross-road through movement.[7] The interior left turns lag the arterial through movements. The disadvantage of the three-phase sequencing for diamond interchange is that the vehicles on the interior of the diamond cannot be guaranteed to clear during one cycle. Three-phase sequencing is applicable for very wide interchanges over 183 m (600 ft) wide and for traffic demands that are directionally balanced and not too heavy. Figure 61 illustrates the time sequencing for three-phase control.[18]

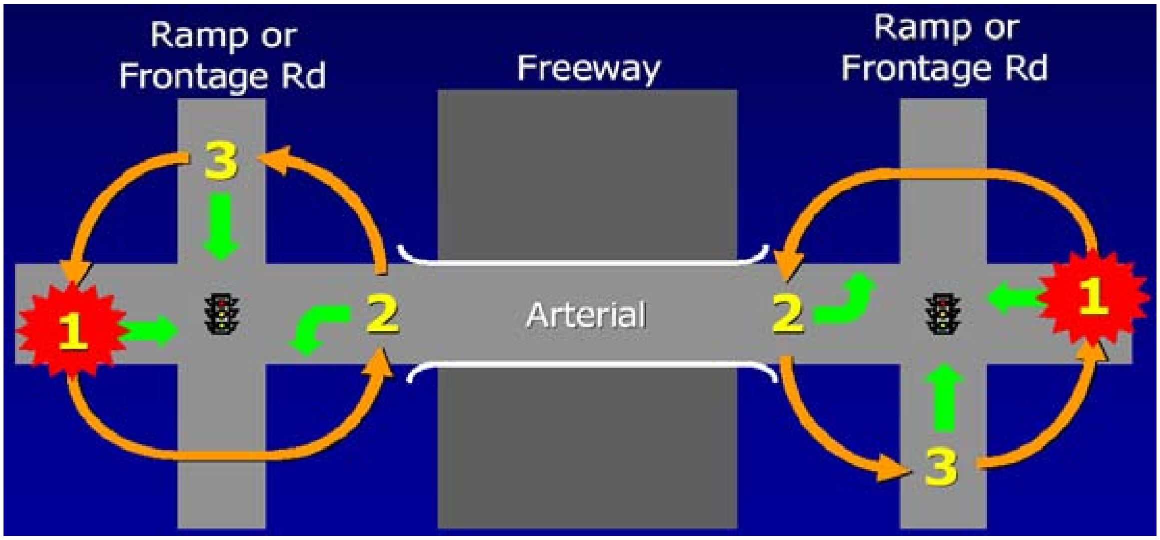


Figure 61. Screen Capture. Three-Phase Sequencing Signal Control for Diamond Interchange.

Four-phase sequencing uses an overlap phase. The overlap period provides extra time for the interior area to clear and provide better progression out of the interchange. This helps to minimize interior delay and queuing even though a longer cycle length may be necessary. The four exterior movements are serviced sequentially. This control logic is suitable for narrow interchanges less than 122 m (400 ft) wide and for traffic demands that are high and/or directionally unbalanced. Figure 62 illustrates the time sequencing for the four-phase control.[18]

According to the available crash prediction models for diamond interchanges, the type of signal-phase timing plan will have no impact on crash frequency. Thus, the crash prediction model will generate the same crash results for both three-phase and four-phase signal control.

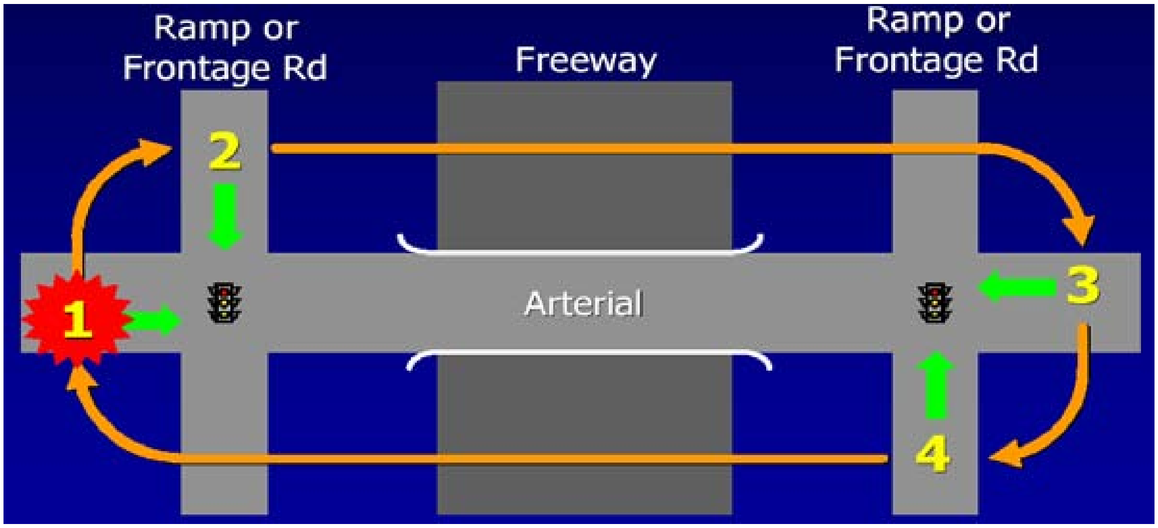


Figure 62. Screen Capture. Four-Phase Sequencing Signal Control for Diamond Interchange.

Intersection Description

The intersection used to test control logic for a diamond interchange is shown in figure 63 and figure 64. Because of the two closely spaced signalized intersections, the left-turn bay for each intersection is 45.75 m (150 ft) long, less than the normal 76.25-m (250-ft) length.

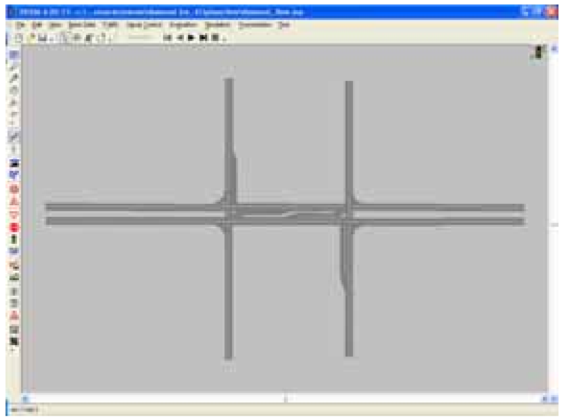


Figure 63. Screen Capture. Intersection for Diamond Interchange with Three-Phase Test.

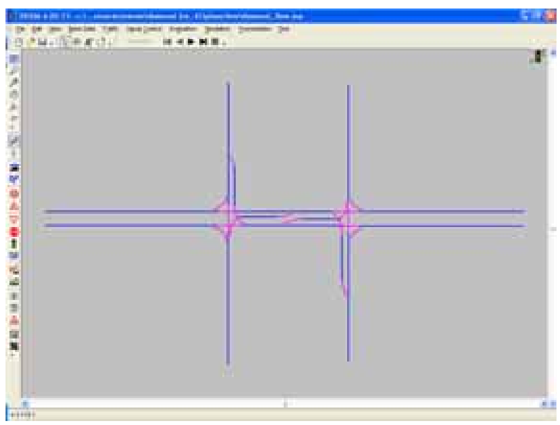


Figure 64. Screen Capture. Intersection for Diamond Interchange with Four-Phase Test.

Table 35 shows the traffic volumes arriving to each approach of the intersection. Fully-actuated traffic control is applied in this test. Figure 65 through figure 70 illustrate the timing plans for each volume-level test scenario.

Table 35. Case 5 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L1	TH	R	L2	TH	R
Phase ID (Three Phase)	4	4		8	8		1	2		5	6	
Phase ID (Four Phase)	4	4		8	8		2	2,4		6,8	6	

Low Volumes	100	200	100	100	200	100	100	200	100	100	200	100
Medium Volumes	400	100	50	350	200	200	200	400	150	300	300	300
High Volumes	400	200	300	400	400	200	500	400	200	500	300	300

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

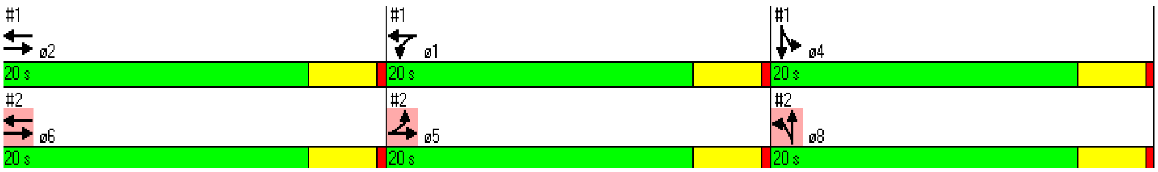


Figure 65. Screen Capture. Timing Plan for Three-Phase Diamond Interchange in Low Volumes.

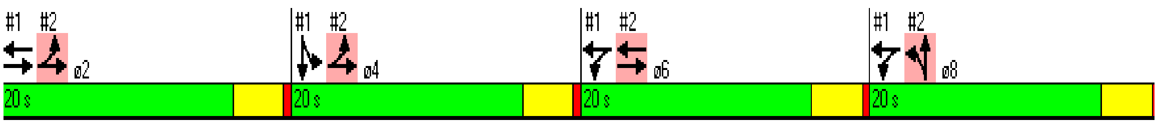


Figure 66. Screen Capture. Timing Plan for Four-Phase Diamond Interchange in Low Volumes.

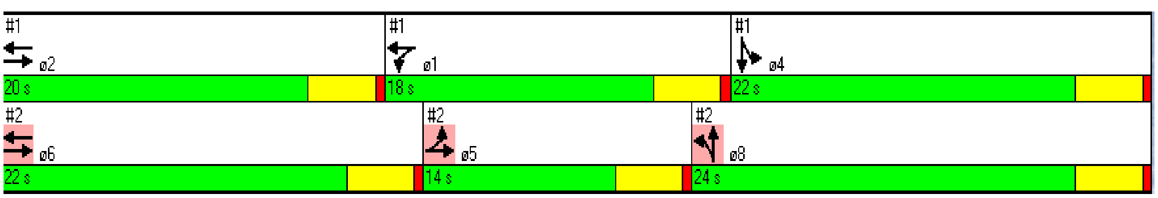


Figure 67. Screen Capture. Timing Plan for Three-Phase Diamond Interchange in Medium Volumes.

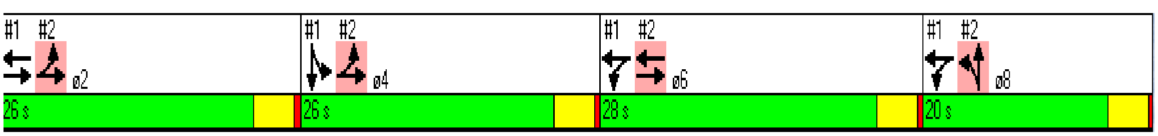


Figure 68. Screen Capture. Timing Plan Four-Phase Diamond Interchange in Medium Volumes.

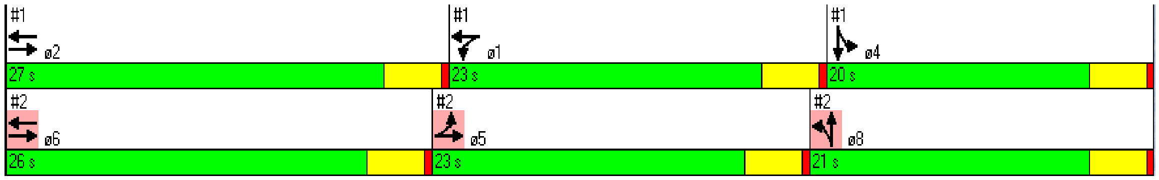


Figure 69. Screen Capture. Timing Plan for Three-Phase Diamond Interchange in High Volumes.

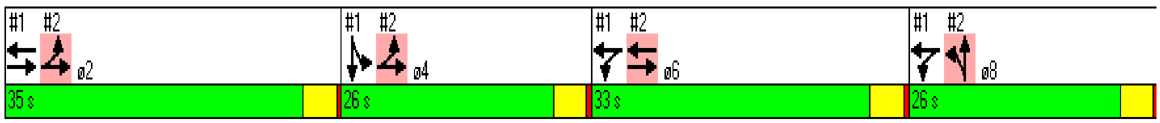


Figure 70. Screen Capture. Timing Plan for Four-Phase Diamond Interchange in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. The *F*-test and *t*-test were applied to compare surrogate measures of safety and the aggregations of those measures. Table 36 through table 39 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 36. Case 5 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	3 phase	**4 phase**	**3 phase**	**4 phase**	**3 phase**	**4 phase**
Low Volume Mean	1.20	1.60	3.60	4.20	24.80	36.30
Variance	0.62	2.04	3.82	3.29	22.18	59.12
***t*-value(95%), difference (%)**	-0.775		-0.712		**-4.033 , -46.4%**	
Medium Volume Mean	3.20	1.60	7.40	3.90	63.30	36.90
Variance	3.29	4.49	12.71	6.54	35.57	60.32
***t*-value(95%), difference (%)**	1.814		**2.522, 47.3%**		**8.525 , 41.7%**	
High Volume Mean	1.80	1.00	6.20	4.30	69.80	47.90
Variance	2.62	0.89	9.07	2.68	214.62	32.54
***t*-value(95%), difference (%)**	1.350		1.753		**4.405 , 31.4%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the three-phase timing plan shows fewer total conflicts at low-traffic volumes but higher total conflicts at medium- and high-traffic volumes. Also, very few conflict events occur with TTC ≤ 1.0 s.

Table 37. Case 5 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	3 phase	4 phase	3 phase	4 phase	3 phase	4 phase
Low Volume Mean	N/A	N/A	N/A	N/A	13.50	21.10
Variance	N/A	N/A	N/A	N/A	13.39	15.43
t-value(95%), difference (%)	N/A		N/A		**-4.477 , -56.3%**	
Medium Volume Mean	N/A	N/A	N/A	N/A	22.80	16.80
Variance	N/A	N/A	N/A	N/A	41.29	6.62
t-value(95%), difference (%)	N/A		N/A		**2.741 , 26.3%**	
High Volume Mean	N/A	N/A	N/A	N/A	35.90	18.20
Variance	N/A	N/A	N/A	N/A	8.54	9.51
t-value(95%), difference (%)	N/A		N/A		**13.172 , 49.3%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Consistent with the result for total conflicts, the three-phase timing plan shows fewer rear-end events for low-traffic volumes and more events for medium- and high-traffic volumes. Rear-end events make up approximately 50 percent of the total conflicts.

Table 38. Case 5 Comparison Results for Lane-Change Conflicts.

Lane Change	TTC ≤ 0.5		TTC ≤1.0		TTC ≤ 1.5	
	3 phase	4 phase	3 phase	4 phase	3 phase	4 phase
Low Volume Mean	1.10	1.60	3.30	3.90	11.20	14.90
Variance	0.54	2.04	2.68	3.21	12.62	32.54
t-value(95%), difference (%)	-0.983		-0.782		-1.741	
Medium Volume Mean	3.20	1.60	5.90	3.60	27.20	18.70
Variance	3.29	4.49	8.32	6.49	28.62	30.23
t-value(95%), difference (%)	1.814		1.890		**3.504, 31.3%**	
High Volume Mean	1.80	1.00	5.50	3.80	46.70	30.90
Variance	2.62	0.89	8.94	2.40	95.79	23.66
t-value(95%), difference (%)	1.350		1.596		**4.572 , 33.8%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

Consistent with the result for total conflicts, the three-phase timing plan shows fewer lane-change events for low-traffic volumes (although this result is not statistically significant) and more events for medium- and high-traffic volumes.

Table 39. Case 5 Comparison Results for Average Surrogate Measures of Safety.

	T3	T4	C3	C4	RE3	RE4	LC3	LC4
TTC (low)	1.29	1.29	N/A	N/A	1.39	1.39	1.17	1.16
t-value, diff(%)	0.000		N/A		0.000		0.208	
TTC (med)	1.29	1.29	N/A	N/A	1.37	1.37	1.18	1.2
t-value, diff(%)	0.000		N/A		0.000		-0.580	
TTC (high)	1.29	1.3	N/A	N/A	1.38	1.39	1.26	1.25
t-value, diff(%)	-0.725		N/A		-0.695		0.531	
PET(low)	2.24	2.31	N/A	N/A	2.72	2.63	1.64	1.87
t-value, diff(%)	-0.955		N/A		0.938		-1.507	
PET(med)	2.47	2.43	N/A	N/A	2.88	3.15	1.93	1.74
t-value, diff(%)	0.520		N/A		**-3.382, -9.38%**		1.740	
PET(high)	2.28	2.27	N/A	N/A	3.14	3.18	1.86	1.77
t-value, diff(%)	0.154		N/A		-0.479		1.310	
MaxS(low)	8.17	7.93	N/A	N/A	6.62	6.78	10.06	9.57
t-value, diff(%)	0.719		N/A		-0.631		0.796	
MaxS(med)	7.33	6.8	N/A	N/A	6.8	6.46	8.05	7.13
t-value, diff(%)	**3.108, 7.23%**		N/A		**2.037, 5%**		**3.259, 11.43%**	
MaxS(high)	6.48	6.32	N/A	N/A	6.37	6.29	6.54	6.34
t-value, diff(%)	1.637		N/A		0.544		1.566	
DeltaS(low)	5.48	5.49	N/A	N/A	5.45	5.57	5.5	5.36
t-value, diff(%)	-0.072		N/A		-0.768		0.576	
DeltaS(med)	3.69	2.91	N/A	N/A	3.37	2.36	4.1	3.44
t-value, diff(%)	**5.966, 21.14%**		N/A		**5.067, 29.97%**		**4.031, 16.1%**	
DeltaS(high)	3.08	2.8	N/A	N/A	2.3	1.76	3.45	3.35
t-value, diff(%)	**3.024, 9.09%**		N/A		**3.086, 23.48%**		1.133	
DR(low)	-2.98	-3.09	N/A	N/A	-2.86	-2.84	-3.11	-3.45
t-value, diff(%)	0.872		N/A		-0.190		1.312	
DR(med)	-2.32	-1.8	N/A	N/A	-2.06	-1.54	-2.65	-2.06
t-value, diff(%)	**-4.073, 22.41%**		N/A		**-4.570, 25.24%**		**-2.479, 22.26%**	
DR(high)	-2.01	-1.57	N/A	N/A	-1.57	-1.23	-2.21	-1.73
t-value, diff(%)	**-3.598, 21.89%**		N/A		**-2.928, 21.66%**		**-2.719, 21.72%**	
MaxD(low)	-3.75	-3.62	N/A	N/A	-3.25	-3.1	-4.36	-4.37
t-value, diff(%)	-0.929		N/A		-1.379		0.036	
MaxD(med)	-4.05	-4.27	N/A	N/A	-3.2	-2.8	-5.17	-5.7
t-value, diff(%)	1.486		N/A		**-3.575, 12.5%**		**2.362, -10.25%**	
MaxD(high)	-4.78	-4.7	N/A	N/A	-3.05	-2.85	-5.62	-5.7
t-value, diff(%)	-0.563		N/A		-1.479		0.472	
MaxDeltaV(low)	2.88	2.88	N/A	N/A	2.85	2.89	2.89	2.84
t-value, diff(%)	0.000		N/A		-0.466		0.394	
MaxDeltaV(med)	1.94	1.52	N/A	N/A	1.77	1.24	2.16	1.8
t-value, diff(%)	**6.026, 21.65%**		N/A		**5.064, 29.94%**		**4.047, 16.67%**	
MaxDeltaV(high)	1.61	1.46	N/A	N/A	1.22	0.92	1.8	1.75
t-value, diff(%)	**3.059, 9.32%**		N/A		**3.232, 24.59%**		1.052	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that four-phase control reduces the severity of conflict events.

Correlations with Predicted Crash Frequency

The predicted crash rates for all scenarios in this test are listed in table 40 with the corresponding average number of conflict events of each type. The Spearman rank correlation coefficients are calculated for each test and listed in the right-most column. Note that because there is no term in the crash prediction model to discriminate between three-phase and four-phase control, the predicted number of crashes for each case is the same. The results from SSAM would indicate that a three-phase design results in more conflict events than a four-phase design and is thus a less safe intersection.

Table 40. Case 5 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		**Rs**
		3	**4**	**3**	**4**	**3**	**4**	
Crash frequency	**M**	3.6	3.6	7.1	7.1	10.2	10.2	**1**
	R	1	1	3	3	5	5	
Total Conflict	**M**	24.8	36.3	63.30	36.90	69.80	47.90	**0.91**
	R	1	2	4	3	6	5	
Crossing Conflict	**M**							**N/A**
	R							
Rear-End Conflict	**M**	13.5	21.1	22.80	16.80	35.90	18.20	**0.46**
	R	1	4	5	2	6	3	
LC Conflict	**M**	11.20	14.90	27.20	18.70	46.70	30.90	**0.94**
	R	1	1	4	3	6	5	

Note: Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the observation on the safety surrogate data obtained from the test, the following conclusions can be drawn:

- There is little appreciable difference for any of the safety measures between three-phase and four-phase control logic. In general, three-phase control produces more conflicts than four-phase control for high-traffic volumes.
- TTC values for rear-end conflicts are typically larger than 1.0s.
- There are only a few crossing conflicts for both designs.

In general, when traffic volume is low, either logic- for diamond-interchange control has similar results for surrogate measures of safety. When traffic volume increases, three-phase control logic generates more conflicts than four-phase control logic and thus could be considered a less safe control strategy. In addition, the average values of the surrogate measures of safety for three-phase control are all consistently worse, reinforcing the determination that three-phase control is a less safe intersection design than four-phase control.

Case 6: Single-Point Urban Interchange Versus Diamond interchange (VISSIM)

The Single-Point Urban Interchange (SPUI) is a relatively new variant of the diamond (shown in figure 71). Where a diamond has two ramp intersections at the surface street (one on each side of the freeway), the ramps of a SPUI are placed so close together to make them effectively part of the same intersection. This allows one traffic signal to control all crossing movements and enables concurrent opposing left turns, which increases the capacity of the interchange above that of the three- and four-phase diamond control schemes.

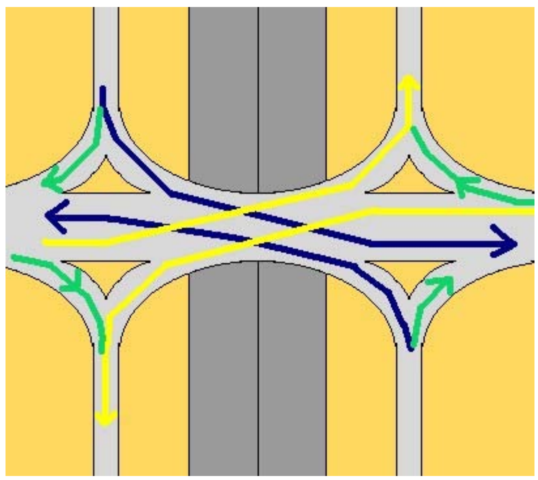


Figure 71. Screen Capture. Single-Point Urban Interchange.

The traffic signal control for the SPUI has three phases, as shown in figure 72, figure 73, and figure 74.[19]

> **PHASE 1**: Cars on the surface street (shown in red) are allowed to drive straight through only (no turns). The yellow cars waiting to turn onto the freeway must wait.
>
> **PHASE 2**: All cars on the surface street proceeding straight through or turning left onto freeway are stopped. Cars exiting the freeway to enter the street (green) are allowed to turn left.
>
> **PHASE 3**: Left-turning vehicles from the freeway (green) and cars proceeding straight through on the surface street (red) are stopped. Cars on the surface street are allowed to turn onto the on-ramp for the freeway (yellow).

Figure 72. Screen Capture. Phase 1.

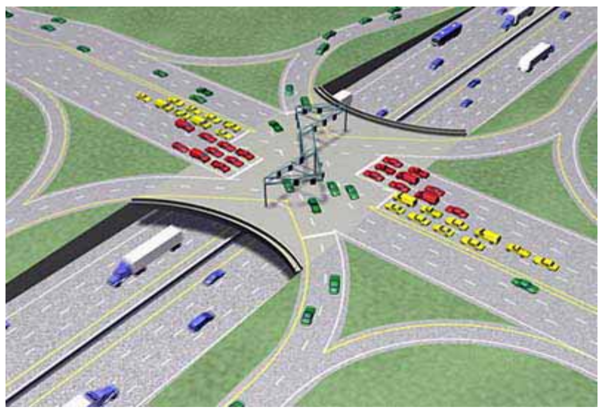


Figure 73. Screen Capture. Phase 2.

Figure 74. Screen Capture. Phase 3.

The disadvantages of a SPUI include the following:

- Complex intersection and signal phases may be unfamiliar to drivers.
- Distance between stop bars on the surface street creates problems for bicycles, which need more time to clear the area between them.
- More free-flow motor vehicle movements (part of what increases the SPUI's capacity) makes it more difficult for pedestrians to safely cross.
- Vehicle clearance time (where all lights must be red) must be longer than three- or four-phase control.

The goal of the comparison is to identify any differences in the safety performance use of the SPUI intersection with traditional diamond-signal control. Comparison of conventional crash prediction models cited earlier (each applied at the same volume) suggests that the SPUI averages slightly more crashes than a conventional diamond interchange at low and moderate volumes, and the trend is reversed at higher volumes (where SPUIs have fewer predicted crashes than diamond-interchange geometry). However, a recent comparison of SPUI and tight diamond-interchange crashes suggests no significant differences in total crashes, though SPUIs incurred fewer injuries/fatalities than comparable diamond interchanges.[20]

Intersection Description

The intersections used to test the diamond interchange versus SPUI are shown in figure 75, figure 76, and figure 77, respectively. All left-turn bays in the networks are 76.25 m (150 ft) long.

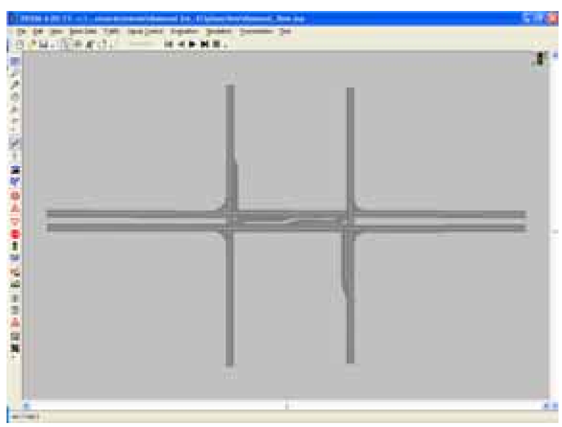


Figure 75. Screen Capture. Diamond Interchange in VISSIM.

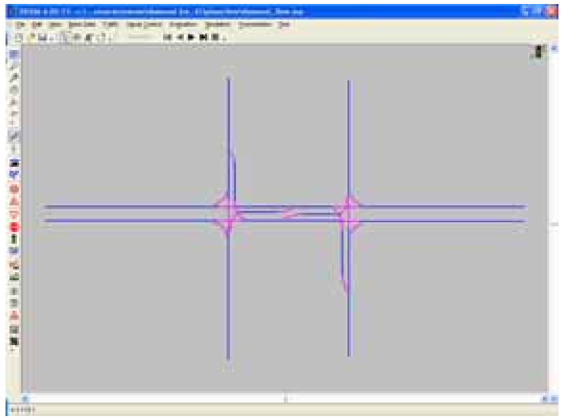


Figure 76. Screen Capture. Link-Connector View of Diamond Interchange Model in VISSIM.

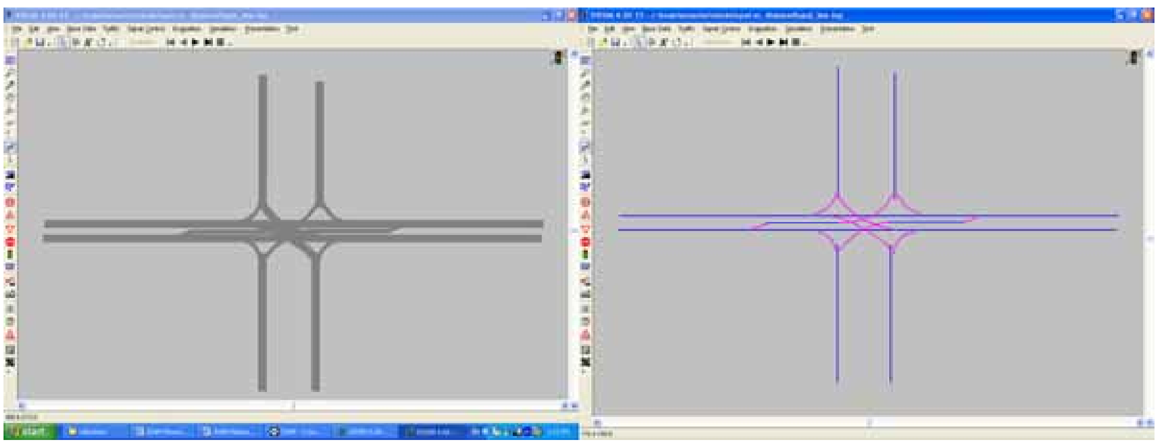


Figure 77. Screen Capture. SPUI in VISSIM.

Table 41 lists the traffic volumes applied for each approach of the intersection. Fully-actuated traffic control is applied in this test. Figure 78 though figure 83 indicate the timing plans for each testing scenario.

Table 41. Case 6 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID (Three Phase)	4	4		8	8		1	2		5	6	
Low Volumes	400	0	100	300	0	200	100	300	100	100	300	100
Medium Volumes	450	0	100	400	0	350	200	400	150	300	300	300
High Volumes	700	0	500	700	0	500	600	600	300	600	600	300

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

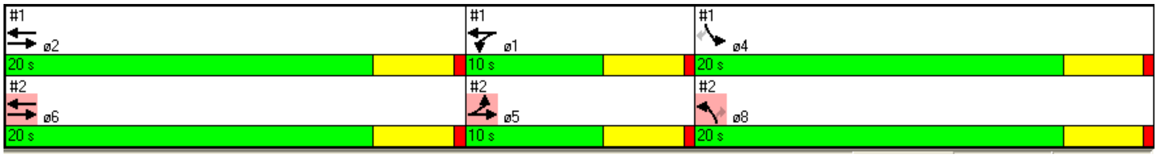


Figure 78. Illustration. Timing Plan for Diamond Interchange in Low Volumes.

Figure 79. Illustration. Timing Plan for SPUI in Low Volumes.

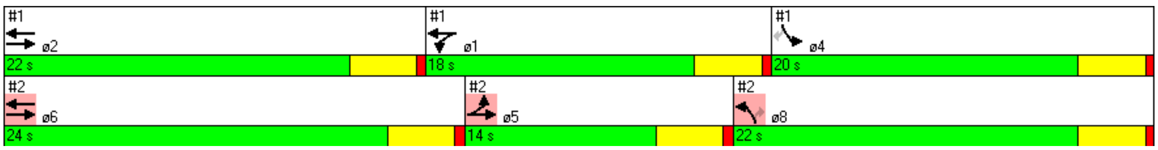


Figure 80. Illustration. Timing Plan for Diamond Interchange in Medium Volumes.

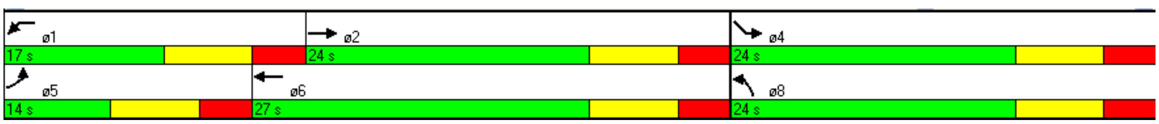


Figure 81. Illustration. Timing Plan SPUI in Medium Volumes.

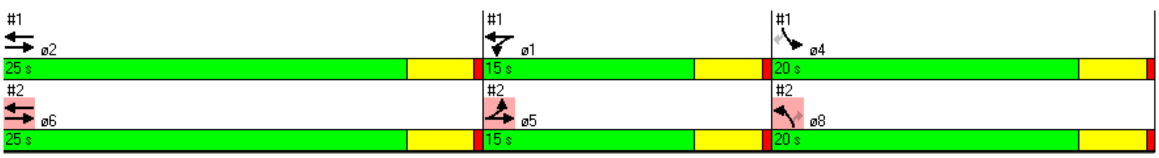


Figure 82. Illustration. Timing Plan for Diamond Interchange in High Volumes.

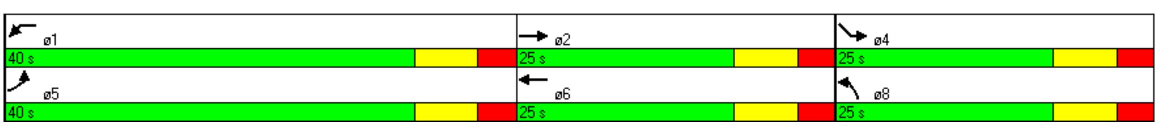


Figure 83. Illustration. Timing Plan for SPUI in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. *F*-test and *t*-tests were applied to identify the statistical significance of each surrogate measure of safety. Table 42 through table 45 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC $\neq$ 0 and MaxS $\geq$ 16.1 km/h (10 mi/h)).

Table 42. Case 6 Comparison Results for Total Conflicts.

Total	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	DIA	SPUI	DIA	SPUI	DIA	SPUI
Low Volume Mean	2.1	1	4	3.2	79.6	35
Variance	3.433	1.778	8.667	3.289	104.489	34.444
***t*-value(95%), difference (%)**	1.524		0.732		**11.966, 56.0%**	
Medium Volume Mean	2.5	2.3	7.6	5.5	143.1	64.1
Variance	1.833	3.567	11.156	4.722	549.211	89.656
***t*-value(95%), difference (%)**	0.272		1.667		**9.884, 55.2%**	
High Volume Mean	0.6	3.4	5.1	10.2	140.7	117.2
Variance	0.933	4.711	5.878	8.178	218.233	130.400
***t*-value(95%), difference (%)**	**-3.727, -466.7%**		**-4.302, -100.0%**		**3.980, 16.7%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates, when considering a threshold value of 1.5 s for TTC, that the SPUI geometry reduces the number of conflict events by 20 percent to 60 percent.

Table 43. Case 6 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	DIA	SPUI	DIA	SPUI	DIA	SPUI
Low Volume Mean	N/A	N/A	N/A	N/A	53	13.4
Variance	N/A	N/A	N/A	N/A	87.778	23.378
***t*-value(95%), difference (%)**	N/A		N/A		**11.878, 74.7%**	
Medium Volume Mean	N/A	N/A	N/A	N/A	100.9	31.2
Variance	N/A	N/A	N/A	N/A	353.433	48.178
***t*-value(95%), difference (%)**	N/A		N/A		**10.998, 69.1%**	
High Volume Mean	N/A	N/A	N/A	N/A	98.5	65.3
Variance	N/A	N/A	N/A	N/A	208.056	54.678
***t*-value(95%), difference (%)**	N/A		N/A		**6.477, 33.7%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates, when considering a threshold value of 1.5 s for TTC, that the SPUI geometry reduces the number of rear-end conflict events by 30 percent to 75 percent.

Table 44. Case 6 Comparison Results for Lane Change Conflicts.

Lane Change	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	DIA	**SPUI**	**DIA**	**SPUI**	**DIA**	**SPUI**
Low Volume Mean	2.1	0.9	3.7	2.9	26.3	21.6
Variance	3.433	1.211	7.344	3.211	26.456	30.044
***t*-value(95%), difference (%)**	1.761		0.779		1.977	
Medium Volume Mean	2.5	2.3	6.4	5.1	42.1	32.4
Variance	1.833	3.567	6.711	4.100	43.211	54.933
***t*-value(95%), difference (%)**	0.272		1.250		**3.096, 23%**	
High Volume Mean	0.6	3.4	3.4	8.6	42	51.5
Variance	0.933	4.711	4.711	6.711	28.000	101.611
***t*-value(95%), difference (%)**	**-3.727, -466.7%**		**-4.866, -152.9%**		**-2.639 -22.6%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

The results shown in this table for lane-change conflicts are inconclusive. For high volumes, there is a definite trend for the SPUI to increase the number of lane-change conflicts.

Table 45. Case 6 Comparison Results for Average Surrogate Measures of Safety.

	TDIA	TSPUI	CDIA	CSPUI	REDIA	RESPUI	LCDIA	LCSPUI
TTC (low)	1.36	1.32	N/A	N/A	1.41	1.39	1.26	1.28
t-value, diff(%)	**2.687, 2.94%**		N/A		1.542		-0.730	
TTC (med)	1.36	1.33	N/A	N/A	1.4	1.41	1.27	1.25
t-value, diff(%)	**2.721, 2.21%**		N/A		-1.544		0.881	
TTC (high)	1.35	1.32	N/A	N/A	1.37	1.38	1.31	1.24
t-value, diff(%)	**3.523, 2.22%**		N/A		-1.401		**3.955, 5.34%**	
PET(low)	2.61	2.23	N/A	N/A	2.83	2.6	2.17	2
t-value, diff(%)	**6.209, 14.56%**		N/A		**3.081, 8.13%**		1.744	
PET(med)	2.7	2.37	N/A	N/A	2.88	2.68	2.27	2.06
t-value, diff(%)	**7.078, 12.22%**		N/A		**3.903, 6.94%**		**2.465, 9.25%**	
PET(high)	3.01	2.59	N/A	N/A	3.13	3.04	2.76	2.03
t-value, diff(%)	**10.373, 13.95%**		N/A		**2.265, 2.88%**		**9.440, 26.45%**	
MaxS(low)	7.33	8.1	N/A	N/A	6.9	6.65	8.16	9.01
t-value, diff(%)	**-3.035, -10.50%**		N/A		1.046		**-2.095, -10.42%**	
MaxS(med)	7.51	7.64	N/A	N/A	7.1	6.55	8.51	8.7
t-value, diff(%)	-0.796		N/A		**3.986, 7.75%**		-0.618	
MaxS(high)	7.4	7.67	N/A	N/A	7.15	7.1	7.99	8.39
t-value, diff(%)	**-2.597, -3.65%**		N/A		0.476		-1.945	
DeltaS(low)	5.45	6.15	N/A	N/A	5.34	5.85	5.63	6.34
t-value, diff(%)	**-8.186, -12.84%**		N/A		**-5.411, -9.55%**		**-5.171, -12.61%**	
DeltaS(med)	5.03	5.89	N/A	N/A	4.97	5.59	5.17	6.17
t-value, diff(%)	**-12.617, -17.10%**		N/A		**-7.585, -12.47%**		**-8.841, -19.34%**	
DeltaS(high)	3.11	3.93	N/A	N/A	2.91	3.56	3.55	4.39
t-value, diff(%)	**-10.447, -26.37%**		N/A		**-6.433, -22.34%**		**-6.850, -23.66%**	
DR(low)	-2.94	-3.11	N/A	N/A	-2.76	-2.87	-3.31	-3.25
t-value, diff(%)	**2.460, -5.78%**		N/A		**2.322, -3.99%**		-0.439	
DR(med)	-2.83	-3.02	N/A	N/A	-2.68	-2.78	-3.2	-3.26
t-value, diff(%)	**3.580, -6.71%**		N/A		**3.173, -3.73%**		0.509	
DR(high)	-2.03	-2.41	N/A	N/A	-2	-2.13	-2.1	-2.77
t-value, diff(%)	**6.323, -18.72%**		N/A		**2.621, -6.50%**		**5.122, -31.90%**	
MaxD(low)	-3.25	-3.39	N/A	N/A	-2.95	-3.01	-3.83	-3.62
t-value, diff(%)	1.746		N/A		0.977		-1.360	
MaxD(med)	-3.25	-3.4	N/A	N/A	-2.97	-2.97	-3.92	-3.82
t-value, diff(%)	**2.494, -4.62%**		N/A		0.000		-0.772	
MaxD(high)	-3.27	-3.76	N/A	N/A	-2.88	-2.91	-4.18	-4.83
t-value, diff(%)	**6.896, -14.98%**		N/A		0.607		**4.366, -15.55%**	
MaxDeltaV(low)	2.86	3.21	N/A	N/A	2.81	3.05	2.94	3.3
t-value, diff(%)	**-7.722, -12.24%**		N/A		**-4.511, -8.54%**		**-5.071, -12.24%**	
MaxDeltaV(med)	2.63	3.09	N/A	N/A	2.6	2.94	2.72	3.24
t-value, diff(%)	**-11.532, -17.49%**		N/A		**-7.386, -13.08%**		**-8.384, -19.12%**	
MaxDeltaV(high)	1.63	2.06	N/A	N/A	1.52	1.86	1.86	2.31
t-value, diff(%)	**-10.406, -26.38%**		N/A		**-6.411, -22.37%**		**-6.99, -24.19%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the average values of surrogate measures of safety (in terms of average severity per conflict) are consistently worse for the SPUI design than the three-phase diamond interchange.

Correlations with Predicted Crash Frequency

The predicted crash rates for all scenarios in this test are in table 46 with the corresponding average number of conflict events of each type. Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test and listed in the right-most column of the table.

Table 46. Case 6 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		***R*s**
		DIA	**SPUI**	**DIA**	**SPUI**	**DIA**	**SPUI**	
Crash Frequency	**M**	4.8	5.5	7.3	7.9	14.1	12.8	**1**
	R	1	2	3	4	6	5	
Total Conflict	**M**	79.6	35	143.1	64.1	140.7	117.2	**0.43**
	R	3	1	6	2	5	4	
Crossing Conflict	**M**							**N/A**
	R							
Rear-End Conflict	**M**	53	13.4	100.9	31.2	98.5	65.3	**0.43**
	R	3	1	6	2	5	4	
LC Conflict	**M**	26.3	21.6	42.1	32.4	42	51.5	**0.69**
	R	1	1	5	3	4	6	

Note: Averages that are not significantly different are assigned the same rank. Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the observation on the safety surrogate data obtained from the test, the following conclusions can be drawn:

- SPUI shows significant reductions in total and rear-end conflicts compared to the conventional diamond interchange at most levels of volume. This finding is perhaps explained by the reduction from two stopping points to a single stopping point for arterial traffic crossing through the interchange and by the known correlation of vehicle stops with rear-end crashes.
- Crossing events are rare for either intersection design.
- Almost all average values of surrogate measures of safety indicate that events that occur at SPUI intersections will be more severe than those at diamond interchanges. However, given that rear-end events are generally less severe that and the SPUI featured a dramatic

reduction in rear-end events, the increase in average severity measures per conflict is consistent and does not conclusively suggest that SPUIs are more dangerous.

- Correlation of the conflict averages for all volume levels is not consistent with crash prediction models

In general, these results indicate that a SPUI-intersection design will reduce the total number of conflicts that occur (primarily the rear-end conflicts), but when conflicts do occur, they will be more severe on average.

Case 7: Cross Four-Leg Intersection Versus Offset T-Intersection (VISSIM)

This comparison is between an unsignalized four-leg intersection and an offset T-intersection. According to Vogt's theory in the development of the crash prediction models for two-lane roads, T-intersections with an obtuse angle from the minor road were found to have fewer crashes than four-legged rural intersections.[21] From the results of recent studies by Bared, on an aggregate level, the expected benefit of converting a cross intersection to an offset T-intersection is a reduction in total crashes of 20 percent to 30 percent for rural 2 x 2-lane, two-way, stop-controlled intersections.[14] The reduction in fatal/injury crashes is expected to be approximately 40 percent for 2 x 2-lane intersections. One reason for this, as shown in figure 84, is the noticeable reduction in conflict points (from 32 to 22) by converting a cross intersection to an offset T-intersection.

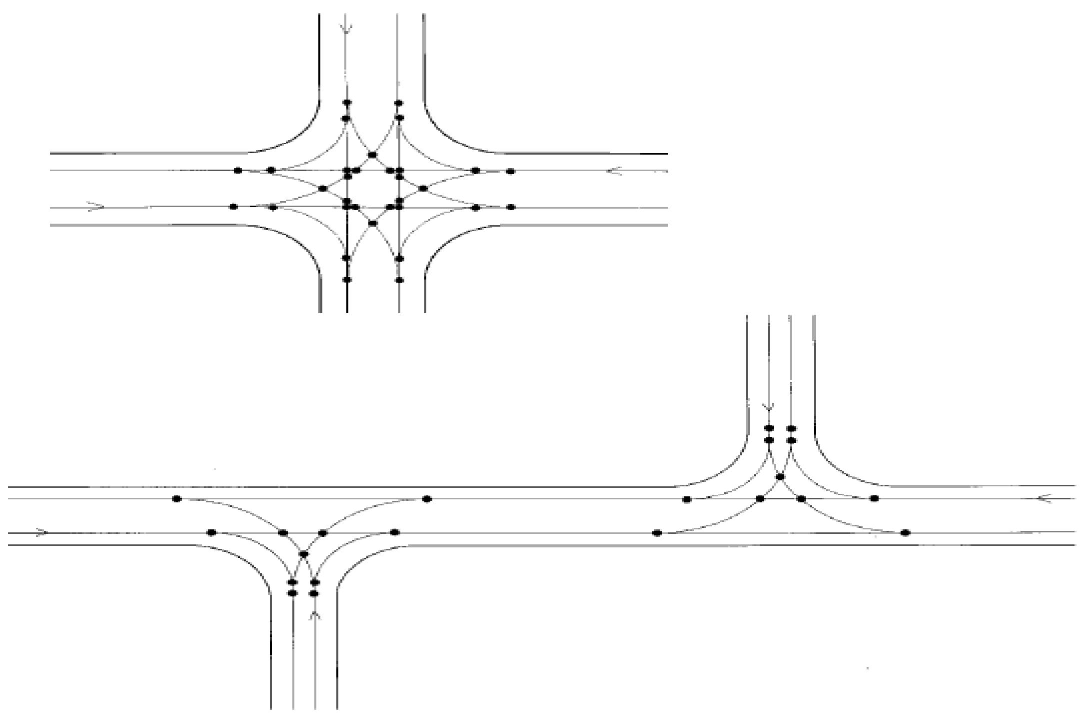


Figure 84. Illustration. Potential Conflict Points for 2 x 2-Lane Intersections.[14]

Intersection Description

The intersections used for this test are shown in figure 85 and figure 86, respectively. All left-turn bays are 76.25 m (250 ft) long.

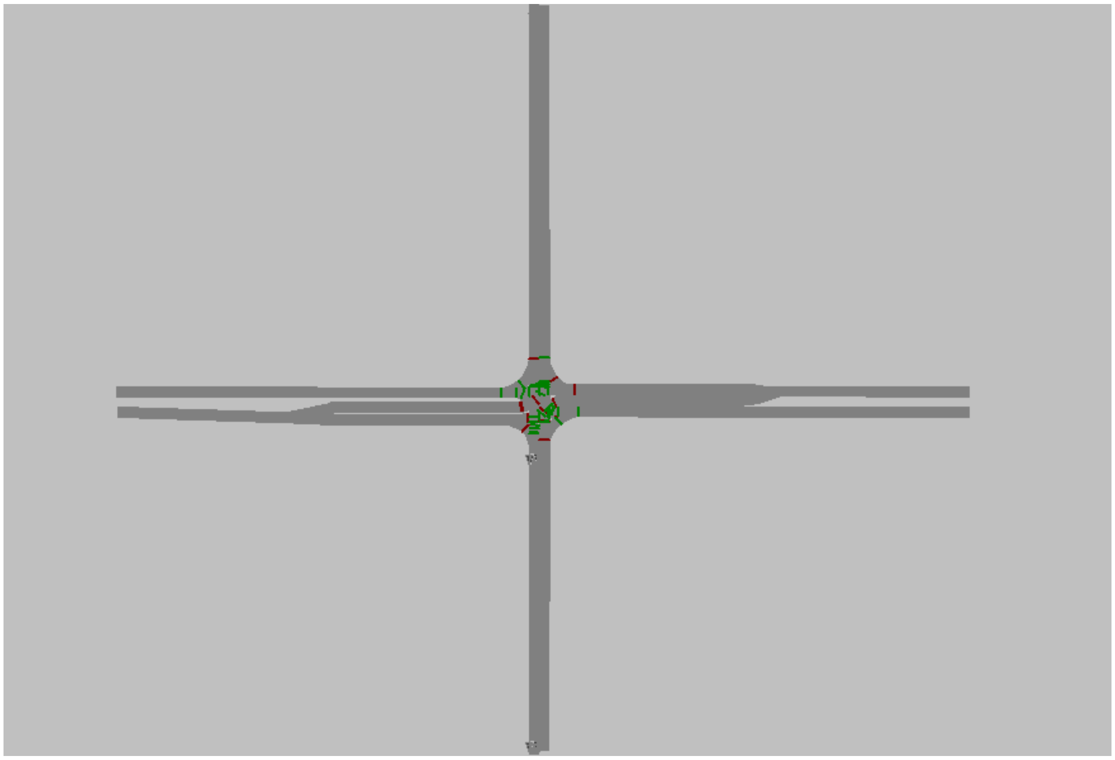


Figure 85. Screen Capture. Conventional Nonsignalized Intersection.

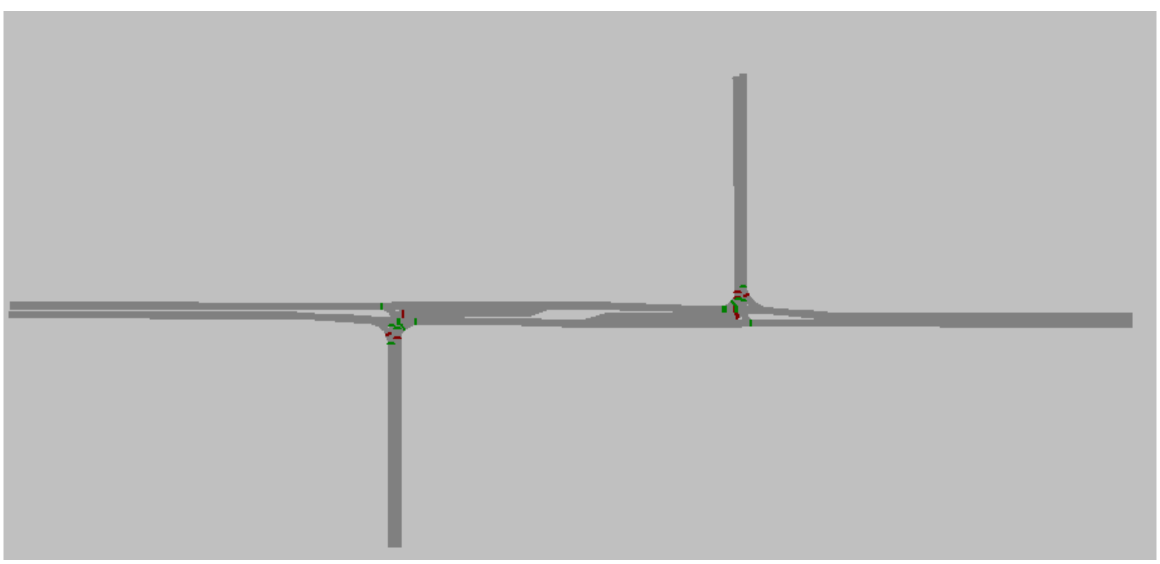


Figure 86. Screen Capture. Offset T-Intersection.

Table 47 shows traffic volumes applied for each approach of the intersection. No traffic control is used in this test.

Table 47. Case 7 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L1	TH	R	L2	TH	R
Low Volumes	25	50	25	25	50	25	60	180	60	60	180	60
Medium Volumes	50	100	50	50	100	50	100	300	100	100	300	100
High Volumes	88	175	88	88	175	88	140	420	140	140	420	140

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. The *F*-test and *t*-test were applied to compare the average number of conflict events of each event type and surrogate measures of safety between the two intersection designs. Table 48 through table 51 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC ≠ 0 and
MaxS ≥ 16.1 km/h (10 mi/h)).

Table 48. Case 7 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	CON	**OFFT**	**CON**	**OFFT**	**CON**	**OFFT**
Medium Volume Mean	N/A	N/A	N/A	N/A	3.5	5.7
Variance	N/A	N/A	N/A	N/A	3.167	7.122
***t*-value(95%), difference (%)**	N/A		N/A		**-2.169, -62.86%**	
High Volume Mean	N/A	N/A	N/A	N/A	4.4	8.7
Variance	N/A	N/A	N/A	N/A	2.933	7.122
***t*-value(95%), difference (%)**	N/A		N/A		**-4.288, -97.73%**	

Note: CON indicates conventional intersection cross and OFFT indicates an offset T-intersection. Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that the total conflicts are increased with the offset T, although as shown in the following tables, those conflicts are comprised of lane changes and rear ends only.

Table 49. Case 7 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	OFFT	CON	OFFT	CON	OFFT
Low Volume Mean	N/A	N/A	N/A	N/A	N/A	N/A
Variance	N/A	N/A	N/A	N/A	N/A	N/A
***t*-value(95%), difference (%)**	N/A		N/A		N/A	
Medium Volume Mean	N/A	N/A	N/A	N/A	1.3	1.9
Variance	N/A	N/A	N/A	N/A	2.900	1.433
***t*-value(95%), difference (%)**	N/A		N/A		-0.911	
High Volume Mean	N/A	N/A	N/A	N/A	1.4	3.9
Variance	N/A	N/A	N/A	N/A	1.600	1.878
***t*-value(95%), difference (%)**	N/A		N/A		**-4.239, -178.57%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

Table 50. Case 7 Comparison Results for Lane-Change Conflicts.

LC	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	OFFT	CON	OFFT	CON	OFFT
Medium Volume Mean	N/A	N/A	N/A	N/A	1.8	3.7
Variance	N/A	N/A	N/A	N/A	1.956	4.678
***t*-value(95%), difference (%)**	N/A		N/A		**-2.333, -105.56%**	
High Volume Mean	N/A	N/A	N/A	N/A	2.7	4.6
Variance	N/A	N/A	N/A	N/A	2.233	3.156
***t*-value(95%), difference (%)**	N/A		N/A		**-2.588, -70.37%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

Table 51. Case 7 Comparison Results for Average Surrogate Measures of Safety.

	TCON	TOFFT	CCON	COFFT	RECON	REOFFT	LCCON	LCOFFT
TTC (med)	1.37	1.45	N/A	N/A	1.4	1.42	1.41	1.46
***t*-value, diff(%)**	**-2.203, -5.84%**		N/A		-0.556		-1.774	
TTC (high)	1.45	1.45	N/A	N/A	1.42	1.46	1.46	1.45
***t*-value, diff(%)**	0.000		N/A		-1.497		0.000	
PET(med)	2.34	2.89	N/A	N/A	2.85	3.17	2.32	2.71
***t*-value, diff(%)**	**-2.457, -23.50%**		N/A		-0.960		-1.377	
PET(high)	2.92	2.86	N/A	N/A	2.88	3.04	2.97	2.73
***t*-value, diff(%)**	0.468		N/A		-0.780		1.417	
MaxS(med)	7.37	6.01	N/A	N/A	7.46	6.58	7.07	5.74
***t*-value, diff(%)**	**2.626, 18.45%**		N/A		1.088		1.670	
MaxS(high)	5.88	6.13	N/A	N/A	6.33	6.52	5.71	5.81
***t*-value, diff(%)**	-1.204		N/A		-0.378		-0.995	
DeltaS(med)	6.13	5.16	N/A	N/A	5.83	4.03	5.93	5.74
***t*-value, diff(%)**	**2.713, 15.8%**		N/A		**3.481, 30.9%**		0.493	
DeltaS(high)	5.38	5.53	N/A	N/A	4.76	5.17	5.71	5.81
***t*-value, diff(%)**	-0.680		N/A		-0.764		-0.995	
DR(med)	-3.12	-2.81	N/A	N/A	-2.88	-2.64	-3.2	-2.89
***t*-value, diff(%)**	-1.370		N/A		-1.222		-1.048	
DR(high)	-2.75	-2.77	N/A	N/A	-2.49	-2.62	-2.9	-2.89
***t*-value, diff(%)**	0.230		N/A		0.611		-0.323	
MaxD(med)	-3.63	-3.37	N/A	N/A	-3.19	-3.22	-3.92	-3.46
***t*-value, diff(%)**	-1.036		N/A		0.131		-1.375	
MaxD(high)	-3.22	-3.28	N/A	N/A	-3.04	-3.16	-3.28	-3.4
***t*-value, diff(%)**	0.467		N/A		0.550		0.724	
MaxDeltaV(med)	3.17	2.64	N/A	N/A	3.06	2.05	3.05	2.93
***t*-value, diff(%)**	**2.915, 16.7%**		N/A		**3.763, 33.0%**		0.598	
MaxDeltaV(high)	2.81	2.87	N/A	N/A	2.46	2.65	3	3.06
***t*-value, diff(%)**	-0.491		N/A		-0.686		-0.679	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that for the statistically significant measures, the offset T design results in a reduction in both the crash probability and the severity for all conflict types.

Correlations with Predicted Crash Frequency

The predicted crash rates for all scenarios in this test are in table 52 with the corresponding surrogate measures of safety. Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test.

Table 52. Case 7 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Medium		High		*R*s
		CON	OFFT	CON	OFFT	
Crash Frequency	M	2.9	2.0	5.0	3.4	1
	R	2	1	4	3	
Total Conflict	M	3.5	5.7	4.4	8.7	0
	R	1	3	2	4	
Crossing Conflict	M					N/A
	R					
Rear-End Conflict	M	1.3	1.9	1.4	3.9	0.7
	R	1	1	3	4	
LC Conflict	M	1.8	3.7	2.7	4.6	0
	R	1	3	2	4	

Note: Averages that are not significantly different are assigned the same rank. Rows labeled "M" provide mean values and rows labeled "R" provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Since the offset T increases the number of conflicts that occur in the simulation model, the correlation with the reduction in crashes that is expected with an offset T is very poor.

Findings and Conclusions

Based on the above observations, the following conclusions can be drawn:

- The number of total conflicts for both cases are low because of the low traffic volumes, which are typical for uncontrolled intersections.
- The conventional intersection generates fewer total and lane-change conflicts than the offset T-intersection.
- The offset T-intersection exhibits lower average values for all severity and probability of crash surrogate measures.

In general, the conventional intersection shows fewer total and lane-change conflicts than the offset T-intersection. The conflicts that occur at the offset T, however, have lower average values of surrogate measures of severity and probability of collisions.

Case 8: Mid-Block U-Turn Versus Left Turn at Signalized Intersection (VISSIM)

The primary objective of the median U-turn design is to remove all left-turn traffic from the main intersection. In this configuration, all left-turn movements are converted to right turns at the intersection and then use uni-directional median crossovers to make U-turns onto major roads to complete their change of direction, as shown in figure 87.[15]

This type of design favors the major street through-movement because time from the signal cycle does not have to be allocated to protected left-turn phases. Because it is possible to control the median U-turn intersection with a simple two-phase cycle, it also eliminates lost time associated with the left-turn phases and facilitates coordinated progression along high-volume arterial corridors. This design also removes (or relocates, for unsignalized median U-turns) all of the conflicts that would normally be associated with left-turn movements. Thus, crashes directly associated with left-turn movements are effectively eliminated. It is understood that the exposure to crashes associated with higher right turn and U-turn volumes would likely increase, although these types of crashes are generally less severe than left-turn crashes.

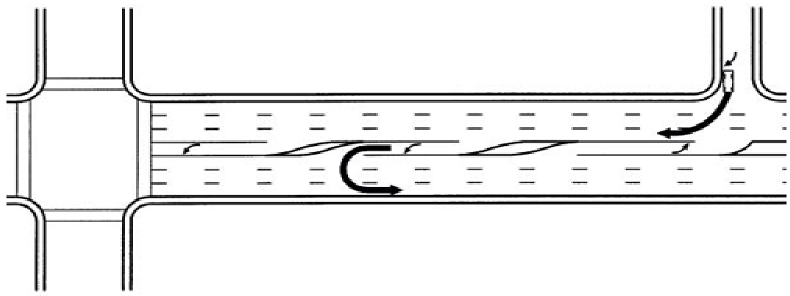


Figure 87. Illustration. Mid-Block U-Turn at Signalized Intersection.

From the perspective of bicycles and pedestrians, the median U-turn design presents fewer threats. Although this design requires a longer time to cross the major roadway, the median can also serve as a refuge area for pedestrians; however, the crossing time can be longer and require two-cycle pedestrian signals.

This study compares the mid-block U-turn design with conventional signal control to evaluate the ability of the mid-block U-turn approach to reduce the number of crossing conflicts.

Intersection Description

The intersections used for this test are shown in figure 88 and figure 89.

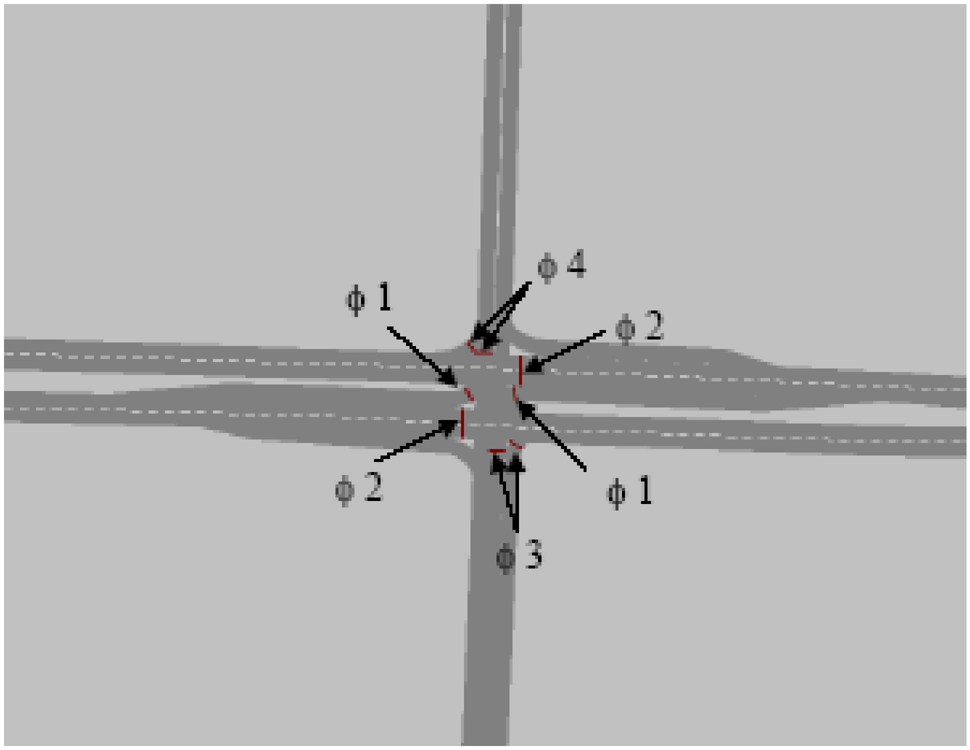


Figure 88. Screen Capture. Conventional Intersection in VISSIM.

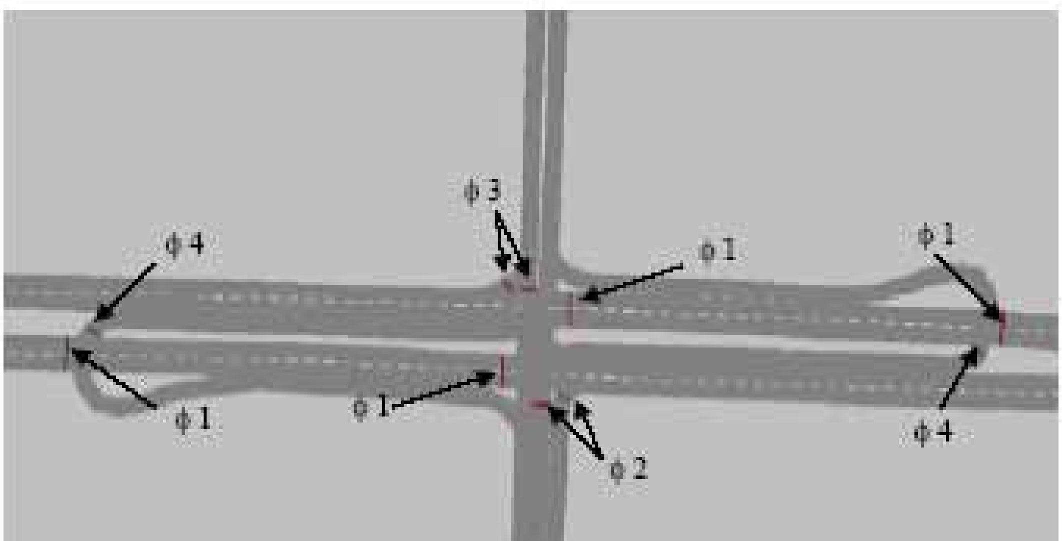


Figure 89. Screen Capture. Intersection with Median U-Turn in VISSIM.

Table 53 shows traffic volumes applied to each approach of the intersection. Fully-actuated traffic control is applied in this test. Figure 90 through figure 95 indicate the timing plans used for each testing scenario.

Table 53. Case 8 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID (Four Phase)	3	3	3	2	2	2	4	1		4	1	
Low Volumes	25	75	25	50	100	50	75	650	125	75	650	125
Medium Volumes	50	150	50	100	200	100	150	1,300	150	150	1,300	150
High Volumes	100	200	100	150	200	150	200	1,400	200	200	1,400	200

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

Figure 90. Illustration. Timing Plan Conventional Intersection in Low Volumes (Cycle: 80; Split: 12, 28, 10, 10).

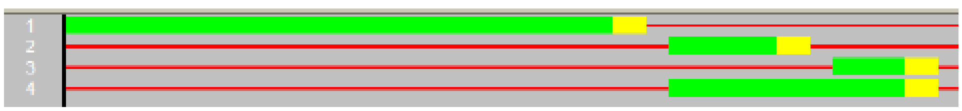


Figure 91. Illustration. Timing Plan for Median U Turn in Low Volumes (Cycle: 80; Split: 49, 9.5, 6.5, 21).

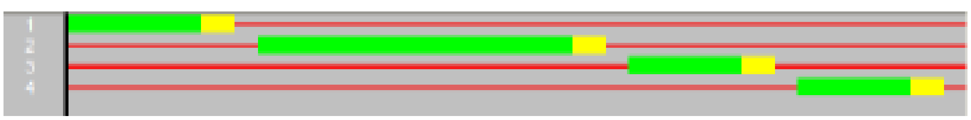


Figure 92. Illustration. Timing Plan for Conventional Intersection in Medium Volumes (Cycle: 80; Split: 12, 28, 10, 10).

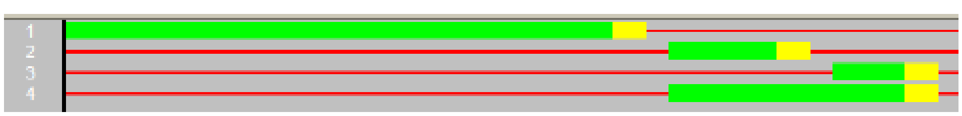


Figure 93. Illustration. Timing Plan for Median U Turn in Medium Volumes (Cycle: 80; Split: 49, 9.5, 6.5, 21).

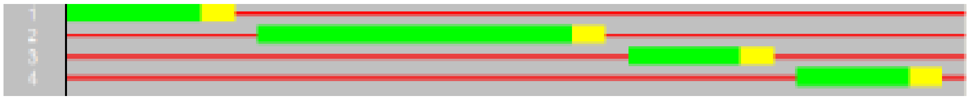


Figure 94. Illustration. Timing Plan for Conventional Intersection in High Volumes (Cycle: 80; Split: 12, 28, 10, 10).

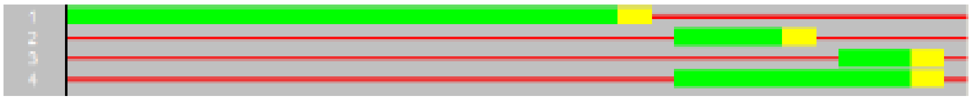


Figure 95. Illustration. Timing Plan for Median U Turn in High Volumes (Cycle: 80; Split: 49, 9.5, 6.5, 21).

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario, and the resulting output trajectory data was analyzed by SSAM. *F*-tests and *t*-tests were applied to compare the average number of conflict events and surrogate measures of safety between the two design options. Table 54 through table 58 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low- speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10mi/h)).

Table 54. Case 8 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	CON	**MED U**	**CON**	**MED U**	**CON**	**MED U**
Low Volume Mean	N/A	N/A	0.5	1.1	35.8	41.3
Variance	N/A	N/A	0.500	1.433	63.511	61.122
***t*-value(95%), difference (%)**	N/A		-1.365		-1.558	
Medium Volume Mean	N/A	N/A	2.1	2.4	96.7	87.3
Variance	N/A	N/A	1.433	2.489	50.011	92.900
***t*-value(95%), difference (%)**	N/A		-0.479		**2.487, 9.72%**	
High Volume Mean	1.2	0.8	3.8	3.2	115.6	100.1
Variance	2.400	0.844	4.400	5.289	199.156	42.767
***t*-value(95%), difference (%)**	0.702		0.610		**3.151, 13.41%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows that the median U-turn design intersection shows fewer total conflicts at medium and high volumes. Also, in either design case, very few conflict events occur with TTC ≤ 1.0 s.

Table 55. Case 8 Comparison Results for Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	MED U	CON	MED U	CON	MED U
Mean	N/A	N/A	N/A	N/A	0.3	0.9
Variance	N/A	N/A	N/A	N/A	0.456	0.989
***t*-value(95%), difference (%)**	N/A		N/A		-1.579	
Mean	N/A	N/A	N/A	N/A	0.5	1.1
Variance	N/A	N/A	N/A	N/A	0.944	0.989
***t*-value(95%), difference (%)**	N/A		N/A		-1.365	

Table 56. Case 8 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	MED U	CON	MED U	CON	MED U
Low Volume Mean	N/A	N/A	N/A	N/A	29.5	30.3
Variance	N/A	N/A	N/A	N/A	67.611	50.233
***t*-value(95%), difference (%)**	N/A		N/A		-0.233	
Medium Volume Mean	N/A	N/A	N/A	N/A	83.6	72.1
Variance	N/A	N/A	N/A	N/A	36.711	64.100
***t*-value(95%), difference (%)**	N/A		N/A		**3.622, 13.76%**	
High Volume Mean	N/A	N/A	N/A	N/A	97.4	80.8
Variance	N/A	N/A	N/A	N/A	93.378	45.733
***t*-value(95%), difference (%)**	N/A		N/A		**4.451, 17.04%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows that the median U-turn intersection has fewer rear-end conflicts at medium and high volumes than the conventional intersection. There are no events that occur with TTC ≤ 1.0 s.

Table 57. Case 8 Comparison Results for Lane-Change Conflicts.

LC	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	MED U	CON	MED U	CON	MED U
Low Volume Mean	N/A	N/A	N/A	N/A	6.2	9.8
Variance	N/A	N/A	N/A	N/A	4.178	7.733
***t*-value(95%), difference (%)**	N/A		N/A		**-3.299, -58.06%**	
Medium Volume Mean	N/A	N/A	1.2	1	12.8	14.3
Variance	N/A	N/A	1.067	1.333	7.733	11.567
***t*-value(95%), difference (%)**	N/A		0.408		-1.080	
High Volume Mean	1.2	0.8	2.8	2.2	17.7	18.2
Variance	2.400	0.844	4.178	2.622	29.344	7.067
***t*-value(95%), difference (%)**	0.702		0.728		-0.262	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows that there is no significant difference for the number of lane-change conflicts between the two scenarios, except a significant increase in the number of lane-change events for median U-turns at low volumes.

Table 58. Case 8 Comparison Results for Average Surrogate Measures of Safety.

	TCON	TMED U	CCON	CMED U	RECON	REMED U	LCCON	LCMED U
TTC (low)	1.4	1.39	N/A	N/A	1.4	1.4	1.37	1.33
t-value, diff(%)	1.144		N/A		0.000		1.148	
TTC (med)	1.38	1.37	N/A	N/A	1.39	1.38	1.32	1.33
t-value, diff(%)	1.515		N/A		1.587		-0.334	
TTC (high)	1.36	1.36	1.4	1.34	1.38	1.38	1.25	1.27
t-value, diff(%)	0.000		0.675		0.000		-0.584	
PET(low)	2.69	2.65	N/A	N/A	2.74	2.72	2.42	2.43
t-value, diff(%)	0.742		N/A		0.364		-0.066	
PET(med)	3.08	3.05	N/A	N/A	3.16	3.13	2.54	2.68
t-value, diff(%)	0.770		N/A		0.765		-1.130	
PET(high)	3.15	3.05	2.96	2.45	3.26	3.14	2.56	2.7
t-value, diff(%)	**2.571, 3.17%**		1.143		**3.322, 3.68%**		-1.003	
MaxS(low)	6.42	6.46	N/A	N/A	6.32	6.28	6.93	7.07
t-value, diff(%)	-0.321		N/A		0.328		-0.364	
MaxS(med)	7.44	7.31	N/A	N/A	7.51	7.15	7.05	8.19
t-value, diff(%)	1.148		N/A		**3.012, 4.79%**		**-3.559, -16.17%**	
MaxS(high)	7.62	7.69	5.32	6.33	7.61	7.44	7.77	8.9
t-value, diff(%)	-0.658		**-3.469, -18.98%**		1.535		**-3.735, 14.54%**	
DeltaS(low)	5.76	5.76	N/A	N/A	5.75	5.67	5.83	6.01
t-value, diff(%)	0.000		N/A		1.013		-0.734	
DeltaS(med)	4.37	4.23	N/A	N/A	4.25	3.99	5.09	5.35
t-value, diff(%)	1.489		N/A		**2.551, 6.12%**		-1.192	
DeltaS(high)	3.26	4.04	5.32	6.33	3.11	3.88	4.01	4.64
t-value, diff(%)	**-9.119, -23.93%**		**-3.469, -18.98%**		**-8.284, -24.76%**		**-2.965, -15.71%**	
DR(low)	-2.78	-2.76	N/A	N/A	-2.77	-2.78	-2.82	-2.69
t-value, diff(%)	-0.625		N/A		0.521		-0.931	
DR(med)	-2.42	-2.38	N/A	N/A	-2.38	-2.29	-2.68	-2.77
t-value, diff(%)	-0.967		N/A		**-2.266, 3.78%**		0.572	
DR(high)	-2.17	-2.38	-2.45	-2.83	-2.1	-2.31	-2.53	-2.66
t-value, diff(%)	**4.548, -9.68%**		1.422		**5.338, -10.00%**		0.665	
MaxD(low)	-2.95	-2.99	N/A	N/A	-2.9	-2.9	-3.2	-3.28
t-value, diff(%)	0.879		N/A		0.000		0.378	
MaxD(med)	-2.88	-2.88	N/A	N/A	-2.79	-2.74	-3.44	-3.59
t-value, diff(%)	0.000		N/A		-1.869		0.677	
MaxD(high)	-2.88	-2.92	-3.7	-3.29	-2.64	-2.76	-4.16	-3.62
t-value, diff(%)	0.796		-0.416		**4.230, -4.55%**		**-2.227, 12.98%**	
MaxDeltaV(low)	2.94	2.96	N/A	N/A	2.93	2.92	2.98	3.08
t-value, diff(%)	-0.424		N/A		0.210		-0.684	
MaxDeltaV(med)	2.23	2.14	N/A	N/A	2.17	2.02	2.59	2.71
t-value, diff(%)	1.865		N/A		**2.856, 6.91%**		-1.076	
MaxDeltaV(high)	1.67	2.06	2.66	3.16	1.59	1.97	2.05	2.39
t-value, diff(%)	**-8.890, -23.35%**		**-3.504, -18.80%**		**-7.982, -23.90%**		**-3.101, -16.59%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates that, for most of the measures, the average values of both severity- and probability-related surrogates are worse for the median U-turn design.

Correlations with Predicted Crash Frequency

Because there is no crash prediction model for median U-turn intersections, no correlation test can be performed.

Findings and Conclusions

Based on the above observations, the following conclusions can be drawn:

- The median U-turn intersection generates fewer total and rear-end conflicts than the conventional intersection.
- There are very few crossing conflicts for both scenarios.
- Most of the conflicts have TTC values greater than 1.0 s.
- The conventional intersection exhibits more favorable average values for most of the surrogate measures related to both the severity and probability of crashes.

The reduction in the number of conflicts is consistent with the conventional understanding of the safety impact of median U-turns, but the increase in the severity of the average values of surrogate measures is counter-indicative.

Case 9 and 10: Single Roundabout Versus Four- and Three-Approach Intersections (AIMSUN)

Roundabouts were first applied in Europe and have achieved significant results, such as reduced travel delay, reduced crash rates, and when crashes do occur, reduced crash severity. Modern roundabouts are circular intersections that incorporate channelized approaches, yield control, and design geometry that facilitate moderate operating speeds, typically less than 48.3 km/h (30 mi/h).(22) They differ from other types of circular intersections (rotaries, traffic circles, etc.) in terms of their operational traffic patterns. Under the right conditions, a properly designed roundabout is thought to offer safety and efficiency benefits greater than conventional intersections.(23)

Roundabouts may improve the safety of intersections by eliminating or altering conflict types, reducing speed differentials at intersections, and forcing drivers to decrease speeds as they proceed into and through intersections. Figure 96 presents a diagram of vehicle-vehicle conflict points for a traditional four-leg intersection and a four-leg roundabout intersection of two-lane roads. Notice that the number of vehicle-to-vehicle conflict points for four-leg intersections drops from 32 to 8 with roundabouts. Figure 97 presents a diagram of vehicle-vehicle conflict points for a traditional three-leg, T-intersection and a three-leg roundabout. As the figure shows, the number of vehicle-to-vehicle conflict points for roundabouts decreases from nine to six for three-leg intersections. Fewer conflict points is conventionally understood to indicate that there are fewer opportunities for collisions.(16)

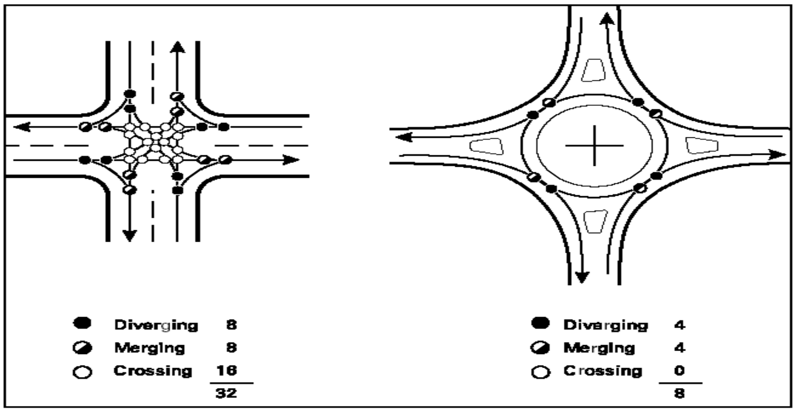


Figure 96. Illustration. Conflict Points for Intersections with Four Single-Lane Approaches.[(23)]

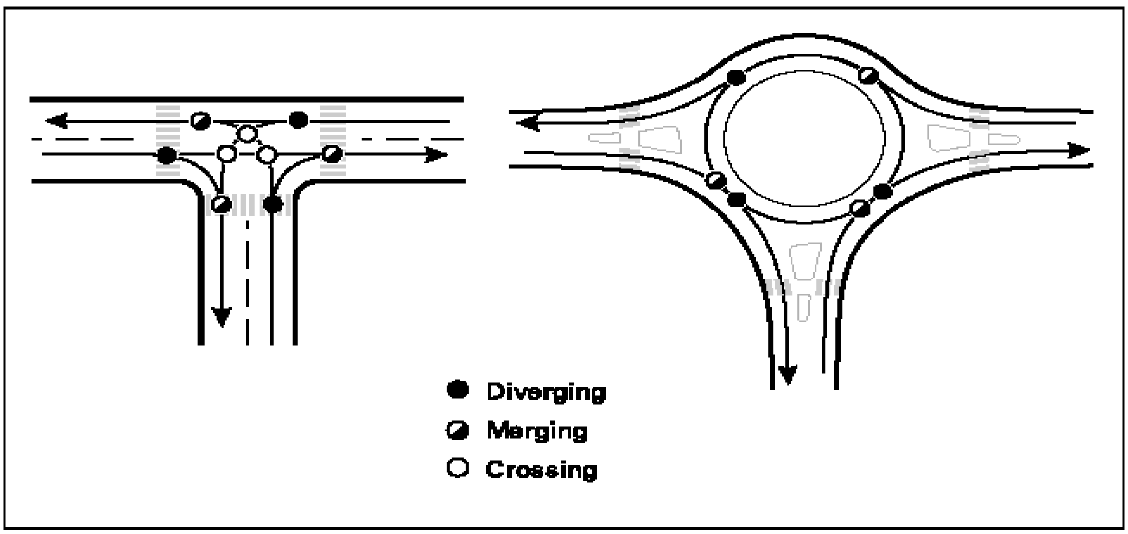


Figure 97. Illustration. Conflict Points for T-Intersections with Single-Lane Approaches.[(23)]

This study examines these effects by comparing a typical single roundabout to a comparable eight-phase, four-approach conventional intersection and a comparable T-intersection.

Intersection Description

Case 9: Single four-approach roundabout versus four-approach intersection

The intersections used for this test are shown in figure 98 and figure 99. All left-turn bays are 76.25 m (250 ft) long.

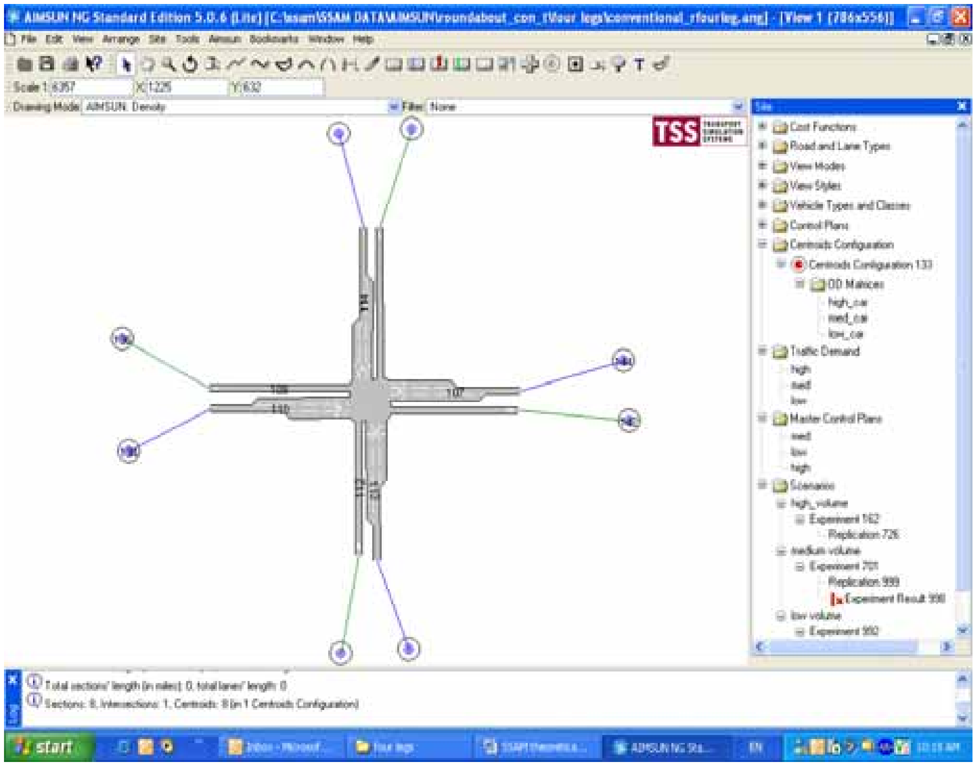


Figure 98. Screen Capture. Conventional Intersection in AIMSUN.

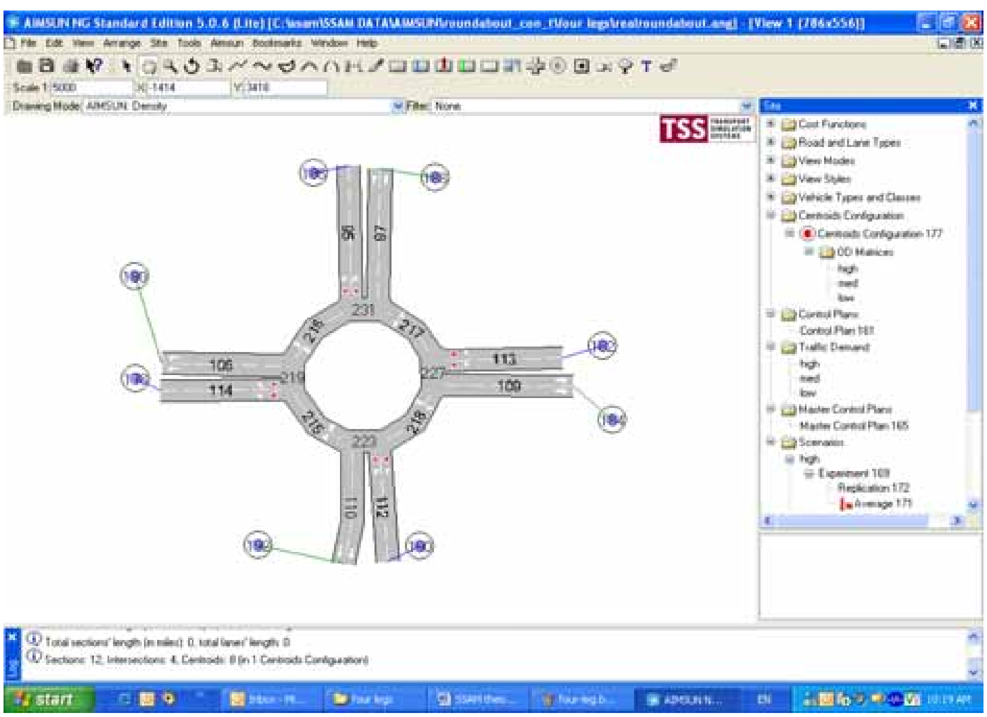


Figure 99. Screen Capture. Four-Approach Roundabout in AIMSUN.

Table 59 shows the traffic volumes applied to each approach of the intersection. Fixed-time traffic control is used in the conventional intersection design for this test. Figure 100 through figure 102 indicate the timing plans used for each testing scenario.

Table 59. Case 9 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID (Four Phase)	3	4	4	7	8	8	5	2	2	1	6	6
Low Volumes	75	100	25	75	100	25	75	100	25	75	100	25
Medium Volumes	150	200	50	150	200	50	150	200	50	150	200	50
High Volumes	200	200	200	200	200	200	200	200	200	200	200	200

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

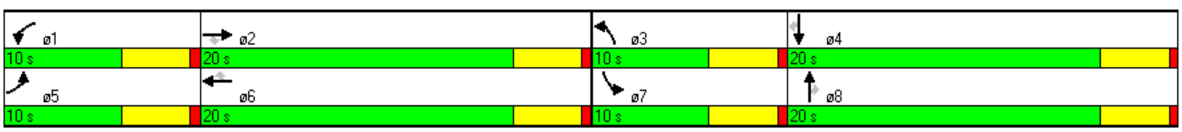


Figure 100. Screen Capture. Timing Plan for Conventional Intersection in Low Volumes.

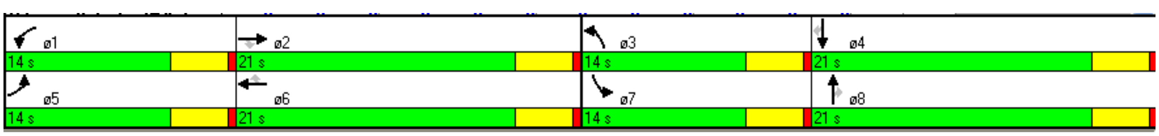


Figure 101. Screen Capture. Timing Plan for Conventional Intersection in Medium Volumes.

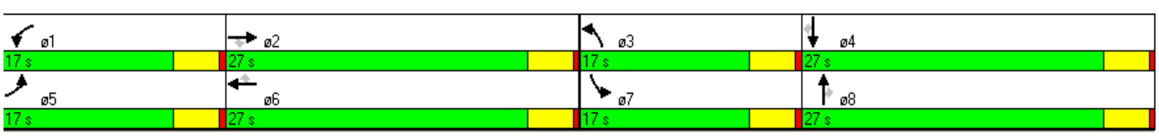


Figure 102. Screen Capture. Timing Plan for Conventional Intersection in High Volumes.

Case 10: Single three-approach roundabout versus T-intersection

The intersections used for this test are shown in figure 103 and figure 104.

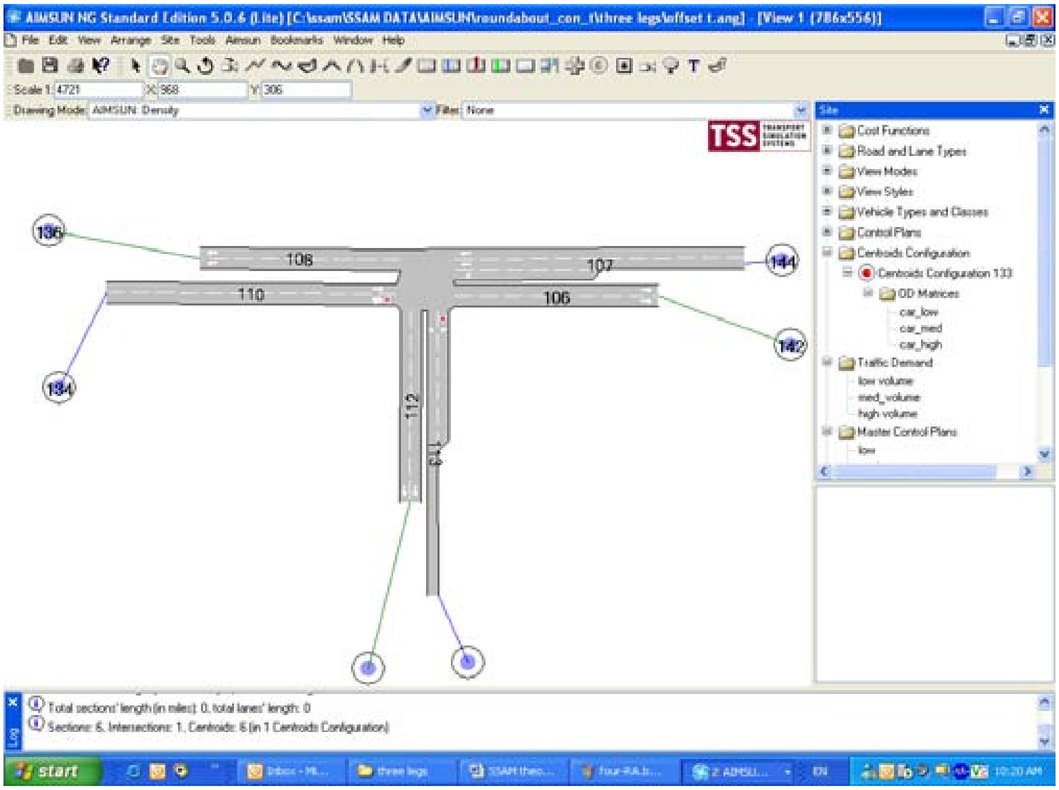


Figure 103. Screen Capture. T-Intersection in AIMSUN.

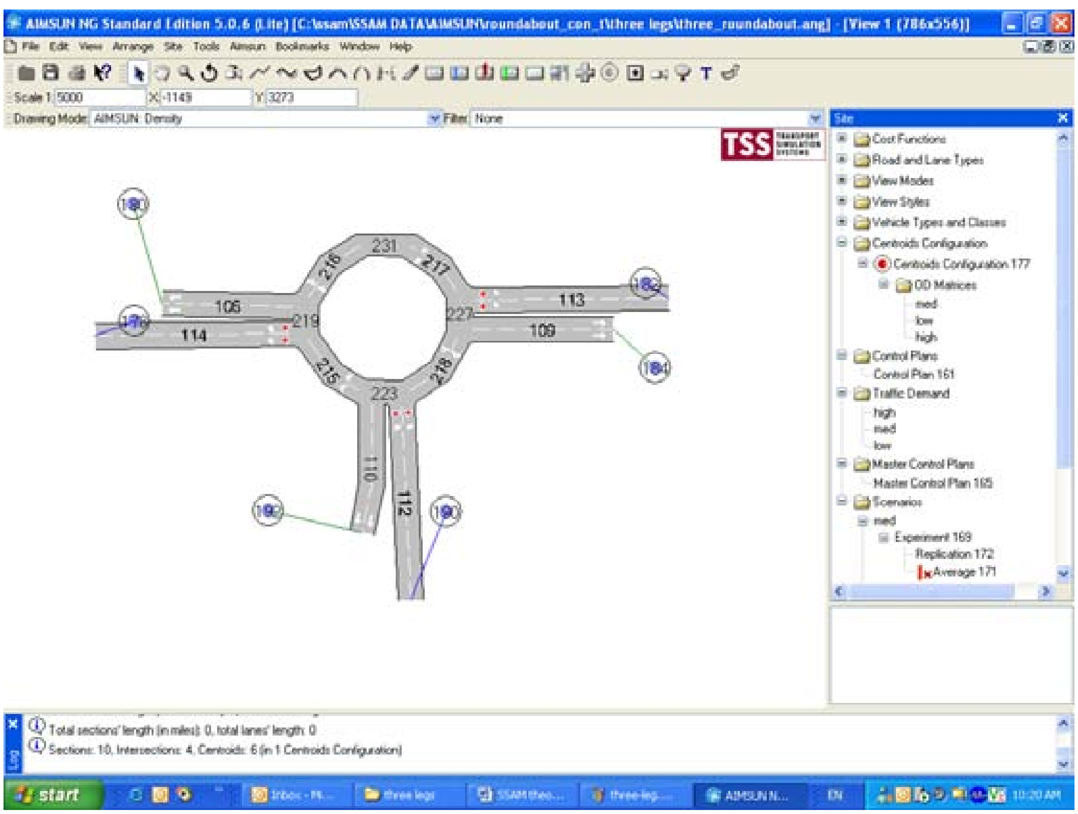


Figure 104. Screen Capture. Three-Approach Roundabout in AIMSUN.

Table 60 shows traffic volumes applied to each approach of the intersection. Fully-actuated traffic control is applied in this test. Figure 105 through figure 107 indicate the timing plans used for each testing scenario.

Table 60. Case 10 Service Flow by Each Approach.

Approach	Northbound		Eastbound		Westbound	
	L	R	TH	R	L	TH
Phase ID (Four Phase)	3	3	2	2	1	1
Low Volumes	200	200	200	100	200	200
Medium Volumes	400	400	300	200	400	400
High Volumes	600	600	600	600	600	600

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

Figure 105. Illustration. Timing Plan for T-Intersection in Low Volumes.

Figure 106. Illustration. Timing Plan for T-Intersection in Medium Volumes.

Figure 107. Illustration. Timing Plan for T-Intersection in High Volumes.

Data Analysis and Comparison Results

Case 9: Single four-approach roundabout versus four-approach intersection:

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. Table 61 through table 65 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed and crash events excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 61. Case 9 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	CON	**RA**	**CON**	**RA**	**CON**	**RA**
Low Volume Mean	N/A	1.0	14.90	2.80	27.10	5.30
Variance	N/A	0.44	6.10	1.51	8.10	9.57
***t*-value(95%), difference (%)**	N/A		**13.87, 81.2%**		**16.401, 80.4%**	
Medium Volume Mean	N/A	5.6	36.90	22.50	66.20	46.60
Variance	N/A	5.6	86.54	14.5	82.40	14.49
***t*-value(95%), difference (%)**	N/A		**4.530, 39.0%**		**6.297, 29.6%**	
High Volume Mean	N/A	12.30	53.00	70.60	93.00	133.70
Variance	N/A	5.79	44.00	64.49	53.33	194.01
***t*-value(95%), difference (%)**	N/A		**-5.343, -33.2%**		**-8.184, -43.8%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the four-approach roundabout has fewer total conflicts at low and medium volumes but more total conflicts at high traffic volumes than the conventional intersection. There are no events, in either case, that occur with TTC ≤ 0.5 s.

Table 62. Case 9 Comparison Results for Crossing Conflicts.

Crossing	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	CON	**RA**	**CON**	**RA**	**CON**	**RA**
Low Volume Mean	N/A	N/A	N/A	N/A	N/A	N/A
Variance	N/A	N/A	N/A	N/A	N/A	N/A
***t*-value(95%), difference (%)**	N/A		N/A		N/A	
Medium Volume Mean	N/A	1.00	N/A	N/A	N/A	N/A
Variance	N/A	0.44	N/A	N/A	N/A	N/A
***t*-value(95%), difference (%)**	N/A		N/A		N/A	
High Volume Mean	N/A	4.00	1.40	6.40	3.10	7.90
Variance	N/A	2.22	2.04	4.93	6.10	5.66
***t*-value(95%), difference (%)**	N/A		**-5.986, -357.1%**		**-4.427, -154.8%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows there are very few crossing conflicts for either scenario. At high volumes, the roundabout has statistically more crossing events, although crossing events amount to approximately only 5 percent of the total events that occur.

Table 63. Case 9 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	RA	CON	RA	CON	RA
Low Volume Mean	N/A	N/A	13.20	0.50	21.30	0.70
Variance	N/A	N/A	10.18	0.50	12.01	0.68
***t*-value(95%), difference (%)**	N/A		**12.290, 96.2%**		**18.288, 96.7%**	
Medium Volume Mean	N/A	N/A	33.20	5.60	57.10	7.90
Variance	N/A	N/A	71.07	6.27	71.21	5.43
***t*-value(95%), difference (%)**	N/A		**9.925, 83.1%**		**17.772, 86.2%**	
High Volume Mean	N/A	N/A	42.60	20.20	70.20	30.20
Variance	N/A	N/A	32.71	16.40	58.84	40.18
***t*-value(95%), difference (%)**	N/A		**10.108, 52.6%**		**12.711, 57.0%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that the four-approach roundabout will, for all traffic volumes, statistically reduce the number of rear-end conflicts, as expected from field experience.

Table 64. Case 9 Comparison Results for Lane Change Conflicts.

Lane Change	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	RA	CON	RA	CON	RA
Low Volume Mean	N/A	0.90	1.70	2.10	5.80	4.40
Variance	N/A	0.54	1.79	1.43	10.18	6.93
***t*-value(95%), difference (%)**	N/A		-0.705		1.070	
Medium Volume Mean	N/A	4.40	3.60	15.50	9.00	37.20
Variance	N/A	5.16	4.71	10.94	6.89	19.96
***t*-value(95%), difference (%)**	N/A		**-9.511, -330.6%**		**-17.212, -313.3%**	
High Volume Mean	N/A	8.20	9.00	44.00	19.70	95.60
Variance	N/A	4.84	11.56	68.00	17.57	115.82
***t*-value(95%), difference (%)**	N/A		**-12.409, -388.9%**		**-20.782, -385.3%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows that the four-approach roundabout has more lane-change conflicts at medium- and high-traffic volumes than the conventional design. This was expected due to the weaving movements that are necessary in a roundabout to complete turning maneuvers.

Table 65. Case 9 Comparison Results for Average Surrogate Measures of Safety.

	TCON	TRA	CCON	CRA	RCON	RRA	LCCON	LCRA
TTC (low)	1.04	0.99	N/A	N/A	1.01	0.99	1.15	1.01
t-value, diff(%)	0.974		N/A		0.211		**2.100, 12.17%**	
TTC (med)	1.04	1.05	N/A	N/A	1.02	0.95	1.14	1.08
t-value, diff(%)	-0.536		N/A		1.984		1.908	
TTC (high)	1.05	1.02	1.14	0.67	1.03	0.98	1.12	1.06
t-value, diff(%)	**2.542, 2.86%**		**8.867, 41.23%**		**2.896, 4.85%**		**2.966, 5.36%**	
PET(low)	1.45	1.24	N/A	N/A	1.46	1.37	1.42	1.23
t-value, diff(%)	**3.662, 14.48%**		N/A		1.048		**2.670, 13.38%**	
PET(med)	1.45	1.32	N/A	N/A	1.45	1.48	1.46	1.31
t-value, diff(%)	**6.905, 8.97%**		N/A		-0.573		**5.141, 10.27%**	
PET(high)	1.44	1.35	1.33	1.03	1.45	1.48	1.4	1.34
t-value, diff(%)	**6.770, 6.25%**		**4.219, 22.56%**		-1.178		**3.259, 4.29%**	
MaxS(low)	34.51	37.35	N/A	N/A	34.46	39.18	34.72	36.59
t-value, diff(%)	**-2.282, -8.23%**		N/A		-1.494		-1.244	
MaxS(med)	33.96	35.07	N/A	N/A	33.99	34.26	33.74	34.81
t-value, diff(%)	**-2.645, -3.27%**		N/A		-0.312		-1.594	
MaxS(high)	32.61	34.71	31.09	44.22	33.08	32.97	31.15	34.47
t-value, diff(%)	**-7.737, -6.44%**		**-10.670, -42.23%**		0.276		**-6.908, -10.66%**	
DeltaS(low)	34.19	29.47	N/A	N/A	34.13	28.03	34.41	29.24
t-value, diff(%)	**4.749, 13.81%**		N/A		**2.511, 17.87%**		**4.134, 15.02%**	
DeltaS(med)	33.19	28.05	N/A	N/A	33.23	27.56	32.89	27.75
t-value, diff(%)	**11.286, 15.49%**		N/A		**4.910, 17.06%**		**6.317, 15.63%**	
DeltaS(high)	31.16	27.65	30.44	36.59	31.98	27.46	28.36	26.97
t-value, diff(%)	**10.168, 11.26%**		**-5.254, -20.20%**		**7.705, 14.13%**		**2.029, 4.9%**	
DR(low)	-12.64	-18.5	N/A	N/A	-12.61	-42.93	-12.72	-15.12
t-value, diff(%)	1.67		N/A		1.477		0.867	
DR(med)	-12.58	-20.67	N/A	N/A	-12.58	-16.08	-12.6	-20.87
t-value, diff(%)	**4.812, -64.31%**		N/A		1.372		**4.273, -65.63%**	
DR(high)	-12.15	-26.82	-11.5	-40.46	-12.4	-13.36	-11.35	-29.94
t-value, diff(%)	**11.118, -120.74%**		**4.176, -251.83%**		1.572		**10.733, -163.79%**	
MaxD(low)	-12.64	-30.44	N/A	N/A	-12.61	-59.98	-12.72	-24.25
t-value, diff(%)	**3.270, -140.82%**		N/A		2.110		**2.166, -90.64%**	
MaxD(med)	-12.6	-33.54	N/A	N/A	-12.59	-24.14	-12.67	-32.74
t-value, diff(%)	**8.791, -166.19%**		N/A		**2.557, -91.74%**		**7.439, -158.41%**	
MaxD(high)	-12.94	-38.36	-19.22	-97.36	-12.59	-17.62	-13.23	-40.04
t-value, diff(%)	**16.188, -196.45%**		**10.203, -406.56%**		**3.659, -39.95%**		**13.390, -202.65%**	
MaxDeltaV(low)	17.93	15.37	N/A	N/A	17.9	14.31	18.01	15.31
t-value, diff(%)	**4.815, 14.28%**		N/A		**4.071, 20.06%**		**4.029, 14.99%**	
MaxDeltaV(med)	17.34	14.68	N/A	N/A	17.36	14.5	17.22	14.51
t-value, diff(%)	**11.094, 15.34%**		N/A		**4.689, 16.47%**		**6.279, 15.74%**	
MaxDeltaV(high)	16.3	14.44	15.9	19.1	16.73	14.32	14.85	14.09
t-value, diff(%)	**10.263, 11.41%**		**-5.133, -20.13%**		**7.837, 14.41%**		**2.117, 5.12%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

In this table, most of the average values of surrogate measures indicate that the roundabout has worse performance than the conventional intersection, except for the DeltaS and MaxDeltaV measures. The reduction in the DeltaS indicates a reduction in the potential severity of resultant crashes by the reduction of relative vehicle speeds. The other surrogate measures indicate a higher propensity for conflicts that have higher probability of resultant collisions.

Case 10: Single three-approach roundabout versus T-intersection:

Ten replications were performed for each simulation scenario, and the resulting output trajectory data were analyzed by SSAM. Table 66 through table 70 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed and crash events excluded from the analysis (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10 mi/h)).

Table 66. Case 10 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	CON	**RA**	**CON**	**RA**	**CON**	**RA**
Low Volume Mean	0.80	2.80	39.40	5.90	65.40	11.20
Variance	0.62	3.73	38.71	6.77	22.71	9.51
***t*-value(95%), difference (%)**	**-3.030, -250.0%**		**15.709, 85.0%**		**30.194, 82.9%**	
Medium Volume Mean	1.90	8.90	80.90	38.50	135.10	82.30
Variance	1.66	9.43	38.32	77.17	86.10	125.34
***t*-value(95%), difference (%)**	**-6.647, -368.4%**		**12.477, 52.4%**		**11.482, 39.1%**	
High Volume Mean	57.20	32.60	305.60	185.10	549.80	344.90
Variance	184.84	34.04	3641.16	200.32	12272.62	374.77
***t*-value(95%), difference (%)**	**5.258, 43.0%**		**6.148, 39.4%**		**5.762, 37.3%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

Similar to the results for the four-leg roundabout, the three-approach roundabout reduces the total conflict events over that of the conventional intersection 40 percent to 80 percent for most traffic volumes and TTC threshold values. The three-approach roundabout and T-intersection exhibit conflict events that have TTC values ≤ 0.5, whereas the four-approach roundabout did not have any events at this level of severity for any traffic volume levels.

Table 67. Case 10 Comparison Results for Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	RA	CON	RA	CON	RA
Low Volume Mean	N/A	N/A	1.90	0.80	3.30	0.90
Variance	N/A	N/A	1.66	0.62	1.34	0.77
***t*-value(95%), difference (%)**	N/A		**2.305, 57.9%**		**5.223, 72.7%**	
Medium Volume Mean	0.50	3.20	6.30	4.00	10.00	5.40
Variance	0.28	3.96	4.90	5.11	10.67	3.82
***t*-value(95%), difference (%)**	**-4.150, -540.0%**		**2.299, 36.5%**		**3.822, 46.0%**	
High Volume Mean	13.90	9.10	83.10	17.30	117.30	21.40
Variance	11.43	3.88	262.10	15.12	569.79	15.38
***t*-value(95%), difference (%)**	**3.879, 34.6%**		**12.497, 79.2%**		**12.537, 81.8%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the three-approach roundabout reduces crossing conflicts 45 percent to 80 percent at almost all traffic volumes.

Table 68. Case 10 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	CON	RA	CON	RA	CON	RA
Low Volume Mean	N/A	N/A	32.70	0.90	49.20	1.20
Variance	N/A	N/A	31.57	0.77	30.40	0.84
***t*-value(95%), difference (%)**	N/A		**17.685, 97.2%**		**27.155, 97.6%**	
Medium Volume Mean	0.90	0.20	71.00	9.60	115.20	15.50
Variance	0.77	0.18	54.44	19.60	131.07	37.83
***t*-value(95%), difference (%)**	**2.278, 77.8%**		**22.564, 86.5%**		**24.259, 86.5%**	
High Volume Mean	17.50	0.60	155.30	59.70	330.10	94.50
Variance	50.06	0.93	1399.79	53.34	5805.43	136.28
***t*-value(95%), difference (%)**	**7.484, 96.6%**		**7.931, 61.6%**		**9.665, 71.4%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

As with the results for total and crossing conflict, this table shows that the three-approach roundabout has significantly fewer rear-end conflicts events than the conventional T-intersection, as expected from the field experience.

Table 69. Case 10 Comparison Results for Lane-Change Conflicts.

Lane Change	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤1.5**	
	CON	**RA**	**CON**	**RA**	**CON**	**RA**
Low Volume Mean	N/A	N/A	4.80	4.20	12.90	9.10
Variance	N/A	N/A	3.07	3.29	9.66	7.88
***t*-value(95%), difference (%)**	N/A		0.753		**2.870, 29.5%**	
Medium Volume Mean	N/A	N/A	3.60	24.90	9.90	61.40
Variance	N/A	N/A	3.60	26.32	11.43	73.16
***t*-value(95%), difference (%)**	N/A		**-12.314, -591.7%**		**-17.707, -520.2%**	
High Volume Mean	25.80	22.90	67.20	108.10	102.40	229.00
Variance	26.62	23.66	147.73	151.21	277.60	198.00
***t*-value(95%), difference (%)**	1.293		**-7.480, -60.9%**		**-18.357, -123.6%,**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table shows that the three-approach roundabout has more lane-change conflicts at medium- and high-traffic volumes. This was expected because of the weaving maneuvers necessary in a roundabout.

Table 70. Case 10 Comparison Results for Average Surrogate Measures of Safety.

	TCON	TRA	CCON	CRA	RCON	RRA	LCCON	LCRA
TTC (low)	1.02	0.96	1.01	0.48	1.00	0.99	1.12	1.01
t-value, diff(%)	1.488		**3.879, 52.48%**		0.139		**2.256, 9.82%**	
TTC (med)	1.02	1.05	0.99	0.69	1.02	1.02	1.11	1.09
t-value, diff(%)	**-2.203, -2.94%**		**5.228, 30.30%**		0.000		0.588	
TTC (high)	0.99	1.02	0.87	0.73	1.07	1.01	0.85	1.05
t-value, diff(%)	**-4.208, -3.03%**		**5.639, 16.09%**		**5.960, 5.61%**		**-13.670, -23.53%**	
PET(low)	1.42	1.22	1.12	0.79	1.46	1.73	1.35	1.19
t-value, diff(%)	**4.108, 14.08%**		1.532		-1.334		**3.286, 11.85%**	
PET(med)	1.4	1.34	1.02	1.06	1.44	1.53	1.3	1.31
t-value, diff(%)	**3.342, 4.29%**		-0.452		-1.834		-0.171	
PET(high)	1.13	1.33	0.64	1.21	1.35	1.45	1.01	1.29
t-value, diff(%)	**-19.321, -17.7%**		**-11.612, -89.06%**		**-7.391, -7.41%**		**-13.856, -27.72%**	
MaxS(low)	33.89	36.29	31.11	46.79	33.96	35.16	34.33	35.4
t-value, diff(%)	**-2.551, -7.08%**		**-12.004, -50.40%**		-0.356		-1.012	
MaxS(med)	33.11	34.62	32.29	46.19	33.15	33.77	33.55	33.82
t-value, diff(%)	**-4.399, -4.56%**		**-17.725, -43.05%**		-0.844		-0.408	
MaxS(high)	25.45	34.06	26.04	43.28	24.36	31.07	28.28	34.42
t-value, diff(%)	**-48.734, -33.83%**		**-34.553, -66.21%**		**-25.057, -27.55%**		**-21.144, -21.71%**	
DeltaS(low)	32.75	26.94	30.03	37.94	33.15	18.58	31.9	26.95
t-value, diff(%)	**6.903, 17.74%**		**-4.675, -26.34%**		**5.826, 43.95%**		**4.956, 15.52%**	
DeltaS(med)	31.22	26.36	31.27	38.51	31.59	23.45	26.9	26.02
t-value, diff(%)	**12.524, 15.57%**		**-7.886, -23.15%**		**9.228, 25.77%**		0.783	
DeltaS(high)	19.58	25.78	29.91	36.44	17.11	25.27	15.69	25
t-value, diff(%)	**-28.502, -31.66%**		**-11.521, -21.83%**		**-23.944, -47.69%**		**-31.253, -59.34%**	
DR(low)	-12.45	-21.18	-13.13	-25.57	-12.46	-9.89	-12.24	-22.24
t-value, diff(%)	**2.234, -70.12%**		0.995		-1.897		**2.151, -81.70%**	
DR(med)	-12.82	-23.63	-13.53	-45.3	-12.8	-14.93	-12.3	-23.92
t-value, diff(%)	**7.064, -84.32%**		**2.941, -234.81%**		1.232		**6.521, -94.47%**	
DR(high)	-21.01	-29.88	-16.17	-55.42	-23.78	-14.29	-17.65	-33.93
t-value, diff(%)	**8.851, -42.22%**		**7.717, -242.73%**		**-10.772, 39.91%**		**9.662, -92.13%**	
MaxD(low)	-12.94	-37.93	-18.35	-108.21	-12.68	-27.52	-12.52	-32.35
t-value, diff(%)	**4.615, -193.12%**		**3.937, -489.7%**		1.004		**3.586, -158.39%**	
MaxD(med)	-14.18	-40.39	-14.54	-111.26	-13.76	-25.89	-18.8	-37.81
t-value, diff(%)	**12.079, -184.84%**		**9.483, -665.20%**		**3.391, -88.15%**		**5.407, -101.12%**	
MaxD(high)	-41.35	-47.62	-25.12	-114.54	-50.53	-18.89	-30.36	-53.23
t-value, diff(%)	**4.780, -15.16%**		**19.911, -355.97%**		**-24.751, 62.62%**		**10.298, -75.33%**	
MaxDeltaV(low)	17.13	14.05	15.81	20.09	17.35	9.61	16.62	14.04
t-value, diff(%)	**6.960, 17.98%**		**-4.593, -27.07%**		**6.096, 44.61%**		**4.927, 15.52%**	
MaxDeltaV(med)	16.29	13.79	16.26	20.17	16.49	12.27	13.99	13.61
t-value, diff(%)	**12.260, 15.35%**		**-7.721, -24.05%**		**9.151, 25.59%**		0.649	
MaxDeltaV(high)	10.23	13.48	15.64	19.06	8.94	13.22	8.21	13.07
t-value, diff(%)	**-28.459, -31.77%**		**-11.447, -21.87%**		**-23.380, -47.86%**		**-31.021, -59.20%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

In general, the data in the table has some counter-indicative results. Some of the average surrogate measures of safety are better for the roundabout and others are worse. Conflicts classified as crossing and lane-changing events generally have worse average values of surrogates, but rear-end events have better average values for the roundabout design.

Correlations with Predicted Crash Frequency

Because all crash prediction models for roundabout are only valid for four-approach roundabout at the current stage of development of roundabout crash prediction models, no correlation test can be performed for the three-approach roundabout versus T-intersection case.

The predicted crash rates for all scenarios of four-approach roundabout versus conventional four-approach intersection are listed in table 71 with the corresponding surrogate measures of safety. Rank orders for each category of data are also listed in the table. The Spearman rank correlation coefficients are calculated for each test. The results indicate a weak correlation between the predicted crash rates and the conflict rates. For the surrogate safety measure of lane-change crashes, there is even no relationship.

Table 71. Case 9 Spearman Rank Correlations Between Conflicts and Crash Frequency.

AADT		Low		Medium		High		**Rs**
		CON	**RA**	**CON**	**RA**	**CON**	**RA**	
Crash Frequency	**M**	1.7	0.2	3	0.6	4.1	1.3	**1**
	R	4	1	5	2	6	3	
Total Conflict	**M**	27.1	5.3	66.2	46.6	93	133.7	**0.54**
	R	2	1	4	3	5	6	
Crossing Conflict	**M**							**N/A**
	R							
Rear-End Conflict	**M**	21.3	0.7	57.1	7.9	70.2	30.2	**0.69**
	R	3	1	5	2	6	4	
LC Conflict	**M**	5.8	4.4	9	37.2	19.7	95.6	**0**
	R	1	1	3	5	4	6	

NOTE: Rates that are not significantly different are assigned the same rank. Rows labeled “M” provide mean values and rows labeled “R” provide the ranking of each alternative. The *R*s column provides Spearman rank correlation coefficients indicating agreement with theoretical crash estimates.

Findings and Conclusions

Based on the above observations, the following conclusions can be drawn:

- Both four-approach and three-approach roundabouts generate fewer total and rear-end conflicts but more lane-change conflicts than the corresponding conventional intersections.

- Three-approach roundabout generates fewer crossing conflicts than T-intersection.
- There are only a few crossing conflicts for both designs.

In general, for most traffic volumes, both four-approach and three-approach roundabouts generate fewer total and rear-end conflicts than the corresponding conventional intersections. Roundabouts show higher rates of lane-change conflicts than conventional intersections, which is expected because of the traffic maneuvers expected in a roundabout. The severity of resulting collisions in a roundabout is most likely lower than that of a conventional intersection, but the probability of collisions occurring is higher when conflicts do occur (at a less frequent rate than that of conventional intersection designs).

Case 11: Double Roundabout Versus Diamond Intersection (AIMSUN)

In both rural and suburban areas, the most predominant interchange type is the diamond interchange, a relatively simple design and implementation that accommodates low- to medium-traffic volumes, with partial access control and limited right of way. Although a diamond interchange is the most common interchange type, it may create unnecessary delay at signals and can at times cause spillback onto a freeway. An alternative to the conventional or tight diamond interchange is a double-roundabout interchange as shown in figure 108. The double roundabout eliminates traffic signals, some costs, and traffic delays resulting from the signals. In addition, it is believed to reduce conflicts and crash frequency.

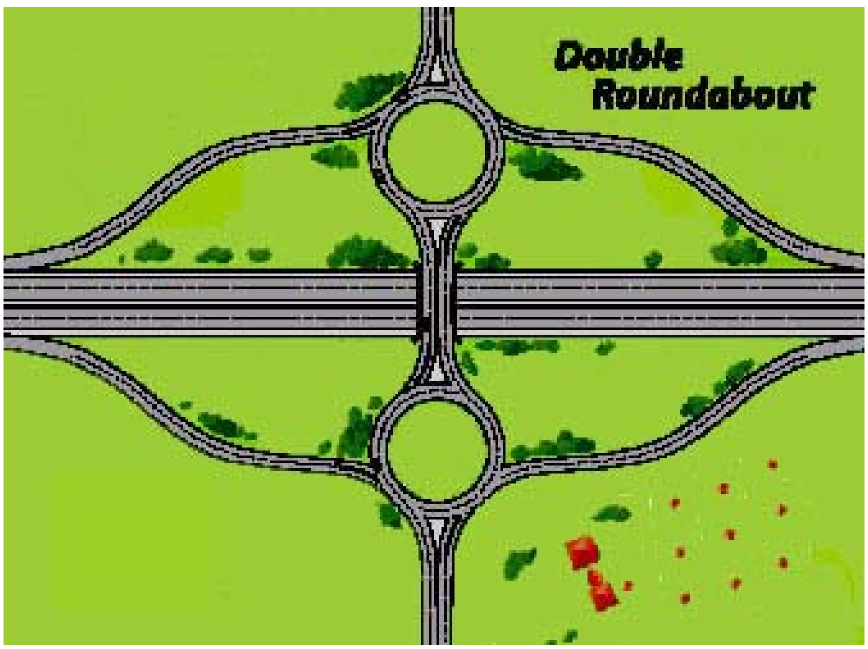


Figure 108. Illustration. Double Roundabout.

Some of the first modern double-roundabout interchanges in the United States were built in the mid 1990s in Colorado and Maryland. Studies show that using double roundabouts at interchange ramp terminals with low and medium flows will result in noticeably less delay than stop-controlled and signalized diamond interchanges. Other benefits include increased safety and the ability to use narrower bridges. This evaluation compares the double roundabout with a comparable diamond interchange to evaluate the comparative safety effect of the two designs.(22)

Intersection Description

The intersections used for this test are shown in figure 109 and figure 110. The left-turn bays are 76.25 m (250 ft) long.

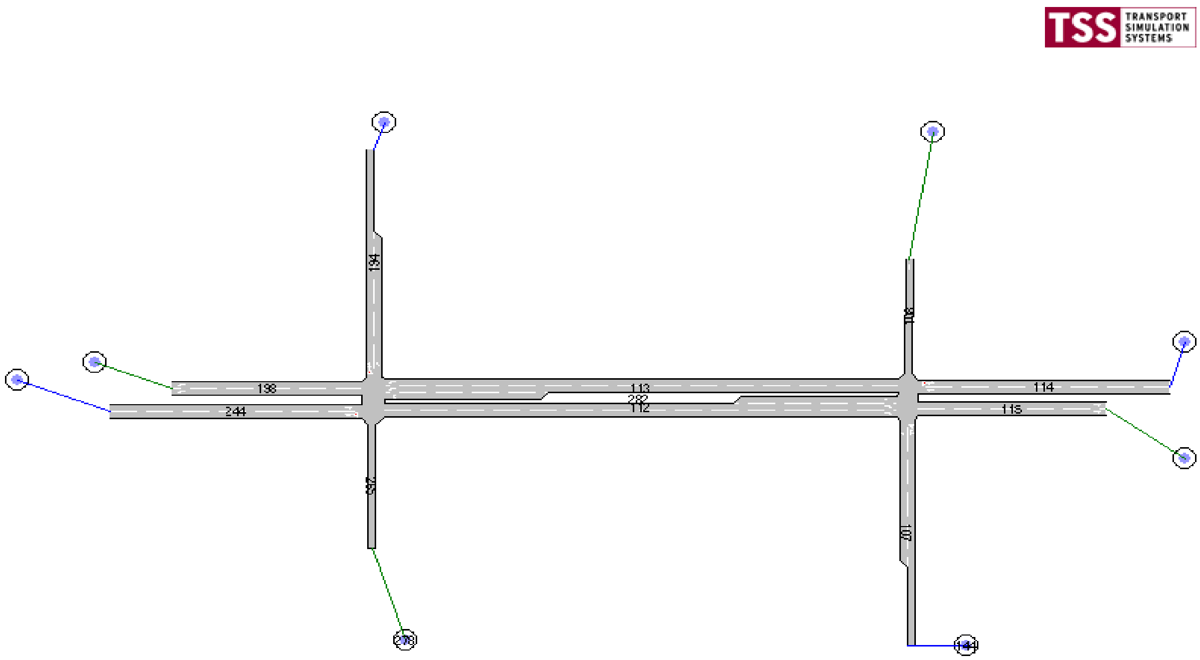


Figure 109. Screen Capture. Diamond Interchange in AIMSUN.

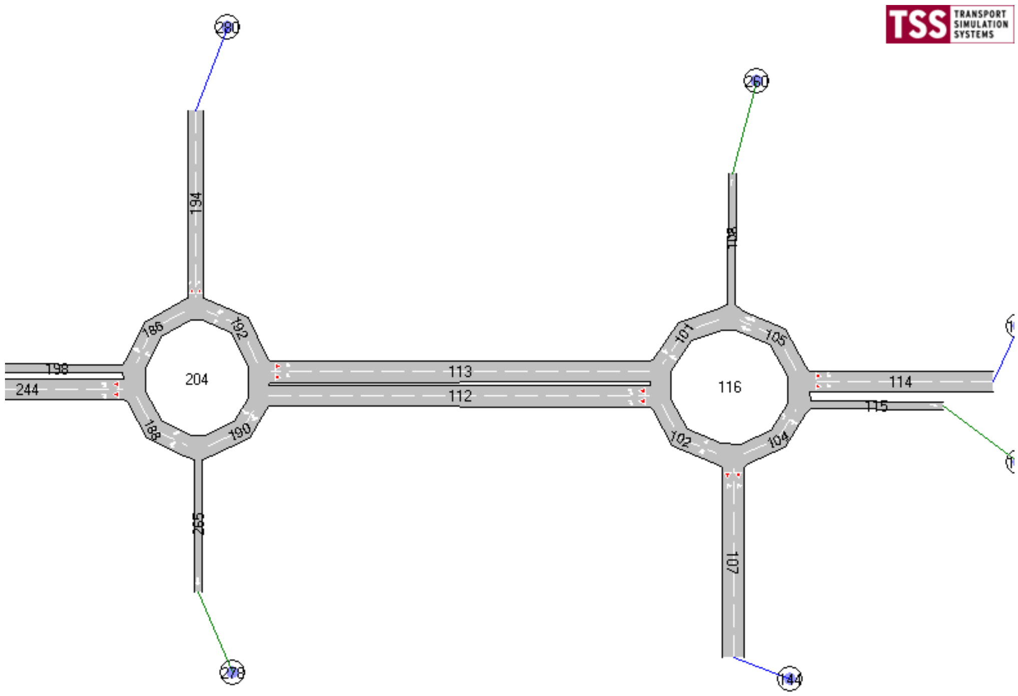


Figure 110. Screen Capture. Double Roundabout in AIMSUN.

Table 72 shows traffic volumes applied to each approach of the intersection. Fully-actuated traffic control for a four-phase diamond interchange is applied in this test. Figure 111 through figure 113 indicate the timing plans used for each testing scenario.

Table 72. Case 11 Service Flow by Each Approach.

Approach	Southbound			Northbound			Eastbound			Westbound		
	L	TH	R	L	TH	R	L	TH	R	L	TH	R
Phase ID (Four Phase)	3	3		7	7		1	1		5	5	
Low Volumes	125	25	100	125	25	100	100	100	100	100	100	100
Medium Volumes	250	50	200	250	50	200	200	150	200	200	150	200
High Volumes	450	50	400	450	50	400	400	300	400	400	300	400

Note: L, TH, and R correspond to vehicles proceeding left, through, or right at the intersection.

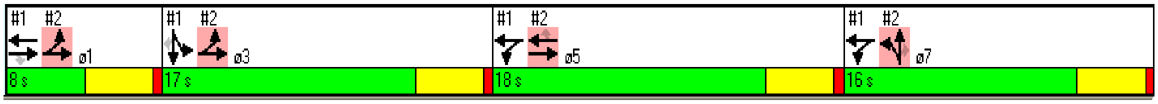


Figure 111. Screen Capture. Timing Plan for Four-Phase Diamond Interchange in Low Volumes.

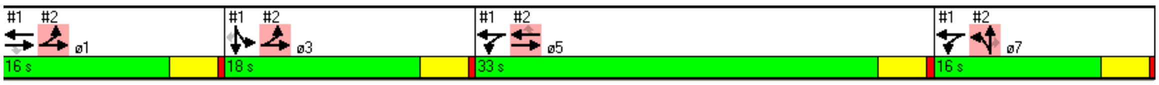


Figure 112. Screen Capture. Timing Plan for Four-Phase Diamond Interchange in Medium Volumes.

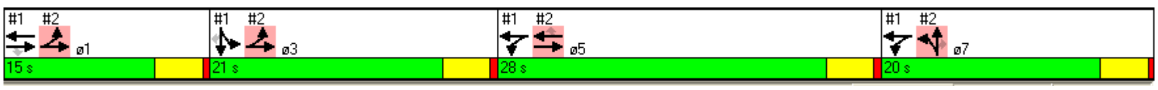


Figure 113. Screen Capture. Timing Plan for Four-Phase Diamond Interchange in High Volumes.

Data Analysis and Comparison Results

Ten replications were performed for each simulation scenario and the resulting output trajectory data was analyzed by SSAM. *F*-tests and *t*-tests were applied to compare the average number of conflict events and surrogate measures of safety between the two design options. Table 73 through table 77 list the values of all surrogate measures of safety and corresponding *t*-test results for different types of aggregations with the low-speed events and crash data excluded (TTC ≠ 0 and MaxS ≥ 16.1 km/h (10mi/h)).

Table 73. Case 11 Comparison Results for Total Conflicts.

Total	**TTC ≤ 0.5**		**TTC ≤ 1.0**		**TTC ≤ 1.5**	
	DIA	**RA**	**DIA**	**RA**	**DIA**	**RA**
Low Volume Mean	2.30	3.40	30.10	10.60	52.60	22.10
Variance	1.12	0.93	19.66	9.16	90.93	28.77
***t*-value(95%), difference (%)**	**-2.426, -47.8%**		**11.488, 64.8%**		**8.816, 58.0%**	
Medium Volume Mean	5.30	13.20	62.10	64.20	110.10	118.10
Variance	3.57	15.51	169.43	58.84	251.88	187.21
***t*-value(95%), difference (%)**	**-5.720, -149.1%**		-0.440		-1.207	
High Volume Mean	16.40	55.70	119.20	444.30	250.80	772.80
Variance	20.93	79.12	203.73	1099.79	979.73	3791.07
***t*-value(95%), difference (%)**	**-12.424, -239.6%**		**-28.475, -272.7%**		**-23.899, -208.1%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table indicates that the total conflicts for the double roundabout is lower at low volumes and higher at high volumes. For all traffic volumes, the double roundabout design has more conflict events that occur at very low values of TTC.

Table 74. Case 11 Comparison Results for Crossing Conflicts.

Crossing	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	DIA	RA	DIA	RA	DIA	RA
Low Volume Mean	N/A	N/A	2.50	1.10	4.60	1.30
Variance	N/A	N/A	2.72	2.32	5.16	3.12
***t*-value(95%), difference (%)**	N/A		1.971		**3.627, 71.7%**	
Medium Volume Mean	0.40	3.30	8.30	4.00	13.20	5.00
Variance	0.93	6.23	13.57	7.78	19.96	11.11
***t*-value(95%), difference (%)**	**-3.426, -725.0%**		**2.943, 51.8%**		**4.652 62.1%**	
High Volume Mean	2.20	13.80	19.80	23.20	41.70	30.20
Variance	3.73	31.96	29.51	46.18	79.34	93.96
***t*-value(95%), difference (%)**	**-6.140, -527.3%**		-1.236		**2.762 27.6%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the dual roundabout has less crossing conflict events than the diamond interchange. Crossing conflicts are a very small part (less than 5 percent) of the total conflicts.

Table 75. Case 11 Comparison Results for Rear-End Conflicts.

Rear End	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	DIA	RA	DIA	RA	DIA	RA
Low Volume Mean	1.20	0.40	22.70	3.10	38.10	5.80
Variance	1.29	0.27	31.57	1.88	88.10	4.84
***t*-value(95%), difference (%)**	2.028		**10.718, 86.3%**		**10.595, 84.8%**	
Medium Volume Mean	2.20	0.80	45.00	18.90	80.90	30.20
Variance	2.84	0.62	113.11	8.99	195.88	27.29
***t*-value(95%), difference (%)**	**2.378, 63.6%**		**7.469, 58.0%**		**10.732, 62.7%**	
High Volume Mean	6.50	3.90	71.30	234.10	165.20	393.80
Variance	4.72	2.99	78.68	526.54	563.51	1872.40
***t*-value(95%), difference (%)**	**2.961, 40.0%**		**-20.927, -228.3%**		**-14.647, -138.4%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

This table shows that the dual roundabout has less rear-end conflict events at low- and medium-traffic volumes but more events at high volumes than the diamond interchange. Rear-end conflicts are more than 50 percent of the total conflicts.

Table 76. Case 11 Comparison Results for Lane Change Conflicts.

Lane Change	TTC ≤ 0.5		TTC ≤ 1.0		TTC ≤ 1.5	
	DIA	RA	DIA	RA	DIA	RA
Low Volume Mean	1.10	2.00	4.90	6.40	9.90	15.00
Variance	0.99	1.33	1.88	4.04	3.88	16.00
t-value(95%), difference (%)	-1.868		-1.949		**-3.617, -51.5%**	
Medium Volume Mean	2.70	9.10	8.80	41.30	16.00	82.90
Variance	1.57	5.21	9.07	45.79	17.11	110.99
t-value(95%), difference (%)	**-7.774, -237.0%**		**-13.876, -369.3%**		**-18.692, -418.1%**	
High Volume Mean	7.70	38.00	28.10	187.00	43.90	348.80
Variance	6.90	45.11	42.77	143.11	76.10	498.40
t-value(95%), difference (%)	**-13.286, -393.5%**		**-36.856, -565.5%**		**-40.227, -694.5%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives.

This table indicates that the dual roundabout has many more lane-change conflict events at all traffic volumes than the diamond interchange, which is consistent with the results for the four- and three-approach roundabout cases compared to conventional intersections.

Table 77. Case 11 Comparison Results for Average Surrogate Measures of Safety.

	TDIA	TRA	CDIA	CRA	RDIA	RRA	LDIA	LRA
TTC (low)	1.03	1.01	1.05	0.55	1.03	1.02	1.03	1.04
t-value, diff(%)	0.686		**5.336, 47.62%**		0.194		-0.205	
TTC (med)	1.03	1.01	1	0.65	1.04	1	0.97	1.03
t-value, diff(%)	1.477		**5.319, 35.00%**		**2.062, 3.85%**		-1.824	
TTC (high)	1.05	1	1	0.72	1.09	1.03	0.91	1.01
t-value, diff(%)	**6.634, 4.76%**		**10.601, 28.00%**		**6.780, 5.50%**		**-5.674, -10.99%**	
PET(low)	1.44	1.16	1.16	0.74	1.53	1.12	1.24	1.22
t-value, diff(%)	**5.730, 19.44%**		**2.814, 36.21%**		**4.096, 26.80%**		0.290	
PET(med)	1.36	1.24	1.02	0.71	1.46	1.35	1.13	1.24
t-value, diff(%)	**5.326, 8.82%**		**3.668, 30.39%**		**2.883, 7.53%**		**-2.407, -9.73%**	
PET(high)	1.22	1.28	0.81	0.67	1.35	1.41	1.12	1.19
t-value, diff(%)	**-4.595, -4.92%**		**3.453, 17.28%**		**-3.898, -4.44%**		**-2.452, -6.25%**	
MaxS(low)	33.54	34.38	34	41.85	33.61	35.95	33.05	33.13
t-value, diff(%)	-1.302		**-5.809, -23.09%**		-1.805		-0.084	
MaxS(med)	32.63	33.1	32.53	40.53	32.65	32.71	32.62	32.79
t-value, diff(%)	-1.494		**-7.923, -24.59%**		-0.111		-0.245	
MaxS(high)	27.26	32.27	24.36	36.33	27.42	31.08	29.4	33.27
t-value, diff(%)	**-26.392, -18.38%**		**-19.853, -49.14%**		**-15.564, -13.35%**		**-9.051, -13.16%**	
DeltaS(low)	30.07	24.22	33.87	38.98	30.87	19.5	25.25	24.76
t-value, diff(%)	**6.727, 19.45%**		-1.555		**6.520, 36.83%**		0.384	
DeltaS(med)	28.52	25.71	31.75	36.98	29.19	22.93	22.44	26.04
t-value, diff(%)	**6.603, 9.85%**		**-3.690, -16.47%**		**8.375, 21.45%**		**-4.144, -16.04%**	
DeltaS(high)	19.84	25.96	24.6	36.98	19.41	25.95	16.93	25.02
t-value, diff(%)	**-25.500, -30.85%**		**-12.686, -50.33%**		**-21.296, -33.69%**		**-19.264, -47.78%**	
DR(low)	-13.51	-22.49	-19.18	-18.2	-12.48	-14.68	-14.84	-25.89
t-value, diff(%)	**3.823, -66.47%**		-0.071		0.930		**3.105, -74.46%**	
DR(med)	-12.5	-17.68	-13.13	-20.62	-12.23	-12.76	-13.34	-19.29
t-value, diff(%)	**6.480, -41.44%**		1.540		0.737		**3.785, -44.60%**	
DR(high)	-15.87	-16.49	-15.8	-19.31	-16.39	-12.53	-13.96	-20.72
t-value, diff(%)	1.183		1.511		**-6.503, 23.55%**		**6.731, -48.42%**	
MaxD(low)	-15.96	-29.65	-20.63	-29.99	-13.85	-23.49	-21.93	-32
t-value, diff(%)	**4.765, -85.78%**		0.674		**2.393, -69.60%**		1.800	
MaxD(med)	-15.38	-25.48	-15.6	-37.45	-14.34	-16.42	-20.45	-28.06
t-value, diff(%)	**8.483, -65.67%**		**3.552, -140.06%**		1.687		**2.856, -37.21%**	
MaxD(high)	-28.6	-23.02	-21.21	-27.16	-30.7	-14.78	-27.74	-31.96
t-value, diff(%)	**-6.750, 19.51%**		**2.175, -28.05%**		**-16.679, 51.86%**		**2.148, -15.21%**	
MaxDeltaV(low)	16.43	13.23	18.11	21.99	16.94	10.96	13.65	13.34
t-value, diff(%)	**6.512, 19.48%**		**-2.254, -21.42%**		**6.037, 35.30%**		0.438	
MaxDeltaV(med)	15.27	13.45	16.75	19.53	15.64	11.97	12.12	13.62
t-value, diff(%)	**8.014, 11.92%**		**-3.592, -16.60%**		**9.300, 23.47%**		**-3.240, -12.38%**	
MaxDeltaV(high)	10.47	13.57	12.97	19.29	10.25	13.57	8.95	13.07
t-value, diff(%)	**-24.556, -29.61%**		**-12.356, -48.73%**		**-20.164, -32.39%**		**-18.456, -46.03%**	

Note: Shaded cells indicate statistically significant differences between the two alternatives. The tan and blue colors indicate extreme values to the right and left columns respectively.

In general, the data in this table have some counter-indicative results. Most of the average surrogate measures of safety are better for the diamond interchange, although the severity of resulting collisions, measured by DeltaS and MaxDeltaV, are lower with the double roundabout. The other results generally indicate that a double roundabout contributes more total conflict events, and those that occur have a higher probability of resulting in a crash.

Correlations with Predicted Crash Frequency

The dual roundabout can be approximately considered as two three-approach single roundabouts. However, because all crash prediction models for roundabout are only valid for four-approach roundabout at current stage, no correlation test can be performed for this case.

Findings and Conclusions

Based on the above observations, the following conclusions can be drawn:

- When traffic volume is low, dual roundabout shows fewer total, crossing and rear-end conflicts. When traffic volume is increasing, dual roundabout generates more conflicts than diamond interchange.
- Double roundabouts have many more lane-change conflict events than conventional diamond interchanges.
- There are only a few crossing conflicts for both designs.
- Most of the average surrogate measures of safety are better for the diamond interchange.

SUMMARY

This chapter has detailed the effort to explore and validate the SSAM approach for discriminating the safety performance of two intersection designs. The SSAM approach is based on evaluating the statistical differences in the following:

- The average number of conflict events of various types that occur in both designs.
- The average value of several measures of severity and probability of collision of those conflict events that occur.

The goal of this validation effort was not to compare the results of the simulation model with traffic at a comparable real-world location. Hence, no "calibration" effort was necessary in this study (although, reasonable driver behavior was verified and appropriate control measures were used to avoid gridlock). No oversaturated conditions were included in any of the test cases. For all the intersection designs, default driving behavior models and parameters were applied for each simulation model.

Eleven comparison cases were executed, amongst the three simulation systems: TEXAS, VISSIM, and AIMSUN.

TEXAS Cases

- Signalized, four-leg intersection with permitted left turn versus protected left turn.
- Signalized, four-leg intersection with and without left-turn bay.
- Signalized, four-leg intersection with and without right-turn bay.

VISSIM Cases

- Signalized, four-leg intersection with leading left turns versus lagging left turns.
- Signalized, four-leg intersection versus offset T-intersection.
- Diamond interchange with three-phase timing versus four-phase timing.
- SPUI versus diamond interchange.

AIMSUN Cases

- Signalized, four-leg intersection with left turns versus signalized intersection with median U-turns.
- Signalized, four-leg intersection versus single roundabout.
- Signalized, three-leg T-intersection versus single roundabout with three legs.
- Diamond interchange versus double roundabout.

Three sets of traffic volumes (low, medium, and high volumes) were applied for each intersection design, and signal timing plans were designed to ensure no oversaturation would occur.

Table 78 summarizes the results from the validation studies for each test case.

- The **first** column lists the **conventional safety indication—**which of the two design types is expected to be safer than the other due to historical crash data.
- The **second** column lists a high-level assessment of the safety preference for one design or the other based on the **statistical significance results** for total as well as individual **conflict types**.
- The **third** column lists a general assessment of the safety preference indication by considering the average value of surrogate measures related to the **probability of collision**. These measures are **PET** and **TTC**.
- The **fourth** column lists a general assessment of the safety preference indication by considering the average values of surrogate measures related to the **severity** of resulting collision, would a collision have occurred. These measures are **DeltaS, DR, MaxS**, and **MaxDeltaV**.
- The **fifth** column lists a **general assessment of the correlation** between the ranking of the surrogate measures results (for total and individual conflict types) with the existing crash prediction model (if available).
- The **final** column lists an **overall assessment** of the result of the validation case.

Table 78. Summary of Theoretical Validation Case Studies.

Scenario	Conventional Safety Indication	Surrogate Safety Indication (Conflicts)	Probability Indicators: TTC/PET	Severity Indicators: Deltas, DR, Maxs, Maxdeltav	Conflict Rate Correlation with Crash Prediction Models	General Assessment
Permitted Versus Protected Left Turn	Protected left	Protected: more total conflicts, but fewer crossing conflicts	Inconclusive	Inconclusive	Good	Inconclusive; insightful
Left-Turn Bay	With bay	With bay: more crossing, fewer lane change, fewer rear ends	Inconclusive	Mostly better with bay	Good, except for crossing conflicts	Inconclusive; insightful
Right-Turn Bay	With bay	With bay	TTC better with bay, PET worse with bay	Without bay	Very good	As expected
Leading Versus Lagging Left Turn	No conclusive difference	Inconclusive	Inconclusive	Lane changes worse for lagging at high vol	N/A	As expected
Three-Phase Versus Four-Phase Diamond	No conclusive difference	Three-phase better at low volumes, worse at high volumes	Four phase	Four phase	N/A	Good insight
Cross Versus Offset T	Offset T	Cross (very few events)	Offset T	Offset T	Poor (very few events)	Inconclusive
Left Turn Versus Median U-Turn	Median U turn	Median U turn: Less total and rear-end conflicts	No difference	Inconclusive	N/A	Inconclusive

Table 78. Summary of Theoretical Validation Case Studies—continued.

Scenario	Conventional Safety Indication	Surrogate Safety Indication (Conflicts)	Probability Indicators: TTC/PET	Severity Indicators: Deltas, DR, Maxs, Maxdeltav	Conflict Rate Correlation with Crash Prediction Models	General Assessment
SPUI Versus Diamond (Three Phase)	Diamond low vol), SPUI (high vol)	SPUI	Three-phase diamond	Three-phase diamond	Poor	Good insight
Roundabout Versus Four Leg	Roundabout	Roundabout: less total and rear end conflicts; more lane change conflicts	Four-leg conventional intersection	Inconclusive	Poor	Inconclusive
Roundabout Versus Three Leg	Roundabout	Roundabout: less total and rear end conflicts; more lane change conflicts	Inconclusive	Mostly better with three-leg intersection	N/A	Inconclusive
Diamond Versus Double Roundabout	Double roundabout	Roundabout: more conflicts at med/high volumes	Diamond interchange	Mostly better with diamond interchange	N/A	Diamond interchange

The overall results from this study are mixed. For some scenarios, the surrogate measures data matches the trend of existing crash prediction models, and the results are consistent with the general understanding of the safety community of the effect of certain design treatments. In other cases, the indication from the simulation model does not match that of the crash prediction models and tends to indicate counterintuitive results.

In many of the test cases, the results fall into the following pattern:

- Design A has statistically fewer conflict events that occur, indicating that A will be a safer design than B.
- Design B has better performance on average values of surrogate measures, indicating that B will be a safer design than A.

In some cases, the following complexities are added to the results:

- The probability of collision indicators (PET, TTC) indicate one conclusion (B is better than A) when the severity of collision indicators (DeltaS, MaxS, DR, etc.) indicate another (A is better than B).
- The conclusions are not consistent for all types of conflict events.

Finally, in some cases the results are complicated by an additional factor:

- Results (either for average values of surrogate measures, number of conflict events, or both) change from one conclusion to the other based on the level of traffic volume.

As an effort in a largely unexplored area of analysis, these complications are not surprising. What the results do indicate is that a more sophisticated normalizing "index" or composite summary measure is needed for comparison of intersection designs (A to B) and comparison of designs in a more objective sense (design A versus all other possible designs, such as that offered by existing regression models for crashes).

Analysis of Conflict Rates by Design Type

To analyze the potential for a normalizing index, we first present the data for conflict rates by design type for the test cases executed in this study. As shown in table 79, the conflict rates by design type vary considerably and tend to increase for more complex intersection types, as expected. In addition, for all the design types, it appears that the (total) conflict rate either increases or remains constant when the traffic volume increases. This is reasonable as the physical proximity of the vehicles in the system increases, resulting in more events at higher levels of severity. However, this phenomenon means that the level of traffic volume needs to be included in a summary "index" measure, which will be explored further in the sensitivity analysis effort of the field validation study.

Table 79. Summary of Conflict Rates by Test Case (Conflicts/100 Entering Vehicles).

Scenario	Low Volumes (%)		Medium Volumes (%)		High Volumes (%)	
	Case1	Case2	Case1	Case2	Case1	Case2
Texas Cases						
Permitted Versus Protected Left Turn	1.6	1.4	1.9	2.3	5.7	22.4
Left-Turn Bay	2.7	2.1	6.6	3.1	20.5	10.1
Right-Turn Bay	1.8	1.2	3.7	2.1	26.2	18.4
Vissim Cases						
Leading Versus Lagging Left Turn	0.6	0.6	0.8	0.7	1.3	1.2
Three-Phase Versus Four-Phase Diamond	1.6	2.3	2.1	1.3	1.7	1.2
SPUI Versus Diamond (Three Phase)	1.8	4.0	2.2	4.9	2.2	2.6
Cross Versus Offset T	0	0	0.3	0.4	0.2	0.4
Left Turn Versus Median U-Turn	1.8	2.1	2.5	2.3	2.6	2.2
Aimsun Cases						
Roundabout Versus Four Leg	0.7	3.4	2.9	4.1	5.6	3.9
Roundabout Versus Three Leg	1.0	5.9	3.9	6.4	9.6	15.3
Diamond Versus Double Roundabout	4.8	2.0	5.2	5.6	6.3	19.3

Analysis of Removed Crashes and Low-Speed Events

In most scenarios evaluated, crashes cannot be completely eliminated from the simulation without modifying driver behavior parameters or design geometry beyond reasonable limits. Table 80 presents some summary analysis of the average crash and low-speed event rates by scenario and traffic-volume level. For each design case, the table lists the percentage of total conflicts that were crashes or low-speed events (a sub-critical TTC value occurring at less than 16.1 km/h (10 mi/h) and not a crash with TTC = 0) and the absolute number of crashes and low-speed events (the average value for one replication of the scenario for 1 hour of simulated time, averaged over the 10 replications executed in the study).

Table 80. Summary of Removed Crash and Low-Speed Event Data.

Scenario	Low Volumes (%)		Medium Volumes (%)		High Volumes (%)	
	Case1	Case2	Case1	Case2	Case1	Case2
Permitted Versus Protected Left Turn	33/16* 65.8%	4/13 42.4%	99/23 69.3%	28/5 23.3%	649/629 80.5%	306/1298 57.0%
Left-Turn Bay	103/33 68.1%	139/43 80.9%	111/239 62.3%	257/116 79.2%	279/2078 70.5%	863/960 78.9%
Right-Turn Bay	17/17 48.9%	17/13 55.0%	34/91 51.4%	38/56 58.4%	373/1730 62.5%	480/1143 64.7%
Leading Versus Lagging Left Turn	1 / 4 32.9%	1 / 4 36.2%	1/12 45.0%	1/10 45.1%	3/17 30.5%	4/28 49.5%
Three-Phase Versus Four-Phase Diamond	5/8 33.5%	7/9 30.8%	44/70 64.3%	44/79 77.2%	61/99 69.4%	53/90 75.1%
SPUI Versus Diamond (Three Phase)	5/8 26.9%	4/15 19.3%	9/19 30.4%	11/27 21.0%	47/94 54.6%	25/94 45.9%
Cross Versus Offset T	0/0 N/A	0/3 36.6%	2/1 43.5%	0/2 8.3%	½ 38.9%	0/3 25.4%
Left Turn Versus Median U-Turn	3/5 17.5%	4/7 20.9%	8/23 24.3%	5/50 38.7%	20/61 41.2%	11/55 39.6%
Roundabout Versus Four Leg	0/0 0	0/0 0	1/1 3.1%	0/0 0	1/3 3%	0/2 1.8%
Roundabout Versus Three Leg	1/0 5.1%	2/2 5.8%	1/1 2.4%	7/10 10.9%	2/10 33.6%	90/331 43.4%
Diamond Versus Double Roundabout	13/4 24.4%	4/1 18.6%	23/11 23.6%	7/5 9.3%	68/69 35.3%	43/105 16.1%

* 33/16 means that there was an average of 33 crashes removed and then another 16 low-speed events removed for each replication of the design case. 65.8% is the average percentage of the removed events of the total conflict events recorded in the replication. In this example, the average of 49 low-speed and crash events constitutes 65.8% of an average 74.5 total conflict events. This would result in an average of 25.5 total valid conflicts.

The results in this table are discouraging because the number of crashes and low-speed events constitutes a large percentage of the total conflict events that occur in most of the scenarios tested. This table also indicates, similarly to the results of table 79, that the percentage of crashes to valid conflicts rises as the traffic volume rises, rather than staying consistent. This is most likely due to the reduction in the physical proximity of all vehicles and thus the increased probability of critical conflict events.

Summary

Based on the results of these theoretical validation case studies, the surrogate safety assessment methodology has some promise, yet additional work is still necessary.

First, some limitations of current microsimulation modeling capabilities have been identified. Up to now, the applications of microsimulation models have been to replicate and predict the capacity and level of service of roadway networks. The level of behavioral analysis necessary for SSAM goes beyond these types of analyses to a level of "nanoscopic" modeling that has not been necessary to date. This is most notably manifested in the occurrence of the vehicle-vehicle "crashes" that are due to approximation logic in the simulation system. These approximations fail to consider the following:

- The full extent of the dimensions of vehicles surrounding the maneuvering vehicle.
- Realistic vehicle dynamics at high-resolution time steps (e.g. articulation in trucks, virtually lateral lane changing at low speeds).

Other phenomena appear to arise as the result of combinations of the approximation logic underlying the rules of driver behavior. One example of this is a reduction in capacity of an approach when certain driver behavior rules are enacted to eliminate the occurrence of crashes on that approach. Improvement of microsimulation systems to remove these undesirable phenomena will improve the credibility of SSAM. To the extent possible, both models (from each pair of design/operational options) utilized identical geometries, traffic conditions, and configuration of parameters/priority-rules to ensure a best possible comparison of the relative safety.

Second, considering the "raw" results of the comparison of two design cases using the SSAM data does not typically result in a set of measures that clearly indicate the superiority of one design over another, at least for the test cases and design parameters exercised in this study. This clearly indicates that a multidimensional "index" is necessary to compare designs in some objective manner based on their performance of the following:

- Conflict occurrence rate.
- Conflict severity (measures of probability of collision).
- Resultant crash severity.

Comparison of two design cases on any one of the above "axes" can result in differing conclusions.

CHAPTER 4. FIELD VALIDATION

This chapter presents the field validation effort, wherein 83 field sites—all four-leg, signalized intersections—were assessed with SSAM, and the results were compared to actual crash histories. This contributes to a three-part overall validation effort consisting of the following:

- Theoretical validation.
- Field validation.
- Sensitivity analysis.

In the preceding chapter, the theoretical validation effort assessed the use of SSAM to discern the relative safety of pairs of intersection/interchange design alternatives in a series of 11 case studies. The field validation in this chapter concerns the direct accuracy of surrogate safety estimates for a signalized, four-leg intersection, which is measured by correlation to actual crash frequencies. This also affords a comparison of surrogate safety estimates with traditional ADT-based models for crash prediction. The validation testing in this chapter is based solely on modeling with the VISSIM simulation. The next chapter completes the validation effort, using SSAM to reassess 5 intersections (of the 83 considered in the field validation) with each of 4 simulation systems: AIMSUN, Paramics, TEXAS, and VISSIM. That effort will characterize the sensitivity and/or bias of the surrogate safety measures as they differ when obtained from each of the four simulations.

This chapter is organized into the following sections:

- Purpose.
- Methodology.
- Field data.
- Simulation modeling of field sites.
- Test results and discussion.
- Simulation modeling issues.
- Summary.

PURPOSE

The main purpose of the field validation effort is to compare the predictive safety performance capabilities of the SSAM approach with actual crash experience at North American signalized intersections. This effort consists of a series of statistical tests to assess the correlation between actual crash frequencies at a series of intersections and the corresponding frequency of conflicts observed in simulation models of these intersections.

Traditional volume-based crash prediction models are used as a basis for comparison. Ideally, SSAM would reveal a more accurate picture of safety than the ADT of intersection crossroads. However, given that SSAM can yield safety assessments over a much more flexible range of traffic facilities than traditional crash prediction models, including simulated designs that have never been built, the standard of *better* performance than traditional models is not a fundamental requirement for utility.

METHODOLOGY

The methodology used in the field validation task is based on relating actual crash data from real-world intersections with the corresponding surrogate safety measures that SSAM derives from simulation models of those same intersections. Throughout this discussion, the term *incidents* will be used in a more abstract sense to refer to either crashes or conflicts. As mentioned previously, the field validation effort entailed the analysis of 83 intersections, modeled with the VISSIM simulation. Selection of the 83 filed sites and VISSIM modeling issues are discussed in subsequent sections. This section introduces a series of five statistical tests used in this validation effort:

- Validation Test 1: Intersection Ranking by Total Incidents.
- Validation Test 2: Intersection Ranking by Incident Types.
- Validation Test 3: Conflicts-Based Crash-Prediction Regression Model.
- Validation Test 4: Identification of Incident-Prone Locations.
- Validation Test 5: Identification of Type-Specific Incident-Prone Locations.

Test 1: Intersection Ranking by Total Incidents

In this test, the ranking of intersections from SSAM according to average conflict frequency is compared to the ranking of the same intersections using actual crash frequency. This test consists of the following three steps (A, B, and C):

Step A: Conflict Ranking

In this step, the average hourly conflict frequency found by SSAM is used as the expected total number of conflicts at each intersection. Each intersection was simulated for five replications, each lasting 1 hour. Thus, the sum of all conflicts recorded over all five replications will be divided by 5 to determine the average hourly conflict frequency in terms of conflicts per hour. In this validation test, the intersections will be ranked based on their average hourly conflict frequency in descending order.

Step B: Crash Ranking

In this step, the average yearly crash frequency for each intersection is determined by dividing the total number of crashes over the observation period by the number of years in the observation period. At least 3 years of crash data are available for all intersections in the study, though some intersections have more data. The intersections are then ranked based on their average yearly crash frequency in descending order.

Step C: Ranking Comparison

The intersection rankings based on average hourly conflict frequency will be compared to the intersection rankings based on average yearly crash frequency. The Spearman rank correlation coefficient can be used to determine the level of agreement between the two rankings. The Spearman rank correlation coefficient is often used as a nonparametric alternative to a traditional coefficient of correlation and can be applied under general conditions. The Spearman rank correlation coefficient (ρ_s) is calculated as shown in figure 114.[6] A score of 1.0 represents perfect correlation and a score of 0 indicates no correlation. An advantage of using (ρ_s) is that when testing for correlation between two sets of data, it is not necessary to make assumptions about the nature of the populations sampled.

$$\rho_s = 1 - \frac{6\sum d_i^2}{n(n^2 - 1)}$$

Figure 114. Equation. Spearman Rank Correlation Coefficient.

Where:

d_i is the difference between two rankings for item i.
n is the number of items ranked.

Under a null hypothesis of no correlation, the ordered data pairs are randomly matched, and thus, the sampling distribution of (ρ_s) has a mean of 0 and the standard deviation (σ_s) as given in figure 115.

$$\sigma_s = \frac{1}{\sqrt{(n-1)}}$$

Figure 115. Equation. Standard Deviation for Paired Data Samples.

Because this sampling distribution can be approximated with a normal distribution even for relatively small values of n, it is possible to test the null hypothesis on the statistic given in figure 115. This value can be compared to a critical z-value. For this analysis, a z-value of 1.64 is selected, representing a 90-percent level of significance, or a z-value of 1.96 for a 95-percent level of significance. Significance levels of 90 percent and 95 percent would be satisfied by the Spearman coefficient (ρ_s) values in excess of 0.18 and 0.22, respectively.

[6] Spearman's rank correlation coefficient is equivalent to a Pearson correlation of ranks; however, the Spearman equation is relatively simple to compute. In the case that there are ties among the rankings, a slightly more complicated procedure is used.

$$z = \rho_s \sqrt{(n-1)}$$

Figure 116. Equation. Critical *Z*-Value.

Test 2: Intersection Ranking by Incident Types

Test 2 repeats the same comparative ranking procedures as test 1, but for subsets of specific incident (i.e., crash/conflict) types. For example, the analysis can be repeated for the following types:

- Rear end.
- Crossing.
- Lane changing.

SSAM classifies all conflicts amongst these three types and provides counts for each type. The average hourly conflict frequency for each conflict type is computed as in test 1, and these results are used to rank the intersections for each conflict type. To provide type-specific crash frequencies, all crash reports from Insurance Corporation of British Columbia (ICBC) were reviewed to determine whether it was a rear-end incident, crossing incident, or lane-changing incident. This classification was readily evident in the vast majority of cases. In the few cases where the classification was not obvious, engineering judgment was applied to determine the most representative type. Average yearly crash frequencies were tabulated for each incident type, rank ordered, and compared using the Spearman's rank correlation test, as in test 1. The results of this step will demonstrate the capability of SSAM to accurately identify and rank intersections that carry a high risk for specific crash types.

Test 3: Conflicts-Based Crash-Prediction Regression Model

Test 3 will establish the correlation between conflicts and crashes by developing a regression equation to estimate average yearly crash frequencies at an intersection as a function of the average hourly conflict frequencies found by SSAM. Thus, a conflicts-based model for crash-prediction will be developed, and goodness-of-fit testing will be used to determine the strength of the relationship between conflicts and crashes. This test could be conducted using either frequency or rate, although exposure can be excluded due to the paired nature of the test.

As a benchmark basis for comparison, a traditional volume-based model for crash prediction will also be developed. The conflicts-based crash-prediction model will then be compared to a volume-based crash-prediction model to gauge the relative capabilities of surrogate safety assessment versus traditional approaches that are primarily driven by traffic volume.

Standard generalized linear modeling (GLM) techniques are used to calculate the expected crash frequency at each intersection,[24, 25] using the GENMOD procedure in the

SAS® 9.1 statistical software package. Three statistical measures are provided to assess the goodness of fit of the models to the raw crash data for the 83 intersections. The first measure is the Pearson chi-squared computed by the following:

$$Pearson\chi^2 = \sum_{i=1}^{n} \frac{[y_i - E(\Lambda_i)]^2}{Var(Y_i)}$$

Figure 117. Equation. Pearson Chi-Squared Goodness of Fit Measure.

Where:

- $E(\Lambda_i)$ is the predicted crash frequency of intersection *i*.
- y_i is the actual crash frequency of intersection *i*.
- n is the number of intersections.

The second statistical measure used for assessing the goodness of fit is the scaled deviance. This is the likelihood ratio test statistic measuring twice the difference between the log-likelihood of the data under the developed model and its log-likelihood under the full ("saturated" model). The scaled deviance is computed by the following:

$$SD = 2\sum_{i=1}^{n}\left[y_i \ln\left(\frac{y_i}{E(\Lambda_i)}\right) - (y_i + \kappa_i)\ln\left(\frac{y_i + \kappa_i}{E(\Lambda_i) + \kappa_i}\right)\right]$$

Figure 118. Equation. Scaled Deviance Measure.

There are several approaches to estimate the shape parameter κ of the negative binomial distribution with the method of maximum likelihood being the most widely used. The method of maximum likelihood will be used in this analysis.

The third goodness-of-fit measure is the R-squared defined by Miaou.(26) The R-squared goodness of fit test is computed as:

$$R_\alpha^2 = 1 - \frac{\alpha}{\alpha_{\max}}$$

Figure 119. Equation. R-Squared Goodness of Fit Measure.

Where:

- α is the model dispersion parameter.
- α_{max} is the maximum dispersion parameter estimated in the model with only the constant term and no predictor variables.

Test 4: Identification of Incident-Prone Locations.

The following fours steps (A, B, C, and D) will be conducted for this test:

Step A

A conflict prediction model will be developed (using standard GLM procedures) to predict intersection conflicts frequency (the data calculated by SSAM) as a function of the intersection traffic volume.

Step B

A crash prediction model will be developed (using standard GLM procedures) to predict intersection crash frequency (the actual crash data) as a function of the intersection traffic volume.

Step C

The two prediction models will be compared to determine whether or not the conflict prediction model can predict risk in a manner similar to the crash prediction model for intersections with the same characteristics. This comparison consists of identification and ranking of crash/conflict prone locations. A crash/conflict prone location is defined as any location that exhibits a significantly higher number of crashes/conflicts as compared to a specific, so-called "normal" value. The Empirical Bayes (EB) technique improves the location-specific prediction and thus is used to identify hazardous locations. The EB refinement method identifies problem sites according to the following four-step process:

1. Estimate the predicted number of crashes/conflicts and its variance for the intersection using the crash/conflict prediction model. This prediction can be assumed to follow a gamma distribution (the prior distribution) with parameters α and β, where:

$$\beta = \frac{E(\Lambda)}{Var(\Lambda)} = \frac{\kappa}{E(\Lambda)} \text{ and } \alpha = \beta \cdot E(\Lambda) = \kappa$$

Figure 120. Equation. Calculation of Gamma Parameters for Prior Distribution.

Where:

$Var(\Lambda)$ is the variance of the predicted crashes/conflicts.

2. Determine the appropriate point of comparison based on the mean and variance values obtained in step 1. Usually the 50th percentile (P_{50}) or the mean is used as a point of comparison. P_{50} is calculated such that

$$\int_0^{P_{50}} \frac{(\kappa / E(\Lambda))^{\kappa} \cdot \lambda^{\kappa-1} \cdot e^{-(\kappa / E(\Lambda))\lambda}}{\Gamma(\kappa)} d\lambda = 0.5$$

Figure 121. Equation. 50th Percentile.

3. Calculate the EB safety estimate and the variance as shown in figure 122 and figure 123.

$$EB_{safety\ estimate} = \left(\frac{\kappa}{\kappa + E(\Lambda)}\right) E(\Lambda) + \left(\frac{E(\Lambda)}{\kappa + E(\Lambda)}\right)(count)$$

Figure 122. Equation. Safety Estimate.

$$Var(EB_{safety\ estimate}) = \left(\frac{E(\Lambda)}{\kappa + E(\Lambda)}\right)^2 (\kappa) + \left(\frac{E(\Lambda)}{\kappa + E(\Lambda)}\right)^2 (count)$$

Figure 123. Equation. Variance.

This is also a gamma distribution (the posterior distribution) with parameters α_1 and β_1 defined as follows:

$$\beta_1 = \frac{EB}{Var(EB)} = \frac{\kappa}{E(\Lambda)} + 1 \quad \text{and} \quad \alpha_1 = \beta_1 \cdot EB = \kappa + count$$

Figure 124. Equation. Gamma Parameters for Posterior Distribution.

Then, the probability density function of the posterior distribution is given by the following:

$$f_{EB}(\lambda) = \frac{(\kappa / E(\Lambda) + 1)^{(\kappa + count)} \lambda^{\kappa + count - 1} e^{-(\kappa / E(\Lambda) + 1)\lambda}}{\Gamma(\kappa + count)}$$

Figure 125. Equation. Probability Density Function for Posterior Distribution.

4. Identify the location as crash/conflict-prone if there is significant probability that the location's safety estimate exceeds the P_{50} value (or the mean). Thus, the location is prone if

$$\left[1 - \int_{0}^{P_{50}} \frac{\left(\kappa / E(\Lambda) + 1\right)^{(\kappa + count)} \lambda^{\kappa + count - 1} e^{-\left(\kappa / E(\Lambda) + 1\right)\lambda}}{\Gamma(\kappa + count)} d\lambda\right] \geq \delta$$

Figure 126. Equation. Criterion for a Crash Prone Site Rating.

Where:

δ is the desired confidence level (usually selected at 0.95).

Once crash/conflict-prone sites are identified, it is important to rank the locations in terms of priority for treatment. Ranking problem sites enables the road authority to establish an effective road safety program, ensuring the efficient use of the limited funding available for road safety. Sayed and Rodriguez suggest using one of two techniques that reflect different priority objectives for a road authority.(25) The first ranking criterion is to calculate the ratio between the EB estimate and the predicted frequency as obtained from the GLM model (a risk-minimization objective). The ratio represents the level of deviation that the intersection is away from a "normal" safety performance value, with the higher ratio representing a more hazardous location. The second criterion, the cost-effectiveness objective, is a "potential for improvement" (PFI) criterion, which is calculated as the difference between the observed crash/conflict frequency and the volume-based estimate of "normal" crash/conflict frequency.

Step D

Two comparisons will be undertaken. The first is to compare the locations identified as crash-prone to intersections identified as conflict-prone. The second is a comparison of both the "risk ratio" and PFI intersection rankings obtained using crash data to the corresponding rankings obtained using conflict data.

Test 5: Identification of Type-Specific Incident-Prone Locations

Test 5 will repeat the same comparative analysis as test 4 for the following subsets of crash/conflict types:

- Rear end.
- Crossing.
- Lane change.

FIELD DATA

Guidelines for the selection of signalized intersections for the field validation included the following:

- A sufficient number of locations are needed to obtain the range of parameters necessary to test the methodology.

- A sufficient number of locations are needed to establish some statistical measure of significance.
- The locations should not be selected based on their crash performance (e.g., the top 10 most dangerous intersections in an area). Otherwise, the analysis will be subject to the regression-to-the-mean (RTM) bias,(27) which is difficult to achieve because safety studies are not typically conducted at locations that do not have any safety performance issues.

Based on these guidelines, 83 signalized intersections, all with four-leg geometry, were selected from a much larger database of Canadian intersections. The information was collected from safety studies performed by Hamilton Associates of Vancouver, BC. The following data were available for each intersection:

- Intersection layout, including the number and width of approach lanes and intersection design.
- Traffic volumes for peak periods, off-peak periods, and AADT, including turning movements.
- Signal timing plans.
- Data on crash frequency, crash type and crash severity. All intersections had at least 3 years of crash data.

Crash records were assembled from the auto insurance claims data files collected by the ICBC. The auto insurance claims data maintained by ICBC are current and comprehensive and are considered reliable for intersections in British Columbia.(28)

Appendix A provides a summary of the 83 intersections used in this study. The appendix shows, for each intersection, the cross street names, number of lanes on each approach, the angle of skew (or at least which approaches are skewed), the signal control type, average daily traffic (ADT) for the major and minor roads, and the AM peak-hour volumes. It is evident from summary descriptions provided in appendix A that although all 83 intersections were four-leg signalized, they still represent a wide range of traffic characteristics.

SIMULATION MODELING OF FIELD SITES

The 83 intersections used in this study were coded in VISSIM simulation system. This selection was based on VISSIM's flexibility to model complex geometric configurations and ability to provide the user with control over operational/driver behavior parameters. Throughout the validation effort, the team iteratively upgraded from VISSIM version 4.0, to versions 4.1 and then 4.2 to take advantage of enhancements, some of which were motivated by preliminary findings of the SSAM validation effort.

Modeling Process

The process of modeling a single intersection in VISSIM starts by tracing an aerial photo of the intersection, specifying each approach number, width, and length of lanes. Once the geometry of the intersection is defined, traffic flows (i.e., vehicles per hour) for each approach are allocated for all directions. Morning peak-hour volumes were utilized for this study. The next step is to encode the signal control parameters. The NEMA-style controller model included with VISSIM was used for all intersections in this study. Detector locations were defined for intersections with full- or semi- actuated control strategies.[7]

Key modeling features of VISSIM related to the evaluation of surrogate safety measures are the implementation of priority rules for permissive left-turn and right-turn-on-red (RTOR) maneuvers and the modeling of reduced-speed areas for turning movements. The inclusion of reduced-speed areas is important not only for realistic modeling of traffic, but it also impacts the measurements of yield points for priority rules. The effects of priority-rule modeling on the surrogate measures of safety outputs from the simulation system are be discussed in subsequent sections. Finally, speed profiles, vehicle-type characteristics, and traffic composition parameters are configured for each intersection.

Each intersection was modeled in VISSIM and tested for realistic and reasonable vehicle behaviors. After this nominal verification, the intersection was simulated five times for a period of 1 hour with different random seed values. Once the VISSIM runs were completed, the TRJ output files from VISSIM were imported into the SSAM application to identify traffic conflicts and calculate corresponding surrogate safety measures.

VISSIM Assumptions

Some assumptions had to be made pertaining to intersection geometry, signal control, speed profiles, vehicle type characteristics, traffic compositions, and priority rules. These assumptions are described in the following subsections.

Intersection Geometry

Only 19 intersections had aerial photos on file. The other 64 intersections were based on schematic photos showing some dimensions and certain provisions were made to trace these intersections into VISSIM. For all 83 intersections, no information was provided on the number or size of the departing traffic lanes. In some cases, this information can be estimated from the aerial photos; in other cases, assumptions had to be made.

Signal Control and Detectors

The simulated intersections included both pre-timed and actuated signal control. Several assumptions were made when modeling the actuated signalized intersections. In cases where a signal has actuated protected/permitted left turning phases, the opposing left turning phases were linked together in order to start and end at the same time. No information on detector locations was available from the safety studies files. Therefore,

[7] NEMA is an acronym for National Electrical Manufacturers Association, an organization that has established a standard specification for traffic signal operations. This standard is commonly used in traffic controllers in North America.

the detectors were assumed to have a length of 3 m (9.28 ft) and were placed 5 (15.28 ft) m before the stop line. Both assumptions are based on the "standard practice" employed in the province of British Columbia.

Speed Profiles, Vehicle Type Characteristics & Traffic Compositions

The traffic composition was assumed to be entirely composed of passenger cars. The desired speed profile was assumed to range from 50 to 65 km/h (31.05 to 40.365 mi/h). Since no information was provided on the percentage of trucks present in each intersection, none were included in the analysis, as the standard practice in British Columbia restricts heavy trucks from using main arterial roads during peak hours. Using VISSIM version 4.0-12, SSAM found an excessive number of lane-change conflicts, as explained in detail later in this chapter. Many of these conflicts occurred during partially complete lane changes where a vehicle slow or stopped at an angle while changing lanes, and trailing vehicles drove right through the tail of this vehicle. Modifications were made to VISSIM and included in versions 4.0-15 and 4.1, introducing new vehicle type codes (or classes) greater than 1 million and greater than 2 million. With types greater than 1 million, the vehicles were modeled as always driving parallel to the travel lane when changing lanes, rather than tilted as before. This reduced the drive-through conflicts, but increased rear-end conflicts when changing into destination lanes with a closely trailing vehicle. Vehicles with a type value greater than 2 million also travel parallel to the link during lane changes and refrain from starting a lane change unless the gap in front of the trailing vehicle in the new lane is sufficient to perform the maneuver, thereby reducing rear-end conflicts with that vehicle.

Priority Rules

A priority rule in VISSIM is the mechanism with which the user can define the yielding and gap-acceptance behavior of vehicles in the simulation. A priority rule is defined through three parameters: minimum gap size, minimum headway, and maximum speed. The VISSIM 4.1-12 user manual suggests defining priority rules for only permissive left turns and right turns on red, although in certain geometric situations it is necessary to add priority rules to be consistent with real driving behavior.[(29)] In general, for free-flow traffic on the main road, the minimum gap time of the priority rule is the most relevant condition to calibrate the performance of crossing vehicles. For slow moving or queuing traffic on the main road, the minimum headway becomes the most relevant parameter in calibrating the priority rule. The default parameters as suggested by PTV for minimum gap, minimum headway, and maximum speed are 3 seconds, 5 m (15.28 ft), and 180 km/h (112 mi/h), respectively.

For the 83 intersections used in this study, a minimum gap of 3 seconds resulted in a large number of simulated crashes. Therefore, the minimum gap size was increased to 5 seconds with an additional 0.5 seconds for any additional crossing lane. More discussion on the effect of varying the minimum gap size is presented in a validation issues section later in this chapter. To be consistent with real-life behavior, additional priority rules were added for exclusive left-turn and right-turn bays. For intersections with no exclusive left-turn and right-turn bays, priority rules were defined to eliminate run-over crashes between through-movement vehicles, right-turn vehicles, and vehicles waiting for a left turn in the middle of the intersection. More discussion on the effect of changing the parameters and the introduction or removal of priority rules are presented in a validation issues section later in this chapter.

Miscellaneous Assumptions

No on-street parking information was available in the safety studies data; therefore, this behavior was not modeled. It is a standard practice in the province of British Columbia to prohibit on-street parking during peak hours, thus justifying this assumption. Furthermore, no pedestrian volumes were available; therefore, pedestrians' behavior and interaction were not accounted for in the analysis. Car-following and lane-changing behavior were set to model urban (motorized) traffic flow using the Wiedemann 74 model with all default parameters used.(29) All traffic flows input to VISSIM were based on AM peak volumes, as recorded in the safety studies database for each intersection. The AM volumes used for simulation are included in table 122 in appendix A.

Modeling Issues

Modeling Schemes

This section describes the inputs of two modeling schemes developed in conjunction with PTV referred to as:

- Scheme 1.
- Scheme 2.

Scheme 1 consists of 16 priority rules, in addition to the modeling assumptions mentioned previously. There are 8 priority rules governing permissive-left and RTOR maneuvers, and there are 8 priority rules governing exclusive left-turn and right-turn bays.

Scheme 1 was adopted in early analysis and certain refinements were proposed.

1. First, reduced speed areas for right (15–20 km/h (9.315–12.4 mi/h)) and left (30–35 km/h (18.63–21.735 mi/h)) were added. This is important not only for realistic modeling of traffic, but it also impacts the measurements of yield points for priority rules.

2. Second, when defining the priority rules, the headway values were defined to minimize the conflict area, thus preventing vehicles from yielding to other vehicles that are yielding to a different priority rule.

3. Third, the minimum gap for run-over priority rules were changed from 1 second to 0 seconds, and the maximum speed was reduced to 10 km/h (6.21 mi/h) to avoid a deadlock resolution state.

4. Fourth, all lane connectors with two or more lanes and located in the middle of the intersection were restricted to prevent lane changing for all vehicle types as suggested by PTV.

5. Fifth, whenever a problem of queue balance existed, the lane-change distance for the connectors were altered from 200 m to 800 m (656 ft to 2,624 ft), allowing vehicles more space to perform the lane-changing maneuver.

6. Last, the number of observed vehicles in the driver behavior tab was increased from two to four, allowing vehicles to predict each others' movements and react accordingly. It should be noted that any entity, including the state of the signal, is considered a "vehicle" in this feature of VISSIM.

Scheme 2, which has 32 priority rules defined, builds on the initial 16 priority rules defined for Scheme 1 and includes an additional 16 rules to compensate for inappropriate behavior during yellow and red clearance intervals. This inappropriate behavior was observed in several situations where the signal state turned from green to yellow and then red with a left-turning vehicle waiting to perform its turning maneuver in the middle of the intersection. During the yellow and red clearance intervals, the vehicles within the intersection were run over by opposing traffic. In real-life behavior, opposing through or other left-turning vehicles will wait for traffic to clear before proceeding into the intersection. The additional 16 priority rules in Scheme 2 were designed to allow for such a behavior. The Scheme 2 rules were adopted for reanalysis of 83 intersections.

To demonstrate the effect of redefining the priority rules on SSAM output, a comparison between the SSAM results for the two modeling schemes is presented later in this chapter.

In addition to the aforementioned rules, the follow changes were made before a final reanalysis of the 83 intersections:

- To compensate for apparently excessive lane-change crash events, driver behavior parameters pertaining to lane-changing were modified such that drivers would choose and begin to seek their desired destination lanes as soon as they entered the network.
- In the collection of conflict event data by SSAM, all conflicts outside of 152.5 m (500 ft) from the intersection were excluded from the analysis.
- All four approaches to each intersection model were extended from their prior lengths (between the network entry point and the intersection) of less than 305 m (1,000 ft) to 915 m (3,000 ft). This provided ample time for vehicles to successfully obtain their desired downstream destination lanes before arriving to the signal, and thereby reduced lane-change crash events.

- Concurrently with these changes, the underlying VISSIM software was upgraded from version 4.1 to 4.2.

Simulated Crashes

Despite all the modeling techniques that were employed, simulated crashes remained in the model. These crashes result from insufficient minimum gap size, a vehicle's failure to yield to a priority rule, or as a result of an abrupt lane change of a vehicle in an intersection or during queuing. All necessary precautions were taken to minimize the number of simulated crashes while maintaining a level of consistency in modeling all intersections. Therefore, certain parameters were adjusted to reduce the number of simulated crashes experienced in VISSIM. As a result, the number of simulated crashes recorded at each intersection was decreased considerably. However, simulated crashes continued to occur, specifically for intersections with high volumes. These intersections experienced a large number of simulated crashes due to the abrupt lane-changing behavior, described in detail in the following subsection. Preliminary analysis with SSAM was conducted with and without simulated crash data to determine if these simulated crash events should be excluded from the analysis. As in the theoretical validation of the previous chapter, it was decided to exclude simulated crashes from the conflict analysis.

Lane-Changing Behavior

A large number of conflicts/simulated crashes were observed during this study as the number of cars queued up waiting to perform a right or left maneuver increased. These conflicts/simulated crashes were often recorded by SSAM as either rear-end or lane-changing maneuvers. While an increase in rear-end conflicts was expected with an increase in vehicle stops, this increase in simulated crashes was due to queued cars changing lanes abruptly. It was also expected that as queues increase in shared-movement (through and turning) lanes, and through-moving vehicles were impeded, there would be an increase in lane-changes to circumvent the queue. However, visual inspection of the lane-changing behavior in this particular situation revealed conspicuous misbehavior (e.g., a trailing vehicle simple drives through a vehicle that was stopped midway through a lane-change). It should be noted that this abrupt lane-changing behavior continued to occur in situations where there was no heavy traffic or amongst through-traveling vehicles queuing up at a red signal. Appendix B provides a sequence of screenshots from the simulation animation during a representative example of this lane-changing behavior.

At this time, there is no clear justification for the unusual lane-changing behavior in VISSIM. The following measures were taken to reduce the effect of such unusual behavior:

- First, the lengths of each approach to the intersection were extended to provide vehicles with significantly more time to decide on their downstream path.
- Second, the driver behavior model was adjusted to allow an additional 0.5 seconds for the minimum lateral clearance. This parameter is defined as the

minimum distance for vehicles passing each other within the same lane. This change, suggested by PTV, is supposed to reduce simulated crashes resulting from lane changes. However, this change also has the effect of decreasing the capacity of the intersection. The impact of this parameter on simulated conflicts/crashes is presented later in this chapter.

- Third, the lane-changing algorithm in VISSIM allows for two types of lane-changes: necessary and free lane changing. In the case of a necessary lane change, the driving behavior parameters include the maximum acceptable deceleration for the vehicle and the trailing vehicle on the new lane. This maximum acceptable deceleration depends on the distance of the emergency stop position of the next connector route. In case of a free lane change, VISSIM checks for the desired speed safety distance of the trailing vehicle on the new lane. This safety distance depends on the vehicle speeds. As mentioned earlier, several situations occurred where free lane changing resulted in simulated crashes due to an abrupt lane-changing behavior. Unlike the necessary lane-change behavior, there is currently no way for the user to manage or change the behavior of free lane changes.

Modeling Left-/Right-Turn Bay Tapers

Generally, left- and right-turn bay tapers can be modeled in different ways in VISSIM. Therefore, two configurations were proposed to simulate vehicle movements for exclusive left-turn and right-turn bays. The first configuration proposes the use of one through link and one link for each of the left- and right-turn storage bays. The through link is then connected to the left- and right-turn storage bays by a connector, emulating the shared roadway and providing a smooth transition from the through movement to the left or right.

During congestion, because the connector may overlap the through lane, a priority rule should be placed on the connector that prohibits vehicles from moving forward due to inadequate space to enter the taper (in VISSIM, vehicles traveling on separate links and connectors are not recognized by other vehicles even though they are traveling in the same direction). Likewise, a priority rule should be placed so that vehicles queued on the connector are recognized by the through vehicles on the link.

This modeling configuration is demonstrated in figure 127, where blue lines indicate links while pink lines indicate connectors. The second modeling configuration proposes the use of two links and a connector between them. The first link will have as many lanes as the through movement requires. The second link will group the left, through, and right lanes with the connector joining the through movements of both links. This configuration will allow vehicles to respond to the internal lane-changing logic to yield to conflicting vehicles for the through, left, and right turn movements. Figure 128 demonstrates this modeling configuration. However, the second configuration has led to a number of problems. Figure 129 shows how the second configuration resulted in an increasingly high number of conflicts with vehicles not queuing up normally. Therefore, the first configuration was used to model all left- and right-turn tapers.

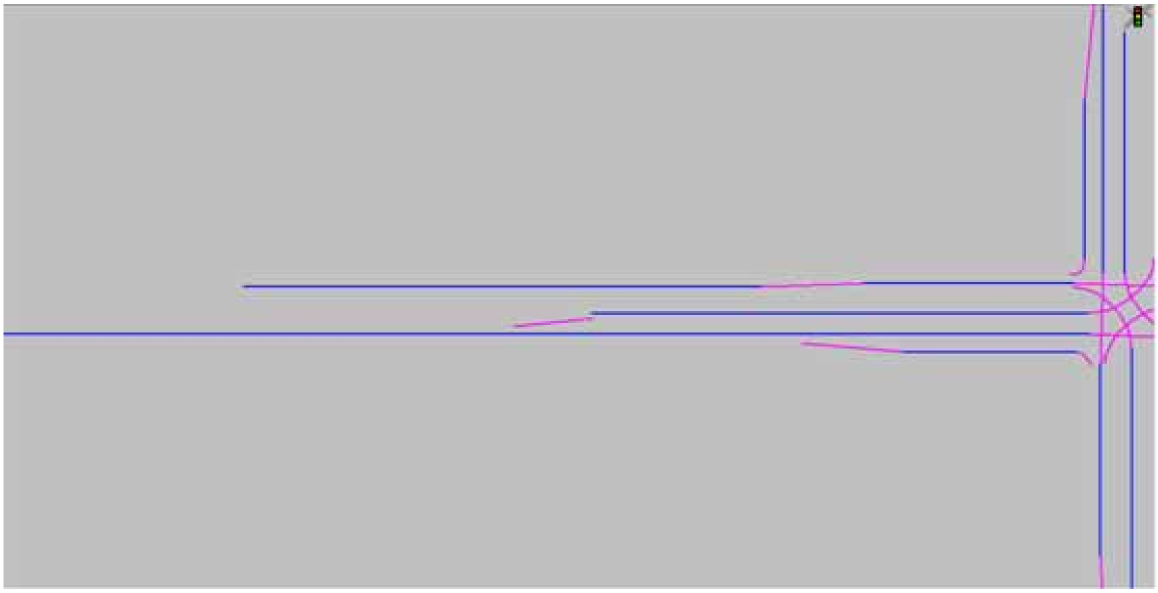


Figure 127. Screen Capture. First Taper Modeling Configuration.

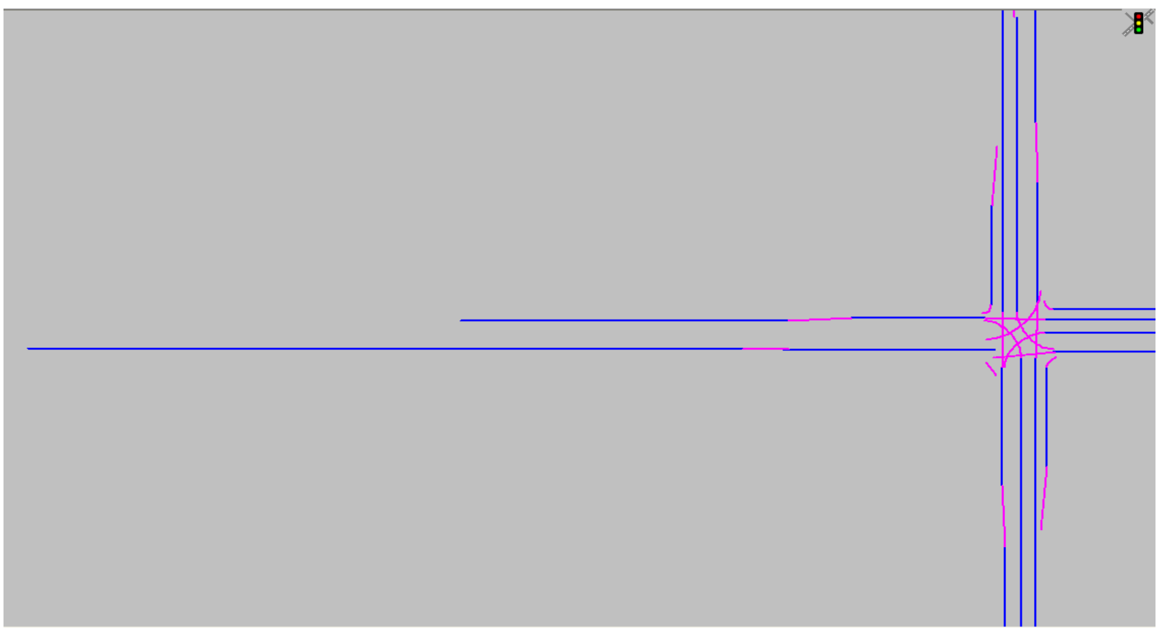


Figure 128. Screen Capture. Second Taper Modeling Configuration.

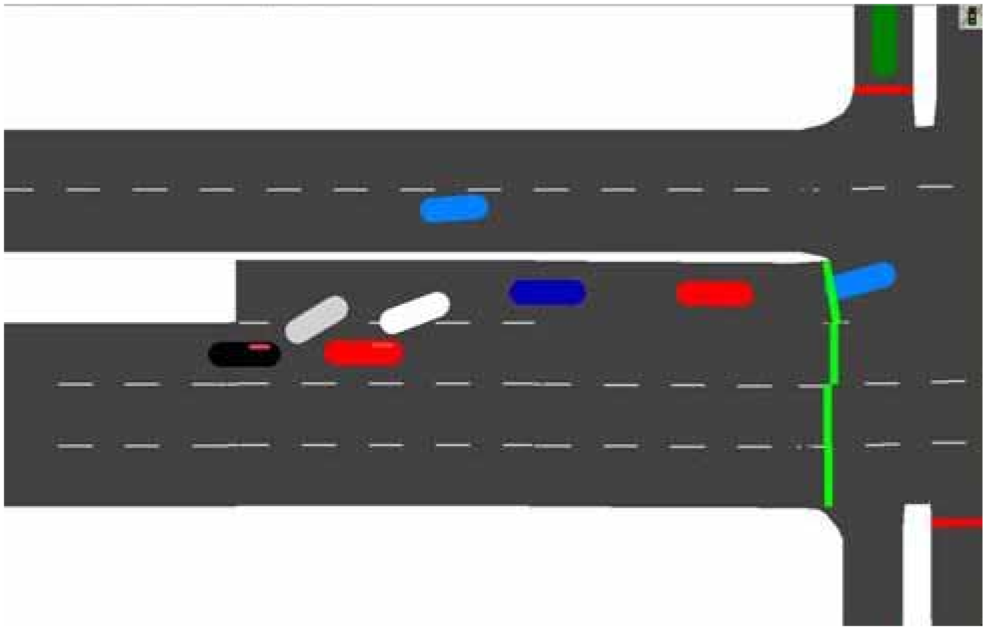


Figure 129. Screen Capture. Queuing Problem Due to the Second Taper Configuration.

VISSIM Modeling Summary

The section presented the modeling process and some key modeling assumptions in VISSIM. Several modeling assumptions were presented including assumptions related to intersection geometry, signal control, detectors, speed profiles, vehicle type characteristics, traffic composition, priority rules, and other aspects. As well, the section discussed a number of important modeling issues. These issues included the modeling schemes, the occurrence of simulated crashes, the abrupt lane-changing behavior experienced, and the modeling of left- and right-turn bay tapers.

TEST RESULTS AND DISCUSSION

This section presents the results of the field validation testing effort, the design of which was described in the preceding sections of this chapter.

The experimental procedure, prior to statistical testing, is summarized as follows. A set of 83 intersections, selected from field sites in North America, were modeled in VISSIM. Each intersection model was simulated for five replications for 1 hour of simulated time, each with different random seeds. The corresponding five output files (i.e.,TRJ files) from VISSIM were then imported into SSAM for identification of conflicts and computation of the surrogate measures of safety for each conflict event. SSAM was configured to use its default values conflict identification thresholds. Namely, the (default) TTC and PET values used were 1.5 seconds and 5.0 seconds, respectively. The results of the SSAM analysis consists of the number of total conflicts and the number of conflicts of each type of vehicle-vehicle interaction: crossing, rear end, and lane changing. Average hourly conflict counts for each intersection are provided in appendix C.

The crash data used for comparison are provided in appendix A, presented in terms of average yearly crash counts for each intersection, including counts by maneuver type and by severity (fatality, injury, and proper damage only). The crash counts were derived by filtering through all intersection crash records to include only two (or more) vehicle crashes. Thus, single-vehicle crashes, such as run-off-road crashes, fixed-object crashes, and animal-, pedestrian-, or bicycle- related crashes, are excluded.

Validation Test 1: Safety Ranking

Test 1 is a comparison of the ranking of intersections based on average hourly conflict frequency versus the ranking of intersections based on average yearly crash frequency. The Spearman rank correlation coefficient (ρ_s) value of this ranking comparison was 0.463, which is significant at a 95-percent level of confidence.

As a basis of comparison, the intersections were ranked on basis of total ADT values, and this was also compared with the ranking based on average yearly crash frequency. The Spearman rank correlation coefficient (ρ_s) value of this ranking comparison was 0.788, which is significant at a 95-percent level of confidence.

The Spearman rank correlation tests show that a significant correlation was found between intersection rankings based on simulated average hourly conflict frequency and average yearly crash frequency; however, a higher correlation was found with intersection rankings based on average daily traffic volume.

It is important to note that the simulated conflict data are based on AM peak-hour volumes and not on ADT volumes. The ratio of ADT to AM peak-hour volume for each intersection is shown in table 122 in appendix A. This table shows that the average ratio of all intersections was 25, with a range spanning from 20 to 51. To quantify this relationship in other terms, a correlation (R-squared) of 0.73 was found in a linear regression between the ADT and AM peak-hour volumes of all intersections.

The differences between simulated (AM peak) volumes and ADT volumes likely degrades the correlation between simulated conflict frequencies and actual crash counts, which were accumulated during all hours of the day. Crashes and conflicts were clearly proportional to volume, and thus simulating volumes at $1/20^{th}$ of the ADT for one intersection and $1/50^{th}$ of the ADT for another intersection does not seem ideal. However, simulating at $1/24^{th}$ of the ADT is questionable as well. Traffic flow can exhibit strong directional bias in one direction during the morning, and the opposite direction during the evening. Thus, traffic flows at $1/24^{th}$ of the total ADT might not capture these directional biases. It would seem that the conflict and crash rates would fluctuate relative to the specific patterns of crossing flows and directional bias throughout the day, particularly at intersections with asymmetrically skewed approaches. It is expected that higher correlations could be obtained if simulated volumes better represented the profile of different directional flows and if all intersections were simulated at volumes in uniform proportion to their corresponding ADT values. Indeed, higher correlations were obtained by scaling each intersection by the ratio of ADT to AM peak-hour flows. However, such a scaling technique might well be subject to scrutiny as well. Rather than provide correlation based on such "corrective" measures, it is simply noted that results of this effort are based on simulation of only the AM peak-hour volumes, which could be inferior to correlations possible with more comprehensive simulation.

Validation Test 2: Safety Ranking by Incident Types

Validation test 2 repeats the same comparative ranking procedures as for validation test 1 for the subsets of crash/conflict types: crossing, rear end, and lane changing. There were an inadequate number of crossing conflicts recorded to perform the ranking comparison for crossing type incidents. Table 81 compares the distribution of conflicts and crashes by incident type. There were very few crossing conflicts recorded, while nearly 20 percent of crashes were crossing maneuvers. Note that the simulated crashes (i.e., conflicts with a TTC of 0 seconds) were excluded from the conflict count data, as in the theoretical validation. If simulated crashes are included, the percentage of crossing, rear-end, and lane-change conflicts are 1.7 percent, 91.0 percent, and 7.3 percent, respectively. However, most "crashes" observed during simulation appeared to reflect anomalous behavior in the traffic model and were filtered out. Additionally, the use of a PET threshold of 5.0 seconds may also have contribute to underreporting of crossing conflicts, such as whenever a crossing vehicle abruptly decelerates to abort a maneuver (e.g., left turn or right turn) and does not complete that maneuver until a few more vehicles have passed or perhaps for a whole signal cycle (in any case, more than 5.0 seconds). While PET seems to be an important surrogate safety measure, it is evident (in hindsight) that this measure may be inappropriate for screening out conflict events.

Table 81. Distribution of Conflicts and Crashes by Incident Type.

	Incident Type			
	Crossing	**Rear End**	**Lane Change**	**All Types**
Average Hourly Conflicts	0.1	53.1	3.1	56.4
Percentage of Conflicts by Type	0.2%	94.2%	5.6%	100.0%
Average Yearly Crashes by Type	7.6	25.8	4.8	38.2
Percentage of Crashes by Type	19.9%	67.5%	12.5%	100.0%

There are significant differences between conflict distributions by type and actual crash distributions by type. The ratios of conflicts-per-hour to crashes-per-year for crossing, rear-end, and lane-change conflicts are 0.01, 2.06, and 0.65, respectively. It seems plausible that conflicts-to-crashes ratios may be lower for more severe incidents and higher for less dangerous incidents. That is, accepting that rear-ends are generally less severe than lane-change and rear-end conflicts, there is an abundance of these "lower risk" conflicts. Conversely, a crossing conflict (such as a left turner colliding with opposing through traffic) might generally be regarded as the most dangerous conflict type, and there are significant fewer conflicts per crash for this incident type. This is an evident trend in the data, though by virtue of being based on simulated conflicts and not real-world conflicts, this potential relationship between conflict frequencies and severity is only a conjecture. The low frequency of crossing conflicts could also be due (in whole or in part) to the efforts of modeling priority rules to reduce simulated crashes.

Moving on to the results of the ranking tests, there is a significant correlation between conflicts and crashes when considered by conflict type. The Spearman rank correlation coefficient (ρ_s) value for the rear-end incident ranking comparison was 0.473, which is significant at a 95-percent level of confidence. Also, the Spearman rank correlation coefficient (ρ_s) value for lane-change incident ranking comparison was 0.469, which is significant at a 95-percent level of confidence.

For comparison, the intersections were ranked on basis of total ADT values, and this was also compared with the rankings based on cross, rear-end, and lane-change crashes. All of these ranking comparisons were significant, with Spearman rank correlation coefficient (ρ_s) values of 0.499, 0.798, and 0.712 for crossing, rear-end, and lane-change incident types, respectively.

Rank correlation testing has shown a significant correlation between rear-end conflicts and rear-end crashes and between lane-change conflicts and lane-change crashes. However, the rank correlation tests have also shown a stronger correlation between ADT and all three incident types.

Validation Test 3: Conflicts-Based Crash-Prediction Regression Model

This test assesses the correlation between conflicts and crashes by using regression to construct a conflicts-based model to predict intersection crash frequency. Additionally, the capabilities of conflict-based crash-prediction will be compared to a traditional volume-based crash-prediction model.

To establish the benchmark for comparison, a standard generalized linear modeling approach (GLM) approach was used to establish a model of the expected crashes at each intersection as a function of ADT. *Crashes* in this model are expressed in terms of average yearly crash frequency, as a function of the model variables which are the ADT volumes of the major and minor roads (in vehicles per day) or ADT_{major} and ADT_{minor}, respectively. The estimates of parameters for this model are shown in table 82.

Table 82. Prediction Model for Crashes as a Function of Major and Minor ADT.

$Crashes = 0.000000776 \times ADT_{minor}^{0.740} \times ADT_{major}^{0.963}$					
Degrees of Freedom	**R-Squared (R^2)**	**Scaled Deviance**	**Pearson χ^2**	$\chi^2_{0.1,79}$	**Shape Parameter κ**
79	0.68	84.25	77.48	95.48	6.575

Variable	**Coefficient**	***t*-ratio**
Constant	7.760E-07	8.746
ADT Minor	0.740	8.597
ADT Major	0.963	6.325

Table 82 shows the estimates of the parameters for the total crash model. The *t*-ratio was used to assess the significance of these estimates. As shown in the table, the measures are all significant at the 90-percent confidence level. Furthermore, the table shows that both the Pearson chi-squared and the scaled deviance values were not significant at the 90-percent confidence level, indicating a good fit. Moreover, the result of the R-squared goodness-of-fit test conforms to those of the Pearson chi-squared and the scaled deviance.

In relating crashes to conflicts, because both actual crashes and predicted conflicts are discrete random variables with long right-tail distributions, such an analysis can be conducted by (1) using natural logarithms to transform both variables, and (2) conducting a conditional analysis of actual crashes given predicted conflicts.

Thus, a regression equation was developed that relates the logarithms of *Crashes*, expressed in terms of average yearly crash frequency, to the logarithms of *Conflict*s, expressed as the average hourly conflict frequency. The resulting equation appears in figure 130. The goodness-of-fit of the regression equation was tested and found to have an R-squared coefficient of determination of 0.27.

$$Ln(Crashes) = 1.09 \times Ln(Conflicts) - 0.98$$

Figure 130. Equation. Normal Linear Regression Model for Crashes as a Function of Conflicts.

However, another regression technique was then employed to relate the actual crash frequency to the conflict frequency predicted by SSAM. It was assumed that both real-life crashes and real-life conflicts were discrete random events with a non-normal error structure. Therefore, the validation test technique assumed that crashes follow a negative binomial distribution while the simulated conflicts follow a Poisson distribution. The resulting nonlinear regression model is shown in figure 131.

$$Crashes = 0.119 \times Conflicts^{1.419}$$

Figure 131. Equation. Nonlinear Regression Model for Crashes as a Function of Conflicts.

Table 83 shows the estimates of the parameters of this nonlinear regression equation. These parameter estimates were obtained using a SAS® macro that was developed to iteratively update the likelihood equations.

Table 83. Nonlinear Regression Model for Crashes as a Function of Conflicts.

$Crashes = 0.119 \times Conflicts^{1.419}$					
Degrees of	**R-Squared**	**Scaled**	**Pearson**	$\chi^2_{0.1,79}$	**Shape Parameter**

Freedom	(R^2)	Deviance	χ^2		κ
80	0.41	85.49	81.28	96.58	3.521

Variable	Coefficient	*t*-ratio
Constant	0.119	2.904
Conflicts	1.419	7.798

As shown in table 83, the estimates of the coefficients were significant at 90-percent confidence level. In addition, the scaled deviance values for both models were not significant at the 90-percent confidence level, indicating good fit.

The R-squared values of 0.27 and 0.41 for the linear and nonlinear regression models is in the range of correlations found with traditional crash prediction models in previous studies with similar traffic facilities. For example, in FHWA-RD-99-094, *Statistical Models of At-Grade Intersections—Addendum*, lognormal regression models were applied to fit 3 years of crash data for a set of 1,309 four-leg, urban, signalized intersections, yielding an R-squared value of 0.25.(30) In FHWA-RD-96-125: *Statistical Models of At-Grade Intersections*, a series of negative binomial regression models were applies to fit 3 years of crash data for a set of 198 urban, four-leg, signalized intersections, yielding R-squared values in the range from 0.33 to 0.41.

The conflicts-based model and volume-based model were compared using the R-squared goodness-of-fit test that was proposed by Miao.(26) The *R*-squared value was recorded to be 0.68 for the crash prediction model based on volumes, as opposed to 0.27 and 0.41 for the linear and nonlinear regression models based on simulated conflicts. Thus, the volume-based model in this study had a better correlation to crash data than the conflict-based model. Again, it should be noted that the conflict counts were based on simulated volumes that were different from the ADT volumes used in the volume-based crash-prediction model, as discussed previously in the results of test 1.

Validation Test 4: Identification of Incident Prone Locations

Development of a Conflict-Prediction Regression Model

The first step of this validation test entailed developing a volume-based conflict-prediction model and a volume-based crash-prediction model. The volume-based crash-prediction model was previously developed in test 3. The parameters of that model are shown in table 82. A volume-based conflict-prediction model was developed using the same procedure but relating conflicts to traffic volumes on the major and minor approach to each intersection. Note that the conflicts identified by SSAM were based on the AM peak-hour volumes used for simulation. The variables used in the conflict-prediction model were: V_{Mi}, vehicle per hour (VPH) on the minor approach, and V_{Ma}, vehicle per hour (VPH) on the major approach. Table 84 shows the estimates of the parameters for total conflict prediction model. The *t*-ratio assessed the significance of the parameter estimates, and they were all found to be significant at the 90-percent confidence level. The table also shows that the scaled deviance values for all models were not significant at the 90-percent confidence level, indicating a good fit.

Table 84. Prediction Model for Total Conflicts as a Function of Volume.

$$\text{Total Conflicts / 1 hr} = 0.2301 \times \text{V}_{\text{Mi}}^{0.2654} \times V_{\text{Ma}}^{0.5089}$$

DF	R^2	Scaled Deviance	Pearson χ^2	$\chi^2_{0.1,79}$	Shape Parameter κ
79	0.75	85.46	85.93	95.48	37.175

Variable	Coefficient	*t*-ratio
Constant	1.764E-01	3.529
VPH Minor	0.2090	5.110
VPH Major	0.5830	8.914

Identification of Incident-Prone Locations

The second step of this validation test was the identification of crash-prone intersections and conflict-prone intersections. A crash/conflict prone location is defined as any location that exhibits a significantly higher number of crashes/conflicts as compared to a specific “normal” value, which in this test is provided by the volume-based crash/conflict prediction models.(25)

The test procedure identified 20 crash-prone locations using the crash-prediction model and 12 conflict-prone locations using the conflict-prediction model. Only one incident-prone intersection was identified by both the crash- and conflict-prediction models. This indicates a poor agreement between the conflicts and actual crash models in identifying incident prone locations.

Ranking Locations

With crash/conflict-prone sites identified, the third step of this test was to rank the locations in terms of priority for treatment using an actual-to-normal incident ratio ranking scheme and a PFI ranking scheme, as described previously. The Spearman rank correlation coefficient (ρ_s) values of the ratio and PFI intersection ranking comparisons were 0.001 and 0.033, respectively, indicating an insignificant correlation between intersections with “excessive crashes” and intersections with “excessive conflicts,” relative to "normal" values dictated by volume-based crash- and conflict-prediction models respectively.

It is notable in this test that the crash-prediction model is a convex function (or concave up), whereas the conflict-prediction model is a concave function (or concave down). In other words, the *slope* of the crash-prediction model increases with increasing volume, whereas the *slope* of the conflict-prediction model (while staying positive) reduces with increasing volume. Having opposite curvature in these models would thus seem to induce opposite biases in a ratio-based and PFI (difference-based) ranking indicators, which both would seem to impose linear assumptions on the prediction models in order to provide comparable intersection rankings across different volumes.

Furthermore, if it were accepted that crashes and conflicts were approximately Poisson distributed, then the standard deviation (and approximate confidence intervals) are related to the square root of the mean. Thus, actual crash counts from an intersection with a means of 25 crashes per year would exhibit a wider range of variation, expressed in proportion to the mean, than an intersection with a mean 36 crashes per year. If both intersections had the same ratio of actual crashes to predicted crashes, which would be ranked equivalently in the ratio test, then this occurrence would be less of a statistical outlier for the intersection with a mean of 36 crashes. The PFI ranking scheme is also subject to similar issues. In hindsight, comparison of intersection rankings on these measures, using two differently shaped prediction models, may not be entirely conclusive.

Validation Test 5: Identification of Type-Specific Incident-Prone Locations

Development of Conflict Models for Specific Incident Types

Validation test 5 repeats the same process for validation test 4 but for each conflict type (rear-end, lane-changing, and crossing) using the GENMOD procedure in the SAS® 9.1 statistical software package.

Due to a very small number of observed crossing conflicts, crossing-type incidents were excluded from this analysis. It is evident that crossing conflicts are not well-correlated with the occurrence of crossing type crashes found in the field data. In addition, lane-change type conflicts were also excluded from the analysis due to an "inadmissible" negative estimate for the dispersion parameter in the SAS® software. This is perhaps due to the relatively low number of lane-change conflicts observed, which averaged only 3.1 events per hour over all 83 intersections.

Table 85 shows the estimates of the parameters for the crossing-conflicts model. The *t*-ratio was used to assess the significance of these estimates, and they were all significant at the 90-percent confidence level. The table also shows that the scaled deviance and Pearson chi-squared values were not significant at the 90-percent confidence level, indicating a good fit.

Table 85. Prediction Models for Crossing Conflicts Based on Traffic Volume.

$$\text{Crossing Conflicts / 1 hr} = 0.1771 \times V_{\text{Mi}}^{0.2125} \times V_{\text{Ma}}^{0.5711}$$

DF	Scaled Deviance	Pearson χ^2	$\chi^2_{0.1,79}$	Shape Parameter κ
79	86.29	86.19	95.48	38.911

Variable	Coefficient	t-ratio
Constant	1.771E-01	3.522
VPH Minor	0.2125	5.196
VPH Major	0.5711	8.746

Table 86 shows the estimates of the parameters for the rear-end crash-prediction model based on ADT volumes, which has a form similar to the total crash-prediction model in test 4. The *t*-ratio was used to assess the significance of these estimates. It was found that the parameters were all statistically significant at the 90-percent confidence level. Also, both the Pearson chi-squared and the scaled deviance indicate a good fit.

Table 86. Prediction Model for Rear-End Crashes Based on Traffic Volume.

$$\text{Crashes / 1 yr} = 0.00000003419 \times ADT_{\text{Minor}}^{0.814} \times ADT_{\text{Major}}^{1.147}$$

DF	Scaled Deviance	Pearson χ^2	$\chi^2_{0.1,79}$	Shape Parameter κ
79	85.44	85.61	95.48	5.035

Variable	Coefficient	t-ratio
Constant	3.419E-08	8.880
AADT Minor	0.814	8.058
AADT Major	1.147	6.380

Identification of Location Prone to Rear-End Incidents

Once the parameters of the prediction models were estimated, the models were then used to identify 19 rear-end-type crash-prone locations and 8 rear-end-type conflict-prone locations. Only one location was identified as prone to both rear-end crashes and rear-end conflicts. This indicates a poor agreement between the models in identifying rear-end prone locations.

Ranking Locations for Specific Incident Types

The PFI and ratio rankings (as explained in previously) were then obtained using the rear-end conflict-prediction model and the corresponding rear-end crash-prediction model. The Spearman rank correlations for the PFI and ratio ranking comparisons were -0.105 and -0.060, respectively. These results indicate an insignificant correlation between intersections with “excessive rear-end incidents” and intersections with “excessive rear-end conflicts,” relative to “normal” values dictated by volume-based prediction models for rear-end type crashes and conflicts. However, the discussion of incident-prone ranking comparisons from test 4 is applicable here as well.

SIMULATION MODELING ISSUES

In interpreting the field validation test results, it should be noted that there are several modeling issues related to VISSIM that have a significant impact on the results. This section discusses the impact of these issues on the number and types of conflicts produced by the simulation system.

Effect of Redefining the Priority Rules

Several researchers have shown that both real-world crashes and real-world conflicts (as measured by field observers using the traffic conflicts measurement techniques) are strongly related to traffic volumes.[28, 31, 32] Therefore, the higher the traffic volumes at an intersection, the more likely that conflicts and crashes occur. When modeling an intersection in VISSIM, two factors govern the discharge of traffic flow at an intersection: signal control and priority rules. The signal design is based on fixed parameters that were provided directly from the safety studies. These values were used in this validation to accurately represent real-life conditions. In “typical” VISSIM traffic modeling for capacity/performance analysis, priority rules are only necessary for permissive left turns and right turns on red. However, additional priority rules were found necessary to reduce the simulated crashes that occur due to the driver behavior logic of VISSIM.

As mentioned earlier, two modeling schemes were adopted. The main difference between scheme 1 and scheme 2 was the addition of the 16 priority rules in scheme 2 to compensate for the run-over behavior observed during yellow and red clearance intervals as discussed in a previous section. For the 83 intersections modeled in this study, figure 132 and figure 133 show plots of the total number of conflicts produced from each scheme, including and excluding simulated crashes, respectively. As shown in figure 132, the number of conflicts including simulated crashes for scheme 1 is higher than scheme 2. This is expected given that the addition of 16 priority rules in scheme 2 will lead to a reduction in simulated conflicts. Figure 133 shows the number of simulated conflicts excluding crashes. The addition of the 16 priority rules in scheme 2 resulted in a reduction of crashes but increased the number of conflicts. This increase might be due to some simulated crashes becoming conflicts with low TTC values.

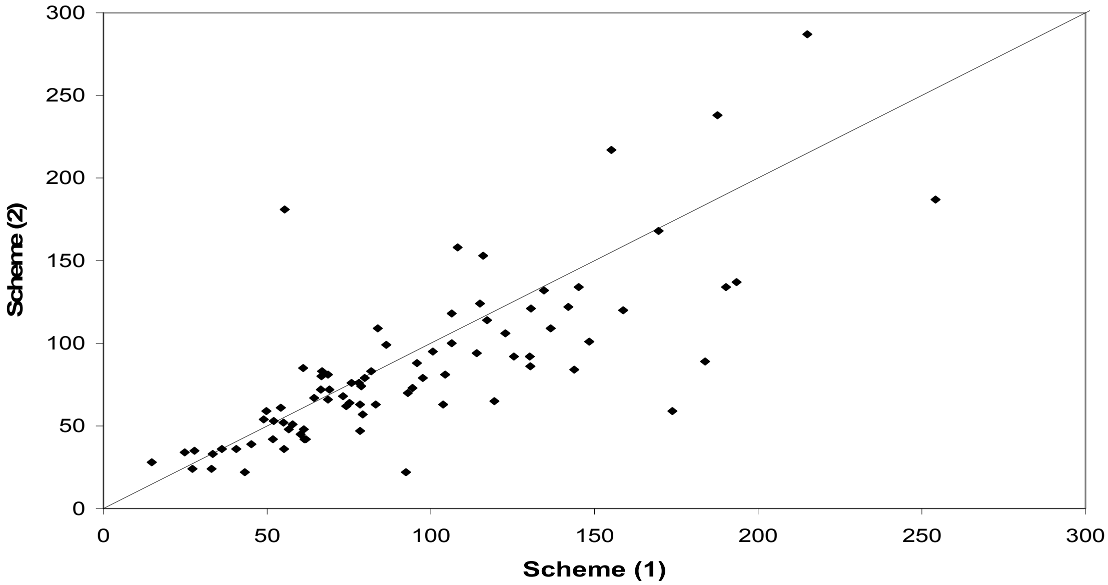


Figure 132. Graph. Effect of Redefining the Priority Rules on Total Conflicts (Including Simulated Crashes).

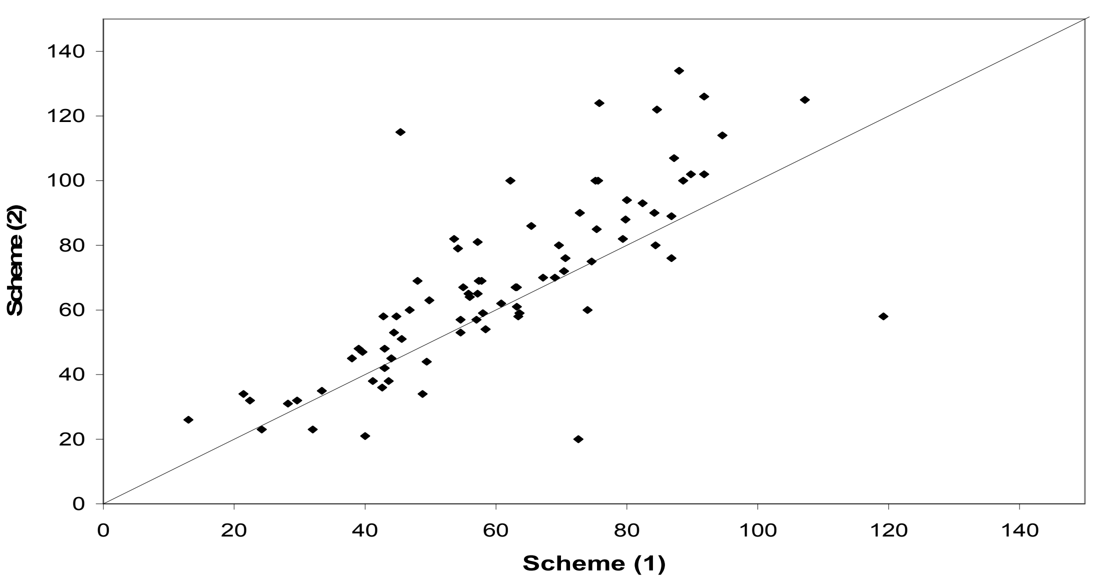


Figure 133. Graph. Effect of Redefining the Priority Rules on Total Conflicts (Excluding Simulated Crashes).

The effect of redefining the priority rules on the total and type of conflicts is demonstrated by comparing three modeling schemes. Schemes 1 and 2 were previously described. The third scheme uses a base case scenario where only 8 priority rules were used for permissive left and right turns on red maneuvers. To demonstrate the effect of redefining the priority rules, a typical intersection was selected and simulated using the three different schemes. The selected intersection was composed of three lanes on all approaches with a pretimed signal controller. The four-leg intersection had a traffic flow of 1,520 vph and 1,660 vph on the minor and major approaches, respectively. Table 87 shows the total and type of conflicts recorded for each scheme at the selected intersection. The results are based on the average value of five simulated runs with different random seeds.

Table 87. Number and Type of Conflicts Based on Different Modeling Schemes.

	Total	Crossing	Rear-End	Lane-Change	Simulated Crashes
Base Case	121	22	73	26	28
Scheme 1	114	22	70	22	27
Scheme 2	95	4	73	18	6

The base case for this sample location has a total of 8 priority rules defined. These priority rules represent the governing rules for permissive left and right turn on red maneuvers. The base case recorded 22 crossing conflicts, 73 rear-end conflicts and 26 lane-changing conflicts, for a total of 121 conflicts over a 1-hour simulation with the AM peak-period volumes provided.

Scheme 1 added 8 more priority rules (for the exclusive left-turn bays) to the base case. These additional priority rules decreased the number of rear-end and lane-changing conflicts by 3 and 4, respectively. However, the number of crossing conflicts remained unchanged. Overall, there were 7 fewer conflicts than the base case modeling scheme.

Scheme 2 added another 16 rules to compensate for the behavior during yellow and red clearance intervals, thereby allowing the left-turning cars to complete their turning movements. The additional rules decreased the number of crossing and lane-changing conflicts by 18 and 8, respectively, but increased the number of rear-end conflicts by 3, for a total in all there were 26 less conflicts than the base case.

Also, compared with the base case, the additional rules of scheme 1 decreased the simulated crashes by only one, while the additional rules of scheme 2 were much more effective in reducing these simulated crashes, resulting in a drop of 22 crashes. However, even with these additional rules defined, the simulated crashes cannot be completely eliminated. This comparison shows that the way in which priority rules are defined can have a significant impact on SSAM output.

In hindsight, it seems plausible that the added rules may have decreased the likelihood of performing a risky crossing maneuver. These vehicles may have suddenly decelerated, coming completely to a stop to avoid a crossing maneuver (e.g., left turn), and in doing so, they slightly increased the likelihood of rear-end conflicts. While this scenario may have constituted an event where a collision was imminent according to the TTC threshold, due to aborting the maneuver, the PET threshold was not satisfied, and thus, several potentially valid crossing conflicts were eliminated. It would seem, in hindsight, that the limits on the PET should not have been used as a conflict rejection criterion.

Effect of Varying the Gap Size

Since most intersections operated under free flow traffic, the minimum gap size becomes the dominant parameter in defining the priority rules. The default gap size used for the 83 simulated intersections was 5 seconds with an additional 0.5 seconds for any extra crossing lane.

It was noted that varying the minimum gap size had a significant effect on the discharge flow rate of an intersection. Therefore, it is expected to have an effect on the number and type of the simulated conflicts. Using the same intersection described in table 87, the effect of varying the minimum gap size on the numbers and types of conflicts was examined. Modeling scheme 2 was adopted and the intersection was modified in VISSIM, to represent minimum gaps of 4, 5, and 6 seconds. Table 88 shows the numbers and types of conflicts obtained from SSAM.

Table 88. Number and Type of Conflicts Based on Gap Size.

Minimum Gap (seconds)	Total	Crossing	Rear-End	Lane-Change	Simulated Crashes
4	111	3	89	19	7
5	93	6	71	16	5
6	104	4	80	20	9

The results show that as the minimum gap size increases from 4 to 5 seconds, the number of conflicts reduced. However, when the minimum gap size was increased from 5 to 6 seconds, there was an increase in the number of conflicts with a marginal change in the conflicts types. This increase was due to the queuing of vehicles waiting to perform a right or left maneuver, which induces the following vehicles to change lanes abruptly causing the increase in conflicts and simulated crashes. Appendix D shows the total number of conflicts produced by each gap size for all of the 83 locations.

Examining table 126 in the appendix, it is evident that increasing the gap size does not necessary reduce the total number of conflicts. On the contrary, increasing the gap size from 4 seconds to 5 seconds decreased the total number of conflicts in only 46 percent of the locations. Furthermore, increasing the gap size from 4 seconds to 6 seconds decreased the total number of conflicts in only 35 percent of the locations. Similar trends were noted for crossing, rear-end, and lane-changing conflicts. Table 89 and table 90 show the percentages of locations exhibiting a decrease in the number of conflicts with and without simulated crashes.

Table 89. Percentages of Locations Exhibiting a Decrease in the Number of Conflicts (Including Simulated Crashes).

	Gap Change from 4 to 5 (seconds)	Gap Change from 4 to 6 (seconds)	Gap Change from 5 to 6 (seconds)
Total	46%	35%	35%
Crossing	40%	43%	30%
Rear End	42%	34%	35%
Lane Changing	46%	37%	39%

Table 90. Percentages of Locations Exhibiting a Decrease in the Number of Conflicts (Excluding Simulated Crashes).

	Gap Change from 4 to 5 (seconds)	Gap Change from 4 to 6 (seconds)	Gap Change from 5 to 6 (seconds)
Total	37%	34%	36%
Crossing	29%	30%	27%
Rear End	42%	34%	36%
Lane Changing	40%	37%	30%

Effect of Changing the Lateral Clearance Parameter

As mentioned earlier the lateral clearance parameter had to be increased from 1.0 second to 1.5 seconds to prevent some of the abrupt lane-changing behavior. Logically, this parameter has a pronounced effect on the capacity of an intersection. This section demonstrates the effect of varying the lateral clearance parameter on the numbers and types of conflicts. Ten intersections were randomly selected to study this effect. The results are shown in table 91 and table 92. The results are based on the average value of five simulated runs with different random seeds.

When simulated crashes were included in the total conflicts, table 91 shows that five locations exhibited an increase in the total number of conflicts, four locations exhibited a decrease, and one location was unaffected by increasing the lateral clearance from 1.0 second to 1.5 seconds. When simulated crashes were excluded from the analysis, table 92 reveals an increase in four locations, a decrease in four locations, while two locations were unaffected. As expected, most of the increase or decrease in the total number of conflicts was due to changes in the numbers of rear-end and lane-changing conflicts, with minimal changes in the number of crossing conflicts. The results in table 91 and table 92 show that the lateral clearance parameter does not have a consistent impact on the number of conflicts produced by SSAM.

Table 91. Effect of Varying Lateral Clearance (Simulated Crashes Included).

ID	Conflicts (Lateral Clearance 1.5 seconds)				Conflicts (Lateral Clearance 1.0 second)			
	Total	Crossing	Rear End	Lane Changing	Total	Crossing	Rear End	Lane Changing
4	43	3	35	5	43	3	35	5
7	130	43	33	54	132	40	39	53
8	101	15	46	40	107	14	48	45
15	116	14	54	48	110	11	55	44
19	120	40	53	27	117	42	54	21
43	62	19	28	15	58	14	32	12
57	215	82	34	99	227	68	35	124
69	25	4	17	4	26	4	18	4
70	36	2	27	7	34	2	26	6
80	27	4	13	10	28	4	14	10

Table 92. Effect of Varying Lateral Clearance (Simulated Crashes Excluded).

ID	Conflicts (Lateral Clearance 1.5 seconds)				Conflicts (Lateral Clearance 1.0 second)			
	Total	Crossing	Rear End	Lane Changing	Total	Crossing	Rear End	Lane Changing
4	40	1	35	4	40	1	35	4
7	73	4	33	36	76	4	38	34
8	76	3	46	27	81	3	48	30
15	79	1	51	27	76	1	54	21
19	74	2	53	19	70	3	54	13
43	41	2	28	11	41	1	32	8
57	88	4	34	50	87	3	34	50
69	22	1	17	4	23	1	18	4
70	34	0	27	7	32	0	26	6
80	22	0	13	9	24	1	14	9

SUMMARY

This chapter has detailed the field validation effort conducted to assess the predictive safety performance capabilities of the SSAM approach with actual crash experience at North American signalized intersections.

Guidelines for the selection of signalized intersections for the field validation were established and used to select 83 intersections, each with four-leg geometry. The intersections were modeled in the VISSIM simulation system, and the simulation results were imported into SSAM to obtain a record of traffic conflicts that exceeded the minimum severity levels (TTC and PET values). Several modeling assumptions were made including assumptions related to intersection geometry, signal control, detectors, speed profiles, vehicle type characteristics, traffic composition, and priority rules.

Crash records were obtained from insurance claim records and manually processed to class crashes by event type (crossing, rear end, or lane changing) and to include intersection-related, multiple-vehicle crashes.

A range of statistical tests were applied to the data to quantify the correlation between intersection conflicts (from simulation) and intersection crashes (from insurance claims records). The tests evaluated total event (crash/conflict) frequencies and event frequencies by maneuver type (crossing, lane change, or rear end). The tests included the following:

- Validation Test 1: Intersection Ranking by Total Incidents.
- Validation Test 2: Intersection Ranking by Incident Types.
- Validation Test 3: Conflicts-Based Crash-Prediction Regression Model.
- Validation Test 4: Identification of Incident-Prone Locations.
- Validation Test 5: Identification of Type-Specific Incident-Prone Locations.

The results of the validation effort demonstrated that the surrogate measures (i.e., conflict frequencies by maneuver type) derived from traffic simulation models were significantly correlated with the crash data collected in the field, with the exception in particular of conflicts during path-crossing maneuvers, which were under-represented in the simulation. The relationship between total conflicts and total crashes exhibited a correlation (R-squared) of 0.41, which is within the range of typical experience using traditional crash prediction models on urban, signalized intersections.

However, as a benchmark basis for comparison, traditional safety assessments based on average daily traffic volumes were also conducted and compared to the conflicts-based safety assessment. The traditional assessments in this study provided better correlations to crash history than the surrogate measures in all cases. For example, ADT-based crash prediction models exhibited a correlation (R-squared) of 0.68 with actual crash frequencies.

It is well established that both conflicts and crashes are correlated with intersection traffic volume. That is, as traffic volume increases, so does the occurrence of conflicts and crashes. Thus, some correlation of conflicts frequencies and crash frequencies is to be expected. This effort found that the correlation between simulated conflicts and actual crashes is significant. A good correlation between intersections with “abnormally high” conflicts and “abnormally high” crashes was not found in this validation effort, though tests conducted to that end proved somewhat unsuitable to the task.

The field validation presented a series of challenges throughout the effort, motivating a corresponding series of smaller-scale experiments to determine what corrections or practical accommodations could be made. These issues, no doubt, had a significant effect on the results:

- The occurrence of traffic conflicts was highly sensitive to the specific configuration of priority rules and a few other parameters in the VISSIM simulation.
- It was not possible to completely prevent crashes (vehicles passing through each other) in the simulation due to the underlying driver behavior rules in VISSIM, such as the lane-changing logic. However, simulated crashes were significantly reduced by a series of modeling countermeasures and ongoing enhancements to VISSIM itself (versions 4.0, 4.1, and 4.2).
- Each intersection was simulated exclusively under morning peak-hour volumes, which were related to the ADT volumes by only a 0.73 (R-squared) correlation. Thus, the simulated conditions provided only a partial representation of typical daily operations.
- There is evidence to suggest that the occurrence of conflicts and crashes may be somewhat distinct while still significantly related. For example, the distribution of conflicts observed seems to lean more heavily toward “less harmful” conflict events (i.e., rear ends) than do police-reported crash records. While the influence of underlying simulation models is in question, it is possible that conflicts of different types (and corresponding severities) may exhibit different conflict-to-crash ratios.
- The prediction models of crashes and conflicts as a function of traffic volumes were found to be convex and concave functions respectively (i.e., shaped concave up and concave down, respectively). This would seem to inject confounding biases into the ranking schemes used to evaluate “abnormally high” incident frequencies, which perhaps could be properly applied only under certain linear conditions of model shape and variance not present in this study.

Summarizing the validation effort of safety assessment via conflict analysis of simulated intersections, it would seem that this technique shows certain potential, and at the same time, the results are not definitive. Aside from intersection safety prediction, SSAM did prove useful as a diagnostic tool toward troubleshooting the configuration of priority rules in VISSIM simulation models by exposing the locations of simulated crashes.

CHAPTER 5. SENSITIVITY ANALYSIS

PURPOSE

The sensitivity analysis serves to supplement the field validation effort. The main purpose of the sensitivity analysis is to capture the differences between using one simulation model versus another and provide guidance to the safety analysis community.

METHODOLOGY

SSAM was tested across the VISSIM, AIMSUN, PARAMICS, and TEXAS microsimulation platforms by implementing five U.S. intersections from the Hamilton Associates' database in all four platforms. The conflict summary results from each simulation for the five U.S. intersections was tabulated and analyzed with and without accounting for crashes (e.g., crashes resulting from lane changing). The performance of SSAM was compared on the various conflict measures output by SSAM (conflict rate, TTC, PET, etc.). Various threshold values were used (e.g., TTC < 1.5 s, TTC < 1.0 s, etc.) to evaluate the differences in output from each microsimulation.

The same five intersections of representative types were implemented in all four of the microsimulation platforms (VISSIM, AIMSUN, PARAMICS, and TEXAS) used in the study. This involved the following steps:

- Implement the same field intersection designs across the four microsimulation platforms.
- Run the simulation with multiple replications and collect trajectory data and measures of effectiveness (MOEs).
- Run the SSAM tool to derive surrogate measures of safety.
- Compare the results from different microsimulation platform for the same simulated case.

Implement Intersection Designs in all four of Microsimulation Platforms

SSAM was tested across VISSIM, AIMSUN, PARAMICS, and TEXAS. The sensitivity analysis was performed by implementing five U.S. intersections from the Hamilton Associates' database in all these four platforms.

For each simulated case, the four simulation models are modeled to keep the geometry data, traffic volume, signal timing, and some important network parameters the same. Other parameters such as driving-behavior parameters remain at default values in each simulation model to avoid unrealistic maneuvers. As indicated in the theoretical analysis report, in most scenarios, evaluated crashes cannot be completely eliminated from the simulation without modifying driver-behavior parameters or design geometry beyond reasonable limits. The number of crashes and low-speed events constituted a large percentage of the total conflict events that occurred in most of the scenarios tested. Moderate adjustment of simulation parameters was made during the sensitivity analysis for each microsimulation platform to reduce such crashes. Multiple replications were implemented for each simulated case in each simulation model to minimize random factors during comparison effort.

Obtain Measures for Each Case

Safety Measures for Each Case

Safety measures recorded from SSAM were tabulated for each simulated case, including total conflicts, conflict number for each conflict type, TTC, PET, etc. Each type of measure was compared across VISSIM, AIMSUN, PARAMICS, and TEXAS.

Conflicts Layout Display for Each Case

Another important task within sensitivity analysis was to compare the conflicts layout across the four simulation platforms for each simulated case.

MOEs for Each Case

Network MOEs for each simulated case were recorded and compared across the four simulation platforms (e.g., travel time and average delay).

SENSITIVITY ANALYSIS RESULTS

Five U.S. intersections from the Hamilton Associates' database were executed in the sensitivity analysis. In terms of traffic volumes and turning counts, each intersection had AM peak-hour data and PM peak-hour data. Two out of the five intersections also had mid-day data.

1. Briarcliff Rd & North Druid Hills Rd, Dekalb County, Atlanta, GA.
2. Roswell Road & Abernathy Road, Fulton County, Atlanta, GA.
3. Lafayette Ave & Fulton Street, Grand Rapids, MI.
4. Ryan Ave & Davison Ave, Detroit, MI.
5. Howe Ave & Fair Oaks Boulevard, Sacramento, CA.

Intersection Descriptions

Intersection 1: Briarcliff Rd & North Druid Hills Rd, Dekalb County, Atlanta, GA

This was a skewed intersection with two approaches having right-turn bays. All four approaches had independent left-turn bays, ranging from 32.9 m (108 ft) to 111.3 m (365 ft). The intersection was under semiactuated signal control and had three timing plans according to three peak-hour periods—AM peak, mid peak, and PM peak. Traffic volumes were around 4,300–4,800 vehicles per hour. The speed limit specified for all approaches was 56.35 km/ h (35 mi/h), and the 3-year annual collision frequency for this intersection was about 27.7. Figure 134 shows a Google™ map view of this intersection. Figure 135 through 138 show the intersection layout modeled within each simulation platform.

Figure 134. Photo. Google™ Map View of Briarcliff Rd & North Druid Hills Rd.

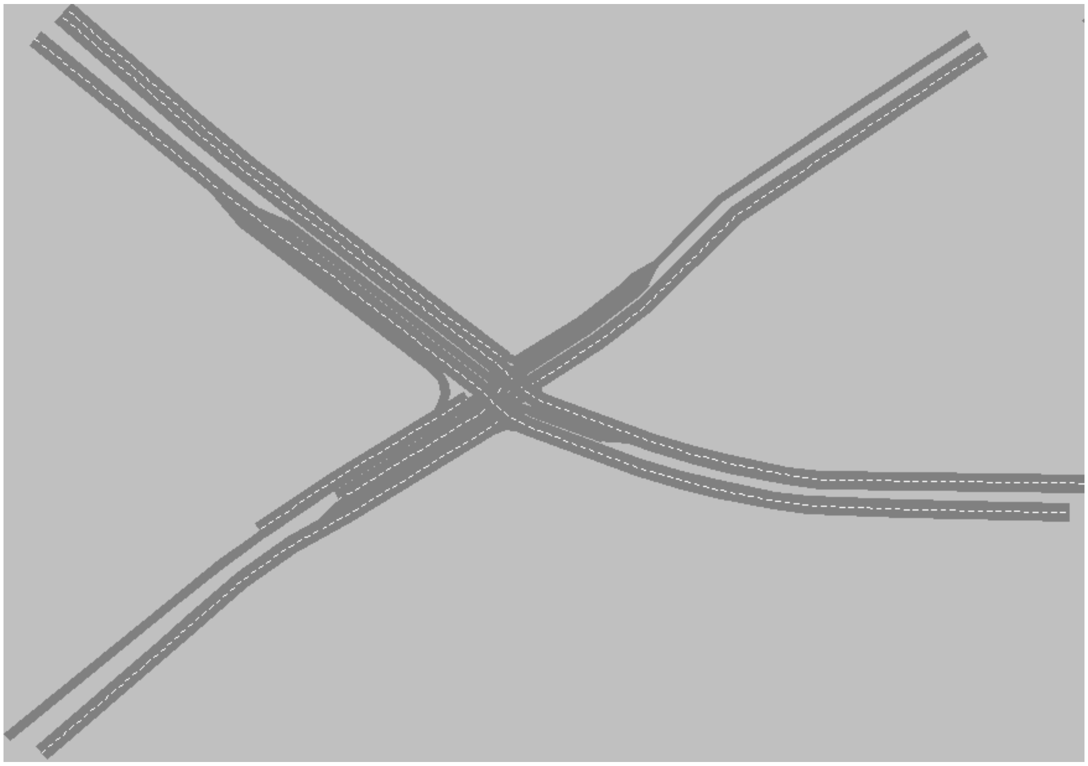


Figure 135. Screen Capture. VISSIM Model of Briarcliff Rd & North Druid Hills Rd.

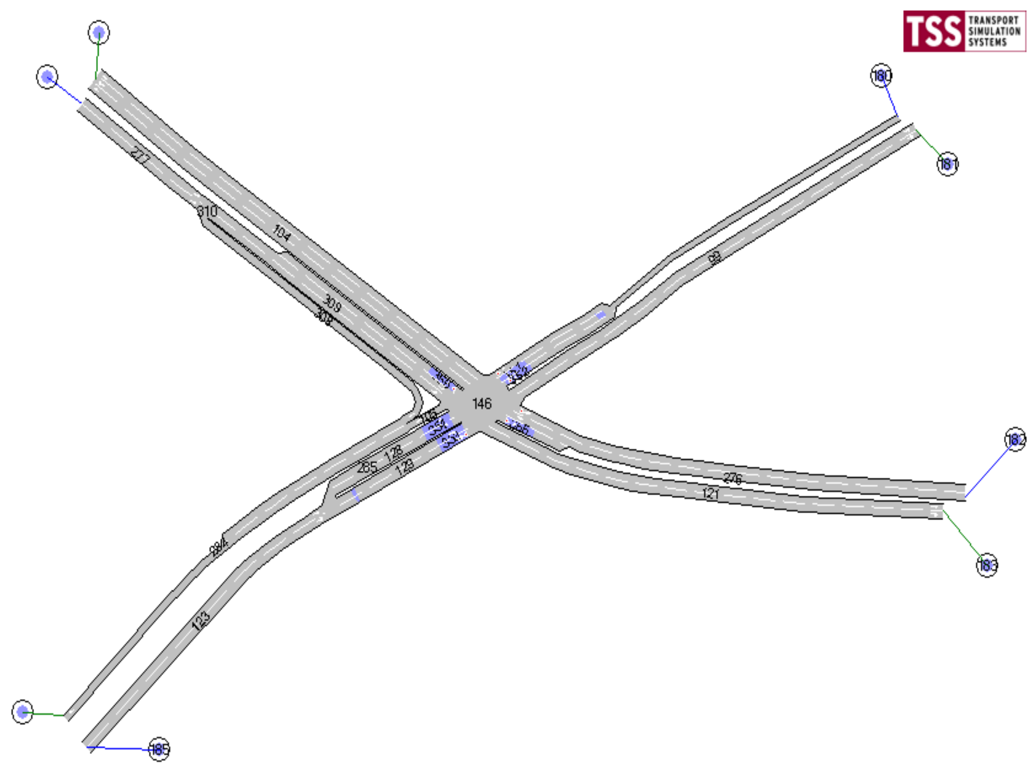


Figure 136. Screen Capture. AIMSUN Model of Briarcliff Rd & North Druid Hills Rd.

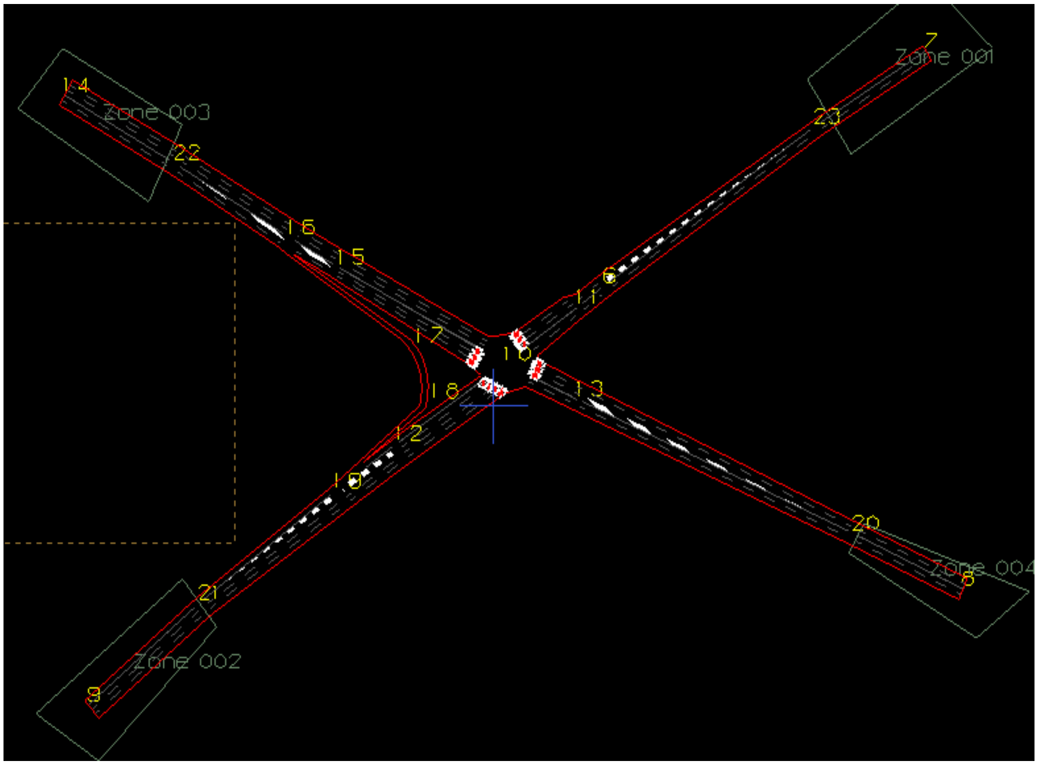


Figure 137. Screen Capture. PARAMICS Model of Briarcliff Rd & North Druid Hills Rd.

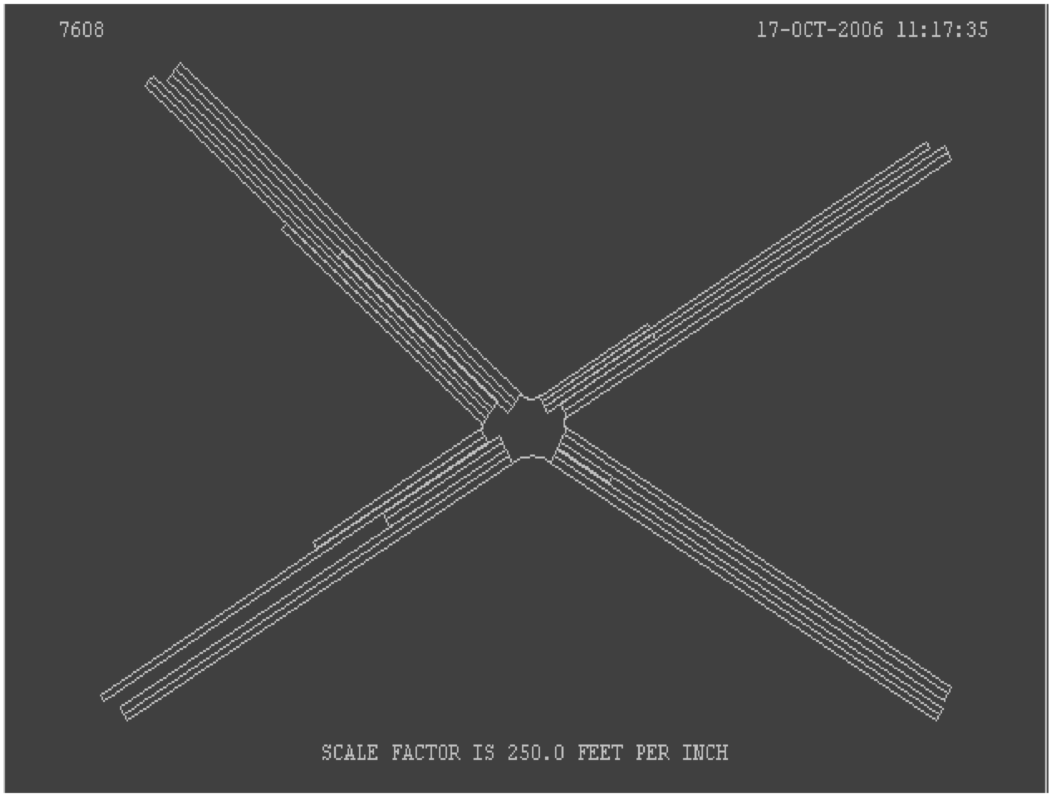


Figure 138. Screen Capture. TEXAS Model of Briarcliff Rd & North Druid Hills Rd.

Intersection 2: Roswell Road & Abernathy Road, Fulton County, Atlanta, GA

This was a skewed intersection with all approaches having right-turn bays and left-turn bays. The intersection was under semiactuated signal control and had three timing plans according to three peak-hour periods—AM peak, mid peak, and PM peak. Traffic volumes were around 5,200–5,700 vehicles per hour. The speed limit specified for all approaches is 56.35 km/h (35 mi/h), and the 3-year annual collision frequency for this intersection is about 92. Figure 139 shows a Google™ map view of this intersection. Figure 140 through figure 143 show the intersection layout modeled within each simulation platform.

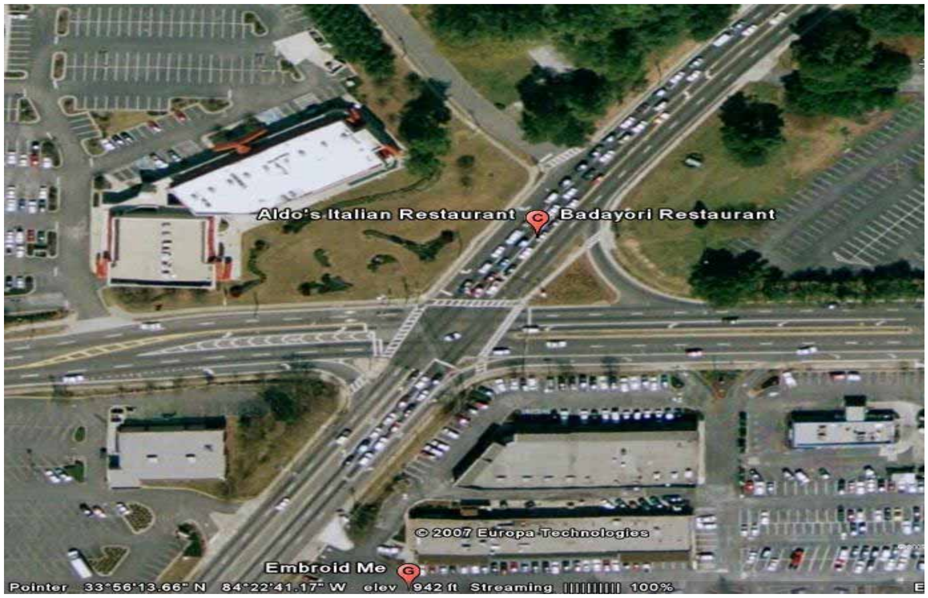


Figure 139. Photo. Google™ Map View of Roswell Road & Abernathy Road.

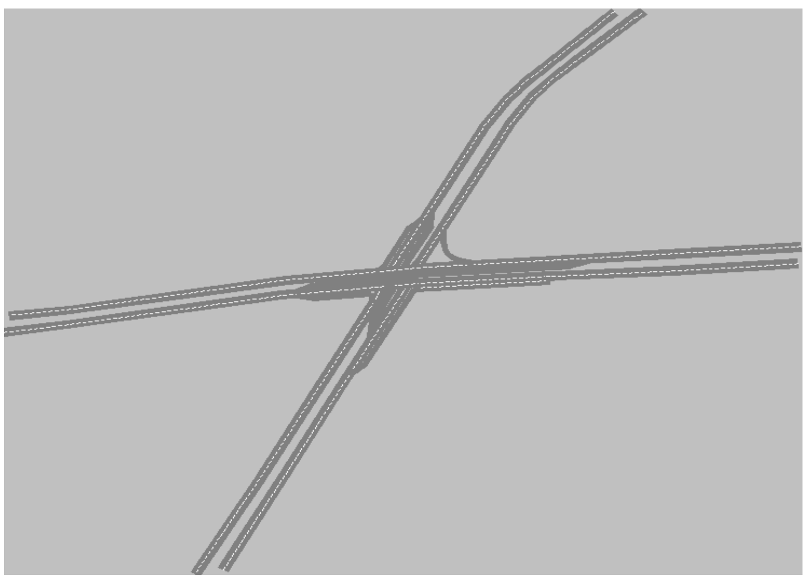


Figure 140. Screen Capture. VISSIM Model of Roswell Road & Abernathy Road.

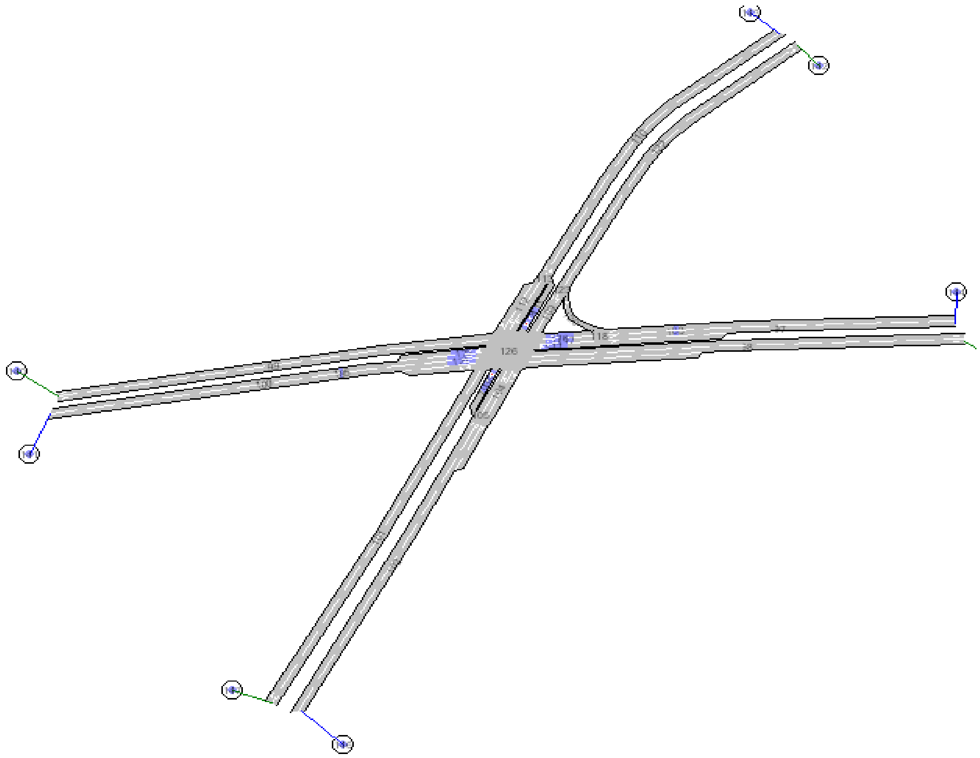


Figure 141. Screen Capture. AIMSUN Model of Roswell Road & Abernathy Road.

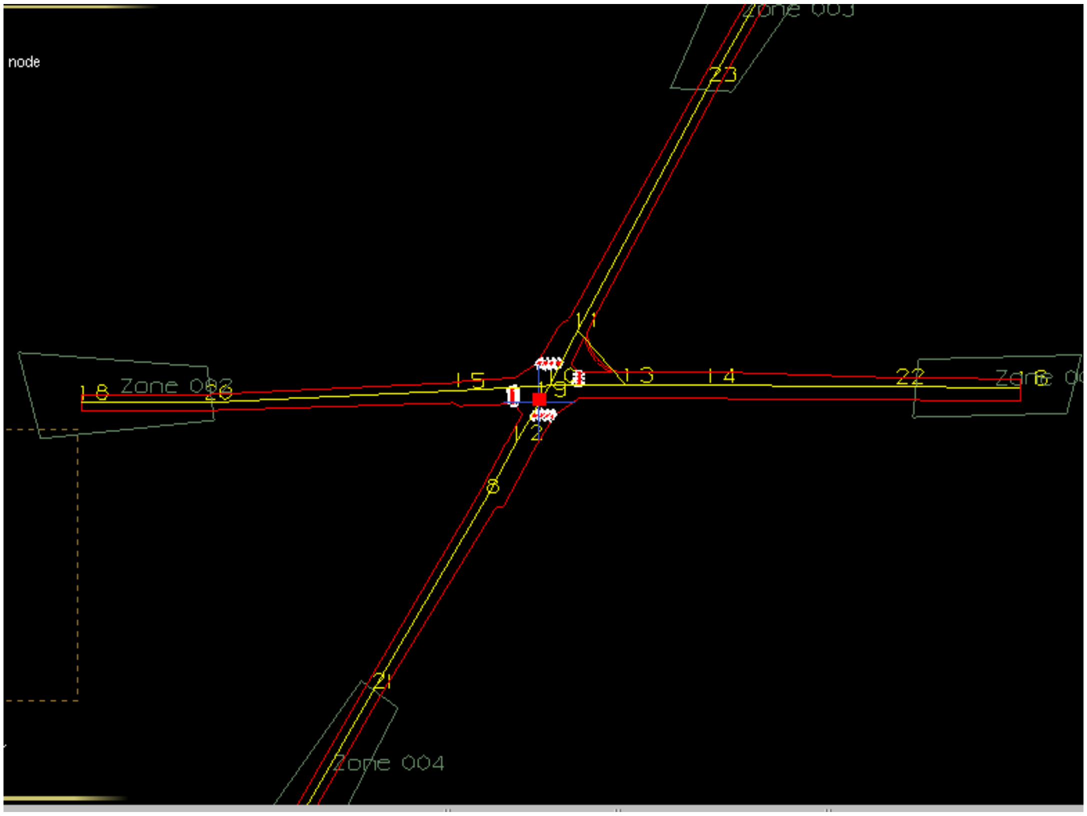


Figure 142. Screen Capture. PARAMICS Model of Roswell Road & Abernathy Road.

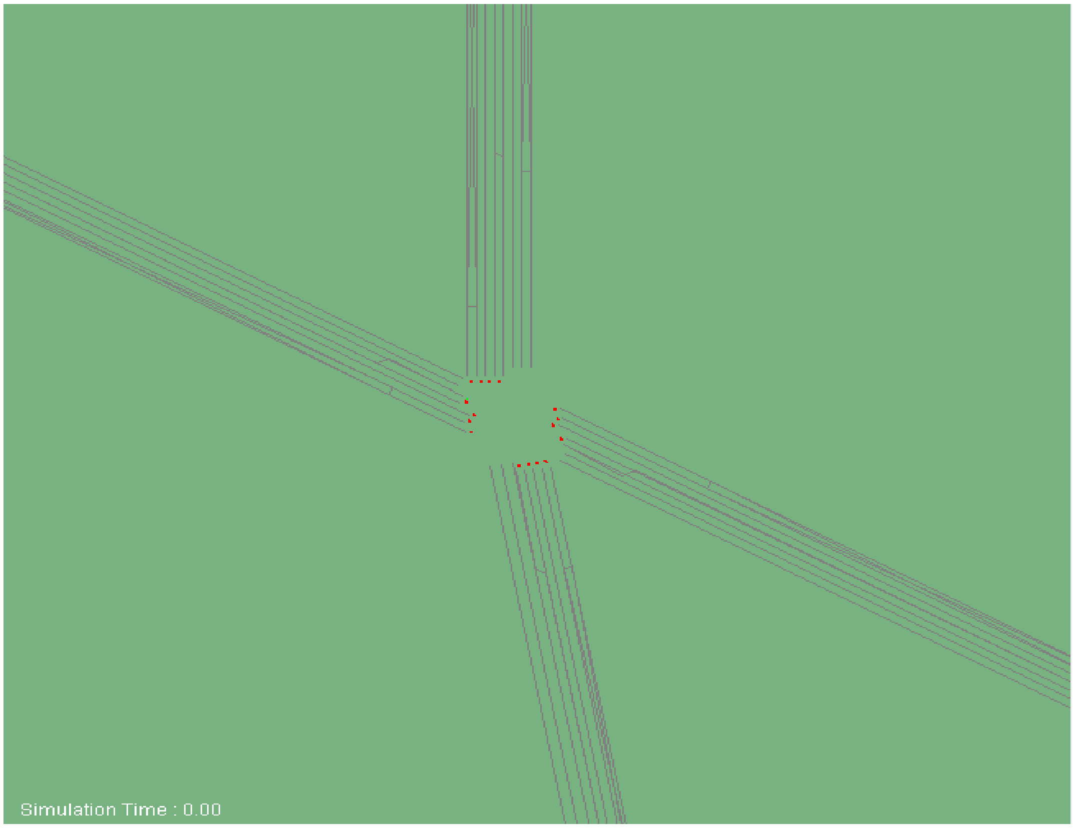


Figure 143. Screen Capture. TEXAS Model of Roswell Road & Abernathy Road.

Intersection 3: Lafayette Ave & Fulton Street, Grand Rapids, MI

This intersection was under semiactuated signal control and had two timing plans according to two peak-hour periods—AM peak and PM peak. Only S-N bound had independent left-turn bays, and there were no right-turn bays for any approach. Traffic volumes were around 1,900–2,400 vehicles per hour. The speed limit specified for all approaches was 48.3 km/h (30 mi/h), and the 4-year annual collision frequency for this intersection is about 33. Figure 144 shows a Google™ map view of this intersection. Figure 145 through figure 148 show the intersection layout modeled within each simulation platform.

Figure 144. Photo. Google™ Map View of Lafayette Ave & Fulton Street.

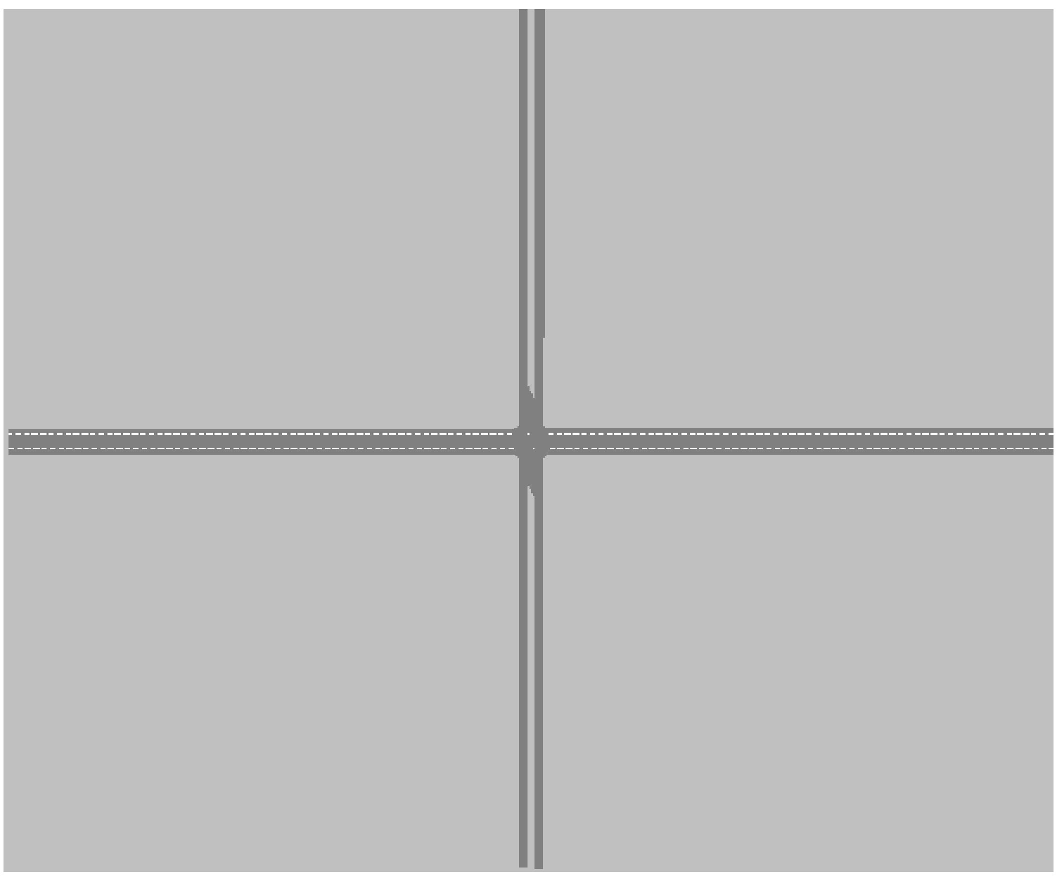


Figure 145. Screen Capture. VISSIM Model of Lafayette Ave & Fulton Street.

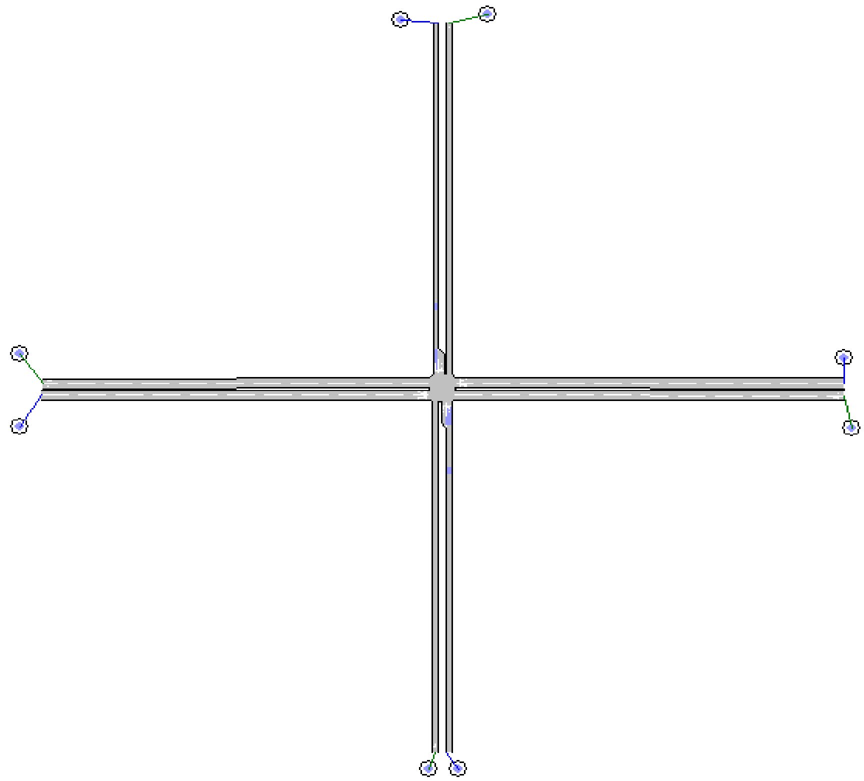


Figure 146. Screen Capture. AIMSUN Model of Lafayette Ave & Fulton Street.

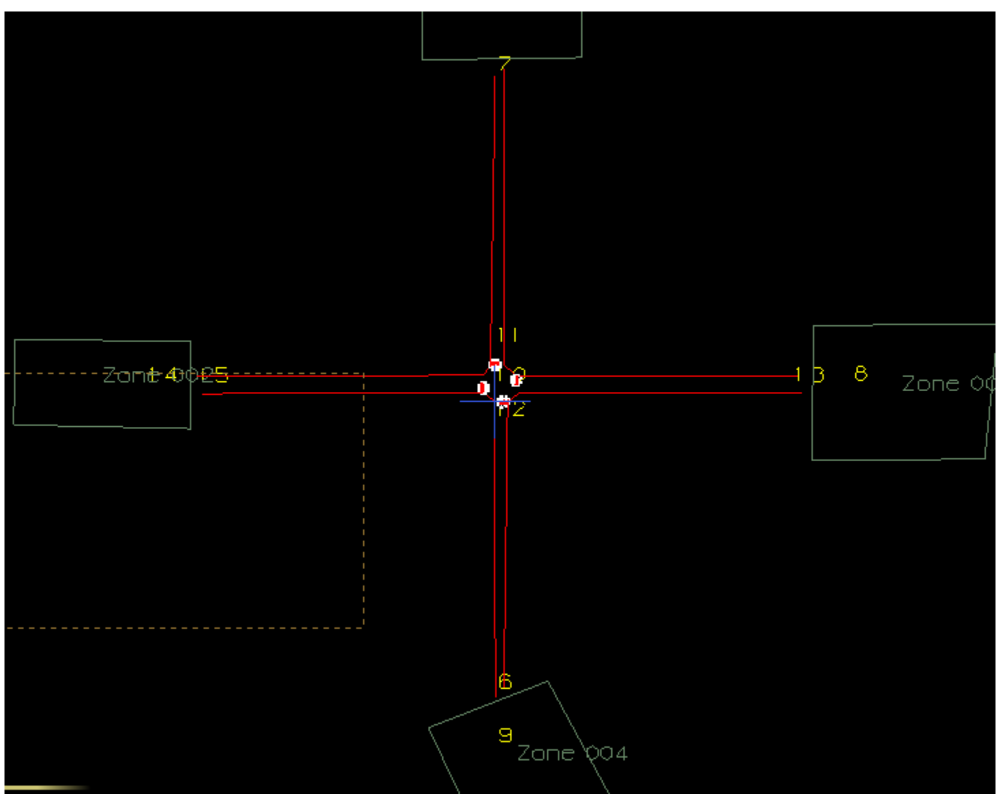


Figure 147. Screen Capture. PARAMICS Model of Lafayette Ave & Fulton Street.

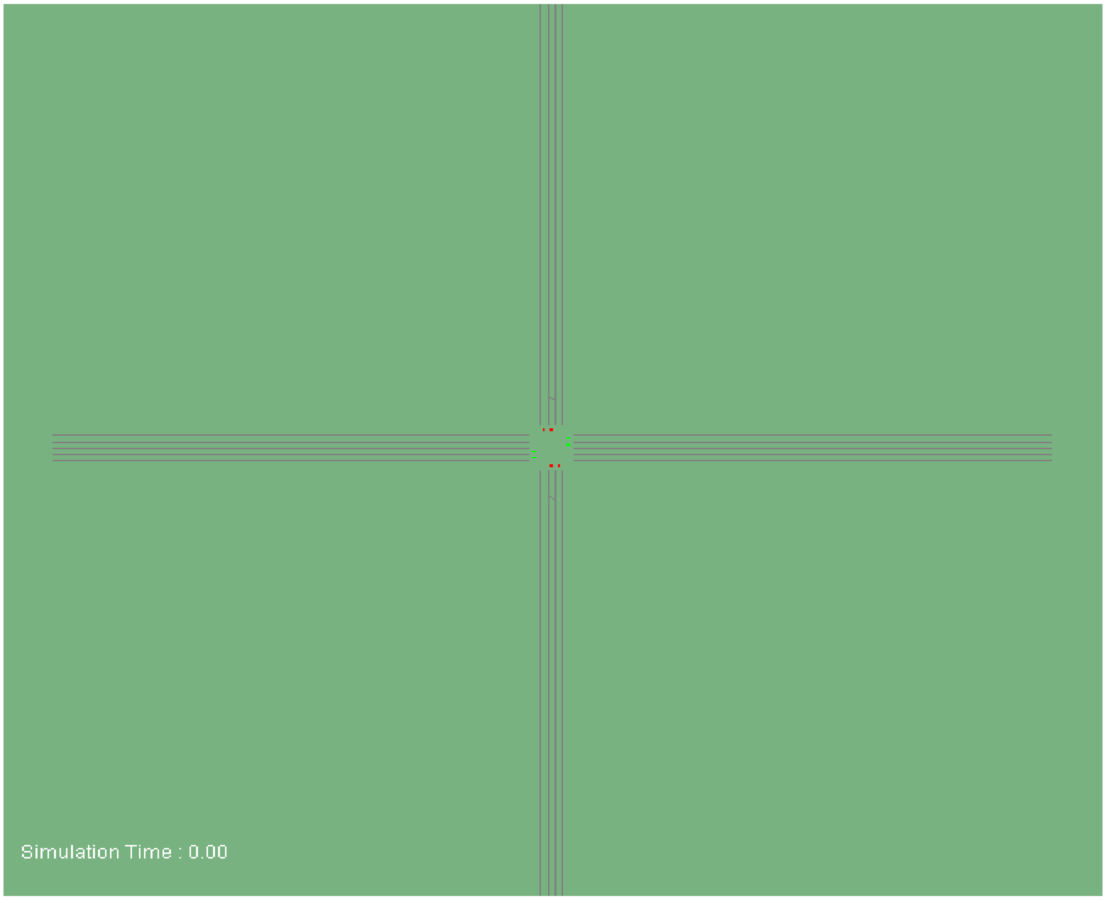


Figure 148. Screen Capture. TEXAS Model of Lafayette Ave & Fulton Street.

Intersection 4: Ryan Ave & Davison Ave, Detroit, MI

This intersection was under fixed-time signal control and had two timing plans according to two peak-hour periods—AM peak and PM peak. Only E-W bound had independent left-turn bays, and there were no right-turn bays for any approach. Traffic volumes were around 2,600–3,000 vehicles per hour. The speed limit specified for N-S approaches was 40.25 km/h (25 mi/h) while the E-W approaches had a 48.36-km/h (30-mi/hr) speed limit. The 2-year annual collision frequency for this intersection was about 20.5. Figure 149 shows a Google™ map view of this intersection. Figure 150 through figure 153 show the intersection layout modeled within each simulation platform.

Figure 149. Photo. Google™ Map View of Ryan Ave & Davison Ave.

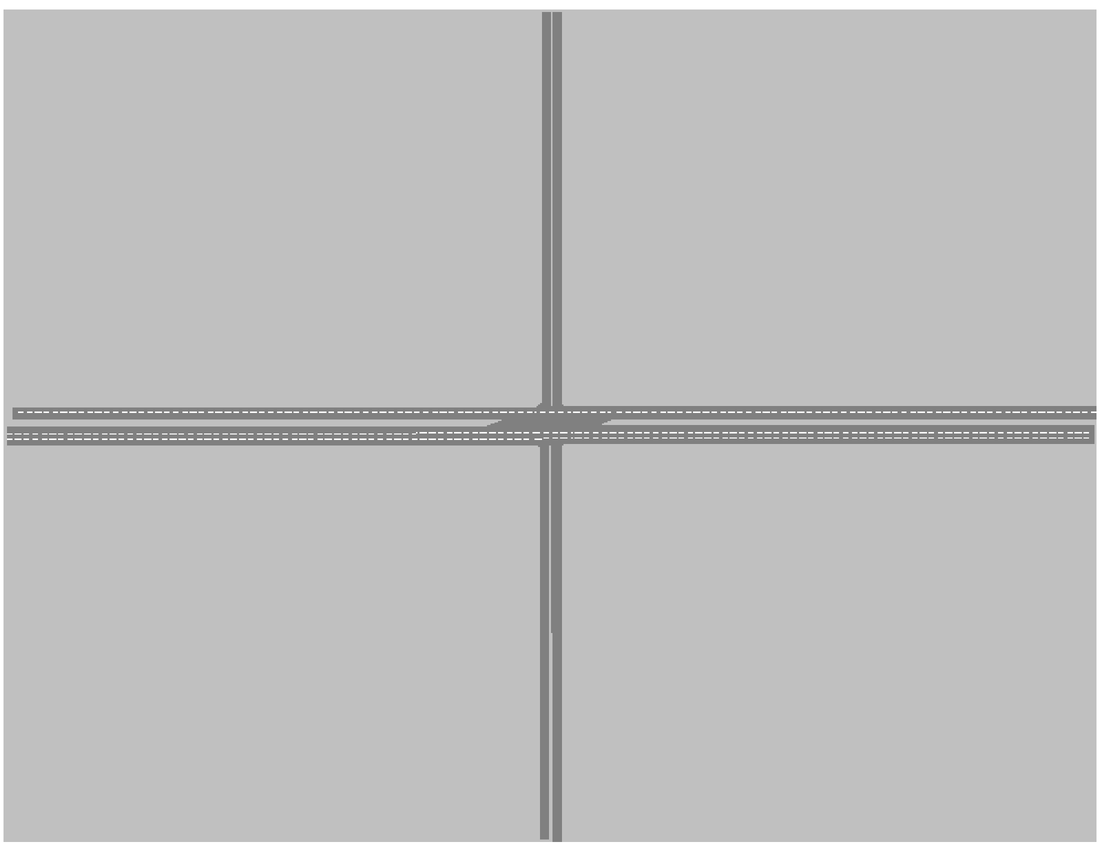


Figure 150. Screen Capture. VISSIM Model of Ryan Ave & Davison Ave.

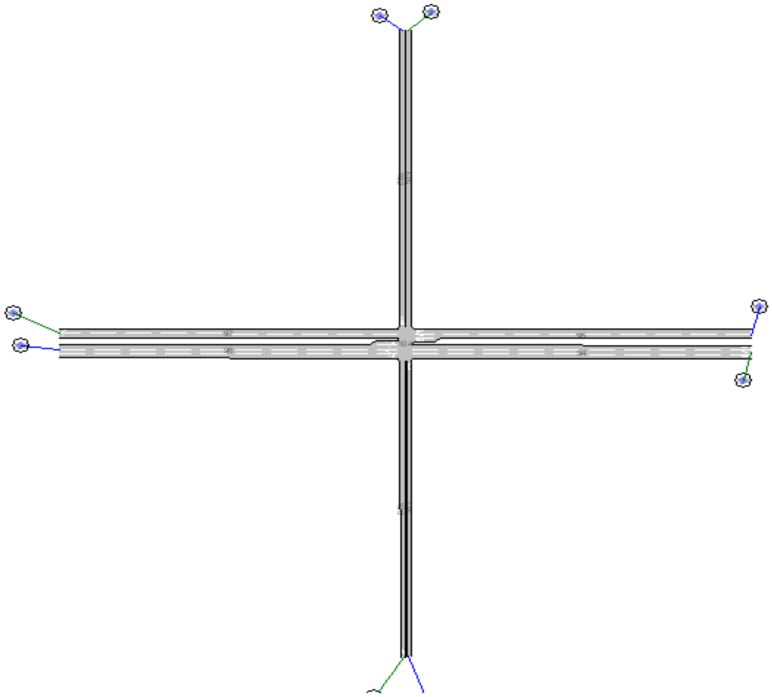


Figure 151. Screen Capture. AIMSUN Model of Ryan Ave & Davison Ave.

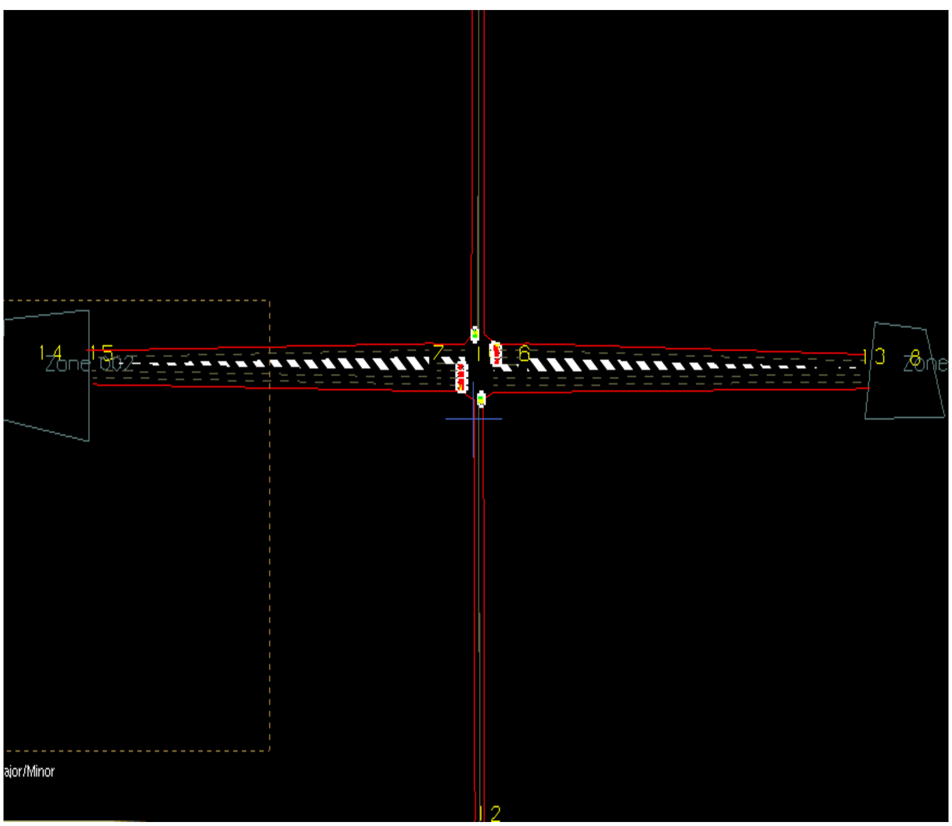


Figure 152. Screen Capture. PARAMICS Model of Ryan Ave & Davison Ave.

Figure 153. Screen Capture. TEXAS Model of Ryan Ave & Davison Ave.

Intersection 5: Howe Ave & Fair Oaks Boulevard, Sacramento, CA

This was a skewed intersection with independent left-turn bays and right-turn bays for all approaches. The intersection was under semiactuated signal control and had two timing plans according to two peak-hour periods—AM peak and PM peak. Traffic volumes were around 6,500–8,800 vehicles per hour. The speed limit specified for N-S approaches was 64.4 km/h (40 mi/h) while the E-W approaches had a 72.45-km/h (45-mi/h) speed limit. The 3-year annual collision frequency for this intersection was about 28.3. Figure 154 shows a Google™ map view of this intersection. Figure 155 through figure 158 show the intersection layout modeled within each simulation platform.

Figure 154. Photo. Google™ Map View of Howe Ave & Fair Oaks Boulevard.

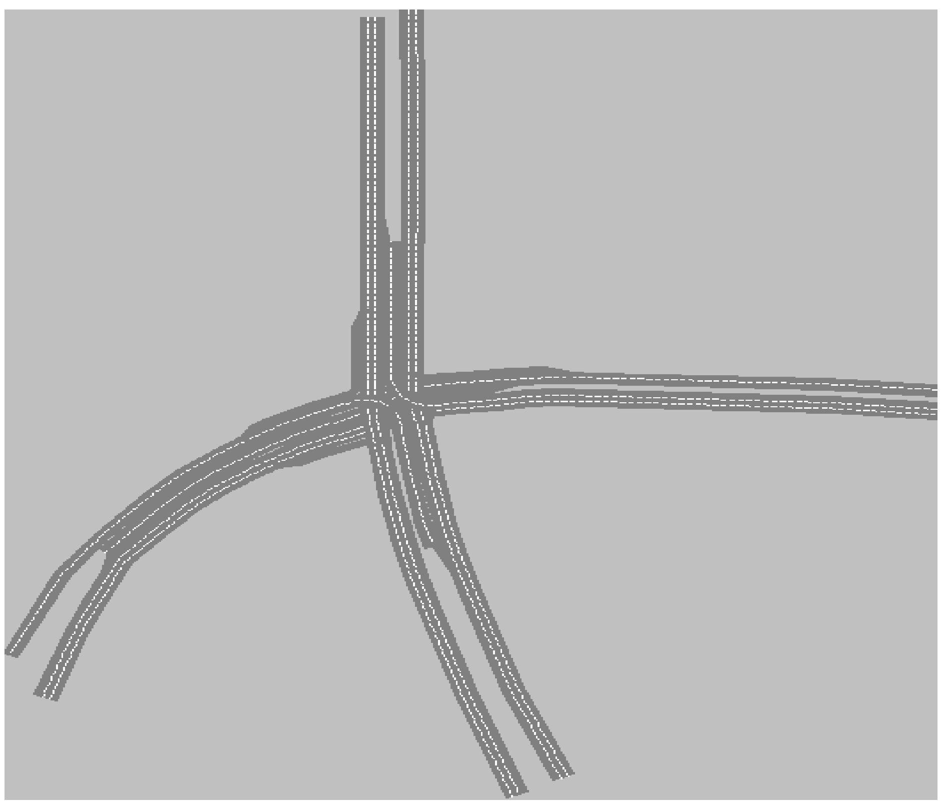


Figure 155. Screen Capture. VISSIM Model of Howe Ave & Fair Oaks Boulevard.

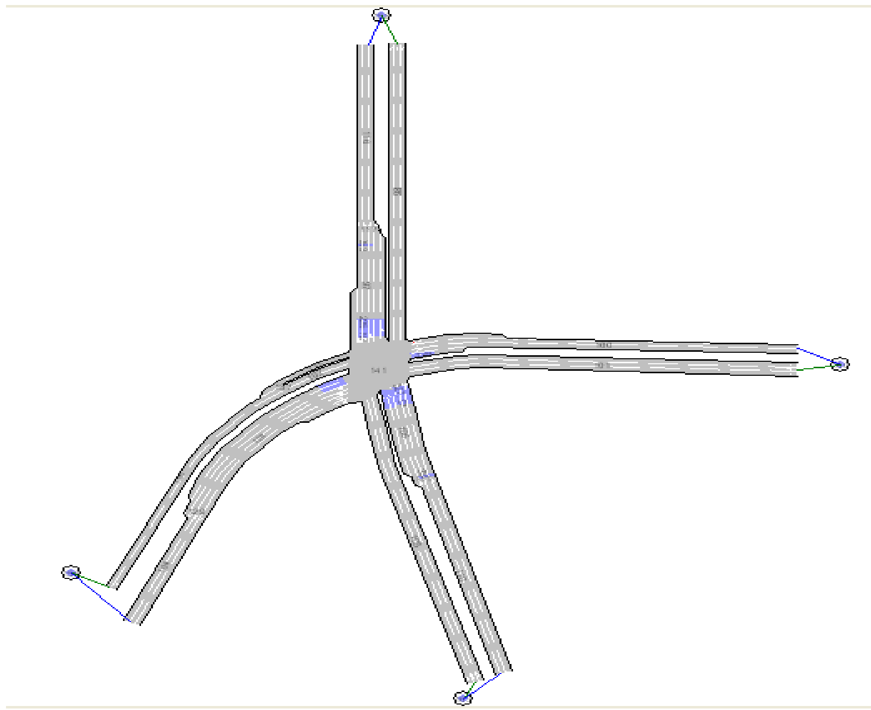


Figure 156. Screen Capture. AIMSUN Model of Howe Ave & Fair Oaks Boulevard.

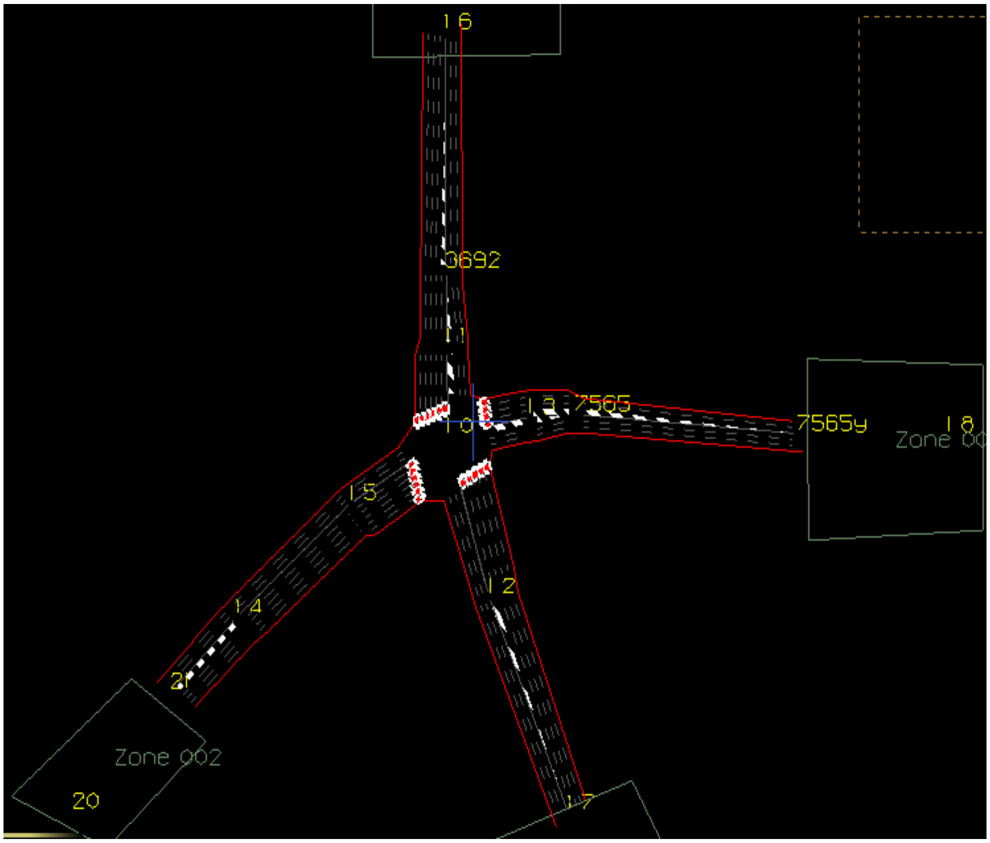


Figure 157. Screen Capture. PARAMICS Model of Howe Ave & Fair Oaks Boulevard.

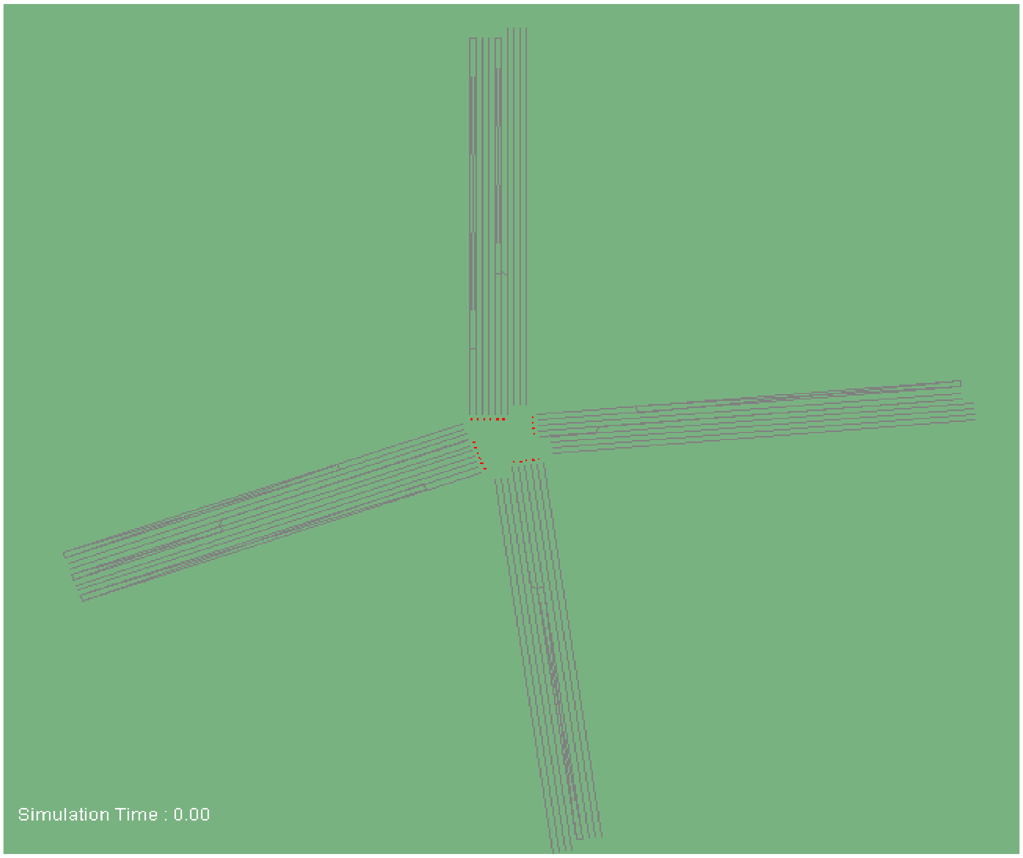


Figure 158. Screen Capture. TEXAS Model of Howe Ave & Fair Oaks Boulevard.

Data Analysis and Comparison Results

Number of Conflicts (Rate)

The number of conflicts was extracted from SSAM for each case. The conflicts rate is expressed as a ratio between number of conflicts and traffic volume. With modeling limitations from each simulation platform, total conflicts were filtered out by SSAM to obtain more accurate data, resulting in three set of conflicts: total conflicts, denoted as C-N1; conflicts without abnormal deceleration (max braking rate less than -9.15 m/sec^2 (-30 ft/sec^2)), denoted as C-N2; and non-crash (TTC > 0) and non-low-speed (max speed ≥ 16.1 km/h (10 mi/h)) conflicts without abnormal deceleration, denoted as C-N3. Conflicts within each TTC category were also tabulated and investigated.

Note that a maximum deceleration rate of 9.15 m/sec^2 (30 ft/sec^2) is considered very extreme. To put this in perspective, consider the results of the recent testing of several fleet vehicles by the Michigan State Police where it was found that among all vehicles tested (including motorcycles), the maximum deceleration rate obtained in was just under 9.15 m/sec^2 (30 ft/sec^2), with emergency (panic) braking conditions using vehicles equipped with anti-lock braking systems (ABS).[(33)]

Intersection 1: Briarcliff Rd & North Druid Hills Rd, Dekalb County, Atlanta, GA:

The number of conflicts/conflict rates under AM, mid, and PM peak-hour conditions was tabulated and is shown in table 93 through table 104. Column charts were created to compare the conflicts number generated from the four simulation platforms, as seen in figure 159 through figure 182.

As shown in the following tables and figures, for all simulation models, most of the conflicts were rear-end conflicts, and crossing conflicts were the least conflicts among all conflicts types. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. The differences among the four simulation models were the following:

- VISSIM had the least conflict number for all categories. TEXAS had the most conflict number for all categories. TEXAS had more than 10 times the conflicts of VISSIM.
- The ascending ranking order in most cases was VISSIM, AIMSUN, PARAMICS, TEXAS. However, the order for C-N3 was VISSIM, PARAMICS, AIMSUN, TEXAS, implying AIMSUN had a higher percentage of low-speed conflicts or crashes than PARAMICS.
- VISSIM and TEXAS had no abnormal deceleration maneuvers while AIMSUN and PARAMICS had 20 to 30 percent conflicts with abnormal deceleration. Most of the abnormal deceleration maneuvers were from rear-end conflicts. More than half of the conflicts with abnormal deceleration had TTC ≥ 1.0.
- Less than 40 percent of the conflicts from VISSIM and AIMSUN were low-speed or crash events; PARAMICS and TEXAS had a higher percentage of low-speed or crash events (60 to 75 percent). Most of the low-speed conflicts were rear-end conflicts.
- More than half of the conflicts in all simulation platforms were less severe conflicts (conflicts with TTC ≥ 0.5), while in PARAMICS, the percentage of severe conflicts was the highest among all of the simulation platforms (based on comparison of C-N2).

Table 93. Conflicts Number Under AM Peak-Hour Condition for Intersection 1.

4,365 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	72.7/1.67**	72.7/1.67	47.6/1.09	19.1/0.44	19.1/0.44	5.7/0.13	16.2/0.37	16.2/0.37	3/0.07
AIMSUN	436.6/10	300.4/6.88	182.8/4.19	236.3/5.41	181.7/4.16	98.8/2.26	90.4/2.07	63.8/1.46	9.2/0.21
PARAMICS	578.4/13.25	412.4/9.45	114.1/2.61	372.2/8.53	300.9/6.89	37.4/0.86	308.3/7.06	268.6/6.15	15.1/0.35
TEXAS	2,138.7/49	2,138.5/48.99	812.5/18.61	857.8/19.6	857.6/19.65	372.1/8.53	413.6/9.48	413.5/9.47	67.7/1.55
Crossing Conflicts									
VISSIM	0.9/0.02	0.9/0.02	0.4/0.01	0.5/0.01	0.5/0.01	0//0	0.5/0.01	0.5/0.01	0/0
AIMSUN	5.5/0.13	3.9/0.09	3.6/0.08	3.5/0.08	3/0.07	2.7/0.06	0.8/0.02	0.6/0.01	0.3/0
PARAMICS	47.3/1.08	43.9/1.01	2.5/0.06	46/1.05	42.8/0.98	1.4/0.03	44.8/1.03	42/0.96	0.6/0.01
TEXAS	123.7/2.83	123.7/2.83	10/0.23	118.5/2.72	118.5/2.72	5.1/0.12	117.2/2.69	117.2/2.69	3.9/0.09
Rear-End Conflicts									
VISSIM	57.5/1.32	57.5/1.32	40.4/0.93	7.8/0.18	7.8/0.18	1.4/0.03	6.5/0.15	6.5/0.15	0.2/0
AIMSUN	364.1/8.34	256.7/5.88	150.6/3.45	206.5/4.73	157.2/3.6	82.2/1.88	83.4/1.91	58.4/1.34	8.1/0.19
PARAMICS	488.5/11.19	330.5/7.57	98.2/2.25	295/6.76	229.6/5.26	30.4/0.7	239.3/5.48	203.5/4.66	13.2/0.3
TEXAS	1921/44.01	1920.9/44.01	774.9/17.75	665.9/15.26	665.8/15.25	352.8/8.08	232.7/5.33	232.7/5.33	56.8/1.3
Lane-Changing Conflicts									
VISSIM	14.3/0.33	14.3/0.33	6.8/0.16	10.8/0.25	10.8/0.25	4.3/0.1	9.2/0.21	9.2/0.21	2.8/0.06
AIMSUN	66/1.51	39.8/0.91	28.6/0.66	26.3/0.6	21.5/0.5	13.9/0.32	6.2/0.14	4.8/0.11	0.8/0.02
PARAMICS	42.6/0.98	38/0.87	13.4/0.31	31.2/0.71	28.5/0.65	5.6/0.13	24.2/0.55	23.1/0.53	1.3/0.03
TEXAS	94/2.15	93.9/2.15	27.6/0.63	73.4/1.68	73.3/1.68	14.2/0.33	63.7/1.46	63.6/1.46	7/0.16

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).
** 72.7 is the conflict number, while 1.67 is the conflict rate, which is the outcome of 72.7 divided by the traffic volume.

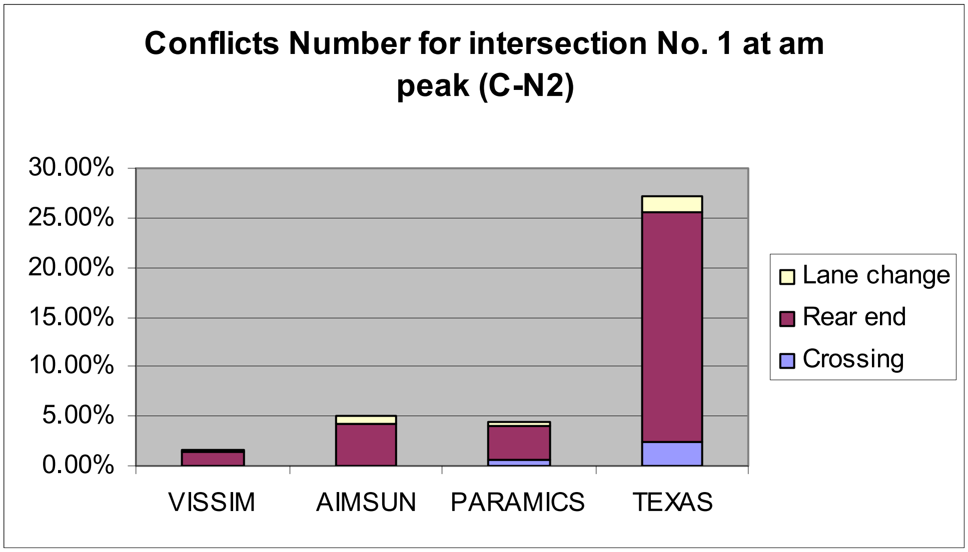


Figure 159. Graph. Conflicts Number C-N2 Comparison for Intersection 1 at AM Peak.

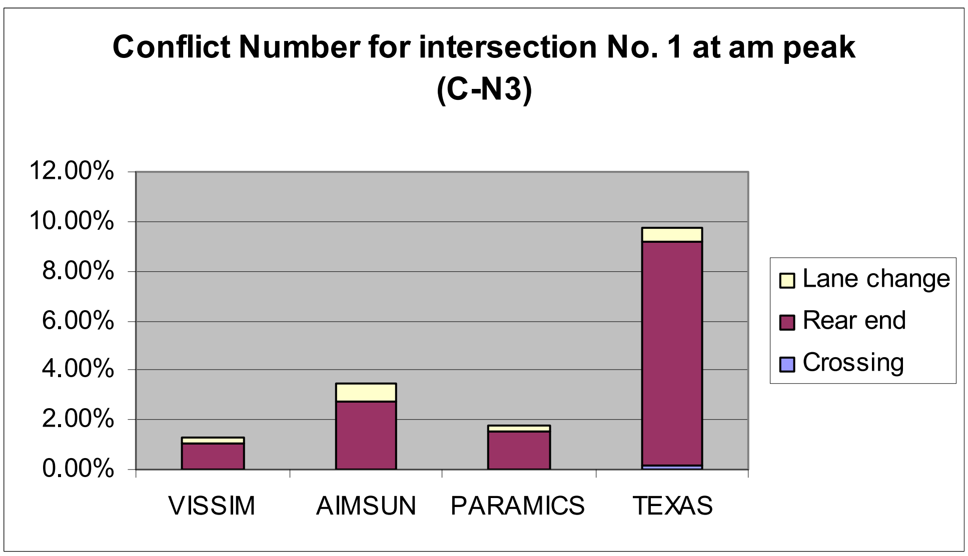


Figure 160. Graph. Conflicts Number C-N3 Comparison for Intersection 1 at AM Peak.

Table 94. Conflicts Number Under Mid Peak-Hour Condition for Intersection 1.

4,640 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	74.7/1.61	74.7/1.61	59.3/1.28	14.9/0.32	14.9/0.32	6.2/0.13	11.9/0.26	11.9/0.26	3.5/0.08
AIMSUN	310/6.68	231.6/4.99	160.1/3.45	190.7/4.11	146.7/3.16	88.7/1.91	190.7/4.11	64.3/1.39	16.5/0.36
PARAMICS	340.1/7.33	208.6/4.5	81.4/1.75	145.45/3.14	109.6/2.36	21/0.45	111/2.39	96.7/2.08	13.1/0.28
TEXAS	1,264.8/27.26	1,264.8/27.26	451.7/9.73	679.4/14.64	679.4/14.64	233.7/5.04	436.8/9.41	436.8/9.41	69.3/1.49
Crossing Conflicts									
VISSIM	2.1/0.05	2.1/0.05	1/0.02	1.2/0.03	1.2/0.03	0.1/0	1.2/0.03	1.2/0.03	0.1/0
AIMSUN	3.3/0.07	2.2/0.05	1.8/0.04	2.3/0.05	1.7/0.04	1.3/0.03	2.3/0.05	1/0.02	0.6/0.01
PARAMICS	31.7/0.68	27.9/0.6	0.8/0.02	35.7/0.77	31.8/0.69	0.7/0.02	35.6/0.77	31.7/0.68	0.6/0.01
TEXAS	109.1/2.35	109.1/2.35	7.5/0.16	106.3/2.29	106.3/2.29	4.8/0.10	104.8/2.26	104.8/2.26	3.4/0.07
Rear-End Conflicts									
VISSIM	59.1/1.27	59.1/1.27	48.8/1.05	5.1/0.11	5.1/0.11	0.9/0.02	4.4/0.09	4.4/0.09	0.3/0.01
AIMSUN	252/5.43	190.2/4.1	126.2/2.72	160.3/3.45	122.9/2.65	70.7/1.52	160.3/3.45	58.3/1.26	14.3/0.31
PARAMICS	284.3/6.13	159.5/3.44	68.6/1.48	95.1/2.05	64.4/1.39	6.3/0.14	63/1.36	52.9/1.14	7/0.15
TEXAS	1,075.8/23.19	1,075.8/23.19	418.3/9.02	511.7/11.03	511.7/11.03	217.7/4.69	277.9/5.99	277.9/5.99	59.1/1.27
Lane-Changing Conflicts									
VISSIM	13.5/0.29	13.5/0.29	9.5/0.2	8.6/0.19	8.60.19	5.2/0.11	6.3/0.14	6.3/0.14	3.1/0.07
AIMSUN	54.7/1.18	39.2/0.84	32.1/0.69	28.1/0.61	22.1/0.48	16.7/0.36	28.1/0.61	5/0.11	1.6/0.03
PARAMICS	24.1/0.52	21.2/0.46	12/0.26	14.7/0.32	13.4/0.29	6.3/0.14	12.4/0.27	12.1/0.26	5.5/0.12
TEXAS	79.9/1.72	79.9/1.72	25.9/0.56	61.4/1.32	61.4/1.32	11.2/0.24	54.1/1.17	54.1/1.17	6.8/0.15

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

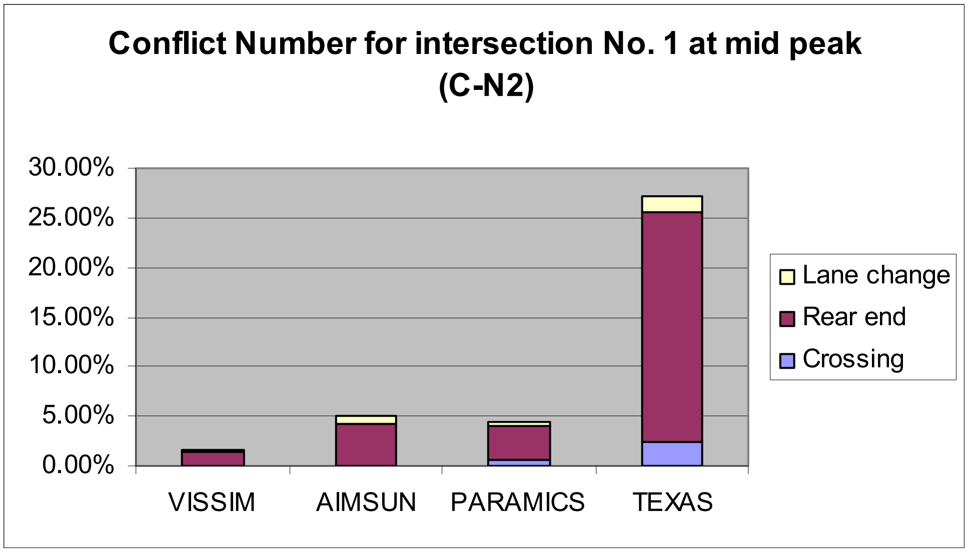


Figure 161. Graph. Conflicts Number C-N2 Comparison for Intersection 1 at Mid Peak.

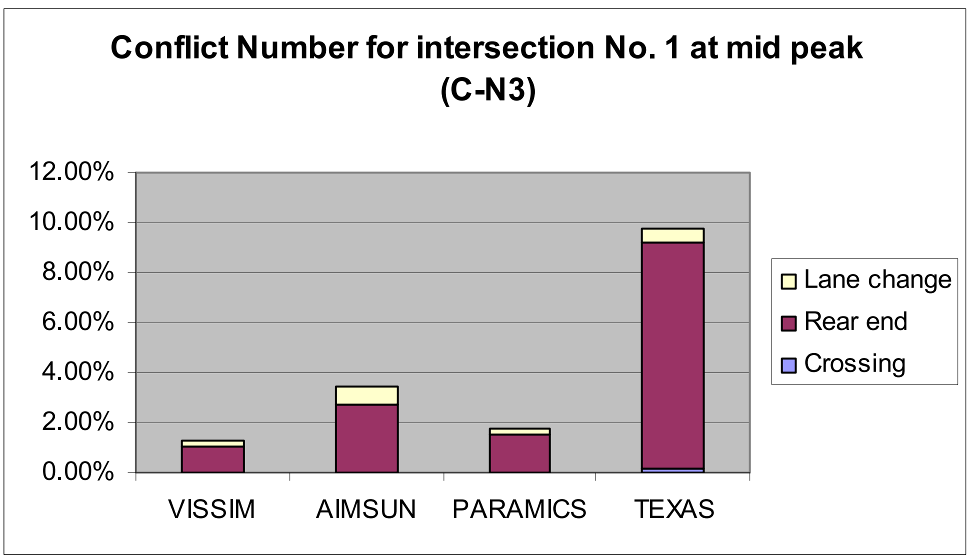


Figure 162. Graph. Conflicts Number C-N3 Comparison for Intersection 1 at Mid Peak.

Table 95. Conflicts Number Under PM Peak-Hour Condition for Intersection 1.

4,790 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	44.7/0.93	44.7/0.93	38.4/0.8	5.4/0.11	5.4/0.11	2.4/0.05	4.1/0.09	4.1/0.09	1.5/0.03
AIMSUN	177.1/36.97	152.4/3.18	111.9/2.34	109.4/2.28	93.5/1.95	59.8/1.25	52.9/1.1	43.9/0.92	13.5/0.28
PARAMICS	285.9/5.97	180.2/3.76	62.2/1.3	145.5/3.04	109.6/2.29	21/0.44	111/2.32	96.7/2.02	13.1/0.27
TEXAS	760.2/15.87	760.1/15.87	283.9/5.93	503.2/10.51	503.1/10.5	170.3/3.56	400.1/8.35	400/8.35	97.8/2.04
Crossing Conflicts									
VISSIM	1.4/0.03	1.4/0.03	0.94/0.02	1.2/0.03	1.2/0.03	0.3/0.01	1/0.02	1/0.02	0.1/0
AIMSUN	1.6/0.03	0.9/0.02	0.7/0.01	1.2/0.03	0.7/0.01	0.5/0.01	0.5/0.01	0.4/0.01	0.2/0
PARAMICS	36/0.75	32.1/0.67	1/0.02	35.7/0.75	31.8/0.66	0.7/0.01	35.6/0.74	31.7/0.66	0.6/0.01
TEXAS	87.9/1.84	87.9/1.84	6.6/0.14	85.1/1.78	85.1/1.78	3.9/0.08	83.8/1.75	83.8/1.75	2.6/0.05
Rear-End Conflicts									
VISSIM	37.6/0.78	37.60.78	33.5/0.7	1.6/0.03	1.6/0.03	0.5/0.01	1.1/0.02	1.1/0.02	0.3/0.01
AIMSUN	146.6/3.06	126.9/2.65	88.7/1.85	93.9/1.96	79.4/1.66	47/0.98	49.9/1.04	41.3/0.86	11.8/0.25
PARAMICS	225.8/4.71	127.7/2.67	49.4/1.03	95.1/1.99	64.4/1.34	14/0.29	63/1.32	52.9/1.1	7/0.15
TEXAS	619.4/12.93	619.4/12.93	262.5/5.48	375.6/7.84	375.6/7.84	158.7/3.31	277.9/5.8	277.9/5.8	91.1/1.9
Lane-Changing Conflicts									
VISSIM	5.7/0.12	5.7/0.12	4.4/0.09	2.6/0.05	2.6/0.05	1.6/0.03	2/0.04	2/0.04	1.1/0.02
AIMSUN	28.9/0.6	24.6/0.51	22.5/0.47	14.3/0.3	13.4/0.28	12.3/0.26	2.5/0.05	2.2/0.05	1.5/0.03
PARAMICS	24.1/0.5	20.4/0.43	11.8/0.25	14.7/0.31	13.4/0.28	6.3/0.13	12.4/0.26	12.1/0.25	5.5/0.11
TEXAS	52.9/1.1	52.8/1.1	14.8/0.31	42.5/0.89	42.4/0.89	7.7/0.16	38.4/0.8	38.3/0.8	4.1/0.09

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

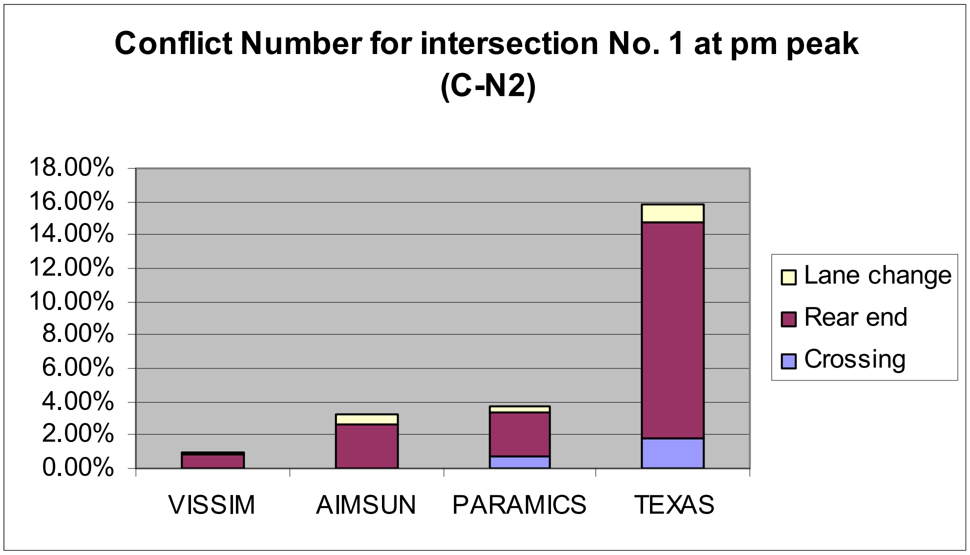


Figure 163. Graph. Conflicts Number C-N2 Comparison for Intersection 1 at PM Peak.

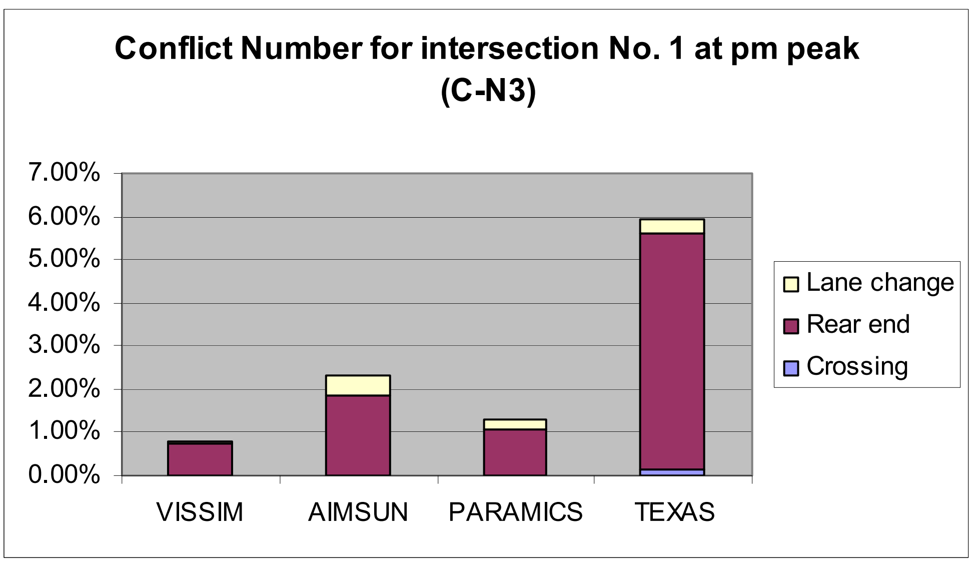


Figure 164. Graph. Conflicts Number C-N3 Comparison for Intersection 1 at PM Peak.

Intersection 2: Roswell Road & Abernathy Road, Fulton County, Atlanta, GA:

The number of conflicts/conflict rates under AM, mid, and PM peak-hour conditions was tabulated and is shown in table 96 to table 98. Column charts were created to compare the conflicts number generated from the four simulation platforms, as seen in figure 165 through figure 170.

As shown in the following tables and figures, for all simulation models, most of the conflicts were rear-end conflicts, and crossing conflicts were the least conflicts among all conflicts types. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. Most of the low-speed conflicts were rear-end conflicts. The differences among the four simulation models were the following:

- VISSIM had the least conflict number for all categories. TEXAS had the most conflict number for all categories. TEXAS had 10 times more conflicts than VISSIM.
- The ascending ranking order in most cases was VISSIM, PARAMICS, AIMSUN, TEXAS. However, for the TTC < 0.5 category, the order was VISSIM, PARAMICS, AIMSUN, TEXAS, implying that PARAMICS had a higher percentage of severe conflicts than AIMSUN.
- VISSIM and TEXAS had almost no abnormal deceleration maneuvers, while AIMSUN and PARAMICS had 10 to 30 percent conflicts with abnormal deceleration. Most of the abnormal deceleration maneuvers were from rear-end conflicts. Conflicts with abnormal deceleration were almost evenly distributed in the three TTC categories for AIMSUN. While in PARAMICS, more than half of the conflicts with abnormal deceleration had a TTC ≥ 1.0.
- Most of the conflicts in TEXAS and AIMSUN were less severe conflicts (conflicts with TTC ≥ 0.5), while in PARAMICS and VISSIM most conflicts were severe conflicts (conflicts with TTC < 0.5) (based on comparison of C-N2).
- The percentage of lane-change conflicts in TEXAS was the smallest.

Table 96. Conflicts Number Under AM Peak-Hour Condition for Intersection 2.

5,260 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	189.3/3.6	189.3/3.6	85.8/1.63	92.9/1.77	92.9/1.77	14.4/0.27	82.9/1.58	82.9/1.58	7.2/0.14
AIMSUN	1091.3/20.75	914.9/17.39	493.8/9.39	548.5/10.43	449.7/8.55	232.2/4.41	138.8/2.64	91.3/1.74	23.6/0.45
PARAMICS	728.6/13.85	515.3/9.8	207.7/3.95	438.7/8.34	347.1/6.6	89.5/1.7	337.2/6.41	283.6/5.39	34.4/0.65
TEXAS	2,679.8/50.95	2,679.8/50.95	991.7/18.85	1,164.7/22.14	1,164.7/22.14	487.7/9.27	559/10.63	559/10.63	92.5/1.76
Crossing Conflicts									
VISSIM	1.3/0.02	1.3/0.02	0/0	1.3/0.02	1.3/0.02	0/0	1.3/0.02	1.3/0.02	0/0
AIMSUN	14.4/0.27	8.9/0.17	7.2/0.14	11.5/0.22	6.7/0.13	5.7/0.11	4.5/0.09	2.8/0.05	2.2/0.04
PARAMICS	12.2/0.23	10.7/0.2	0.5/0.01	11.8/0.22	10.4/0.2	0.2/0	11.6/0.22	10.2/0.19	0/0
TEXAS	109.1/2.07	109.1/2.07	13.8/0.26	103/1.96	103/1.96	8.4/0.16	98.3/1.87	98.3/1.87	3.9/0.07
Rear-End Conflicts									
VISSIM	141.4/2.69	141.4/2.69	66.5/1.26	58.3/1.11	58.3/1.11	4.9/0.09	53.2/1.01	53.2/1.01	1.6/0.03
AIMSUN	899.5/17.1	742/14.11	376.9/7.17	434.6/8.26	348.2/6.62	169.1/3.21	115.4/2.19	71.4/1.36	11.9/0.23
PARAMICS	653.8/112.43	449.5/8.55	181.4/3.45	382.3/7.27	296.8/5.64	77/1.46	290.8/5.53	241.9/4.6	29.8/0.57
TEXAS	2,360.8/44.88	2,360.8/44.88	931.2/17.7	892.1/16.96	892.1/16.96	452.9/8.61	311.6/5.92	311.6/2.92	75.4/1.43
Lane-Changing Conflicts									
VISSIM	46.6/0.89	46.6/0.89	19.3/0.37	33.3/0.63	33.3/0.63	9.5/0.18	28.4/0.54	28.4/0.54	5.6/0.11
AIMSUN	177.4/3.37	164/3.12	109.7/2.09	102.4/1.95	94.8/1.8	57.4/1.09	18.9/0.36	17.1/0.33	9.5/0.18
PARAMICS	62.6/1.19	55.1/1.05	25.8/0.49	44.6/0.85	39.9/0.76	12.3/0.23	24.8/0.66	31.5/0.6	4.6/0.09
TEXAS	209.9/3.99	209.9/3.99	46.7/0.89	169.6/3.22	169.6/3.22	26.4/0.5	149.1/2.83	149.1/2.83	13.2/0.25

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

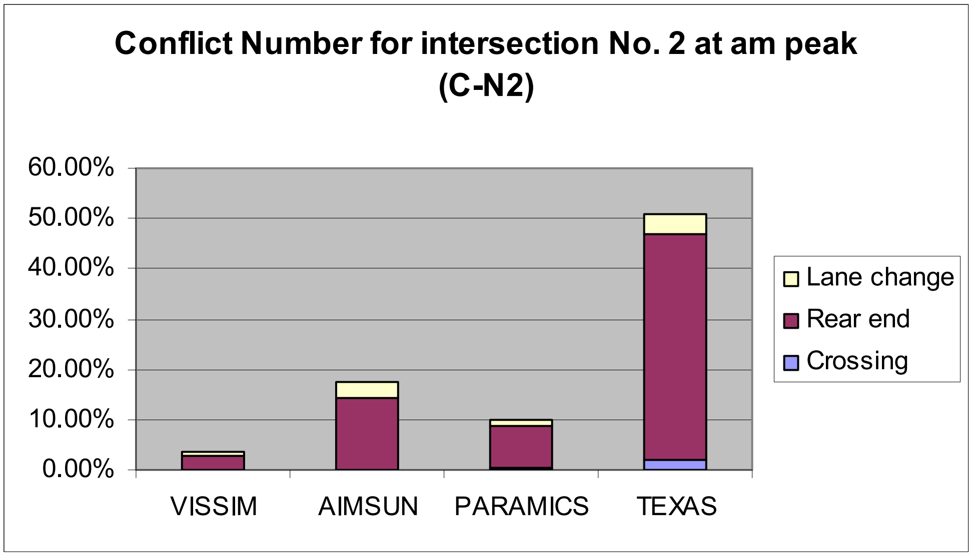


Figure 165. Graph. Conflicts Number C-N2 Comparison for Intersection 2 at AM Peak.

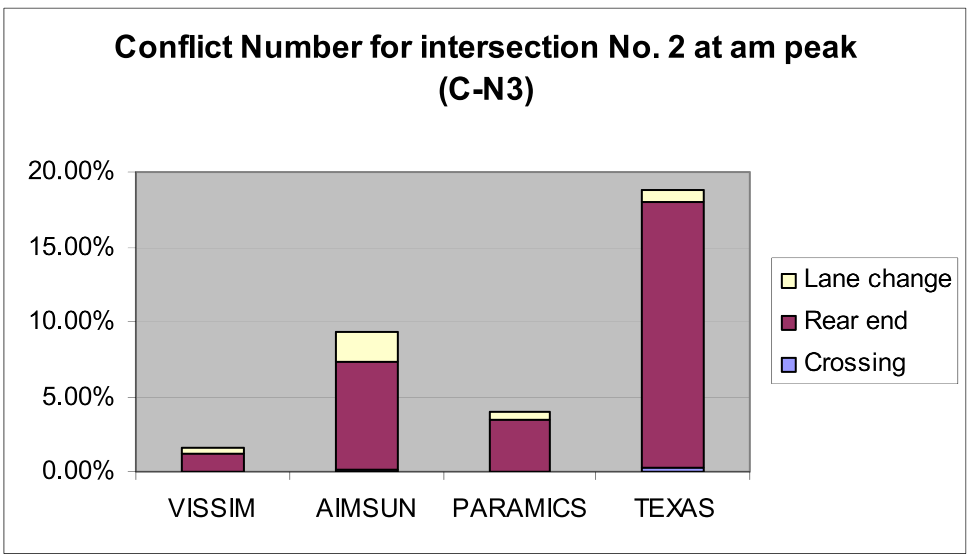


Figure 166. Graph. Conflicts Number C-N3 Comparison for Intersection 2 at AM Peak.

Table 97. Conflicts Number Under Mid Peak-Hour Condition for Intersection 2.

5,685 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	246.3/4.33	246.3/4.33	107.2/1.89	114.7/2.02	114.7/2.02	13.7/0.24	104.3/1.83	104.3/1.83	7.1/0.12
AIMSUN	1173.9/20.65	1021.2/17.96	622.6/10.95	628.2/11.05	531/9.34	308.4/5.42	135.1/2.38	80.8/1.42	19.8/0.35
PARAMICS	989.1/17.4	692.8/12.19	271/4.77	576.1/10.13	457.8/8.05	105.1/1.85	452.6/7.96	358.1/6.77	45.5/0.8
TEXAS	5,101.6/89.74	5,101.6/89.74	1,197.3/21.06	1,735/30.52	1,735/30.52	574.4/10.1	818.8/14.4	818.8/14.4	130.9/2.3
Crossing Conflicts									
VISSIM	2.8/0.05	2.8/0.05	0.2/0	2.6/0.05	2.6/0.05	0/0	2.6/0.05	2.6/0.05	0/0
AIMSUN	7.9/0.14	6/0.11	3.8/0.07	5.4/0.09	4/0.07	2.5/0.04	2.5/0.04	1.8/0.03	0.3/0.01
PARAMICS	18.4/0.32	15.8/0.28	1.6/0.03	17.4/0.31	14.9/0.26	0.9/0.02	16.5/0.29	14.2/0.25	0.2/0
TEXAS	113.2/1.99	113.2/1.99	13.1/0.23	107.5/1.89	107.5/1.89	7.9/0.14	103.7/1.82	103.7/1.82	4.2/0.07
Rear-End Conflicts									
VISSIM	181.2/3.19	181.2/3.19	84.5/1.49	70.8/1.25	70.8/1.25	6/0.11	64.8/1.14	64.8/1.14	2.3/0.04
AIMSUN	967.6/17.02	827.9/14.56	489.9/8.62	504.5/8.87	413.6/7.28	238.2/4.19	118.3/2.08	65.9/1.16	12.8/0.23
PARAMICS	880.4/15.49	595.3/10.47	245.3/4.31	489.1/8.6	378.4/6.66	94.4/1.66	375.2/6.6	313.5/5.51	41.9/0.74
TEXAS	4,585.7/80.66	4,585.7/80.66	1,107.8/19.49	1,309/23.03	1,309/23.03	522.3/9.19	425.8/7.49	425.8/7.49	99.7/1.75
Lane-Changing Conflicts									
VISSIM	62.3/1.1	62.3/1.1	22.5/0.4	41.3/0.73	41.3/0.73	7.7/0.14	36.9/0.65	36.9/0.65	4.8/0.08
AIMSUN	198.4/3.49	187.3/3.29	128.9/2.27	118.3/2.08	113.4/1.99	67.7/1.19	14.3/0.25	13.1/0.23	6.7/0.12
PARAMICS	90.3/1.59	81.7/1.44	24.1/0.42	69.6/1.22	64.5/1.13	9.8/0.17	60.9/1.07	57.4/1.01	3.4/0.06
TEXAS	402.7/7.08	402.7/7.08	76.4/1.34	318.5/5.6	318.5/5.6	44.2/0.78	289.3/5.09	289.3/5.09	27/0.47

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

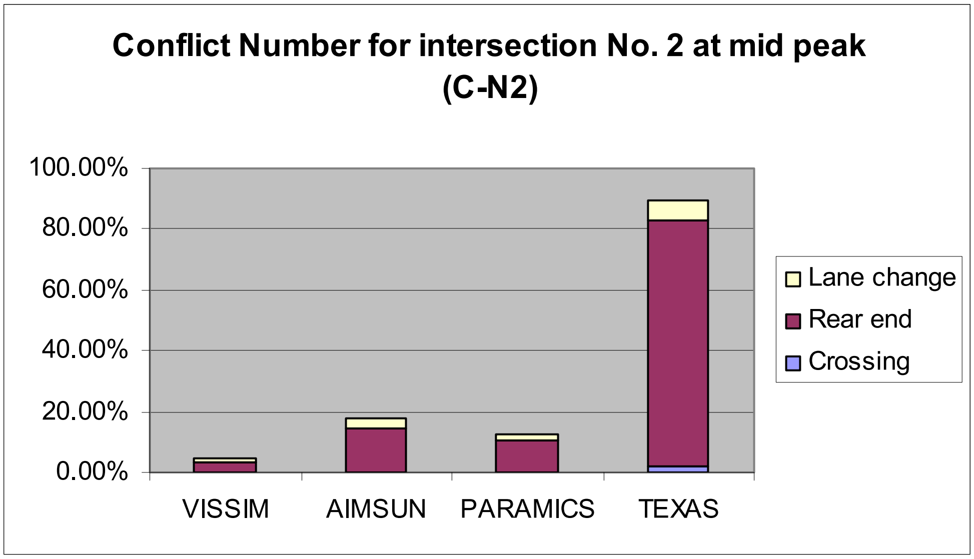


Figure 167. Graph. Conflicts Number C-N2 Comparison for Intersection 2 at Mid Peak.

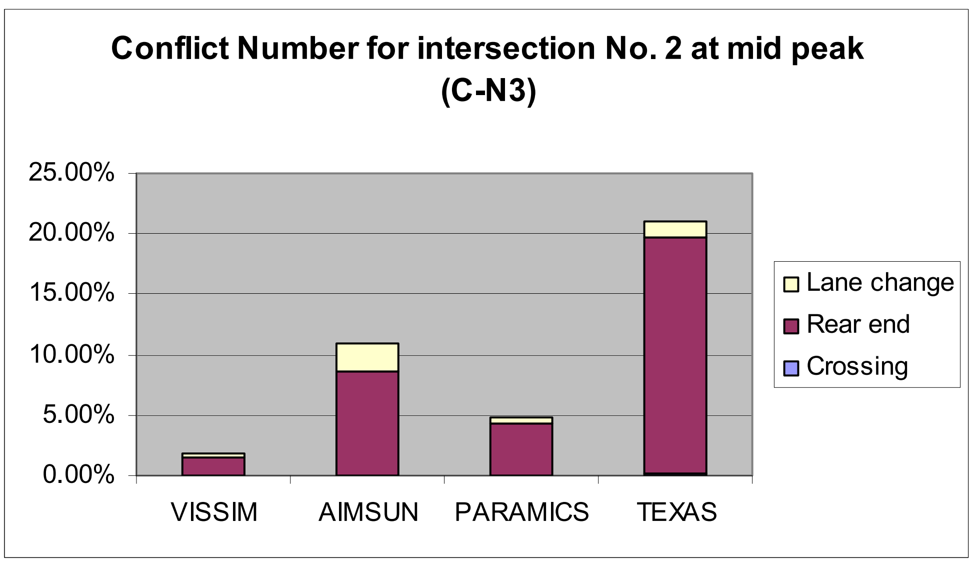


Figure 168. Graph. Conflicts Number C-N3 Comparison for Intersection 2 at Mid Peak.

Table 98. Conflicts Number Under PM Peak-Hour Condition for Intersection 2.

5,585 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	226.8/4.06	226.8/4.06	101.2/1.81	119.4/2.14	119.4/2.14	22.1/0.4	104.6/1.87	104.6/1.87	11.1/0.2
AIMSUN	786.6/14.08	687/12.3	415/7.43	445.5/7.98	380.3/6.81	215.1/3.85	109.4/1.96	71.7/1.28	14.7/0.26
PARAMICS	708.6/12.69	485.1/8.69	169.8/3.04	387.7/6.94	313.8/5.62	61.7/1.1	302.1/5.41	269.3/4.82	30.4/0.54
TEXAS	4,209.1/75.36	4,208.9/75.36	1,366.2/24.46	1,670.3/29.91	1,670.1/29.9	663.9/11.89	789.7/14.14	789.5/14.14	142.6/2.55
Crossing Conflicts									
VISSIM	1.7/0.03	1.7/0.03	0.2/0	1.6/0.03	1.6/0.03	0.1/0	1.6/0.03	1.6/0.03	0.1/0
AIMSUN	14.9/0.27	11.3/0.2	6.4/0.11	10.3/0.18	8.1/0.15	3.4/0.06	6.3/0.11	6/0.11	1.4/0.03
PARAMICS	17.3/0.31	16/0.29	1.2/0.02	16.8/0.3	15.5/0.28	0.7/0.02	16.3/0.29	15/0.27	0.2/0
TEXAS	98/1.75	98/1.75	14.1/0.25	94.1/1.68	94.1/1.68	10.3/0.18	91.4/1.64	91.4/1.64	7.9/0.14
Rear-End Conflicts									
VISSIM	149.3/2.67	149.3/2.67	70.5/1.26	62.6/1.12	62.6/1.12	6.4/0.11	57/1.03	57/1.02	2.8/0.05
AIMSUN	626.4/11.22	542.7/9.72	321.4/5.75	345.5/6.19	287.8/5.15	162.8/2.91	90.1/1.61	53.8/0.96	8.3/0.15
PARAMICS	612.7/10.97	396.6/7.1	147.4/2.64	313.3/5.61	244.5/4.38	55/0.98	235.1/4.21	205.8/3.68	28.1/0.5
TEXAS	3,744.9/67.05	3,744.9/67.05	1,340/23.99	1,280.9/22.93	1,280.9/22.93	609/10.9	442.9/7.93	442.9/7.93	113.2/2.03
Lane-Changing Conflicts									
VISSIM	75.8/1.36	75.8/1.36	30.5/0.55	55.2/0.99	55.2/0.99	15.6/0.28	46/0.82	46/0.82	8.2/0.15
AIMSUN	145/2.6	133/2.38	87.2/1.56	89.7/1.61	84.4/1.51	48.9/0.88	13/0.23	11.9/0.21	5/0.09
PARAMICS	78.6/1.41	72.5/1.3	21.2/0.38	57.6/1.03	53.8/0.96	6/0.11	50.7/0.91	48.5/0.87	2.1/0.04
TEXAS	366.2/6.56	366/6.55	8.2/0.15	295.3/5.29	295.1/5.28	44.6/0.8	255.4/4.57	255.2/4.57	21.5/0.38

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

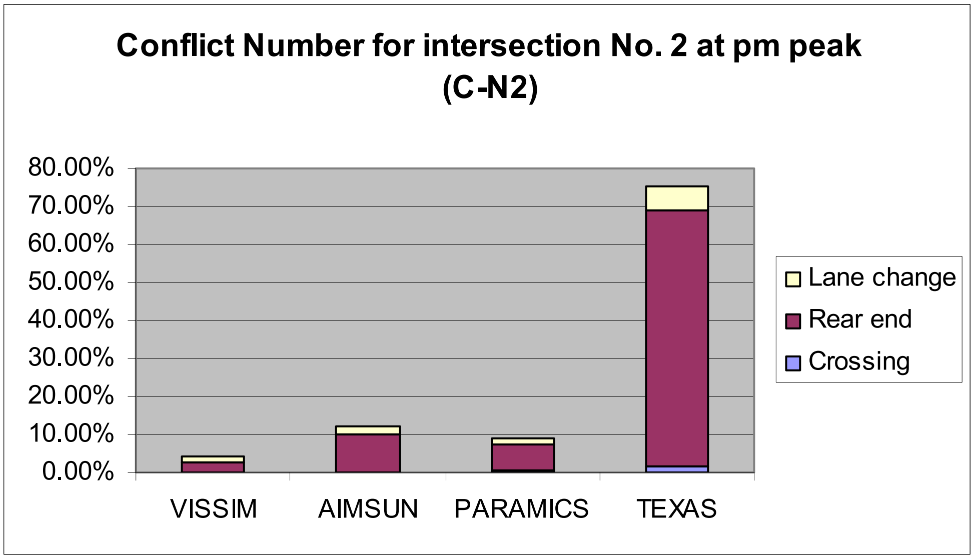


Figure 169. Graph. Conflicts Number C-N2 Comparison for Intersection 2 at PM Peak.

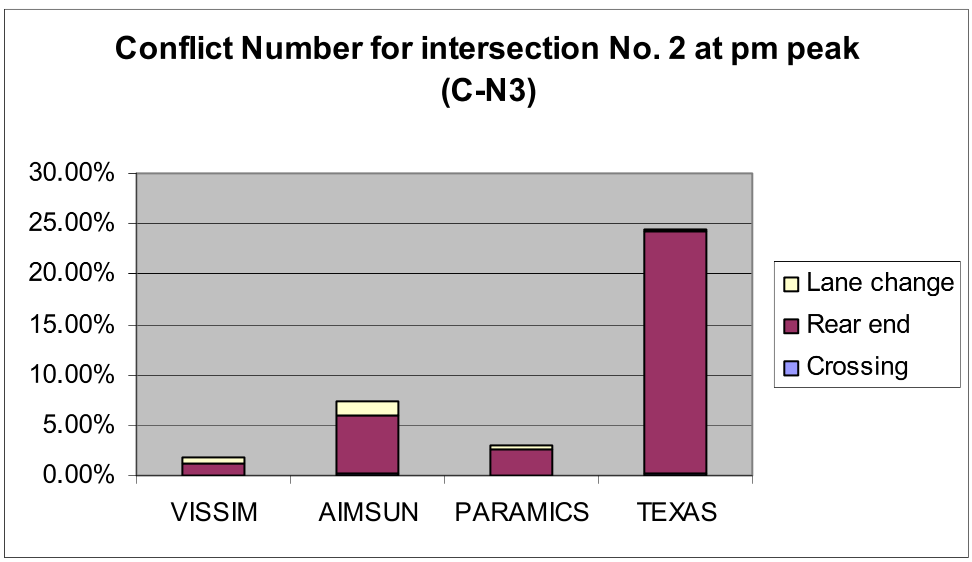


Figure 170. Graph. Conflicts Number C-N3 Comparison for Intersection 2 at PM Peak.

Intersection 3: Lafayette Ave & Fulton Street, Grand Rapids, MI:

The number of conflicts/conflict rates under AM and PM peak-hour conditions was tabulated and is shown in table 99 and table 100. Column charts were created to compare the conflicts number generated from the four simulation platforms, as shown in figure 171 through figure 174.

As shown in the following tables and figures, for all simulation models, most of the conflicts were rear-end conflicts, and crossing conflicts were the least conflicts among all conflicts types. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. The differences among the four simulation models were the following:

- VISSIM had the least conflict number for all categories.
- The ascending ranking order in most cases was VISSIM, PARAMICS, TEXAS, AIMSUN. However, for the TTC < 0.5 category, the order was VISSIM, AIMSUN, TEXAS, PARAMICS, implying that PARAMICS had a higher percentage of severe conflicts than AIMSUN.
- VISSIM and TEXAS had almost no abnormal deceleration maneuvers, while AIMSUN and PARAMICS had 9 to 15 percent conflicts with abnormal deceleration. Most of the abnormal deceleration maneuvers were from rear-end conflicts.
- Less than 15 percent of conflicts from VISSIM were low-speed or crash events; AIMSUN, PARAMICS, and TEXAS had a higher percentage of low-speed or crash events (25 to 70 percent). Most of the low-speed conflicts were rear-end conflicts.
- Most of the conflicts in VISSIM and AIMSUN were less severe conflicts (conflicts with TTC ≥ 0.5), while in PARAMICS and TEXAS, the percentage of severe conflicts (conflicts with TTC < 0.5) was higher than in the other two simulation platforms (based on comparison of C-N2).
- The percentage of lane change conflicts in TEXAS was the smallest.

Table 99. Conflicts Number Under AM Peak-Hour Condition for Intersection 3.

1,975 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	47.8/2.42	47.8/2.42	41.1/2.08	4.2/0.21	4.2/0.21	0.9/0.05	3.7/0.19	3.7/0.19	0.6/0.03
AIMSUN	138.3/7.00	126.7/6.42	104.6/5.3	79/4	71.5/3.62	55.3/2.8	9.8/0.5	7.4/0.37	1/0.05
PARAMICS	72.6/3.68	63.1/3.19	27.2/1.38	50.9/2.58	46.6/2.36	12/0.61	39.9/2.02	37.3/1.89	3.2/0.16
TEXAS	104.8/5.31	104.7/5.3	45.2/2.29	45.7/2.31	45.6/2.31	15/0.76	30.3/1.53	30.2/1.53	2/0.1
Crossing Conflicts									
VISSIM	0.8/0.04	0.8/0.04	0/0	0.8/0.04	0.8/0.04	0/0	0.8/0.04	0.8/0.04	0/0
AIMSUN	6.8/0.34	3.2/0.16	3.2/0.16	2.9/0.15	0.5/0.03	0.5/0.03	0.2/0.01	0.1/0.01	0.1/0.01
PARAMICS	2/0.1	2/0.1	0.4/0.02	2/0.1	2/0.1	0.4/0.02	1.7/0.09	1.7/0.09	0.1/0.01
TEXAS	31.9/1.62	31.8/1.61	3.8/0.19	30.9/1.56	30.8/1.56	2.8/0.14	29.7/1.5	29.6/1.5	1.6/0.08
Rear-End Conflicts									
VISSIM	42.4/2.15	42.4/2.15	37.9/1.92	1.6/0.08	1.6/0.08	0.1/0.01	1.4/0.07	1.4/0.07	0/0
AIMSUN	119.3/6.04	111.9/5.67	91.6/4.64	68.7/3.48	63.8/3.23	49/2.48	9.3/0.47	7/0.35	0.6/0.03
PARAMICS	54.9/2.78	48.9/2.48	26.1/1.32	36.5/1.85	32.8/1.66	11.2/0.57	26.7/1.35	24.1/1.22	3/0.15
TEXAS	70.9/3.59	70.9/3.59	39.9/2.02	14.4/0.73	14.4/0.73	11.8/0.6	0.6/.03	0.6/0.03	0.4/0.02
Lane-Changing Conflicts									
VISSIM	4.6/0.23	4.6/0.23	3.2/0.16	1.8/0.09	1.8/0.09	0.8/0.04	1.5/0.08	1.5/0.08	0.6/0.03
AIMSUN	12.2/0.62	11.6/0.59	9.8/0.5	7.4/0.37	7.2/0.36	5.8/0.29	0.3/0.02	0.3/0.02	0.3/0.02
PARAMICS	15.7/0.79	12.2/0.62	0.7/0.04	12.4/0.63	11.8/0.6	0.4/0.02	11.5/0.58	11.5/0.58	0.1/0.01
TEXAS	2/0.1	2/0.1	1.5/0.08	0.4/0.02	0.4/0.02	0.4/0.02	0/0	0/0	0/0

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

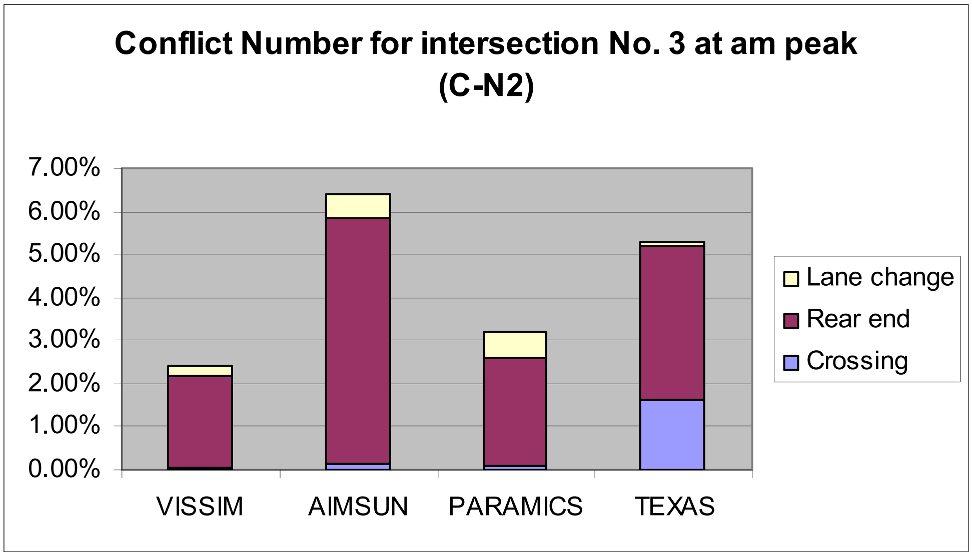


Figure 171. Graph. Conflicts Number C-N2 Comparison for Intersection 3 at AM Peak.

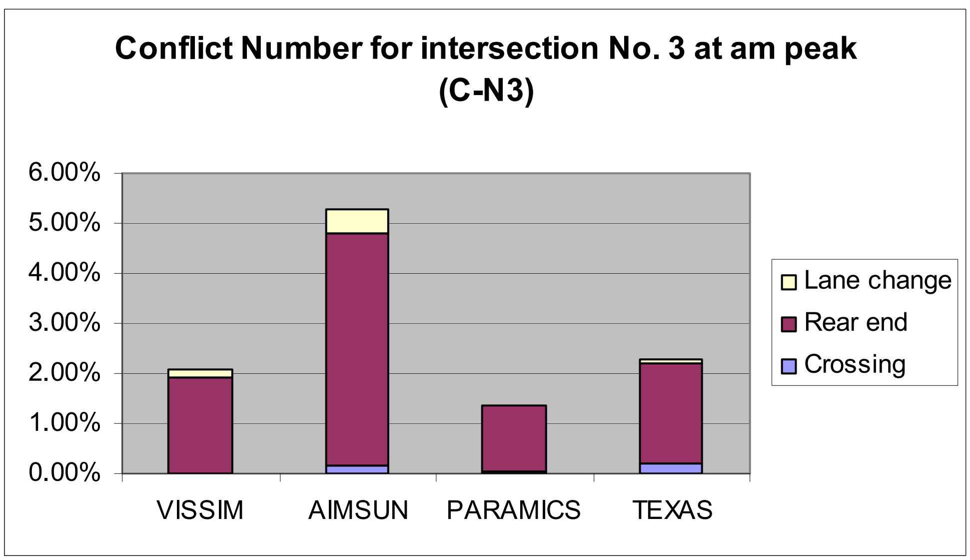


Figure 172. Graph. Conflicts Number C-N3 Comparison for Intersection 3 at AM Peak.

Table 100. Conflicts Number Under PM Peak-Hour Condition for Intersection 3.

2,400 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	73.6/3.07	73.6/3.07	59.9/2.5	9/0.38	9/0.38	2.1/0.09	8.1/0.34	8.1/0.34	1.2/0.05
AIMSUN	218.4/9.1	199/8.29	148.6/6.19	133.3/5.55	120.3/4.01	82.8/3.45	19.1/0.8	15.5/0.65	1.4/0.06
PARAMICS	124.1/5.17	98.5/4.1	41.2/1.72	76.5/3.19	67.3/2.8	15.2/0.63	59.9/2.5	55.3/2.3	4/0.17
TEXAS	179.7/7.49	179.6/7.48	62.2/2.59	70.5/2.94	70.4/0.93	19.9/0.83	43.1/1.8	43/1.79	3.4/0.14
Crossing Conflicts									
VISSIM	1.5/0.06	1.5/0.06	0.2/0.01	1.4/0.06	1.4/0.06	0.1/0	1.3/0.05	1.3/0.05	0/0
AIMSUN	13.3/0.55	7.5/0.31	6.9/0.29	6.7/0.28	2.1/0.09	1.5/0.06	0.6/0.03	0.6/0.03	0.2/0.01
PARAMICS	2.6/0.11	2.3/0.1	0.9/0.04	1.8/0.08	1.8/0.08	0.4/0.61	1.5/0.06	1.5/0.06	0.1/0
TEXAS	41.9/1.75	41.8/1.74	4.5/0.19	40.7/1.7	40.6/1.69	3.3/0.14	40/1.67	39.9/1.66	2.6/0.11
Rear-End Conflicts									
VISSIM	61.4/2.56	61.4/2.56	52.6/2.19	4.4/0.18	4.4/0.18	0.5/0.02	4/0.17	4/0.17	0.1/0
AIMSUN	176.6/7.36	165.5/6.9	122/5.08	108.8/4.53	101.6/4.23	68.9/2.87	18.1/0.75	14.5/0.6	0.9/0.04
PARAMICS	102/4.25	80.3/3.35	39.3/1.64	58.3/2.43	50.7/2.11	14.6/0.61	43.3/1.8	39.1/1.63	3.8/0.16
TEXAS	134.6/5.61	134.6/5.61	55.4/2.31	29.3/1.22	29.3/1.22	16.2/0.68	3.1/0.13	3.1/0.13	0.8/0.03
Lane-Changing Conflicts									
VISSIM	10.7/0.45	10.7/0.45	7.1/0.3	3.2/0.13	3.2/0.13	1.5/0.06	2.8/0.12	2.8/0.12	1.1/0.05
AIMSUN	28.5/1.19	26/1.08	19.7/0.82	17.8/0.74	16.6/0.69	12.4/0.52	0.4/0.02	0.4/0.02	0.3/0.01
PARAMICS	19.5/0.81	15.9/0.66	1/0.04	16.4/0.68	14.8/0.62	0.2/0.01	15.1/0.63	14.7/0.61	0.1/0
TEXAS	3.2/0.13	3.2/0.13	2.3/0.1	0.5/0.02	0.5/0.02	0.4/0.02	0/0	0/0	0/0

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

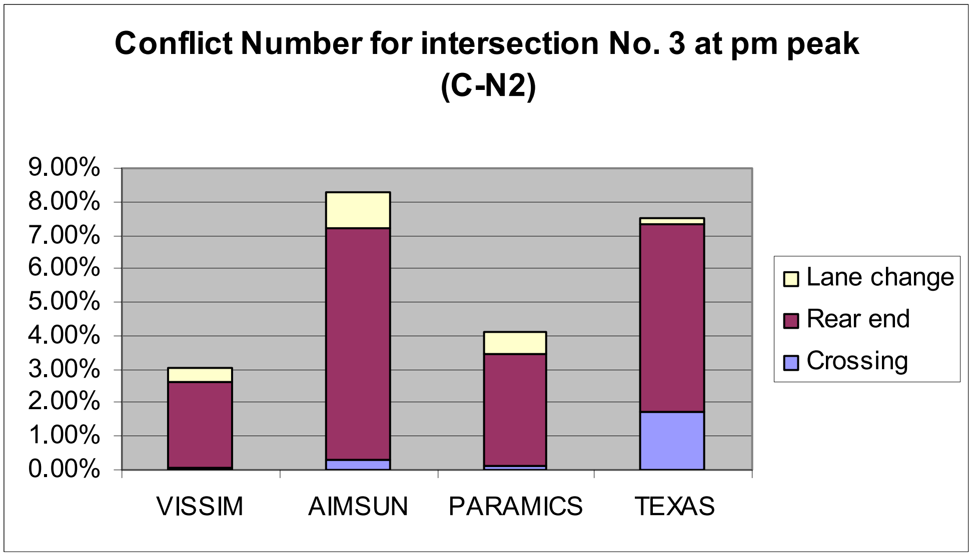


Figure 173. Graph. Conflicts Number C-N2 Comparison for Intersection 3 at PM Peak.

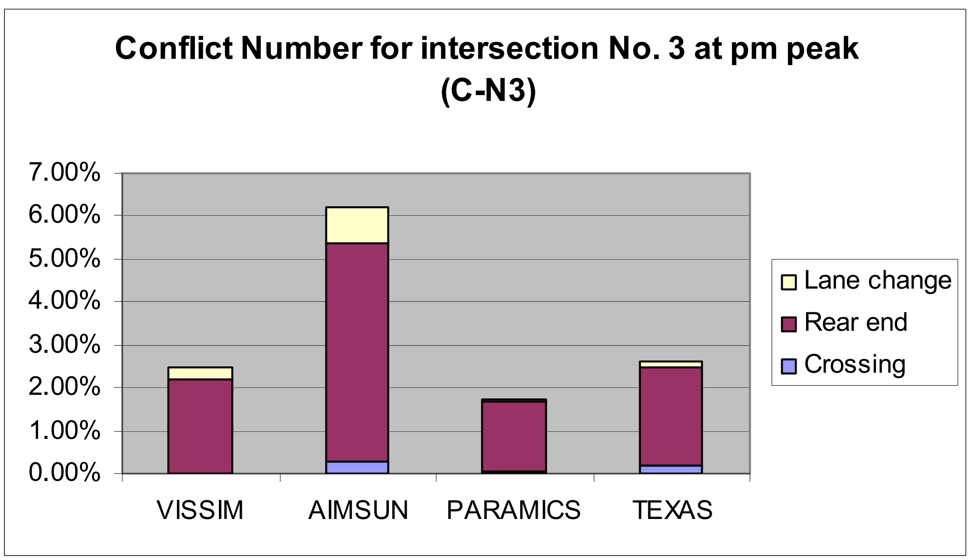


Figure 174. Graph. Conflicts Number C-N3 Comparison for Intersection 3 at PM Peak.

Intersection 4: Ryan Ave & Davison Ave, Detroit, MI:

The number of conflicts/conflict rates under AM and PM peak-hour conditions was tabulated and is shown in table 101 and table 102. Column charts were created to compare the conflicts number generated from the four simulation platforms, as seen in figure 175 to figure 178.

As shown in the following tables and figures, for all simulation models, most of the conflicts were rear-end conflicts, and crossing conflicts were the least conflicts among all conflicts types. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. The differences among the four simulation models were the following:

- TEXAS had the most conflict number for most of the categories.
- PARAMICS had a higher percentage of severe conflicts than AIMSUN.
- VISSIM and TEXAS had almost no abnormal deceleration maneuvers, while AIMSUN and PARAMICS had 10 percent conflicts with abnormal deceleration, and most of the abnormal deceleration maneuvers were from rear-end conflicts.
- PARAMICS and TEXAS had a higher percentage of low-speed or crash events (over 50 percent). Most of the low-speed conflicts were rear-end conflicts.
- Most of the conflicts in VISSIM, AIMSUN, and TEXAS were less severe conflicts (conflicts with $TTC \geq 0.5$), while in PARAMICS, most conflicts were severe conflicts (conflicts with $TTC < 0.5$), based on comparison of C-N2.
- The percentage of lane change conflicts in TEXAS was the smallest.

Table 101. Conflicts Number Under AM Peak-Hour Condition for Intersection 4.

2,613 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	64.8/2.48	64.8/2.48	44.1/1.69	13.4/0.51	13.4/0.51	3.3/0.13	11.1/0.42	11.1/0.42	1.3/0.05
AIMSUN	158.4/6.06	146.5/5.61	117.6/4.5	96.9/3.71	89.4/3.42	67.6/2.59	22.9/0.88	18.9/0.72	6.3/0.24
PARAMICS	60.8/2.33	54/2.07	17.7/0.68	44.6/1.71	42.8/1.64	7.8/0.3	36.7/1.4	36.2/1.39	1.7/0.07
TEXAS	170.5/6.53	170.5/6.53	58.1/2.22	75.4/2.89	75.4/2.89	23.2/0.89	51.5/1.97	51.5/1.97	7.2/0.28
Crossing Conflicts									
VISSIM	1/0.04	1/0.04	0.1/0	1/0.04	1/0.04	0.1/0	0.9/0.03	0.9/0.03	0/0
AIMSUN	3.8/0.15	3.3/0.13	1.6/0.06	3/0.11	2.6/0.1	0.9/0.03	2.3/0.09	2.3/0.09	0.6/0.02
PARAMICS	16.1/0.62	16.1/0.62	3.4/0.13	15.9/0.61	15.9/0.61	3.2/0.12	13.1/0.5	13.1/0.5	0.4/0.02
TEXAS	36.6/1.4	36.6/1.4	3.8/0.15	35.5/1.36	35.5/1.36	2.7/0.1	35/1.34	35/1.34	2.2/0.08
Rear-End Conflicts									
VISSIM	54.8/2.1	54.8/2.1	38.9/1.49	6.3/0.24	6.3/0.24	0.4/0.02	6.1/0.23	6.1/0.23	0.3/0.01
AIMSUN	126.6/4.85	119.2/4.56	96/3.67	78.9/3.02	73.5/2.81	55.9/2.14	19.8/0.76	16/0.61	5.5/0.21
PARAMICS	40.2/1.54	34.1/1.31	11.8/0.45	26.8/1.03	25.3/0.97	4.3/0.16	22.2/0.85	21.8/0.83	1.2/0.05
TEXAS	123.3/4.72	123.3/4.72	50.9/1.95	32.5/1.24	32.5/1.24	18.6/0.71	10.2/0.39	10.2/0.39	4.2/0.16
Lane-Changing Conflicts									
VISSIM	9/0.34	9/0.34	5.1/0.2	6.1/0.23	6.1/0.23	2.8/0.11	4.1/0.16	4.1/0.16	1/0.04
AIMSUN	28/1.07	24/0.92	20/0.77	15/0.57	13.3/0.51	10.8/0.41	0.8/0.03	0.6/0.02	0.2/0.01
PARAMICS	4.5/0.17	3.8/0.15	2.5/0.1	1.9/0.07	1.6/0.06	0.3/0.01	1.4/0.05	1.3/0.05	0.1/0
TEXAS	10.6/0.41	10.6/0.41	3.4/0.13	7.4/0.28	7.4/0.28	1.9/0.07	6.3/0.24	6.3/0.24	0.8/0.03

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

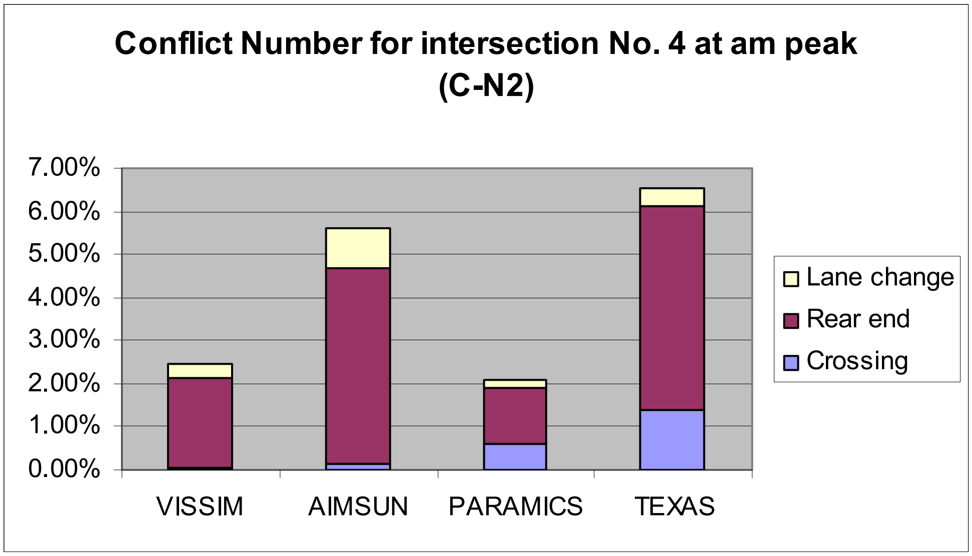


Figure 175. Graph. Conflicts Number C-N2 Comparison for Intersection 4 at AM Peak.

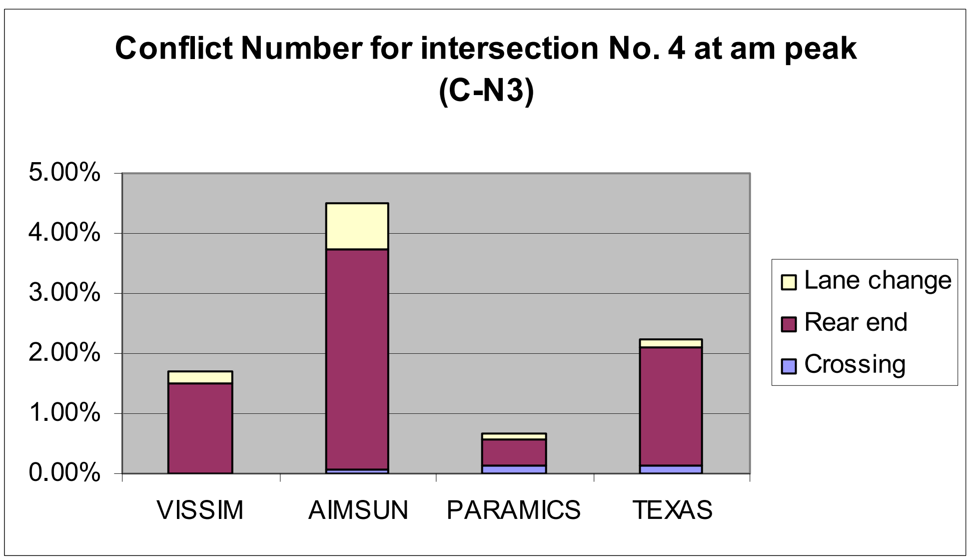


Figure 176. Graph. Conflicts Number C-N3 Comparison for Intersection 4 at AM Peak.

Table 102. Conflicts Number Under PM Peak-Hour Condition for Intersection 4.

3,017 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	111.1/3.68	111.1/3.68	61.4/2.04	37.9/1.26	37.9/1.26	5.3/0.18	33.8/1.12	33.8/1.12	1.5/0.05
AIMSUN	227.5/7.54	208.1/6.9	161.1/5.34	135/4.47	123.4/4.09	89/2.95	30.5/1.01	24.2/0.8	8.9/0.29
PARAMICS	88.7/2.94	72.8/2.41	22.7/0.75	60.7/2.01	56.7/1.88	9.4/0.31	50.1/1.66	48.7/1.61	2.4/0.08
TEXAS	408/13.52	408/13.52	155.7/5.16	226.6/7.51	226.6/7.51	85.6/2.84	173.2/5.74	173.2/5.74	40/1.33
Crossing Conflicts									
VISSIM	18.6/0.62	18.6/0.62	0.8/0.03	18.6/0.62	18.6/0.62	0.8/0.03	18.1/0.6	18.1/0.6	0.3/0.01
AIMSUN	5/0.17	4.4/0.15	2.5/0.08	3.5/0.12	3.3/0.11	1.4/0.05	2.1/0.07	2.1/0.07	0.2/0.01
PARAMICS	11.5/0.38	11.5/0.38	1.2/0.04	11.5/0.38	11.5/0.38	1.2/0.04	10.2/0.34	10.2/0.34	0/0
TEXAS	49.6/1.64	49.6/1.64	4.9/0.16	48.5/1.61	48.5/1.61	3.8/0.13	47.4/1.57	47.4/1.57	2.8/0.09
Rear-End Conflicts									
VISSIM	73.6/2.44	73.6/2.44	52.3/1.73	9.9/0.33	9.9/0.33	1.6/0.05	8.4/0.28	8.4/0.28	0.3/0.01
AIMSUN	176.5/5.85	164.5/5.45	124.3/4.12	107.2/3.55	98.5/3.26	69.3/2.3	27/0.89	21.1/0.7	7.8/0.26
PARAMICS	67.9/2.25	54.3/1.8	17/0.56	45.4/1.5	41.9/1.39	7.2/0.24	37.3/1.24	36.2/1.2	2.1/0.07
TEXAS	280/9.28	280/9.28	130.1/4.31	110.6/3.67	110.6/3.67	66.7/2.21	63.2/2.09	63.2/2.09	26.1/0.87
Lane-Changing Conflicts									
VISSIM	18.9/0.63/	18.90.63	8.3/0.28	9.4/0.31	9.4/0.31	2.9/0.1	7.3/0.24	7.3/0.24	0.9/0.03
AIMSUN	46/1.52	39.2/1.3	34.3/1.14	24.3/0.81	21.6/0.72	18.3/0.61	1.4/0.05	1/0.03	0.9/0.03
PARAMICS	9.3/0.31	7/0.23	4.5/0.15	3.8/0.13	3.3/0.11	1/0.03	2.6/0.09	2.3/0.08	0.3/0.01
TEXAS	78.4/0.6	78.4/2.6	20.7/0.69	67.5/2.24	67.5/2.24	15.1/0.5	62.6/2.07	62.6/2.07	11.1/0.37

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

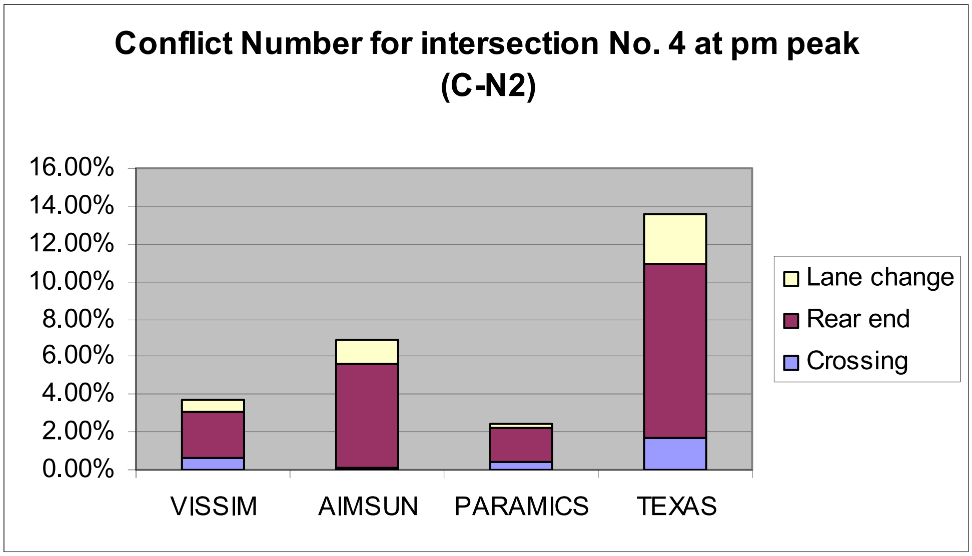


Figure 177. Graph. Conflicts Number C-N2 Comparison for Intersection 4 at PM Peak.

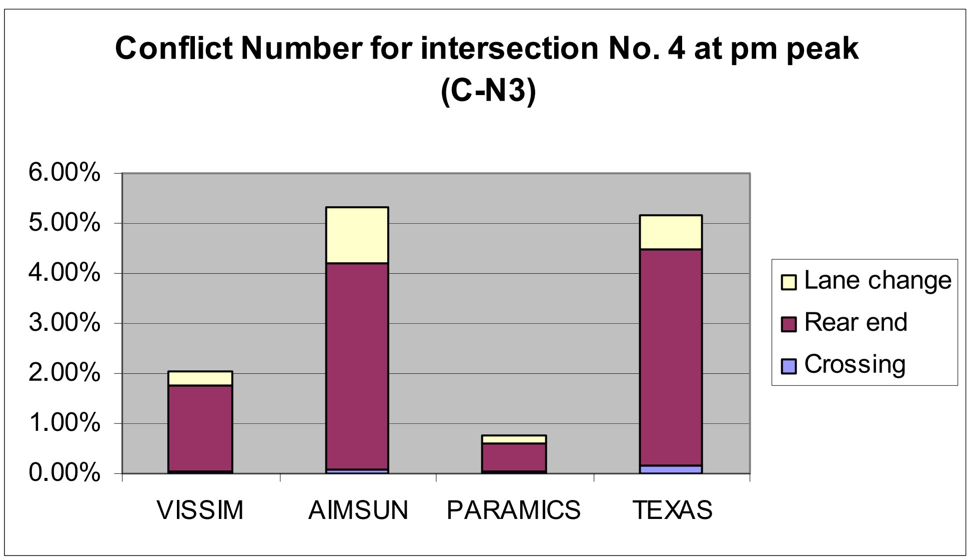


Figure 178. Graph. Conflicts Number C-N3 Comparison for Intersection 4 at PM Peak.

Intersection 5: Howe Ave & Fair Oaks Boulevard, Sacramento, CA:

The number of conflicts/conflict rates under AM and PM peak-hour conditions was tabulated and are shown in table 103 and table 104. Column charts were created to compare the conflicts number generated from the four simulation platforms, as seen in figure 179 through figure 182.

As shown in the following tables and figures, for all simulation models, most of the conflicts were rear-end conflicts, and crossing conflicts were the least conflicts among all conflicts types. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. The differences among the four simulation models were the following:

- VISSIM had the least conflict number for all categories. TEXAS had the most conflict number for all categories except for lane change category.
- The ascending ranking order in most cases was VISSIM, PARAMICS, AIMSUN, TEXAS.
- VISSIM and TEXAS had almost no abnormal deceleration maneuvers, while AIMSUN and PARAMICS had 30 to 40 percent conflicts with abnormal deceleration).
- Most of the abnormal deceleration maneuvers were from rear-end conflicts. Conflicts with abnormal deceleration were almost evenly distributed in the three TTC categories for AIMSUN. While in PARAMICS, more than half of the conflicts with abnormal deceleration have TTC ≥ 1.0.
- Most of the conflicts were less severe conflicts (conflicts with TTC ≥ 0.5), and PARAMICS had a higher percentage of severe conflicts (conflicts with TTC < 0.5) than others, based on comparison of C-N2.
- The percentage of lane change conflicts in TEXAS was the smallest.

Table 103. Conflicts Number Under AM Peak-Hour Condition for Intersection 5.

6,425 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	180.9/2.82	180.9/2.82	102.4/1.59	69.1/1.08	69.1/1.08	13.8/0.21	57.6/0.9	57.6/0.9	5.2/0.08
AIMSUN	899/13.99	561.6/8.74	418/6.51	567.7/8.84	355.7/5.54	237.3/3.69	250.7/3.9	140.8/2.19	48.4/0.75
PARAMICS	527.5/8.21	330.4/5.14	146.4/2.28	227.2/3.54	164.5/2.56	74.5/1.16	133.8/2.08	121.7/1.89	74.5/1.16
TEXAS	1,970.6/30.67	1,769.5/27.54	584.4/9.1	641.8/9.99	640.9/9.98	294.9/4.59	301/4.68	300.3/4.67	75.9/1.18
Crossing Conflicts									
VISSIM	0.1/0	0.1/0	0/0	0.1/0	0.1/0	0/0	0/0	0/0	0/0
AIMSUN	8/0.12	7.2/0.11	6.6/0.1	5.8/0.09	5.5/0.09	5.4/0.08	0.4/0.01	0.1/0	0/0
PARAMICS	1.4/0.02	1.4/0.02	0.2/0	0.7/0.01	0.7/0.01	0/0	0.7/0.01	0.7/0.01	0/0
TEXAS	12.5/0.19	12.5/0.19	0/0	12.5/0.19	12.5/0.19	0/0	12.4/0.19	12.4/0.19	0/0
Rear-End Conflicts									
VISSIM	124.4/1.94	124.4/1.94	79.8/1.24	30.1/0.47	30.1/0.47	3.7/0.06	26.7/0.42	26.7/0.42	0.8/0.01
AIMSUN	736.1/11.46	431.3/6.71	303.9/4.73	475/7.39	282.6/4.4	175.7/2.73	237.4/3.69	133.8/2.08	46.1/0.72
PARAMICS	457.8/7.13	289.2/4.5	128.2/2	185.2/2.88	138.5/2.16	55.2/0.86	111.1/1.73	101.1/1.57	55.2/0.86
TEXAS	1,854.6/28.87	1,854.2/28.86	551.4/8.58	557.7/8.68	557.5/8.68	277.2/4.31	229.8/3.58	229.8/3.58	67.6/1.05
Lane-Changing Conflicts									
VISSIM	56.4/0.88	56.4/0.88	22.6/0.35	38.9/0.61	38.9/00.61	10.1/0.16	30.9/0.48	30.9/0.48	4.4/0.07
AIMSUN	154.9/2.41	123.1/1.92	107.5/1.67	86.9/1.35	67.6/1.05	56.2/0.87	12.9/0.2	6.9/0.11	2.3/0.04
PARAMICS	68.3/1.06	39.8/0.62	18/0.28	41.3/0.64	25.3/0.39	19.3/0.3	22/0.34	19.9/0.31	19.3/0.3
TEXAS	103.5/1.61	102.8/1.6	33/0.51	71.6/1.11	70.9/1.1	17.7/0.28	58.8/0.92	58.1/0.9	8.3/0.13

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

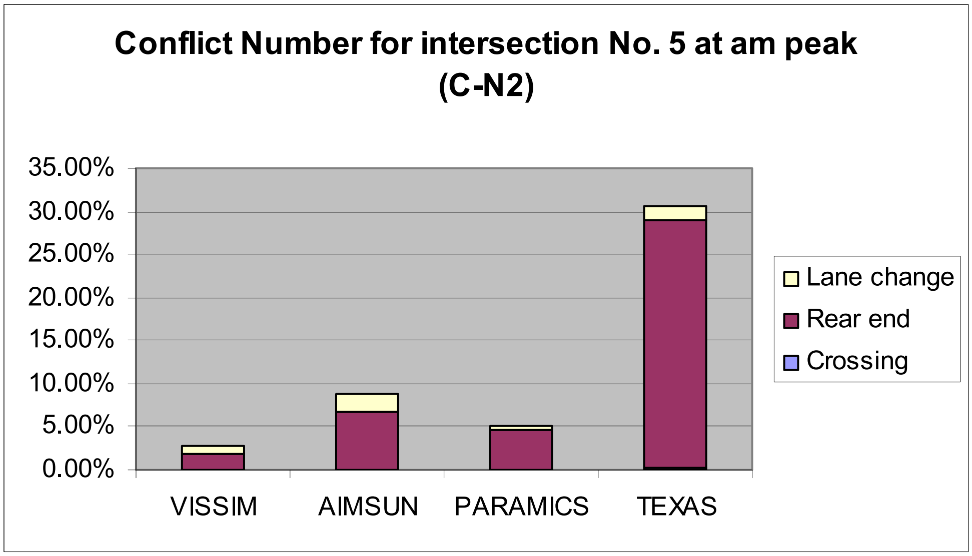


Figure 179. Graph. Conflicts Number C-N2 Comparison for Intersection 5 at AM Peak.

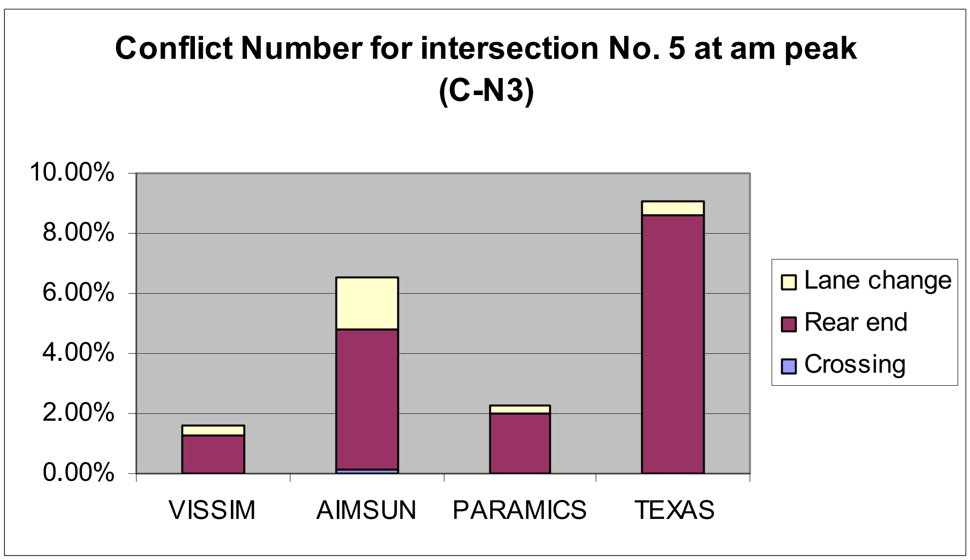


Figure 180. Graph. Conflicts Number C-N3 Comparison for Intersection 5 at AM Peak.

Table 104. Conflicts Number Under PM Peak-Hour Condition for Intersection 5.

8,815 v/hr	TTC ≤ 1.5			TTC ≤ 1.0			TTC ≤ 0.5		
	C-N1*	C-N2	C-N3	C-N1	C-N2	C-N3	C-N1	C-N2	C-N3
ALL									
VISSIM	307.7/3.49	307.7/3.49	157.9/1.79	137.7/1.56	137.7/1.56	29.3/0.33	114.2/1.3	114.2/1.3	10.6/0.12
AIMSUN	1339.8/15.2	1016.8/11.53	663.8/7.53	827.1/9.38	619.1/7.02	356.1/4.04	387.4/4.39	247.6/2.81	70.7/0.8
PARAMICS	828.5/9.4	537.8/6.1	217.4/2.47	419.8/4.76	298.5/3.39	74.5/0.85	276.9/3.14	222.5/2.52	74.5/0.85
TEXAS	4,580/51.96	4,579.7/51.95	1,610/18.26	1,967/22.31	1,966.8/22.31	847/9.61	1,066.6/12.1	1,066.4/12.1	265.6/3.01
Crossing Conflicts									
VISSIM	0.4/0	0.4/0	0/0	0.4/0	0.4/0	0/0	0.4/0	0.4/0	0/0
AIMSUN	12.7/0.14	11.2/0.13	8.2/0.09	10.3/0.121	9.4/0.11	7.4/0.08	2.1/0.02	1.8/0.02	0.4/0
PARAMICS	0.6/0.01	0.6/0.01	0/0	0.6/0.01	0.6/0.01	0/0	0.5/0.01	0.5/0.01	0/0
TEXAS	33.9/0.38	33.9/0.38	0.2/0	33.2/0.38	33.2/0.38	0.2/0	32.5/0.37	32.5/0.37	0.2/0
Rear-End Conflicts									
VISSIM	190.5/2.16	190.5/2.16	110.3/1.25	58/0.66	58/0.66	7.8/0.09	51.2/0.58	51.2/0.58	2.5/0.03
AIMSUN	1080.6/12.26	813.9/9.23	498.4/5.65	696.8/7.9	509.8/5.78	270.1/3.06	372.3/4.22	238.3/2.7	65.9/0.75
PARAMICS	734.8/8.34	474.6/5.38	181.2/2.06	359.8/4.08	256.6/2.91	55.2/0.63	242.2/2.75	191.4/2.17	55.2/0.63
TEXAS	4,126/46.81	4,125.8/46.8	1,487.5/16.87	1,600.3/18.15	1,600.2/18.15	776.3/8.81	749.8/8.51	749.7/8.5	230.9/2.62
Lane-Changing Conflicts									
VISSIM	116.8/1.33	116.8/1.33	47.6/0.54	79.3/0.9	79.3/0.9	21.5/0.24	62.6/0.71	62.6/0.71	8.1/0.09
AIMSUN	246.5/2.8	191.7/2.17	157.2/1.78	120/1.36	99.9/1.13	78.6/0.89	13/0.15	7.5/0.09	4.4/0.05
PARAMICS	93.1/1.06	62.6/0.71	36.2/0.41	59.4/0.67	41.3/0.47	19.3/0.22	34.2/0.39	30.6/0.35	19.3/0.22
TEXAS	420.1/4.77	420/4.76	122.3/1.39	333.5/3.78	333.4/3.78	70.5/0.8	284.3/3.23	284.2/3.22	34.5/0.39

* C-N1: total conflict analysis by SSAM.
C-N2: Conflicts with MaxD ≥ -9.15 m/sec^2 (-30 ft/sec^2).
C-N3: Conflicts with MaxD greater than and equal to -9.15 m/sec^2 (-30 ft/sec^2) TTC > 0 and MaxS ≥ 16.1 km/h (10 mi/h).

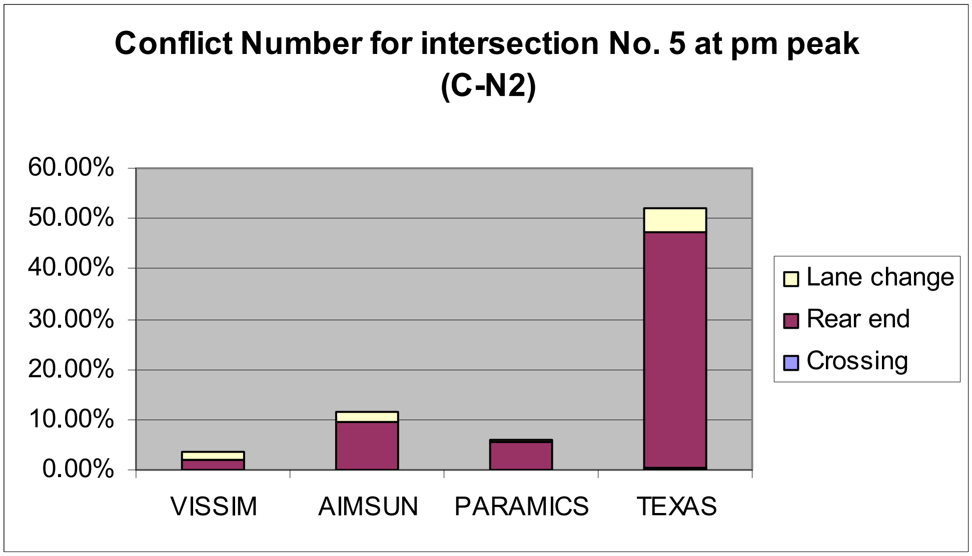


Figure 181. Graph. Conflicts Number C-N2 Comparison for Intersection 5 at PM Peak.

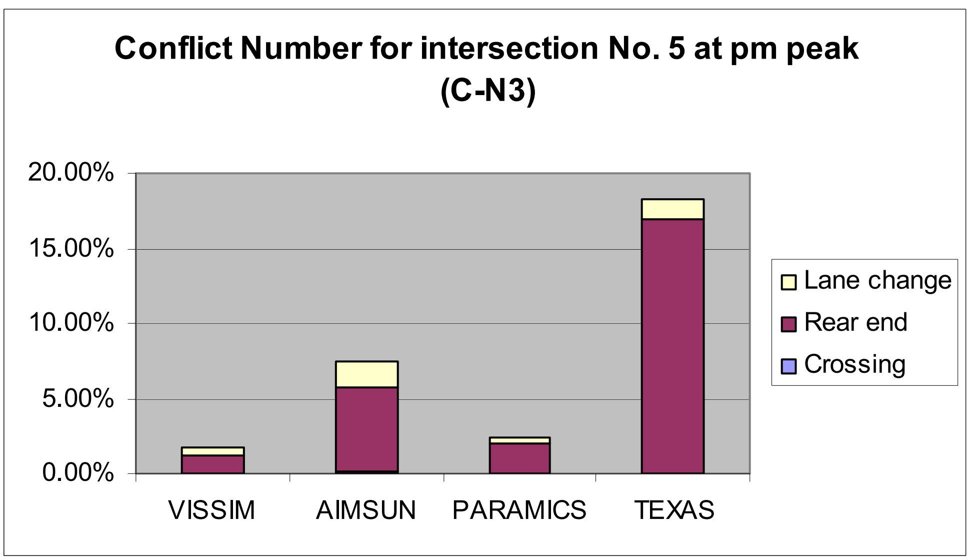


Figure 182. Graph. Conflicts Number C-N3 Comparison for Intersection 5 at PM Peak.

In general, most of the conflicts were rear-end conflicts, and Crossing conflicts were the least. Crossing conflicts had a smaller TTC value while rear-end conflicts had a larger TTC value. Differences among VISSIM, AIMSUN, PARAMICS, and TEXAS were as follows:

- For all cases, VISSIM had the least conflict number across all categories.
- For most of the cases, TEXAS had the most conflict number across all categories. When traffic volume was increasing, the ratio between conflicts number from VISSIM and conflicts number from TEXAS also increased.
- The ascending ranking order in most cases was VISSIM, AIMSUN, PARAMICS, TEXAS. When there was less traffic, the ranking order was VISSIM, PARAMICS, TEXAS, AIMSUN.
- AIMSUN had a higher percentage of low-speed conflicts or crashes than PARAMICS, while PARAMICS had a higher percentage of severe conflicts than AIMSUN.
- VISSIM and TEXAS had no abnormal deceleration maneuvers, while AIMSUN and PARAMICS had 10 to 40 percent conflicts with abnormal deceleration. Most of the abnormal deceleration maneuvers were from rear-end conflicts. More than half of the conflicts with abnormal deceleration had $TTC \geq 1.0$.
- Conflicts with abnormal deceleration were almost evenly distributed in the three TTC categories for AIMSUN. In PARAMICS, more than half of the conflicts with abnormal deceleration had $TTC \geq 1.0$.
- VISSIM and AIMSUN had a smaller percentage of low-speed or crash events than PARAMICS and TEXAS. PARAMICS and TEXAS had over 50 percent of total conflicts as low-speed conflicts or crashes. Most of the low-speed conflicts were rear-end conflicts.
- Most conflicts in VISSIM, AIMSUN, and TEXAS were less severe conflicts (conflicts with $TTC \geq 0.5$), while in PARAMICS, most conflicts were severe conflicts (conflicts with $TTC < 0.5$), based on comparison of C-N2.
- The percentage of lane change conflicts in TEXAS was the smallest.

Conflicts Layout Display

Conflict layouts displayed on the map screen of SSAM are shown below. For better visualization, each figure shows only conflicts with one replication. Different types of conflicts are shown with different shapes—crossing conflict with ovals, rear-end conflicts with rectangles, and lane-changing conflicts with triangles. Different colors represent different levels of severity of conflicts—Red represents crashes, orange represents conflicts with $0 < TTC \leq 0.5$, blue represents conflicts with $0.5 < TTC \leq 1.0$, and green represents conflicts with $1.0 < TTC \leq 1.5$.

As shown in the following figures, VISSIM always generated the least conflicts among the simulation platforms, and TEXAS generated the most conflicts. When the intersection was relatively simple (less lanes, less or no left-turn/right-turn bay), most conflicts generated by VISSIM were green, which meant those conflicts fall into the category of $1.0 < TTC \leq 1.5$ and had the least severity level. AIMSUN generated more conflicts in the category of 0.5 < TTC ≤ 1.0 than other categories. Also, more crashes were observed in the area of the intersections in most of the cases for PARAMICS and TEXAS.

Intersection 1: Briarcliff Rd & North Druid Hills Rd, Dekalb County, Atlanta, GA:

Figure 183 through figure 186 show the conflicts layout for intersection 1 under AM peak-hour condition. Figure 187 through figure 190 show the conflicts layout for intersection 1 under mid peak-hour condition, and figure 191 through figure 194 show the conflicts layout for intersection 1 under PM peak-hour condition. The following can be seen in the figures below:

- VISSIM and AIMSUN have few crossing conflicts, while PARAMICS and TEXAS have numerous crashes within the intersection area.
- Most of the rear-end conflicts are blue and green, implying that these are lower severity conflicts.
- There are many rear-end crashes at the exit of the network in AIMSUN.
- A noteworthy number of lane-change conflicts happen in the entrance of some links in VISSIM, while in others lane-change conflicts oocur in the middle of each link or close to the intersection.

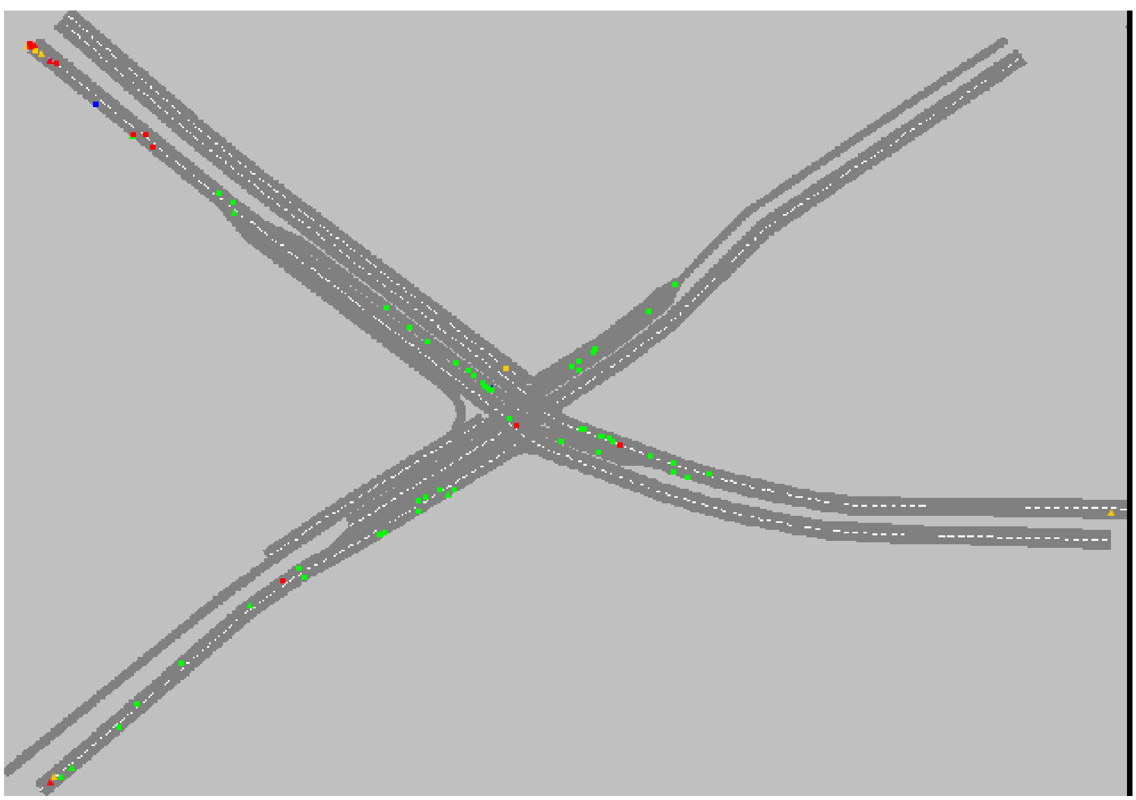


Figure 183. Screen Capture. VISSIM Conflict Layout for AM Peak Hour of Intersection 1 (Total 85).

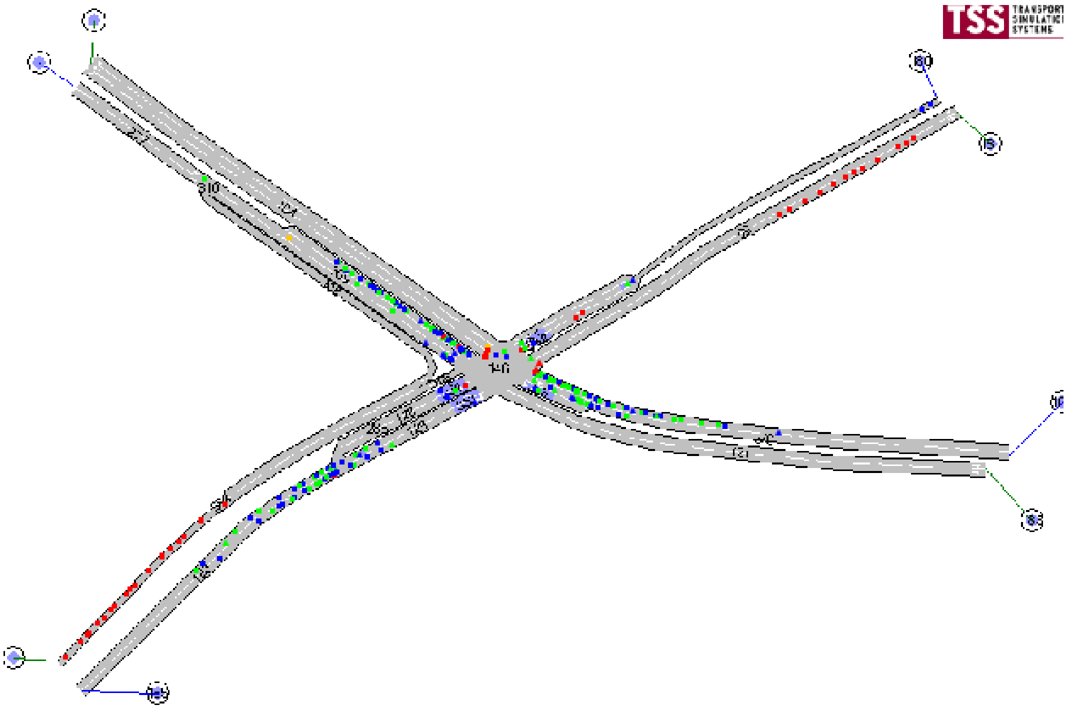


Figure 184. Screen Capture. AIMSUN Conflict Layout for AM Peak Hour of Intersection 1 (Total 271).

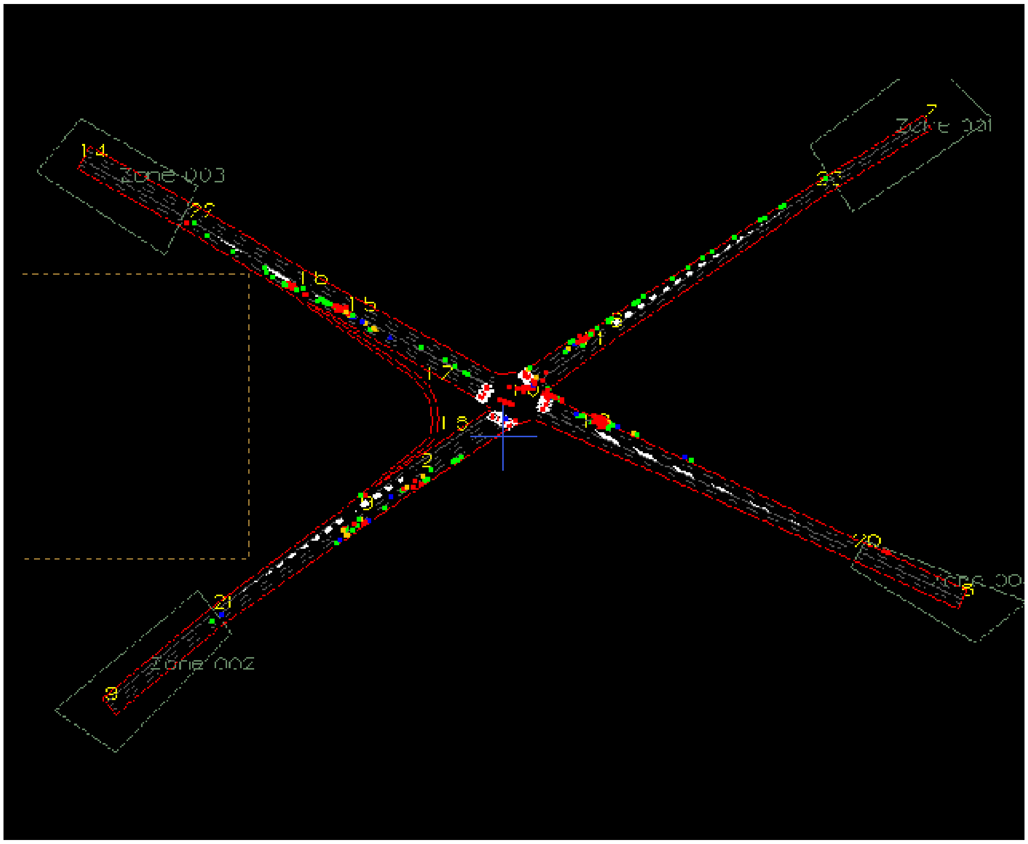


Figure 185. Screen Capture. PARAMICS Conflict Layout for AM Peak Hour of Intersection 1 (Total 427).

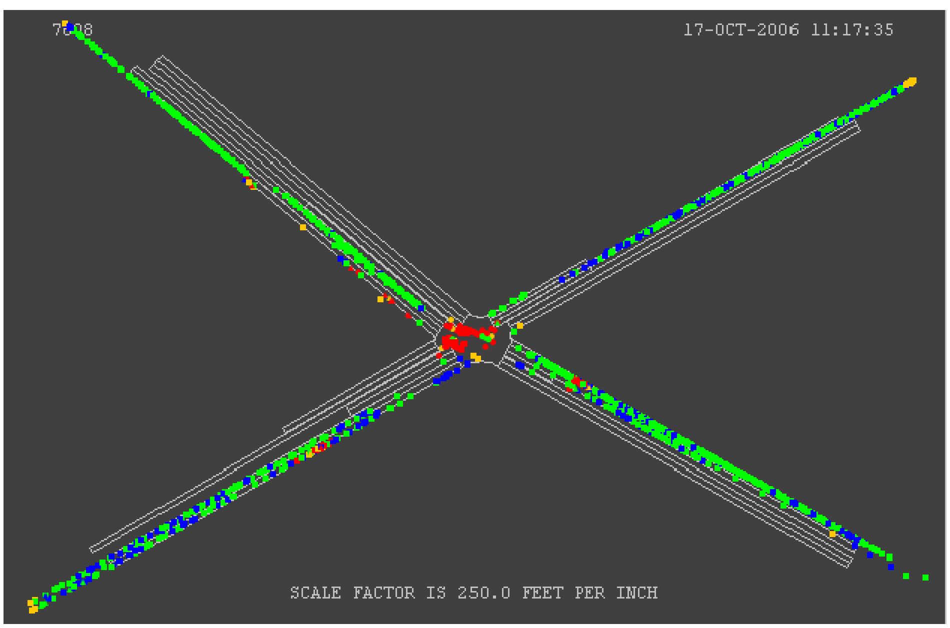


Figure 186. Screen Capture. TEXAS Conflict Layout for AM Peak Hour of Intersection 1 (Total 2,178).

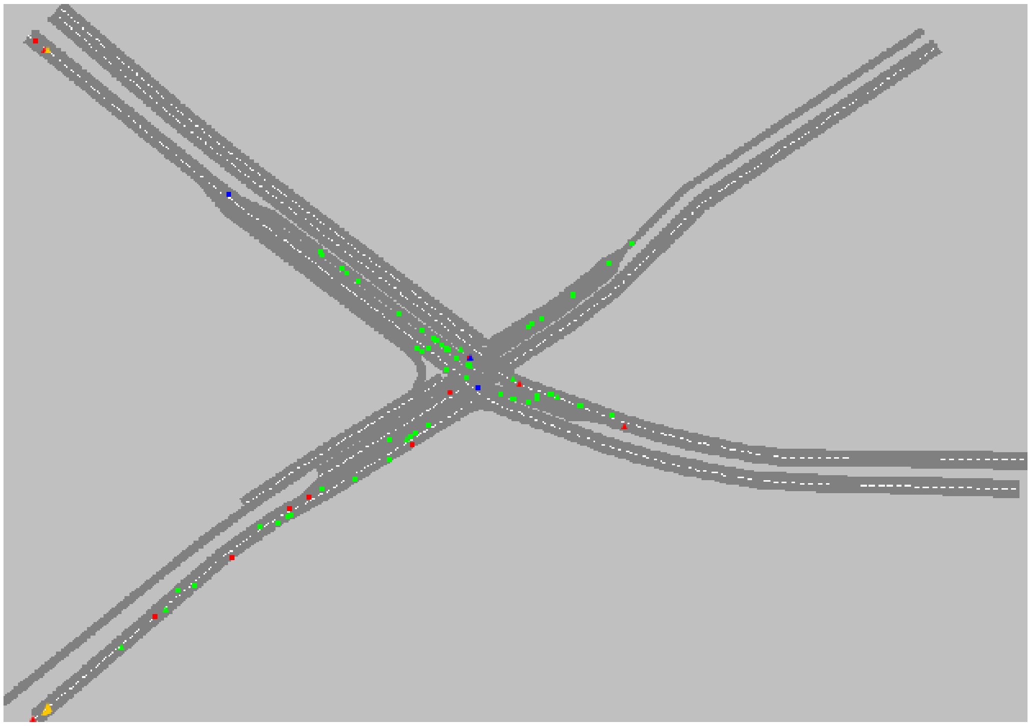


Figure 187. Screen Capture. VISSIM Conflict Layout for Mid Peak Hour of Intersection 1 (Total 84).

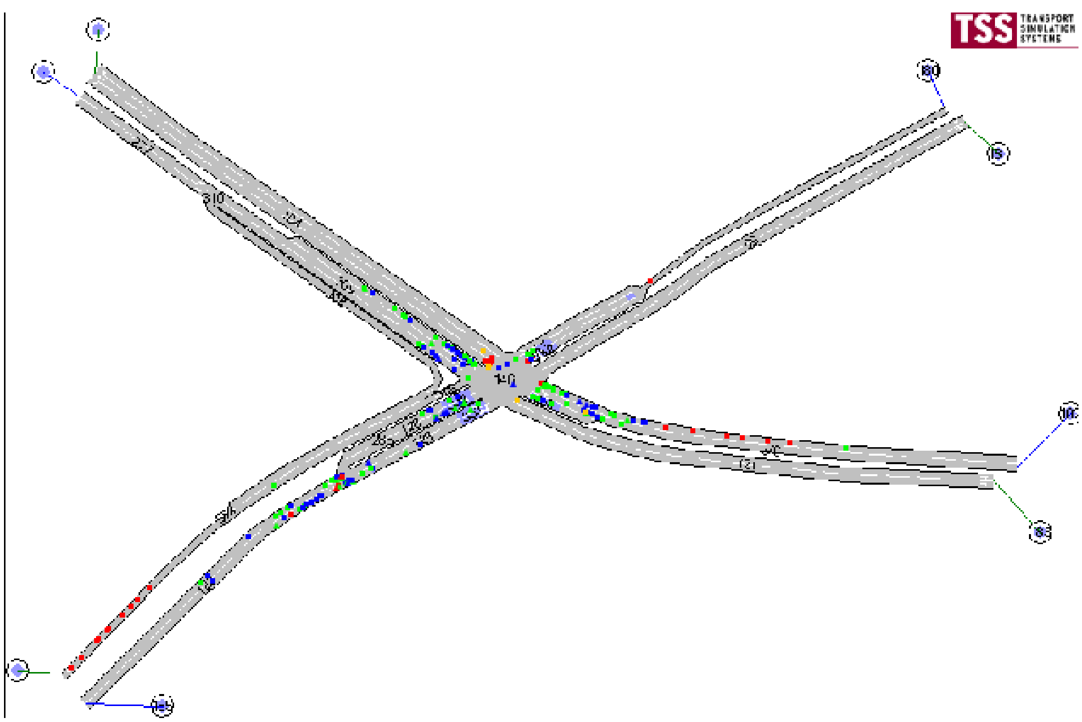


Figure 188. Screen Capture. AIMSUN Conflict Layout for Mid Peak Hour of Intersection 1 (Total 222).

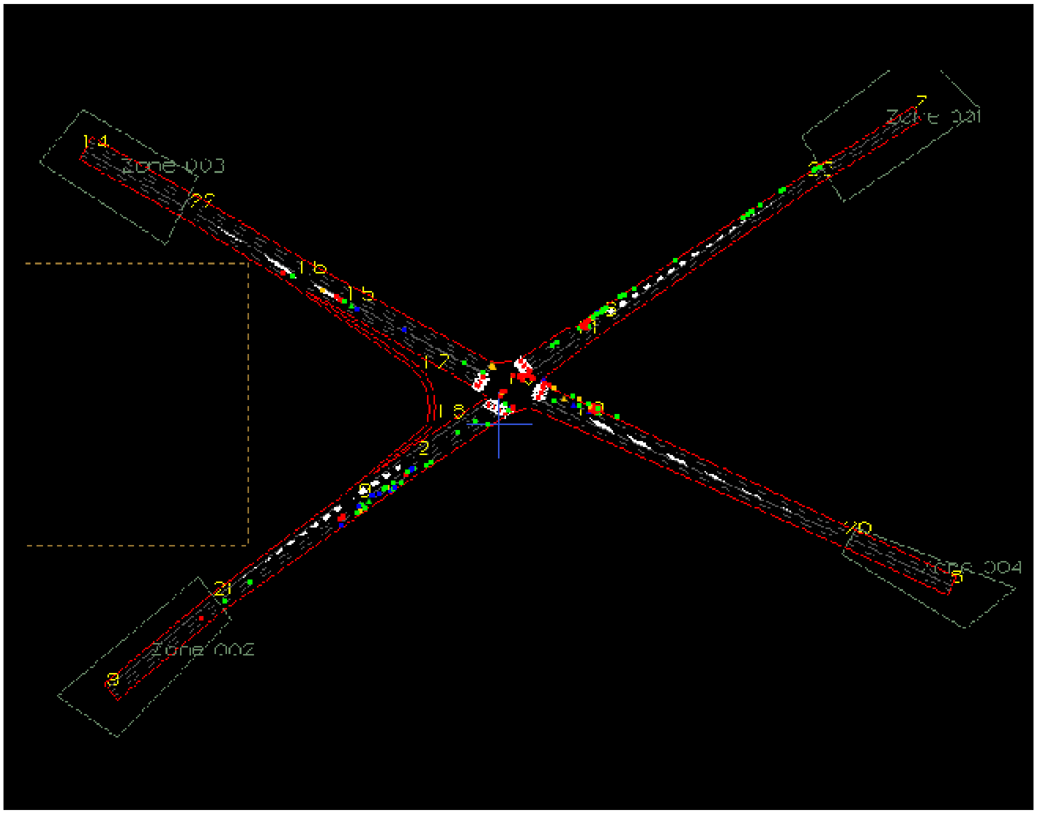


Figure 189. Screen Capture. PARAMICS Conflict Layout for Mid Peak Hour of Intersection 1 (Total 209).

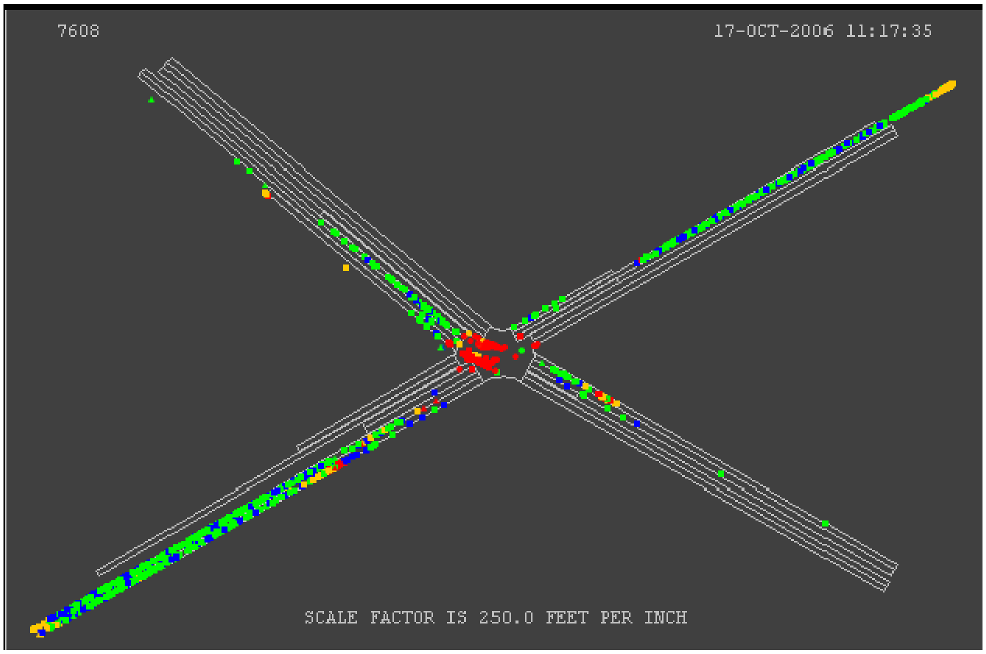


Figure 190. Screen Capture. TEXAS Conflict Layout for Mid Peak Hour of Intersection 1 (Total 1,359).

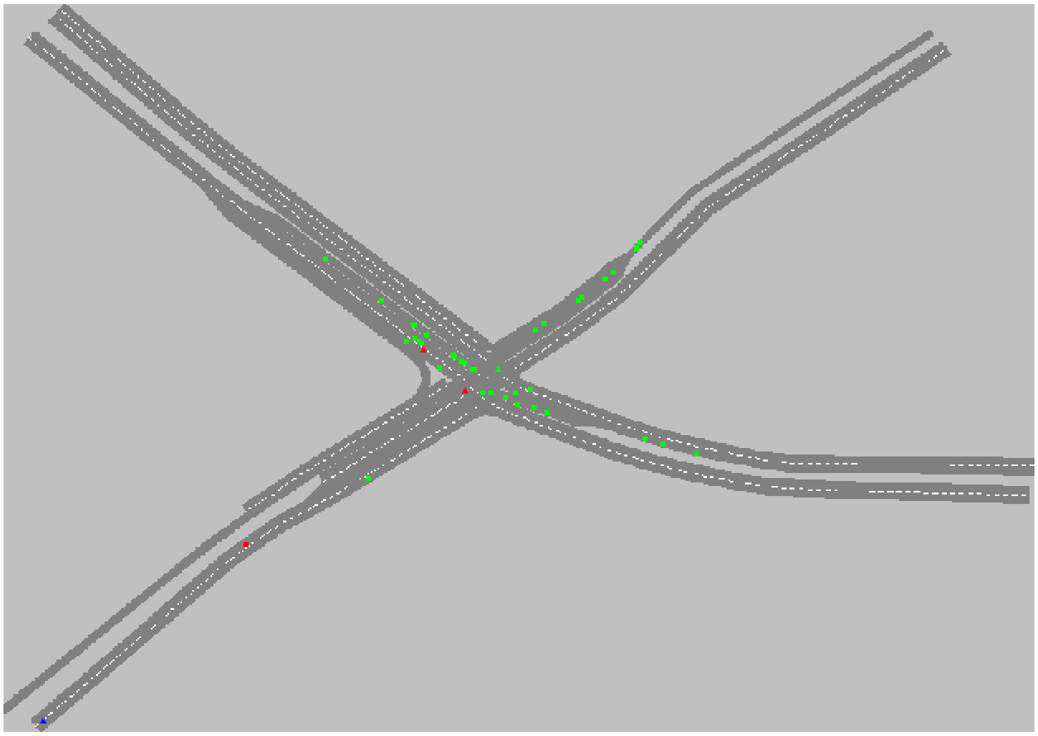


Figure 191. Screen Capture. VISSIM Conflict Layout for PM Peak Hour of Intersection 1 (Total 47).

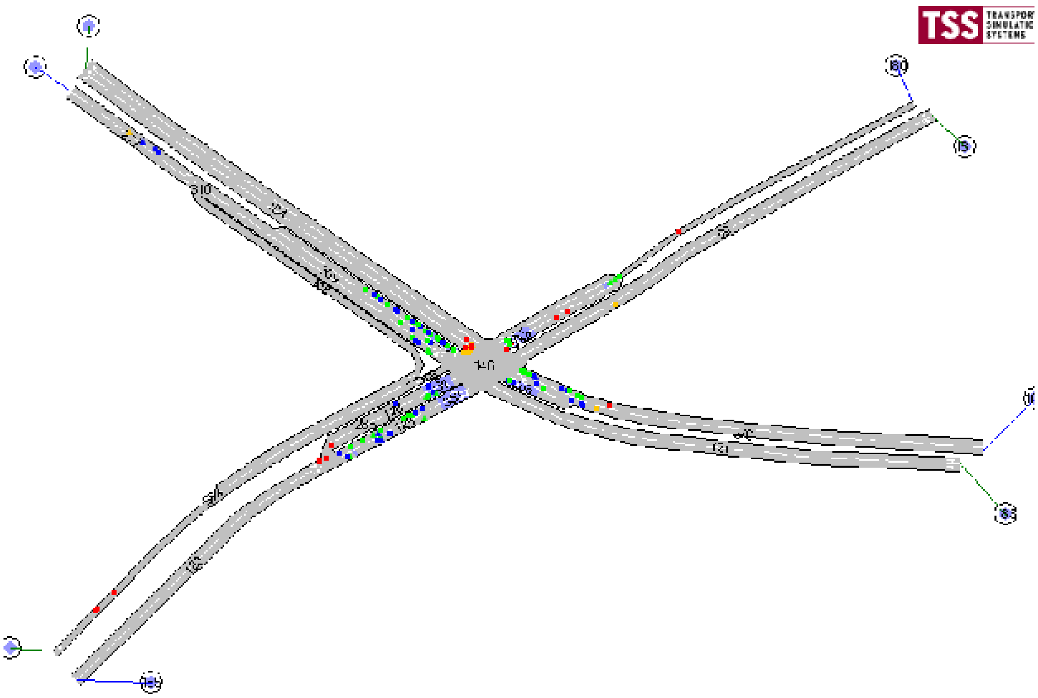


Figure 192. Screen Capture. AIMSUN Conflict Layout for PM Peak Hour of Intersection 1 (Total 156).

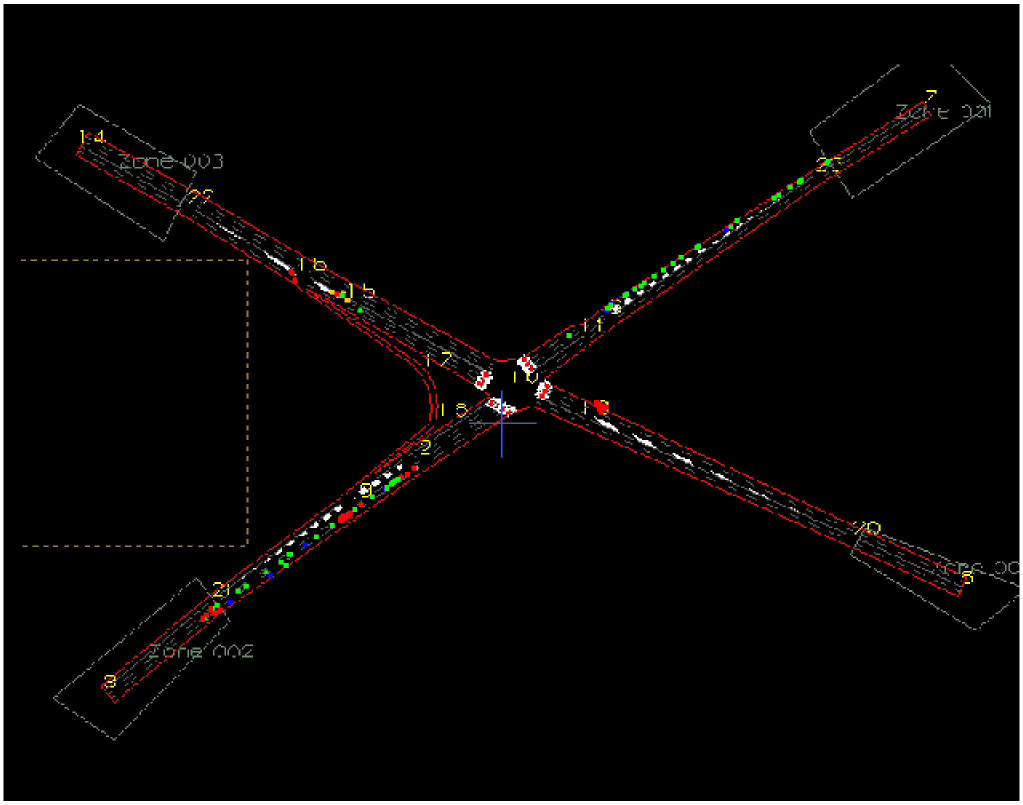


Figure 193. Screen Capture. PARAMICS Conflict Layout for PM Peak Hour of Intersection 1 (Total 118).

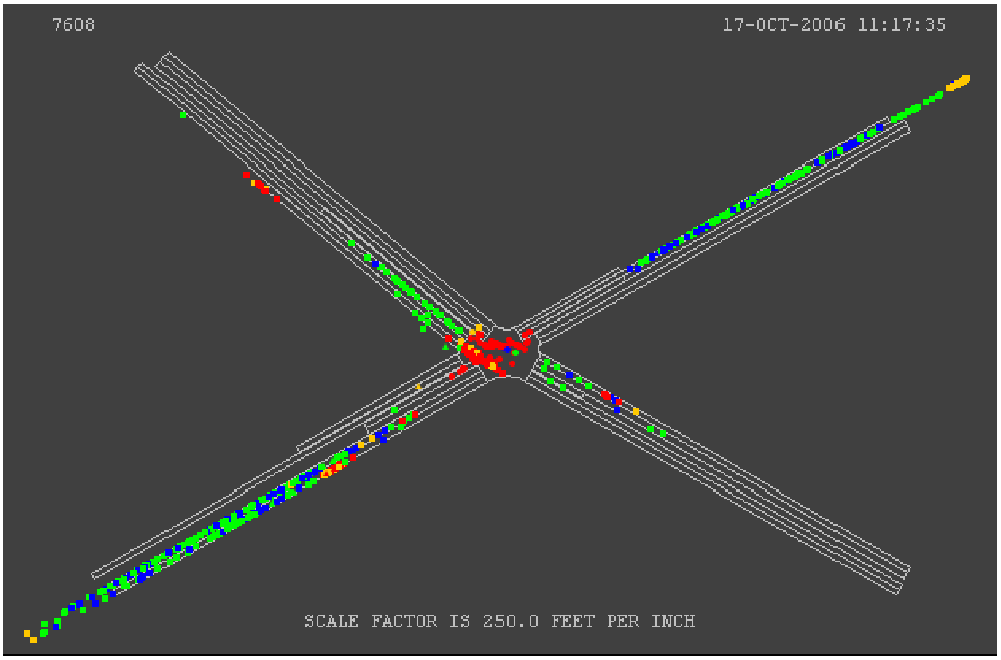


Figure 194. Screen Capture. TEXAS Conflict Layout for PM Peak Hour of Intersection 1 (Total 878).

Intersection 2: Roswell Road & Abernathy Road, Fulton County, Atlanta, GA:

Figure 195 through figure 198 show the conflicts layout for intersection 2 under AM peak-hour condition. Figure 199 through figure 202 show the conflicts layout for intersection 2 under mid peak-hour condition. And figure 203 to figure 206 shows the conflicts layout for intersection 2 under PM peak-hour condition. The following can be seen in the figures below:

- VISSIM and AIMSUN have few crossing conflicts, while PARAMICS and TEXAS have numerous crossing crashes within the intersection.
- Most of the rear-end conflicts are blue and green, implying less severity of conflicts.
- Most of the lane-change conflicts occur in the southbound link, which is related to higher volume.
- Lane-change conflicts in VISSIM show higher severity level than others.
- Lane-change conflicts in AIMSUN show the least level of severity.

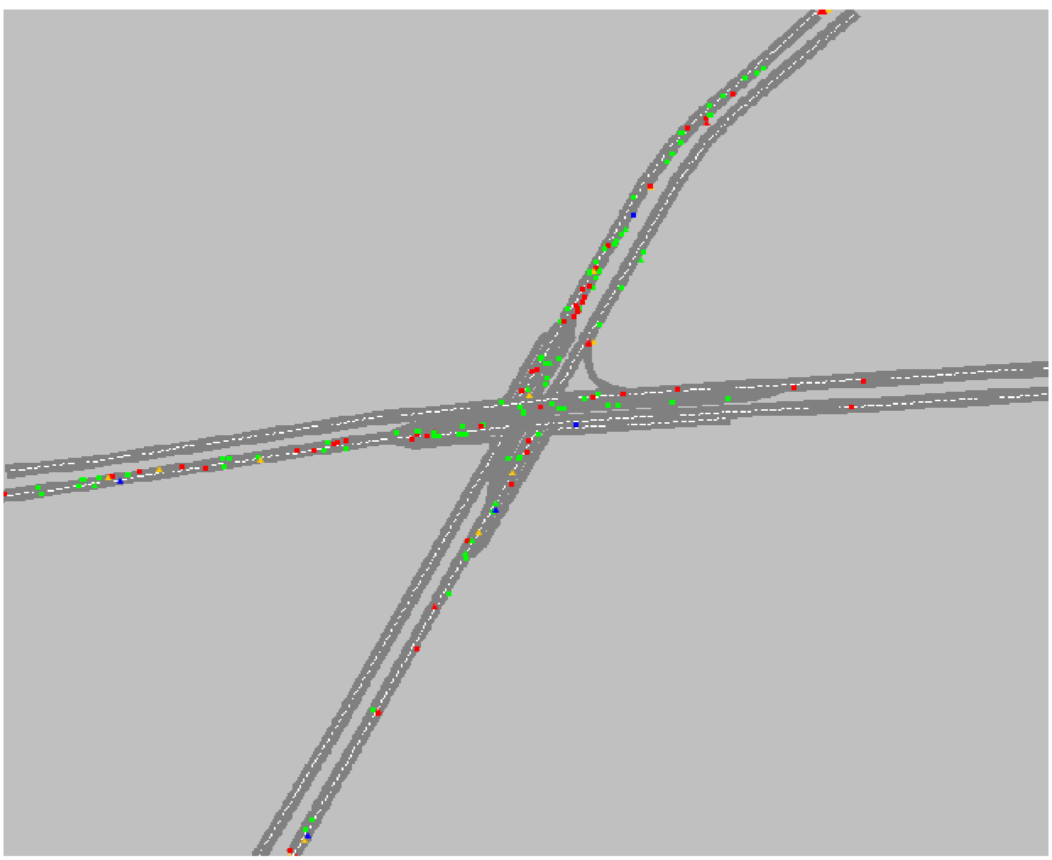


Figure 195. Screen Capture. VISSIM Conflict Layout for AM Peak Hour of Intersection 2 (Total 181).

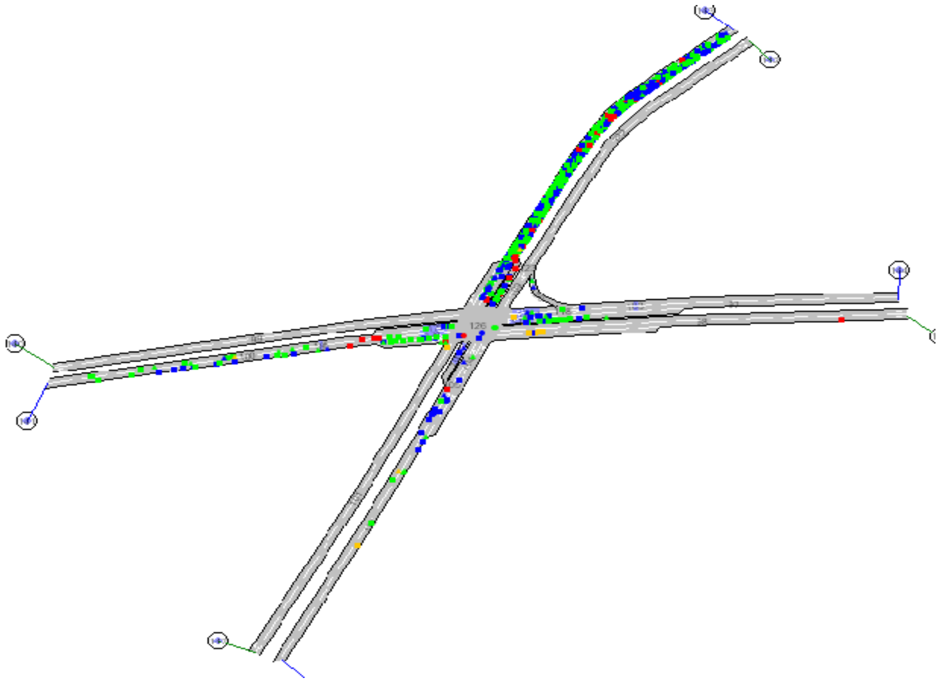


Figure 196. Screen Capture. AIMSUN Conflict Layout for AM Peak Hour of Intersection 2 (Total 997).

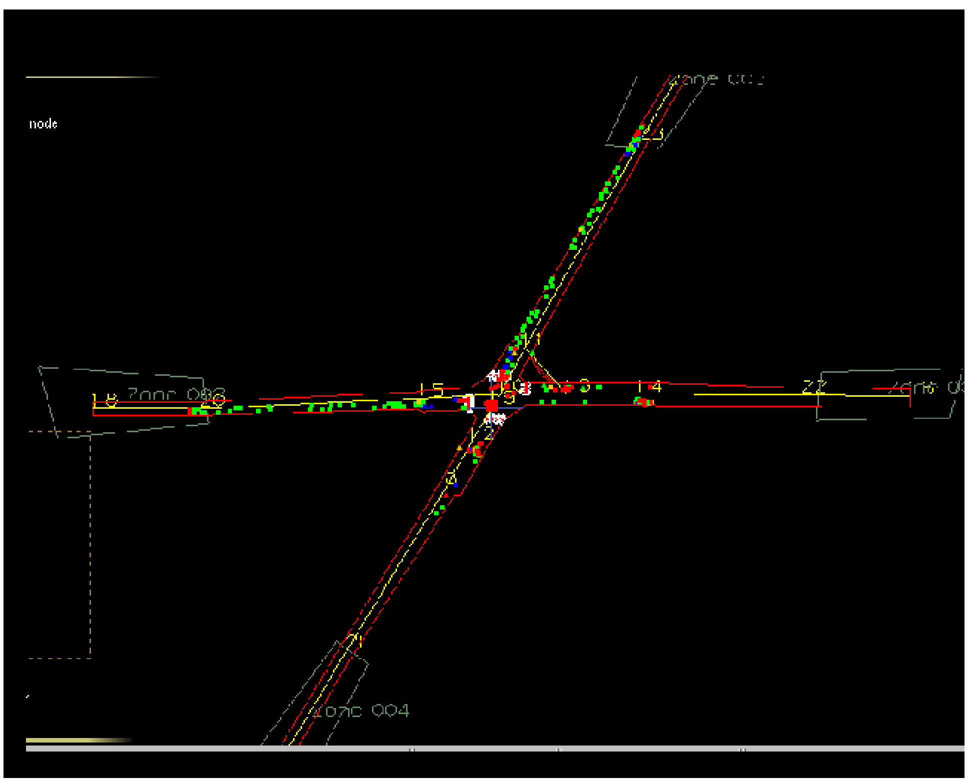


Figure 197. Screen Capture. PARAMICS Conflict Layout for AM Peak Hour of Intersection 2 (Total 565).

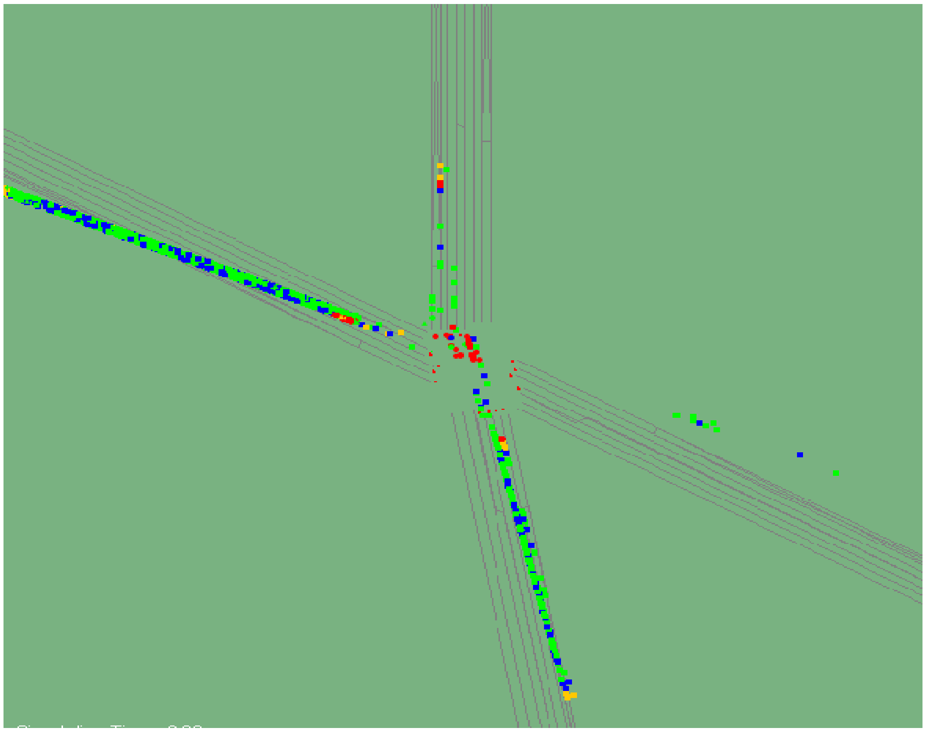


Figure 198. Screen Capture. TEXAS Conflict Layout for AM Peak Hour of Intersection 2 (Total 2,242).

Figure 199. Screen Capture. VISSIM Conflict Layout for Mid Peak Hour of Intersection 2 (Total 215).

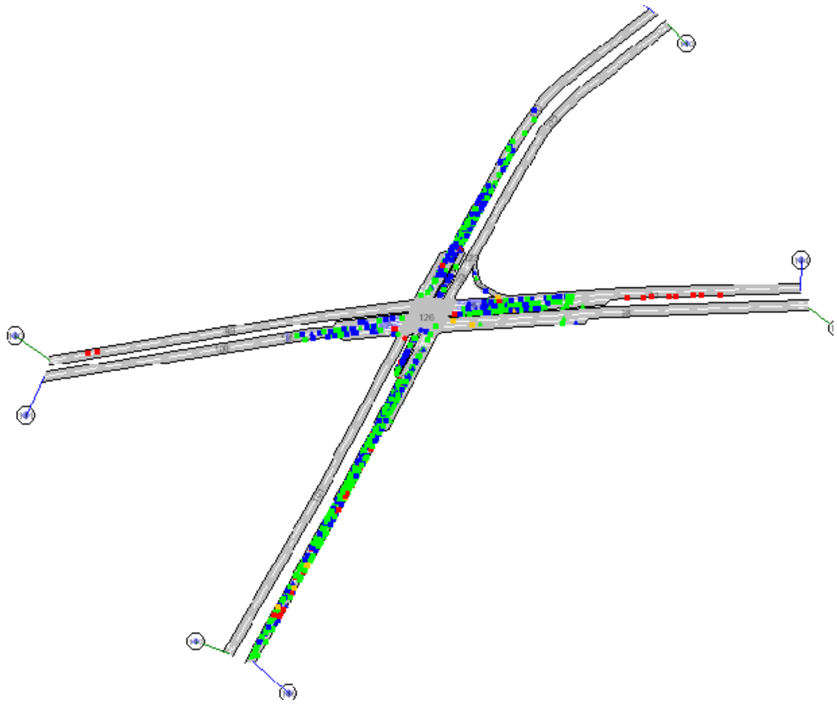


Figure 200. Screen Capture. AIMSUN Conflict Layout for Mid Peak Hour of Intersection 2 (Total 1,107).

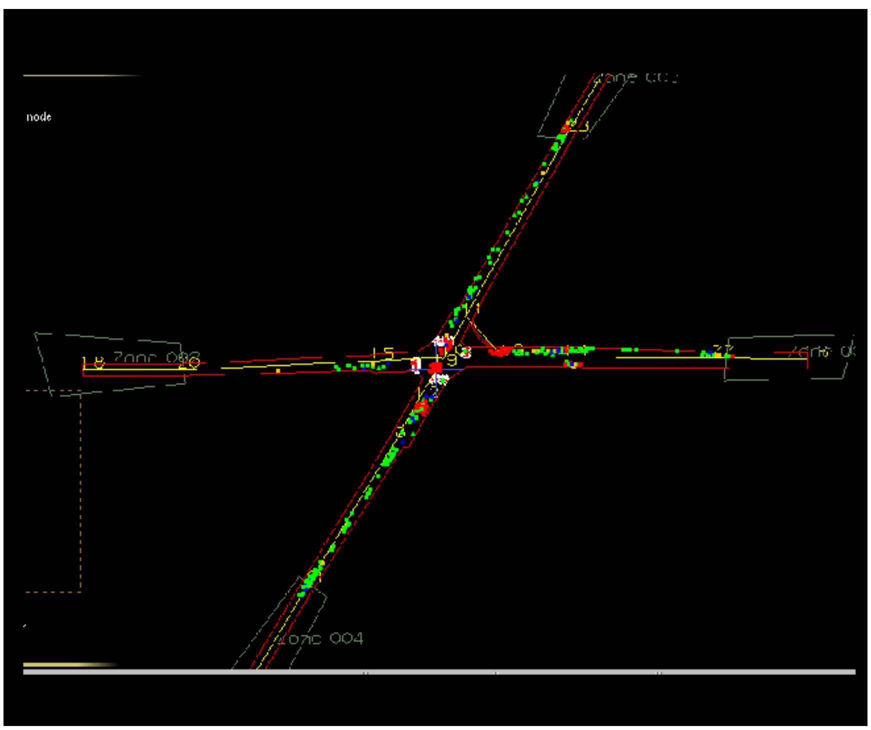


Figure 201. Screen Capture. PARAMICS Conflict Layout for Mid Peak Hour of Intersection 2 (Total 708).

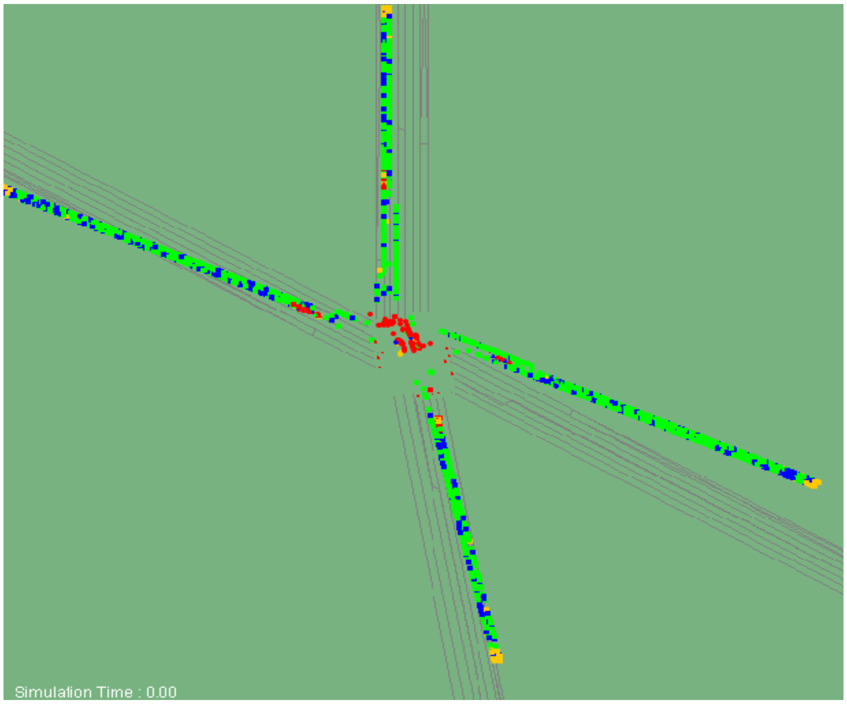


Figure 202. Screen Capture. TEXAS Conflict Layout for Mid Peak Hour of Intersection 2 (Total 5,173).

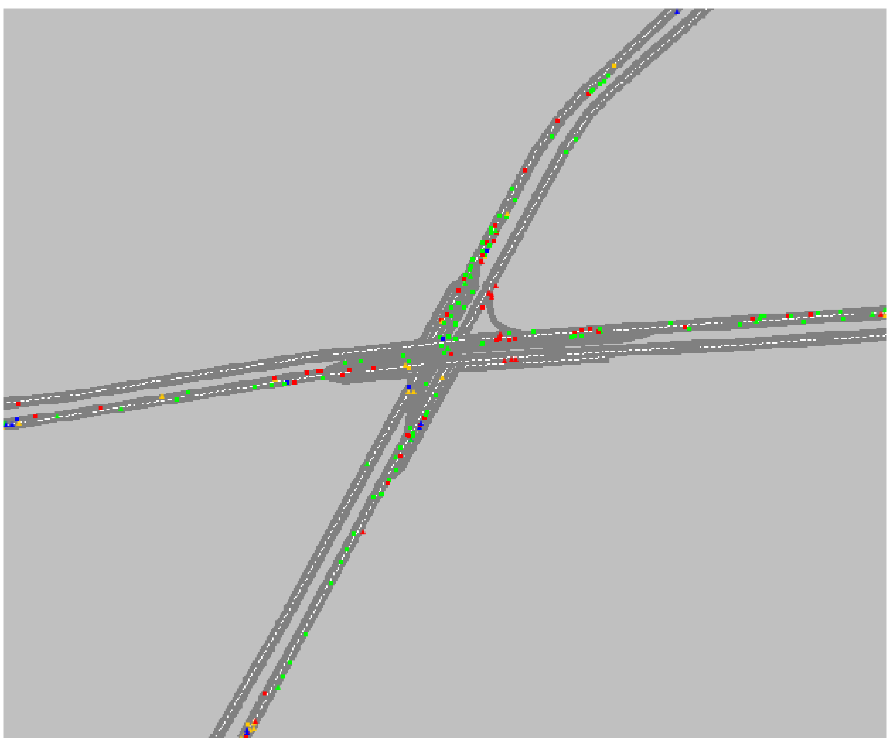


Figure 203. Screen Capture. VISSIM Conflict Layout for PM Peak Hour of Intersection 2 (Total 214).

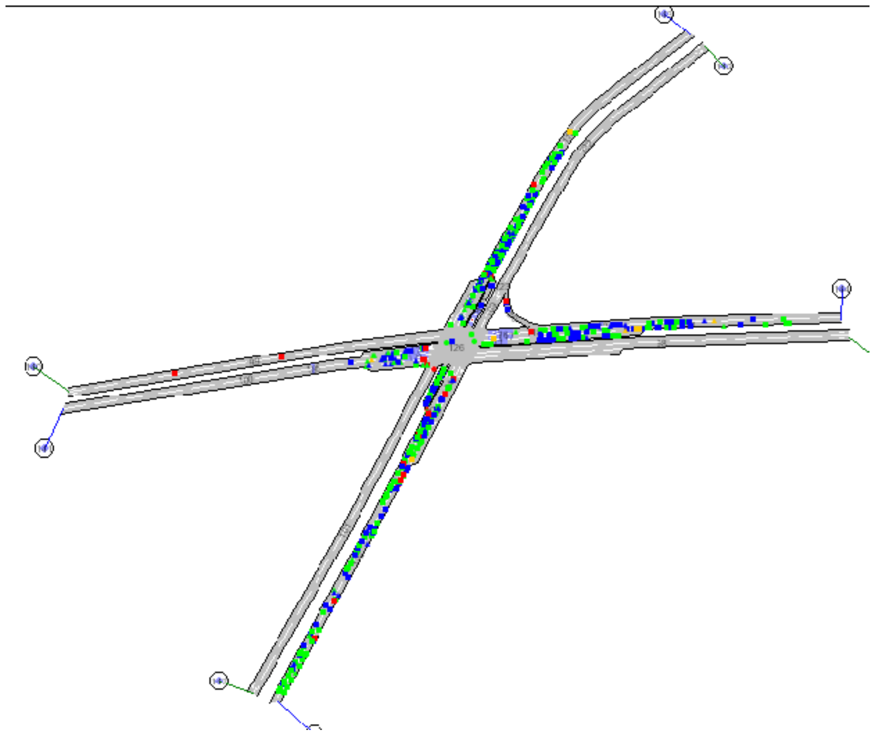


Figure 204. Screen Capture. AIMSUN Conflict Layout for PM Peak Hour of Intersection 2 (Total 619).

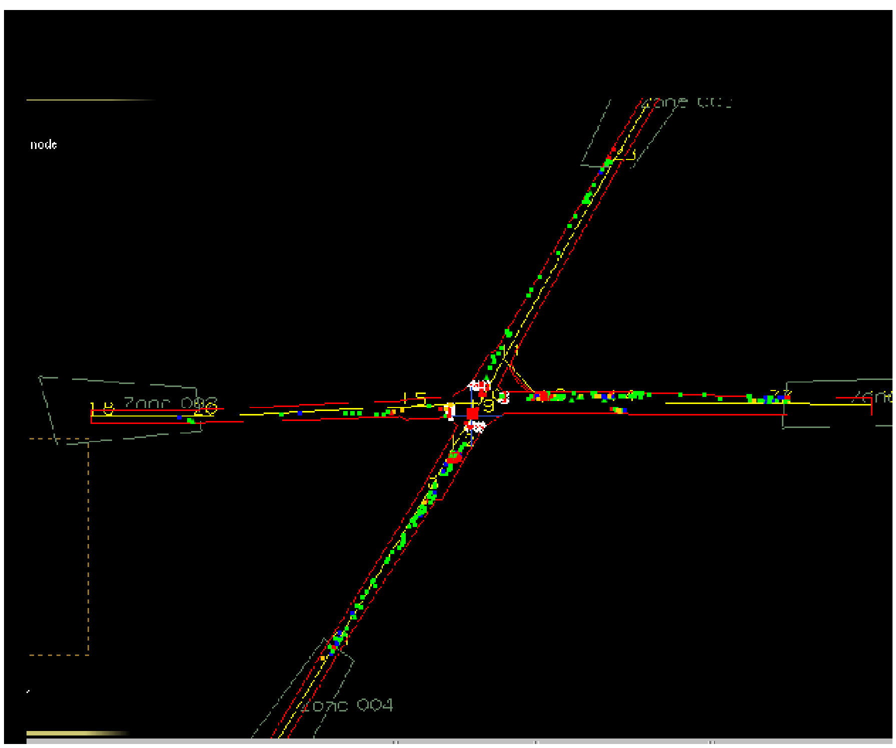


Figure 205. Screen Capture. PARAMICS Conflict Layout for PM Peak Hour of Intersection 2 (Total 485).

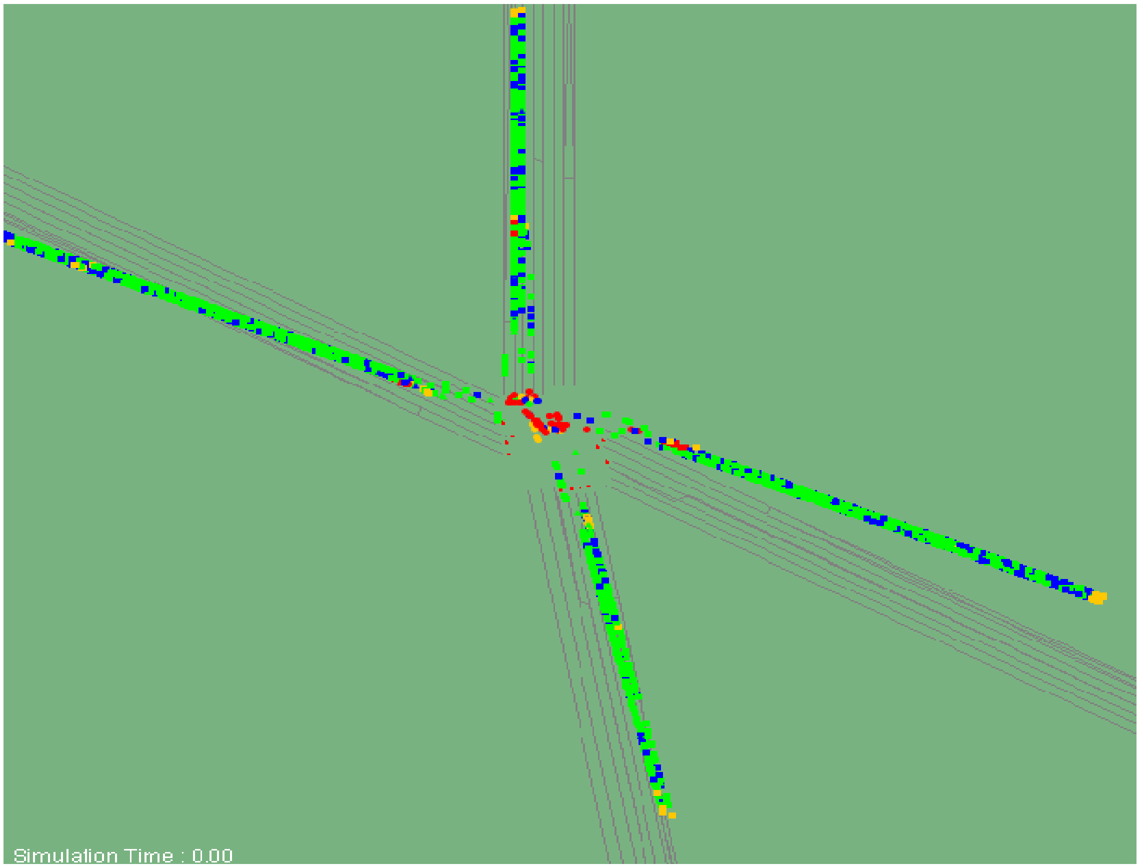


Figure 206. Screen Capture. TEXAS Conflict Layout for PM Peak Hour of Intersection 2 (Total 4,652).

Intersection 3: Lafayette Ave & Fulton Street, Grand Rapids, MI:

Figure 207 through figure 210 show the conflicts layout for intersection 3 under AM peak-hour condition. Figure 211 through figure 214 show the conflicts layout for intersection 3 under PM peak-hour condition. The following can be seen in the figures below:

- AIMSUN has few crossing conflicts; VISSIM, PARAMICS, and TEXAS has some crashes in the node area.
- Most of the rear-end conflicts are located close to intersection.
- Most of the rear-end conflicts are blue and green, implying less severity. Most of the rear-end conflicts in VISSIM are green; few are crashes.
- VISSIM and TEXAS have almost no lane-change conflicts; PARAMICS has many lane-change crashes. Lane-change conflicts in AIMSUN are green and blue.

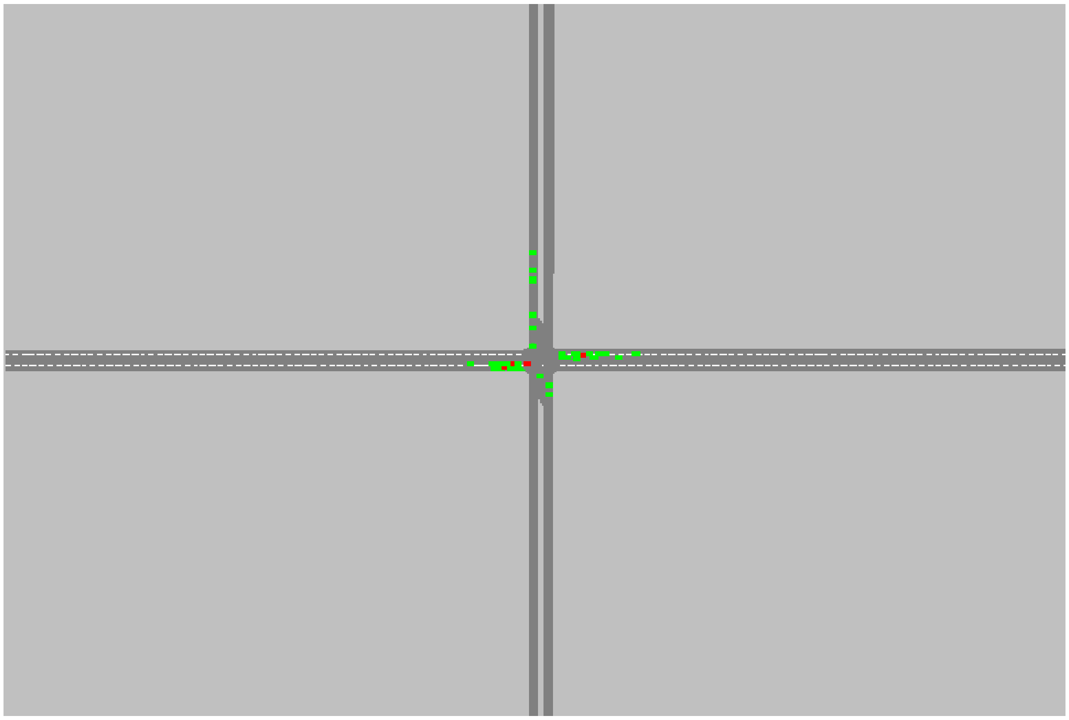


Figure 207. Screen Capture. VISSIM Conflict Layout for AM Peak Hour of Intersection 3 (Total 59).

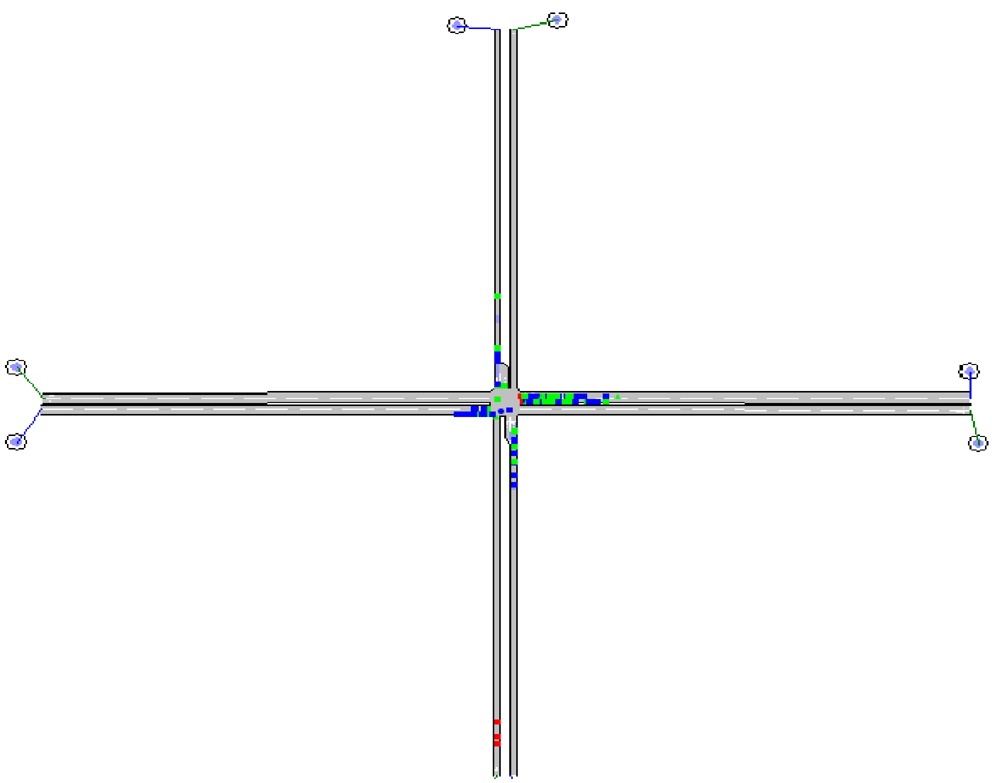


Figure 208. Screen Capture. AIMSUN Conflict Layout for AM Peak Hour of Intersection 3 (Total 128).

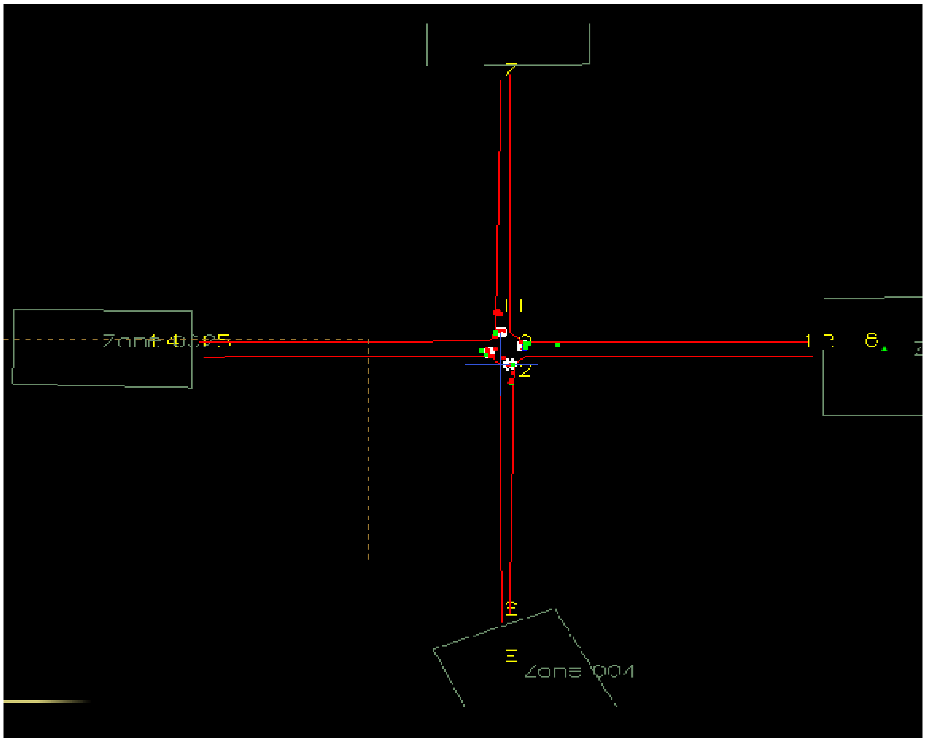


Figure 209. Screen Capture. PARAMICS Conflict Layout for AM Peak Hour of Intersection 3 (Total 46).

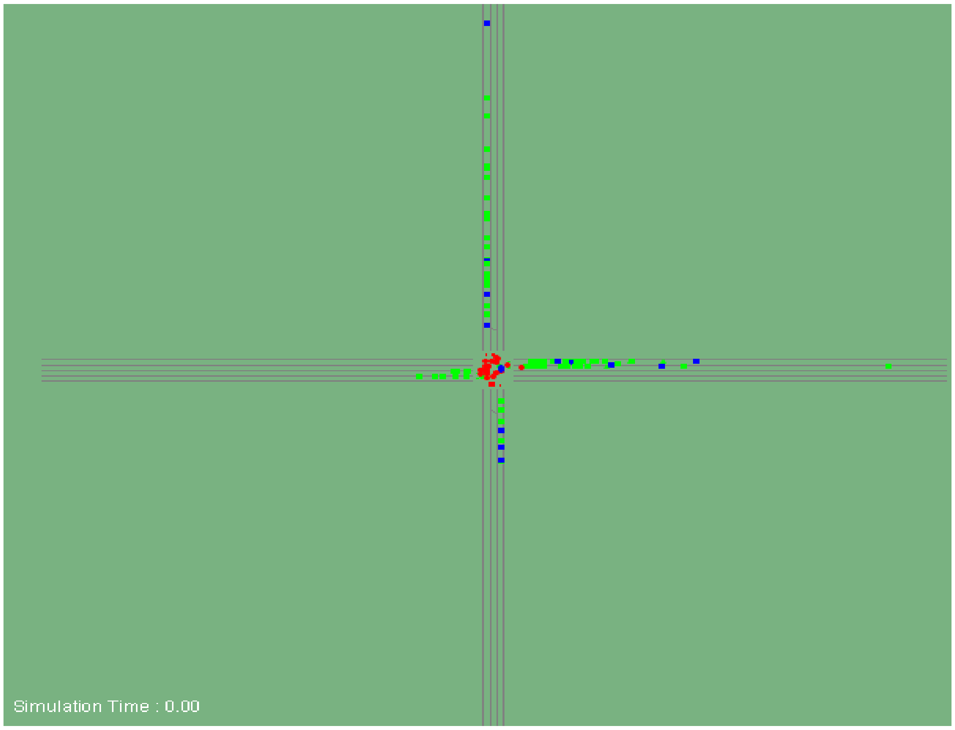


Figure 210. Screen Capture. TEXAS Conflict Layout for AM Peak Hour of 7,500B (Total 138).

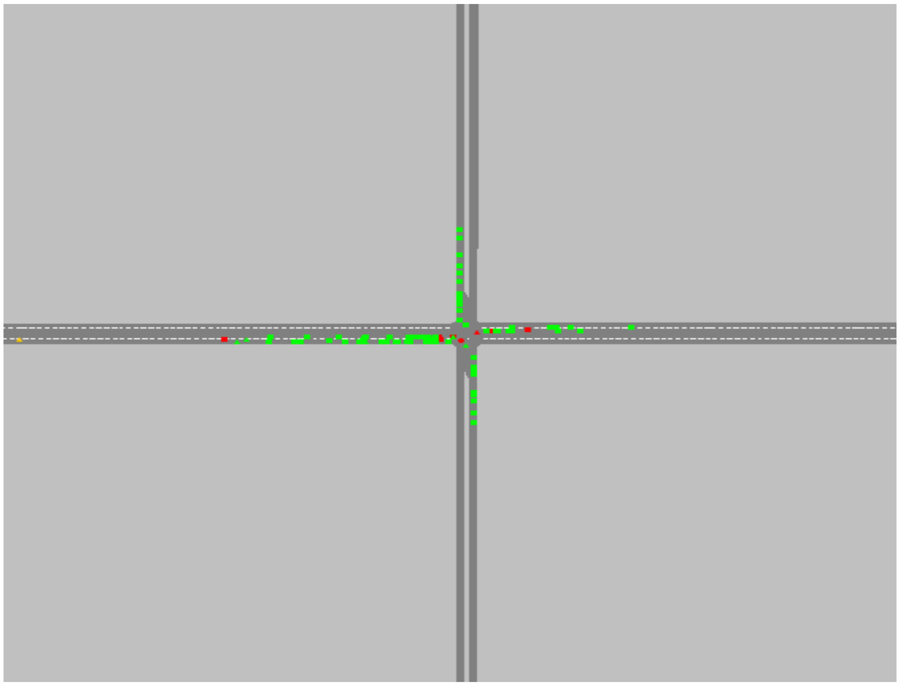


Figure 211. Screen Capture. VISSIM Conflict Layout for PM Peak Hour of Intersection 3 (Total 93).

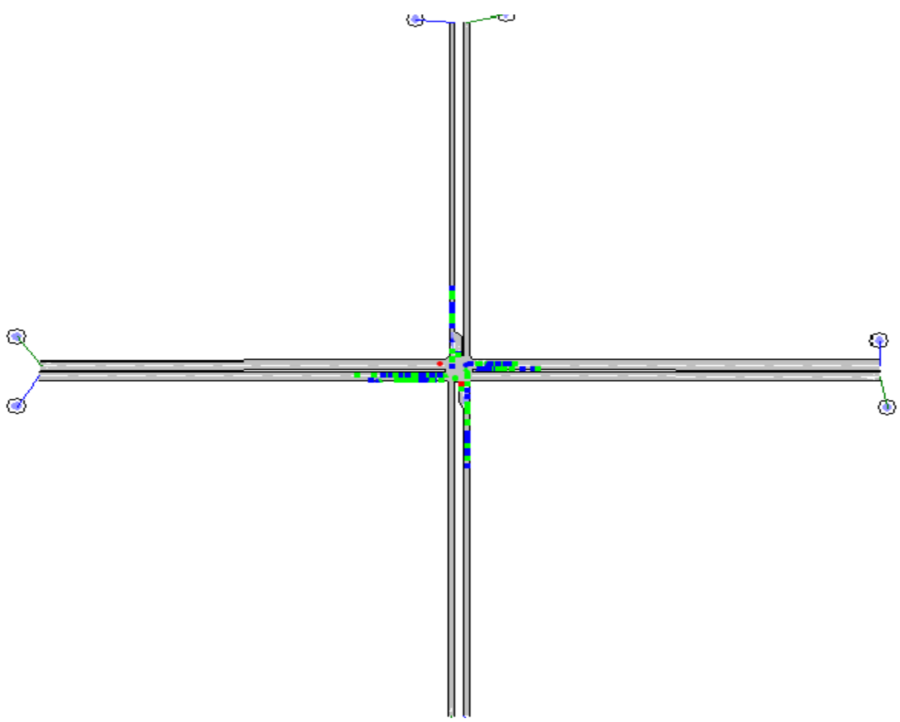


Figure 212. Screen Capture. AIMSUN Conflict Layout for PM Peak Hour of Intersection 3 (Total 184).

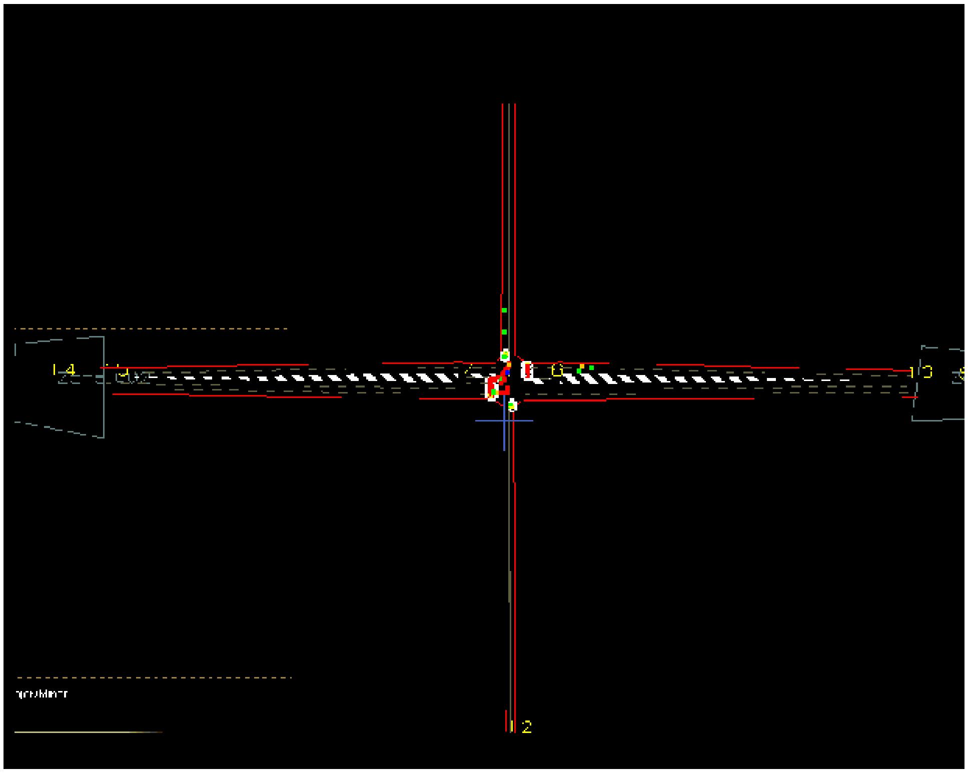


Figure 213. Screen Capture. PARAMICS Conflict Layout for PM Peak Hour of Intersection 3 (Total 45).

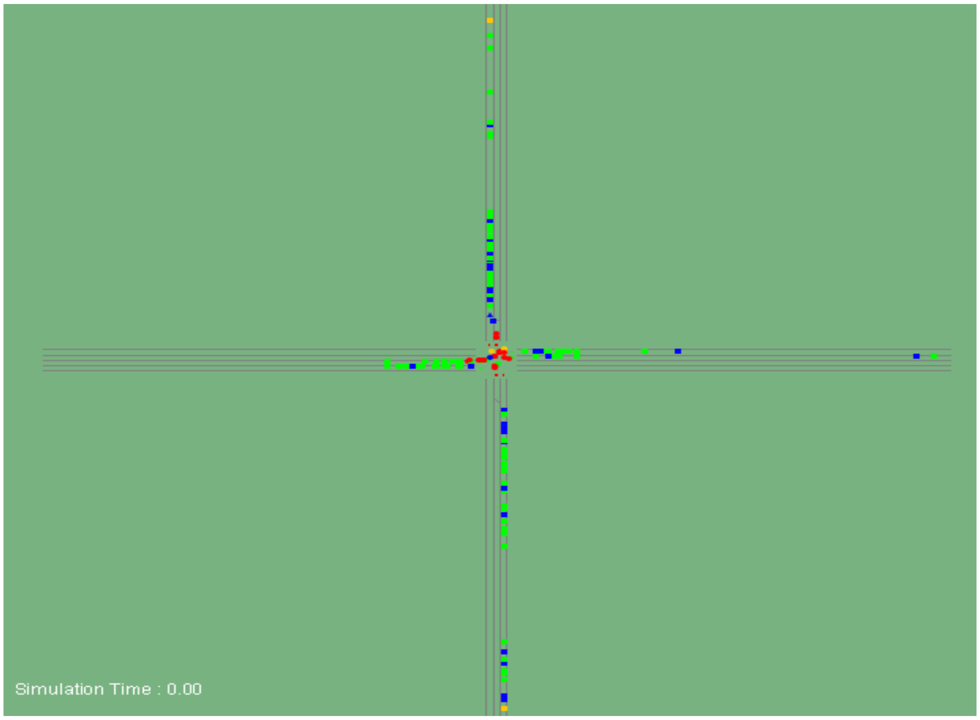


Figure 214. Screen Capture. TEXAS Conflict Layout for PM Peak Hour of Intersection 3 (Total 182).

Intersection 4: Ryan Ave & Davison Ave, Detroit, MI:

Figure 215 through figure 218 show the conflicts layout for intersection 4 under AM peak-hour condition. Figure 219 through figure 222 shows the conflicts layout for intersection 4 under PM peak-hour condition. The following can be seen from the figures below:

- VISSIM and AIMSUN have few crossing conflicts; PARAMICS and TEXAS have many crashes in the node area.
- Most rear-end conflicts occur on the southbound, eastbound, and westbound for all simulation platforms. Most of the rear-end conflicts are blue and green, implying less severity of conflicts.
- VISSIM has some rear-end crashes and has almost no rear-end conflicts with $0.5 < TTC < 1.5$.
- AIMSUN has numerous rear-end crashes at one of the exit links.
- Lane-change conflicts occur near the intersection.

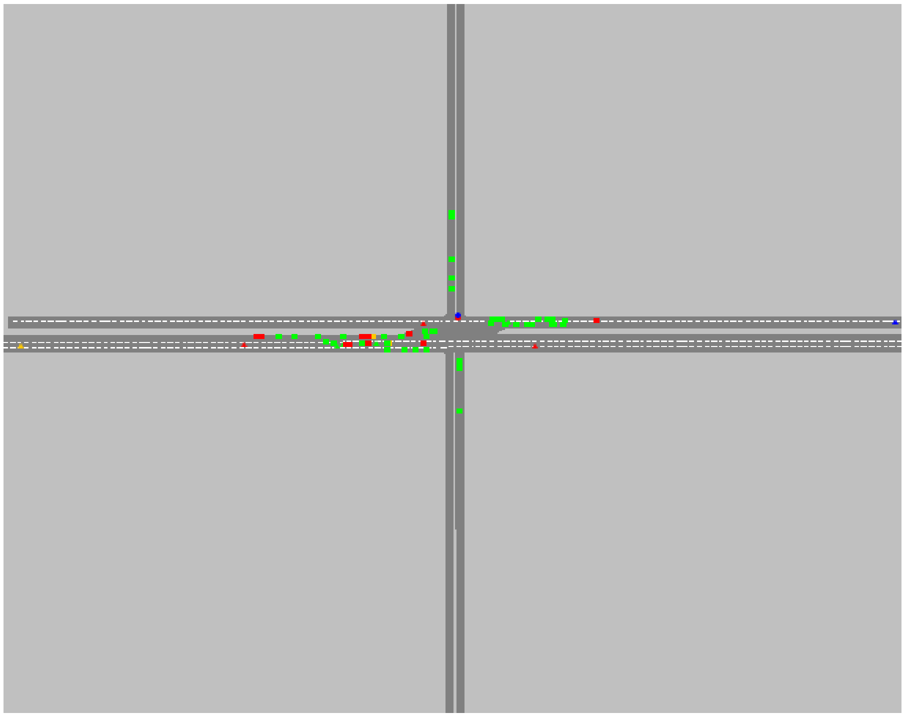


Figure 215. Screen Capture. VISSIM Conflict Layout for AM Peak Hour of Intersection 4 (Total 78).

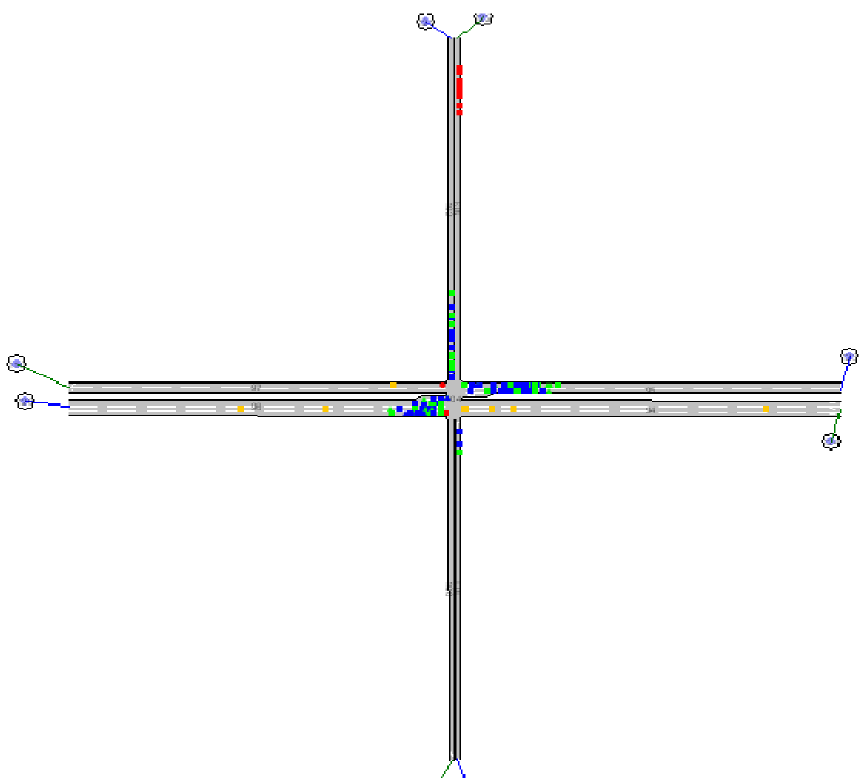


Figure 216. Screen Capture. AIMSUN Conflict Layout for AM Peak Hour of Intersection 4 (Total 143).

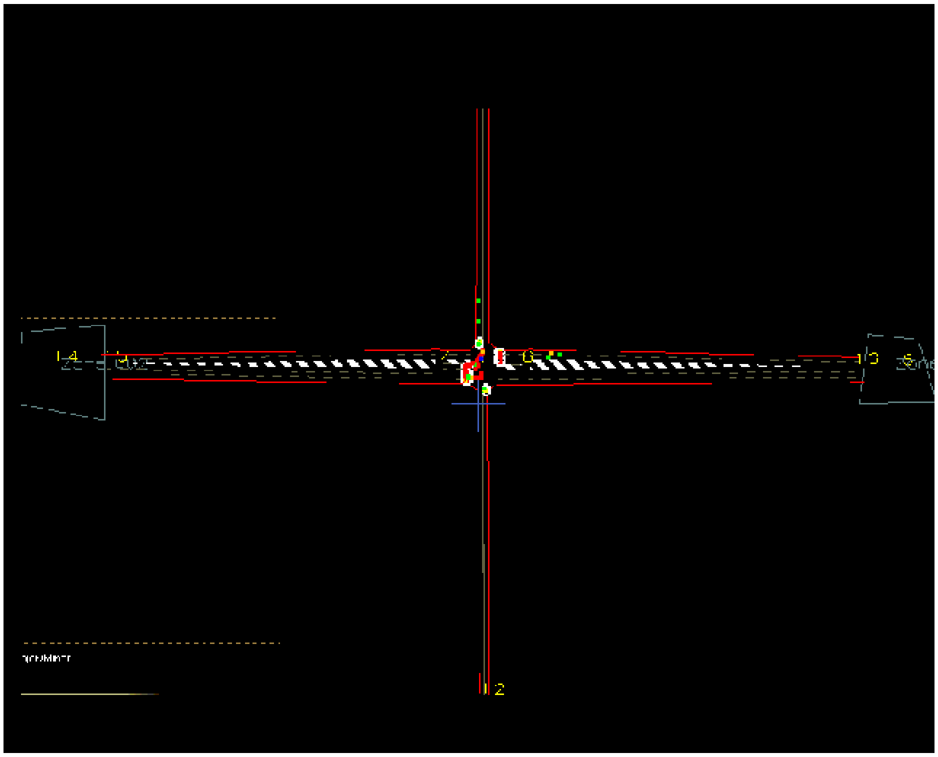


Figure 217. Screen Capture. PARAMICS Conflict Layout for AM Peak Hour of Intersection 4 (Total 45).

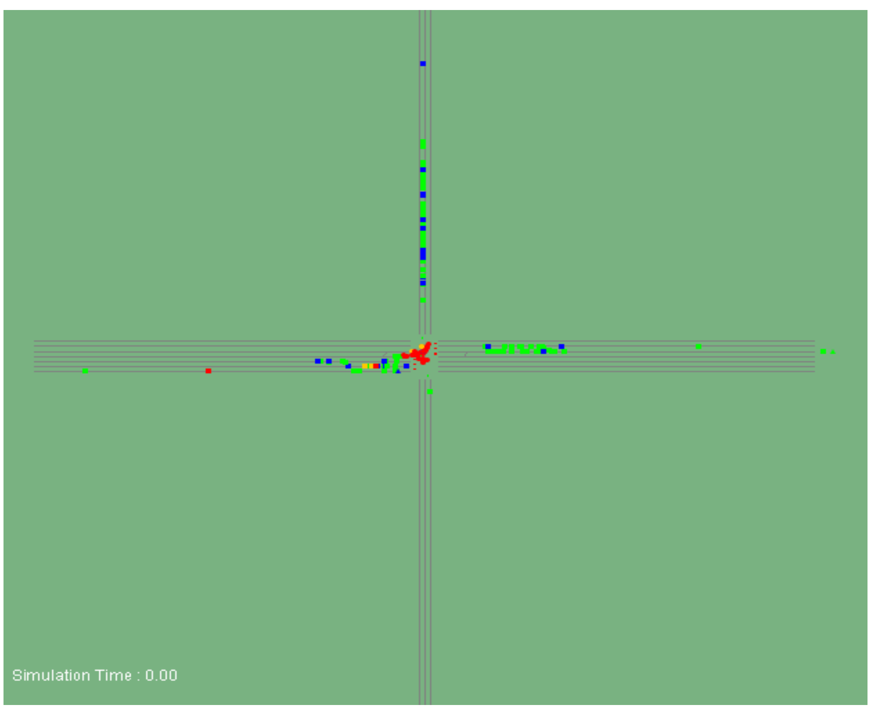


Figure 218. Screen Capture. TEXAS Conflict Layout for AM Peak Hour of Intersection 4 (Total 206).

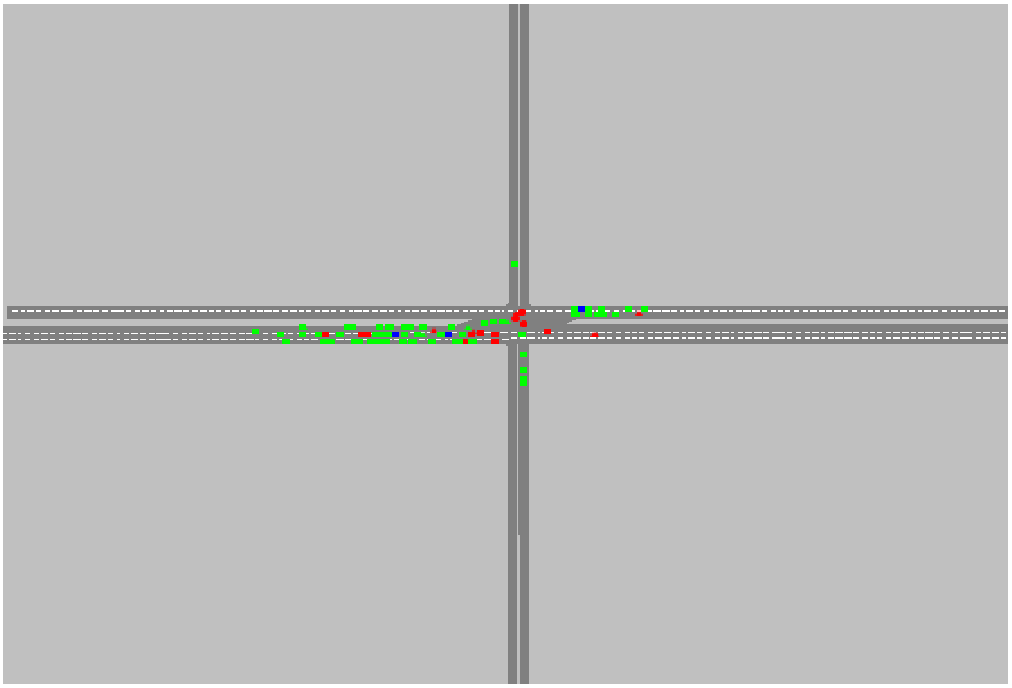


Figure 219. Screen Capture. VISSIM Conflict Layout for PM Peak Hour of Intersection 4 (Total 104).

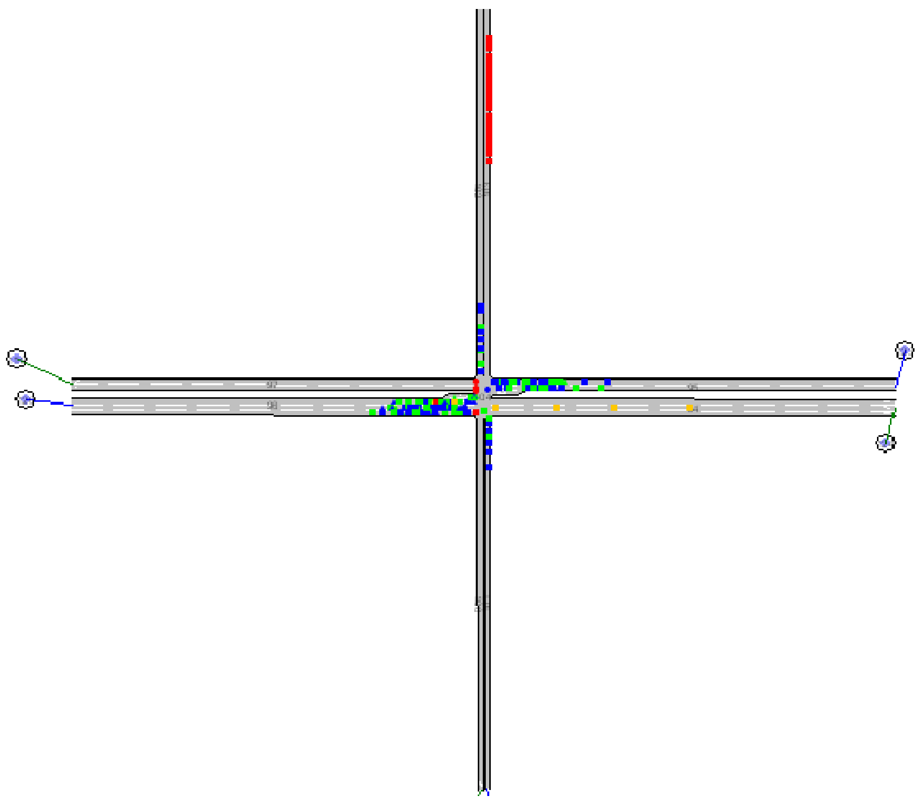


Figure 220. Screen Capture. AIMSUN Conflict Layout for PM Peak Hour of Intersection 4 (Total 229).

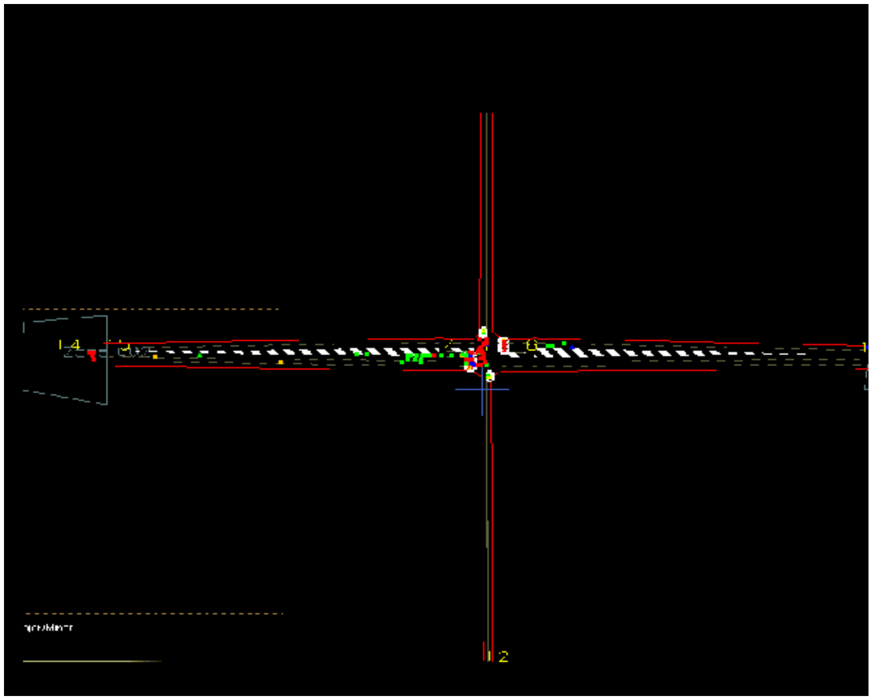


Figure 221. Screen Capture. PARAMICS Conflict Layout for PM Peak Hour of Intersection 4 (Total 111).

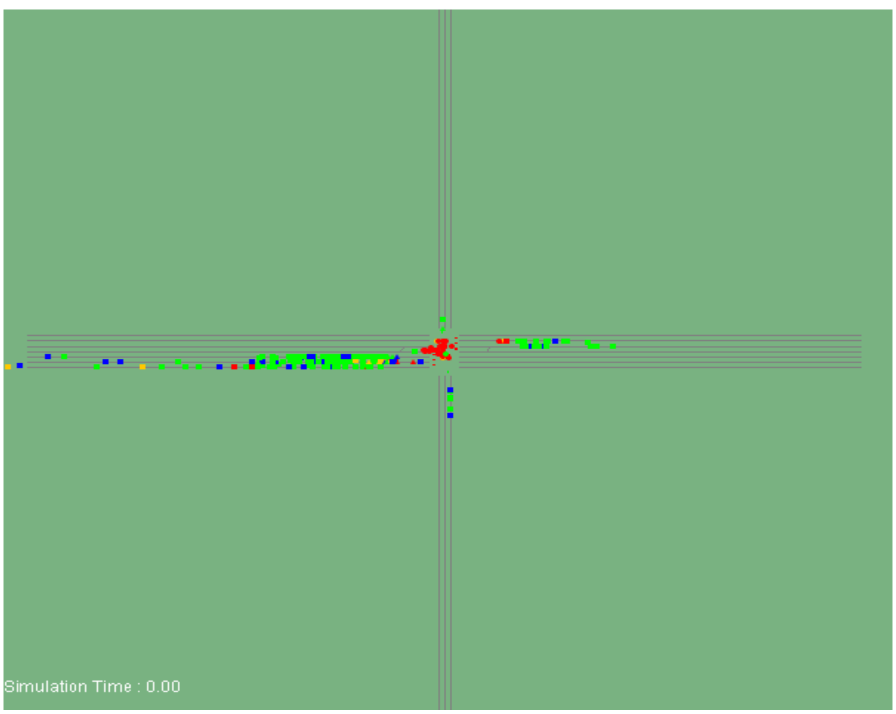


Figure 222. Screen Capture. TEXAS Conflict Layout for PM Peak Hour of Intersection 4 (Total 379).

Intersection 5: Howe Ave & Fair Oaks Boulevard, Sacramento, CA:

Figure 223 through figure 226 shows the conflicts layout for intersection 5 under AM peak-hour condition. Figure 227 to figure 230 shows the conflicts layout for intersection 5 under PM peak-hour condition. The following can be seen in the figures below:

- TEXAS has some crossing crashes.
- Most rear-end conflicts are blue and green, implying less severity of conflicts.
- PARAMICS has some rear-end crashes within the intersection.
- There are fewer lane-change conflicts in PARAMICS.
- There are some lane-change conflicts at the link entrance in VISSIM.
- TEXAS has many lane-change crashes in the middle of each link.

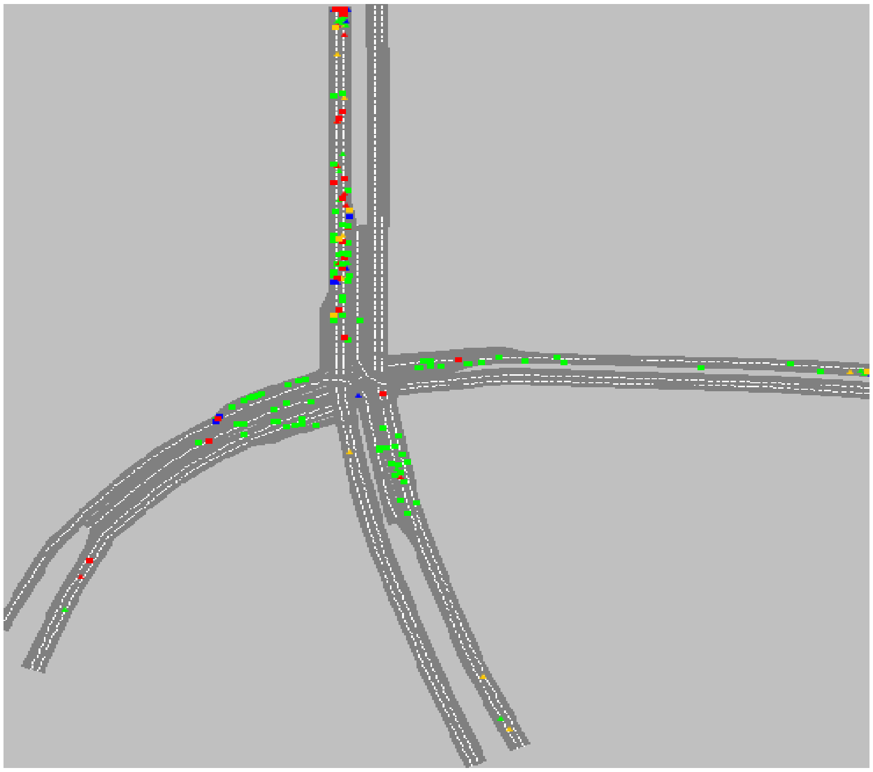


Figure 223. Screen Capture. VISSIM Conflict Layout for AM Peak Hour of Intersection 5 (Total 185).

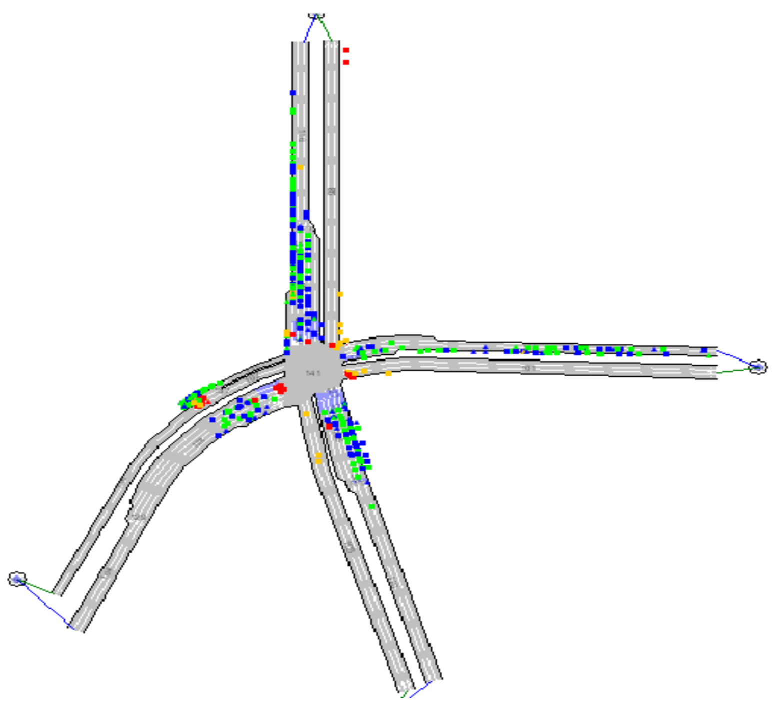


Figure 224. Screen Capture. AIMSUN Conflict Layout for AM Peak Hour of Intersection 5 (Total 558).

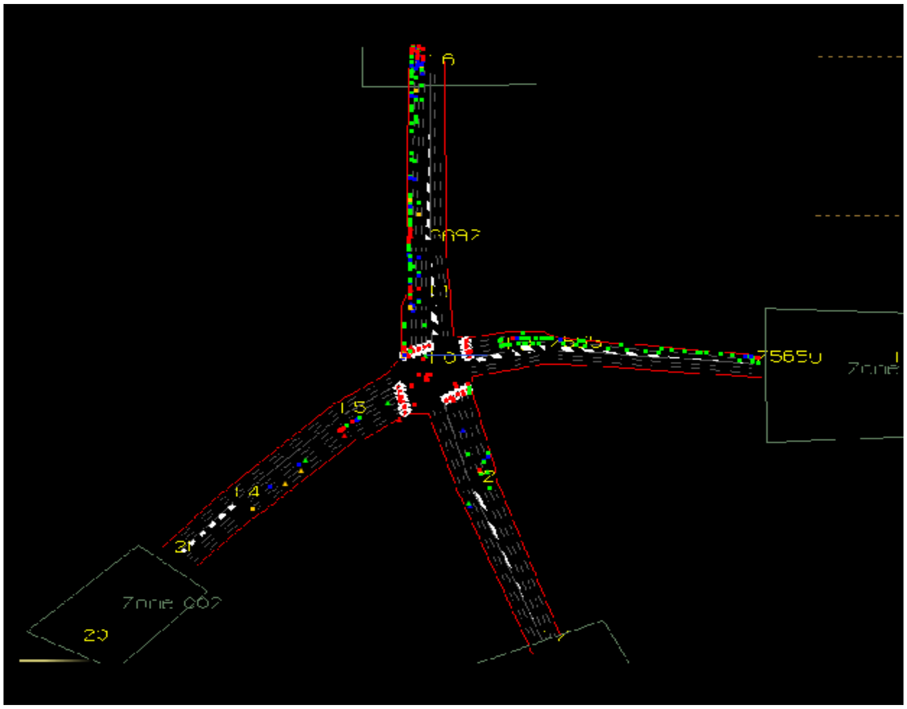


Figure 225. Screen Capture. PARAMICS Conflict Layout for AM Peak Hour of Intersection 5 (Total 352).

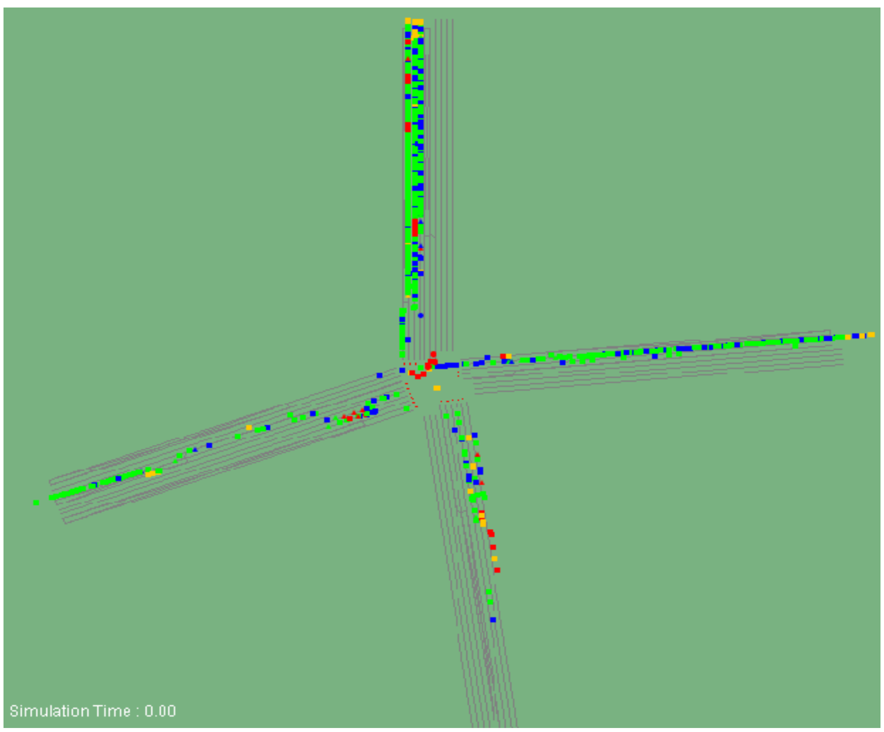


Figure 226. Screen Capture. TEXAS Conflict Layout for AM Peak Hour of Intersection 5 (Total 1,972).

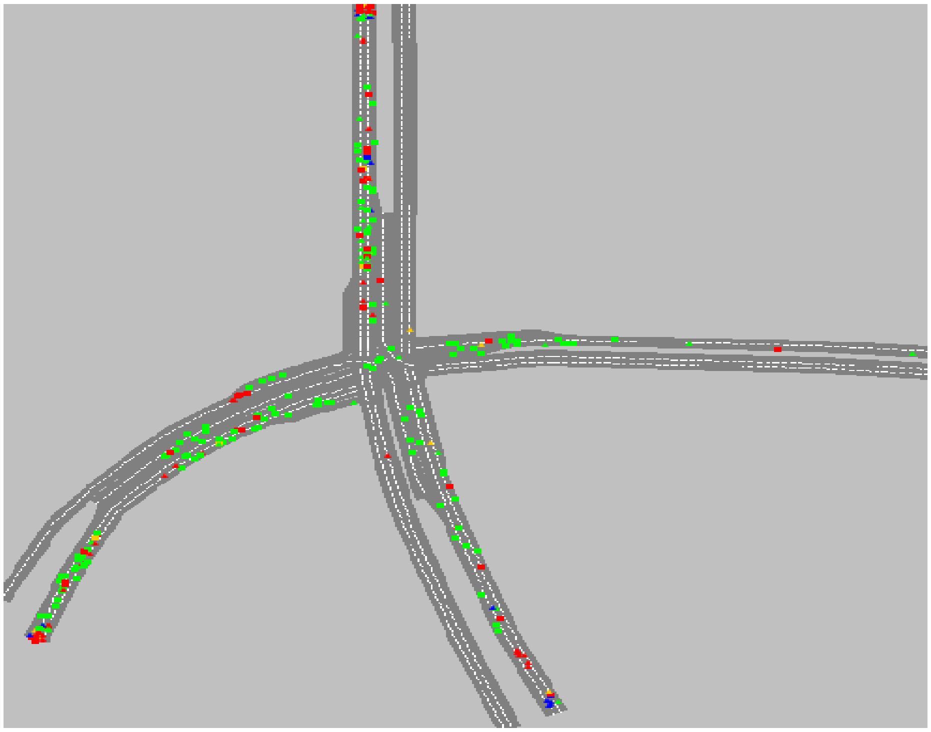


Figure 227. Screen Capture. VISSIM Conflict Layout for PM Peak Hour of Intersection 5 (Total 301).

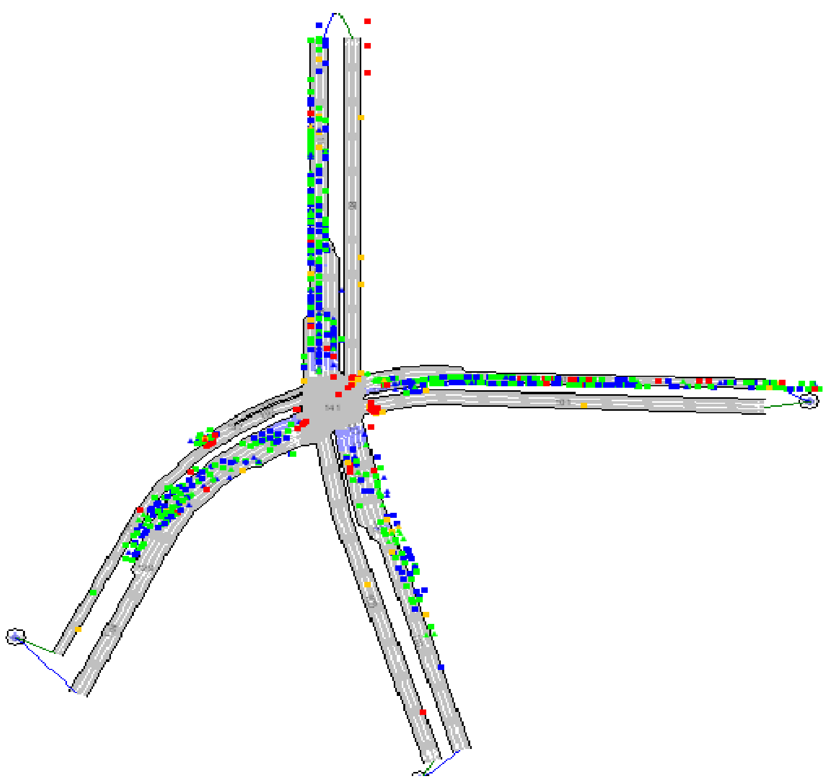


Figure 228. Screen Capture. AIMSUN Conflict Layout for PM Peak Hour of Intersection 5 (Total 988).

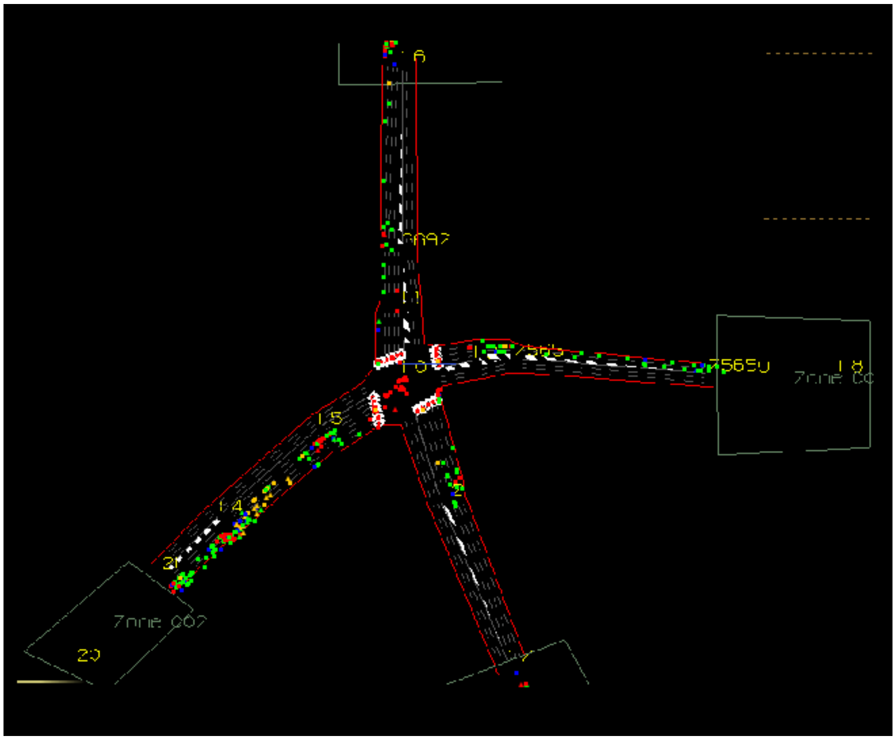


Figure 229. Screen Capture. PARAMICS Conflict Layout for PM Peak Hour of Intersection 5 (Total 389).

Figure 230. Screen Capture. TEXAS Conflict Layout for PM Peak Hour of Intersection 5 (Total 4,349).

In general, the following observations can be made:

- VISSIM and AIMSUN exhibit few crossing conflicts, while PARAMICS and TEXAS has numerous (crossing) crashes within the intersection.
- Most of the crossing conflicts are within the intersection/node area, implying improved SSAM algorithms.
- Most of the rear-end conflicts are blue and green, indicating that they tend to be lower severity conflicts.
- There are numerous rear-end crashes at the exit link in AIMSUN.
- VISSIM has some rear-end crashes in some cases and almost no crossing conflicts with 0.5 < TTC < 1.5.
- There are some lane-change conflicts (even crashes) at the link entrance in VISSIM.
- When traffic volume is light, rear-end conflicts occur mostly near the intersection. When traffic volume gets heavier, rear-end conflicts are located in the whole links in PARAMICS and TEXAS.
- Most of AIMSUN’s conflicts are blue and green.

Other Safety Measures

Beside number of conflicts, SSAM also extracted other surrogate safety measures, such as TTC, PET, and so on. In this section, those measures are tabulated and analyzed.

Intersection 1: Briarcliff Rd & North Druid Hills Rd, Dekalb County, Atlanta, GA:

Table 105 through table 108 list the surrogate safety measures generated from running the four simulation models for intersection 1. Corresponding figures provide 3-D views of the comparison for some of the measures among the four simulation models.

Table 105. Safety Measures Under AM Peak Hour for Intersection 1.

Volume: 4,365 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.29	1.04	1.13	1.05
PET (s)	2.96	1.35	1.82	2.47
MaxS (feet/s)	23.78	30.45	26.24	21.91
DeltaS (feet/s)	9.58	24.96	14.01	18.18
DR (feet/s^2)	-8.10	-11.13	-6.76	-5.48
MaxD (feet/s^2)	-10.33	-13.04	-12.89	-11.32
MaxDeltaV (feet/s)	5.08	13.23	7.54	10.26
Crossing				
TTC (s)	1.2	0.84	0.93	0.82
PET (s)	3.23	1.57	1.06	2.05
MaxS (feet/s)	22.04	31.56	33.26	35.59
DeltaS (feet/s)	30.73	43.83	44.51	47.00
DR (feet/s^2)	-8.23	-10.38	-5.02	0.79
MaxD (feet/s^2)	-8.23	-12.66	-6.59	-0.06
MaxDeltaV (feet/s)	15.97	23.95	24.44	27.99
Rear End				
TTC (s)	1.37	1.04	1.14	1.05
PET (s)	3.21	1.39	1.95	2.5
MaxS (feet/s)	22.53	30.42	25.78	21.69
DeltaS (feet/s)	8.72	24.23	12.37	17.86
DR (feet/s^2)	-6.76	-11.07	-6.72	-5.61
MaxD (feet/s^2)	-8.76	-12.88	-13.25	-11.56
MaxDeltaV (feet/s)	4.56	12.83	6.63	10.05
Lane Change				
TTC (s)	0.8	1.06	1.08	0.93
PET (s)	1.5	1.15	1.01	1.91
MaxS (feet/s)	31.29	30.48	28.24	23.19
DeltaS (feet/s)	13.35	26.44	20.27	16.55
DR (feet/s^2)	-15.97	-11.58	-7.18	-3.97
MaxD (feet/s^2)	-19.88	-13.91	-11.32	-8.60
MaxDeltaV (feet/s)	7.61	13.96	11.02	9.66

1 ft = 0.305 m

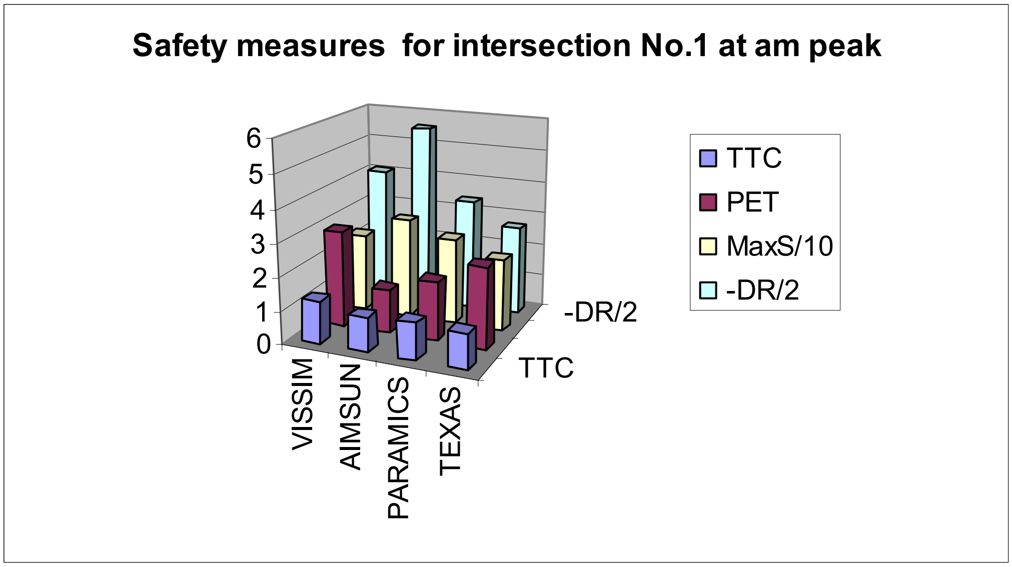


Figure 231. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 1 at AM Peak.

Table 106. Safety Measures Under Mid Peak Hour for Intersection 1.

Volume: 4,640 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.31	1	1.16	0.98
PET (s)	2.8	1.24	1.8	2.25
MaxS (feet/s)	23.03	30.85	26.86	21.27
DeltaS (feet/s)	12.56	24.83	13.19	15.95
DR (feet/s^2)	-8.13	-10.56	-6.17	-4.68
MaxD (feet/s^2)	-10.69	-11.94	-13.35	-10.22
MaxDeltaV (feet/s)	6.56	13.20	6.66	9.09
Crossing				
TTC (s)	1.09	0.81	1.04	0.7
PET (s)	2.88	1.14	1.17	1.71
MaxS (feet/s)	22.93	35.50	32.28	33.89
DeltaS (feet/s)	30.57	53.64	42.57	46.59
DR (feet/s^2)	-7.05	-8.77	-1.48	-0.46
MaxD (feet/s^2)	-7.15	-10.57	-1.57	-1.80
MaxDeltaV (feet/s)	16.30	30.72	22.66	28.20
Rear End				
TTC (s)	1.39	1	1.22	0.99
PET (s)	3.01	1.27	1.95	2.28
MaxS (feet/s)	21.94	30.70	25.72	21.05
DeltaS (feet/s)	11.84	23.67	11.15	15.55
DR (feet/s^2)	-7.45	-10.31	-6.23	-4.84
MaxD (feet/s^2)	-9.12	-11.73	-13.81	-10.47
MaxDeltaV (feet/s)	6.17	12.57	5.64	8.82
Lane Change				
TTC (s)	0.9	1.05	0.87	0.95
PET (s)	1.73	1.12	1	1.85
MaxS (feet/s)	28.54	31.18	33.19	21.13
DeltaS (feet/s)	14.43	27.74	22.70	13.51
DR (feet/s^2)	-11.74	-11.65	-6.13	-3.34
MaxD (feet/s^2)	-19.29	-12.84	-11.35	-8.51
MaxDeltaV (feet/s)	7.54	14.69	11.41	7.88

1 ft = 0.305 m

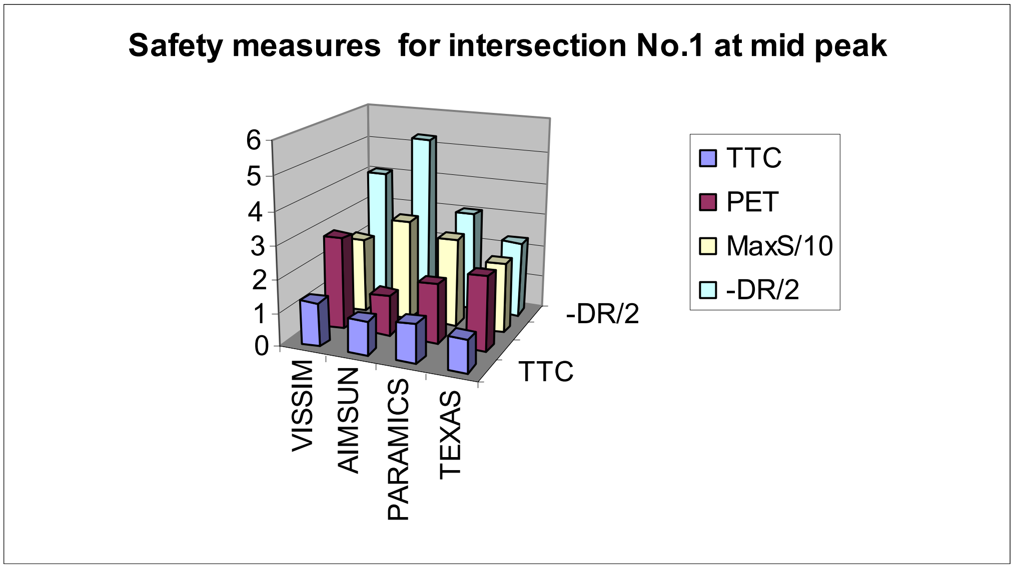


Figure 232. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 1 at Mid Peak.

Table 107. Safety Measures Under PM Peak Hour for Intersection 1.

Volume: 4,790 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.35	1	1.09	0.8
PET (s)	2.82	1.21	1.78	1.8
MaxS (feet/s)	21.91	31.39	27.29	21.44
DeltaS (feet/s)	14.43	24.91	14.79	13.44
DR (feet/s^2)	-8.56	-10.48	-6.82	-3.51
MaxD (feet/s^2)	-9.91	-11.41	-12.43	-8.11
MaxDeltaV (feet/s)	7.58	13.22	7.48	7.77
Crossing				
TTC (s)	2.68	0.69	0.75	0.75
PET (s)	7.82	1.06	0.89	1.85
MaxS (feet/s)	31.16	39.85	32.41	35.00
DeltaS (feet/s)	34.93	68.27	41.49	48.89
DR (feet/s^2)	-3.87	-7.14	0.00	-0.57
MaxD (feet/s^2)	-5.44	-7.26	0.00	-1.23
MaxDeltaV (feet/s)	20.83	38.06	21.22	31.30
Rear End				
TTC (s)	1.4	1	1.15	0.79
PET (s)	2.95	1.24	1.95	1.8
MaxS (feet/s)	20.80	31.11	26.50	21.08
DeltaS (feet/s)	14.10	23.55	12.60	12.48
DR (feet/s^2)	-8.17	-10.29	-7.05	-3.61
MaxD (feet/s^2)	-9.09	-11.12	-13.28	-8.32
MaxDeltaV (feet/s)	7.35	12.52	6.36	7.12
Lane Change				
TTC (s)	1.05	1.02	0.89	0.91
PET (s)	1.85	1.11	1.16	1.76
MaxS (feet/s)	29.78	32.23	30.04	21.83
DeltaS (feet/s)	15.06	28.91	21.75	14.70
DR (feet/s^2)	-11.84	-11.33	-6.33	-3.17
MaxD (feet/s^2)	-16.60	-12.71	-9.84	-7.40
MaxDeltaV (feet/s)	7.97	15.24	10.99	8.82

1 ft = 0.305 m

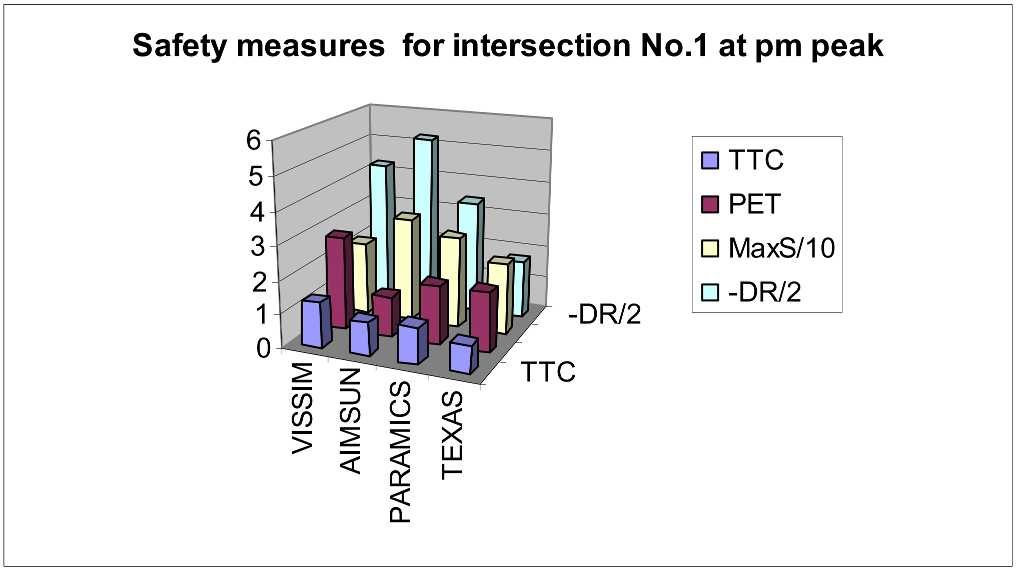


Figure 233. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 1 at PM Peak.

Intersection 2: Roswell Road & Abernathy Road, Fulton County, Atlanta, GA:

Table 108 through table 110 list the surrogate safety measures generated from running the four simulation models for intersection 2. Corresponding figures provide 3-D views of the comparison for some of the measures among the four simulation models.

Table 108. Safety Measures Under AM Peak Hour for Intersection 2.

Volume: 5,260 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.24	1.07	1.02	1.03
PET (s)	2.75	1.29	1.22	2.36
MaxS (feet/s)	22.53	26.33	34.70	21.19
DeltaS (feet/s)	9.74	18.90	19.52	17.00
DR (feet/s^2)	-7.77	-10.69	-7.18	-5.01
MaxD (feet/s^2)	-13.64	-13.17	-13.91	-10.68
MaxDeltaV (feet/s)	5.18	10.02	9.81	9.59
Crossing				
TTC (s)	n/a	0.75	1.16	0.84
PET (s)	n/a	0.67	1.08	1.26
MaxS (feet/s)	n/a	30.01	34.87	29.15
DeltaS (feet/s)	n/a	46.08	50.38	44.21
DR (feet/s^2)	n/a	-9.95	-0.95	-1.39
MaxD (feet/s^2)	n/a	-12.27	-9.05	-2.48
MaxDeltaV (feet/s)	n/a	24.82	25.19	25.93
Rear End				
TTC (s)	1.34	1.1	1.03	1.04
PET (s)	3.09	1.39	1.25	2.42
MaxS (feet/s)	6.63	25.89	34.54	20.98
DeltaS (feet/s)	2.70	17.96	18.83	16.68
DR (feet/s^2)	-1.93	-10.75	-7.18	-5.16
MaxD (feet/s^2)	-3.71	-13.28	-14.10	-10.95
MaxDeltaV (feet/s)	1.42	9.53	9.45	9.38
Lane Change				
TTC (s)	0.91	1	0.98	0.88
PET (s)	1.57	1.01	0.96	1.64
MaxS (feet/s)	25.22	27.57	35.85	23.03
DeltaS (feet/s)	12.76	20.37	23.68	15.31
DR (feet/s^2)	-12.76	-10.52	-7.38	-3.13
MaxD (feet/s^2)	-18.76	-12.86	-12.50	-7.69
MaxDeltaV (feet/s)	7.05	10.74	8.63	9.06

1 ft = 0.305 m

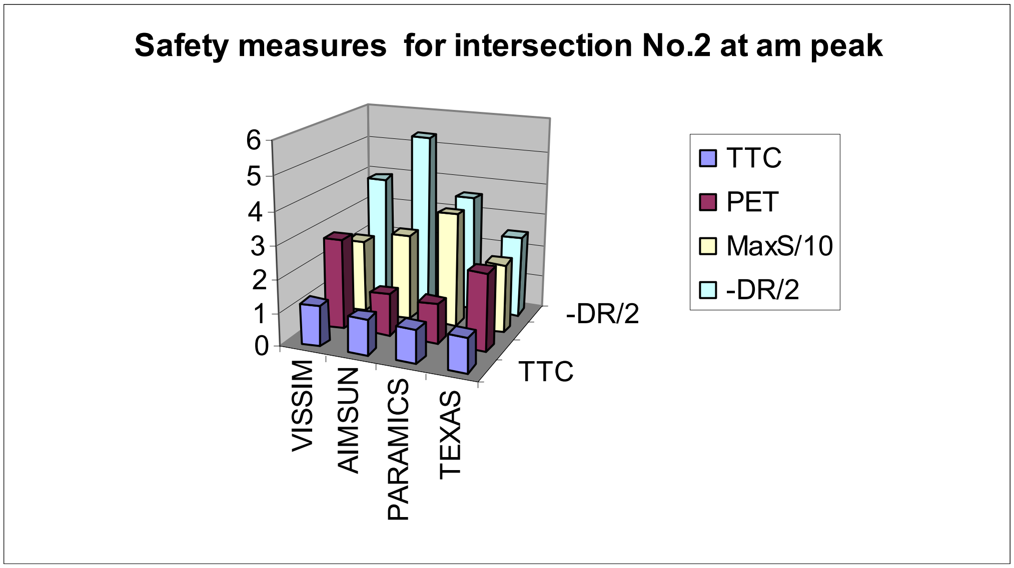


Figure 234. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 2 at AM Peak.

Table 109. Safety Measures Under Mid Peak Hour for Intersection 2.

Volume: 5,685 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.27	1.06	1.06	1.03
PET (s)	2.88	1.32	1.44	2.31
MaxS (feet/s)	21.32	28.35	31.52	20.75
DeltaS (feet/s)	8.72	22.19	17.45	16.54
DR (feet/s^2)	-6.63	-10.84	-6.86	-4.47
MaxD (feet/s^2)	-12.99	-13.01	-13.87	-10.51
MaxDeltaV (feet/s)	4.59	11.76	8.79	9.35
Crossing				
TTC (s)	n/a	0.96	0.97	0.81
PET (s)	n/a	1.34	1.28	1.26
MaxS (feet/s)	n/a	33.44	40.28	28.10
DeltaS (feet/s)	n/a	44.35	52.51	41.66
DR (feet/s^2)	n/a	-11.53	-3.02	-0.11
MaxD (feet/s^2)	n/a	-12.59	-7.02	-1.20
MaxDeltaV (feet/s)	n/a	23.87	26.93	25.13
Rear End				
TTC (s)	1.33	1.07	1.06	1.04
PET (s)	3.13	1.4	1.46	2.37
MaxS (feet/s)	6.38	28.09	31.78	20.67
DeltaS (feet/s)	2.34	21.82	17.09	16.38
DR (feet/s^2)	-1.84	-10.82	-6.82	-4.68
MaxD (feet/s^2)	-3.57	-13.09	-13.97	-10.88
MaxDeltaV (feet/s)	1.23	11.56	8.59	9.22
Lane Change				
TTC (s)	1.03	1.03	1.06	0.83
PET (s)	1.98	1.01	1.21	1.56
MaxS (feet/s)	22.73	29.18	28.37	20.70
DeltaS (feet/s)	12.53	22.94	18.83	14.53
DR (feet/s^2)	-8.92	-10.91	-7.45	-2.24
MaxD (feet/s^2)	-17.71	-12.73	-13.45	-6.67
MaxDeltaV (feet/s)	6.69	12.16	9.48	8.64

1 ft = 0.305 m

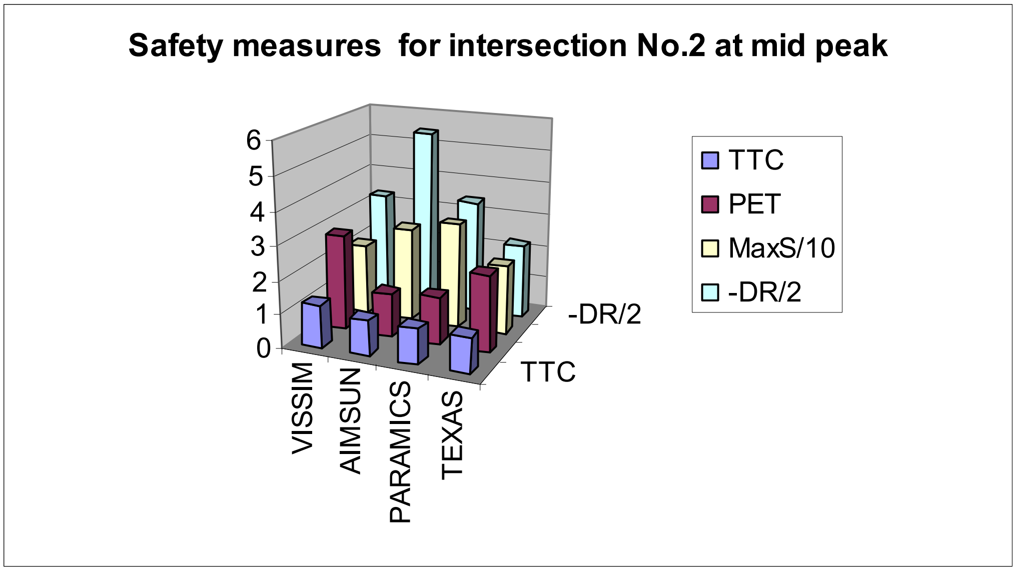


Figure 235. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 2 at Mid Peak.

Table 110. Safety Measures Under PM Peak Hour for Intersection 2.

Volume: 5,585 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.19	1.05	1.07	1.02
PET (s)	2.61	1.34	1.52	2.36
MaxS (feet/s)	22.53	29.01	27.42	20.74
DeltaS (feet/s)	9.71	23.87	13.84	16.60
DR (feet/s^2)	-8.69	-10.93	-6.82	-4.89
MaxD (feet/s^2)	-14.73	-12.78	-13.19	-10.74
MaxDeltaV (feet/s)	5.15	12.64	6.95	9.40
Crossing				
TTC (s)	n/a	0.99	0.92	0.59
PET (s)	n/a	1.28	0.97	1.18
MaxS (feet/s)	n/a	34.97	35.65	34.75
DeltaS (feet/s)	n/a	50.07	40.51	46.86
DR (feet/s^2)	n/a	-8.82	-0.98	0.40
MaxD (feet/s^2)	n/a	-10.34	-2.69	-0.28
MaxDeltaV (feet/s)	n/a	26.32	20.80	28.65
Rear End				
TTC (s)	1.31	1.06	1.06	1.04
PET (s)	3.04	1.41	1.55	2.41
MaxS (feet/s)	6.58	28.59	27.13	20.55
DeltaS (feet/s)	2.47	23.14	12.79	16.46
DR (feet/s^2)	-1.94	-10.96	-6.59	-5.07
MaxD (feet/s^2)	-3.83	-12.81	-13.25	-11.04
MaxDeltaV (feet/s)	1.30	12.26	6.43	9.29
Lane Change				
TTC (s)	0.92	1	1.14	0.88
PET (s)	1.62	1.08	1.33	1.66
MaxS (feet/s)	24.63	30.12	28.83	21.28
DeltaS (feet/s)	13.35	24.65	19.65	13.44
DR (feet/s^2)	-14.14	-10.97	-8.79	-2.82
MaxD (feet/s^2)	-19.75	-12.84	-13.32	-7.74
MaxDeltaV (feet/s)	7.05	13.04	9.91	7.82

1 ft = 0.305 m

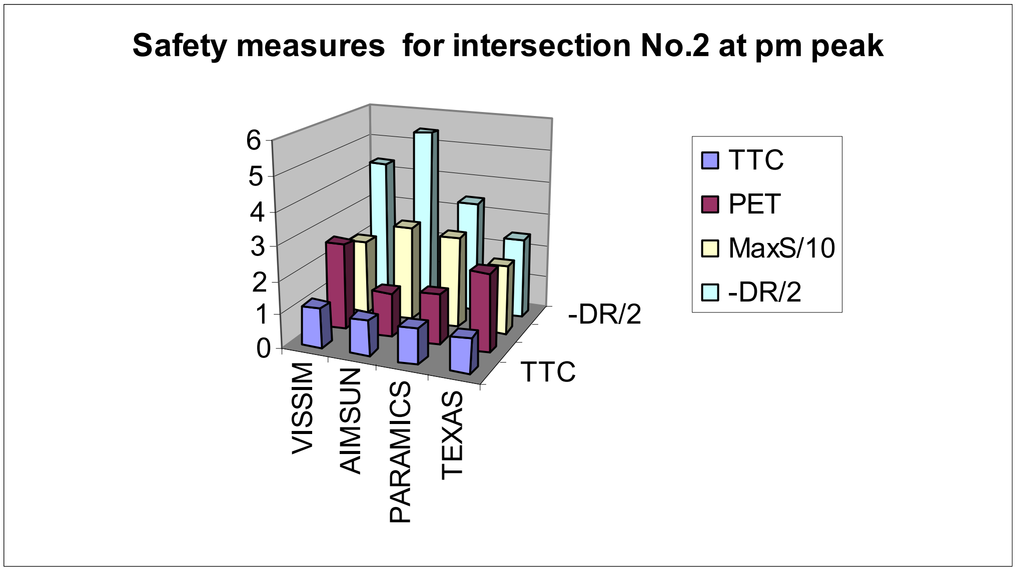


Figure 236. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 2 at PM Peak.

Intersection 3: Lafayette Ave & Fulton Street, Grand Rapids, MI:

Table 111 and table 112 list the surrogate safety measures generated from running the four simulation models for intersection 3. Corresponding figures provide 3-D views of the comparison for some of the measures among the four simulation models.

Table 111. Safety Measures Under AM Peak Hour for Intersection 3.

Volume: 1,975 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.4	1.06	1.05	1.13
PET (s)	2.85	1.47	0.88	2.54
MaxS (feet/s)	20.30	31.17	30.44	23.15
DeltaS (feet/s)	16.86	29.36	18.40	22.14
DR (feet/s^2)	-8.66	-11.88	-3.71	-5.86
MaxD (feet/s^2)	-9.74	-12.63	-5.18	-11.61
MaxDeltaV (feet/s)	8.76	15.58	9.28	12.80
Crossing				
TTC (s)	n/a	1.17	0.67	0.66
PET (s)	n/a	2.59	0.8	1.26
MaxS (feet/s)	n/a	24.04	39.82	33.75
DeltaS (feet/s)	n/a	33.17	56.68	46.85
DR (feet/s^2)	n/a	-9.95	-10.36	-1.55
MaxD (feet/s^2)	n/a	-13.10	-11.35	-2.65
MaxDeltaV (feet/s)	n/a	17.67	28.34	30.41
Rear End				
TTC (s)	1.42	1.06	1.06	1.17
PET (s)	2.9	1.47	0.89	2.66
MaxS (feet/s)	20.04	31.41	30.21	22.05
DeltaS (feet/s)	16.73	29.42	17.58	19.99
DR (feet/s^2)	-8.66	-11.99	-3.44	-6.28
MaxD (feet/s^2)	-9.38	-12.62	-4.95	-12.45
MaxDeltaV (feet/s)	8.69	15.62	8.86	11.23
Lane Change				
TTC (s)	1.16	1.01	0.93	1.24
PET (s)	2.22	1.07	0.8	2.47
MaxS (feet/s)	23.52	31.28	33.65	25.76
DeltaS (feet/s)	18.37	27.51	27.06	16.89
DR (feet/s^2)	-8.86	-11.43	-9.94	-5.63
MaxD (feet/s^2)	-13.94	-12.58	-10.46	-12.17
MaxDeltaV (feet/s)	9.51	14.52	14.66	9.93

1 ft = 0.305 m

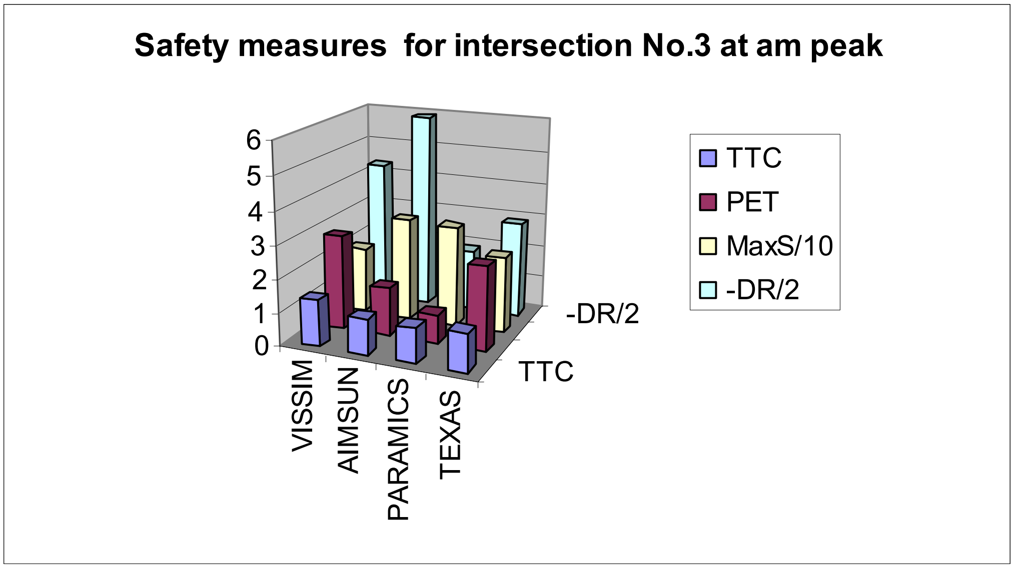


Figure 237. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 3 at AM Peak.

Table 112. Safety Measures Under PM Peak Hour for Intersection 3.

Volume: 2,400 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.39	1.04	1.1	1.13
PET (s)	2.88	1.45	0.98	2.52
MaxS (feet/s)	21.32	30.63	28.57	23.10
DeltaS (feet/s)	15.09	28.46	16.92	21.07
DR (feet/s^2)	-8.53	-11.84	-1.08	-5.53
MaxD (feet/s^2)	-10.00	-12.76	-2.72	-11.60
MaxDeltaV (feet/s)	7.84	15.03	8.63	12.15
Crossing				
TTC (s)	n/a	1.15	1.02	0.56
PET (s)	n/a	2.48	1.29	1.18
MaxS (feet/s)	n/a	25.09	38.51	35.26
DeltaS (feet/s)	n/a	34.23	53.40	46.55
DR (feet/s^2)	n/a	-11.44	-9.35	-1.09
MaxD (feet/s^2)	n/a	-13.90	-10.50	-1.42
MaxDeltaV (feet/s)	n/a	18.21	28.67	30.10
Rear End				
TTC (s)	1.42	1.04	1.1	1.17
PET (s)	2.94	1.45	0.97	2.64
MaxS (feet/s)	20.86	30.85	28.47	22.17
DeltaS (feet/s)	14.92	28.27	16.07	19.23
DR (feet/s^2)	-8.10	-11.94	-0.82	-5.92
MaxD (feet/s^2)	-9.09	-12.71	-2.43	-12.51
MaxDeltaV (feet/s)	7.74	14.94	8.17	10.84
Lane Change				
TTC (s)	1.17	0.99	1.17	1.25
PET (s)	2.46	1.09	1.16	2.13
MaxS (feet/s)	24.96	31.25	23.68	21.61
DeltaS (feet/s)	15.88	27.61	17.32	15.71
DR (feet/s^2)	-11.87	-11.39	-4.79	-4.97
MaxD (feet/s^2)	-16.89	-12.66	-7.38	-9.53
MaxDeltaV (feet/s)	8.40	14.49	8.66	8.55

1 ft = 0.305 m

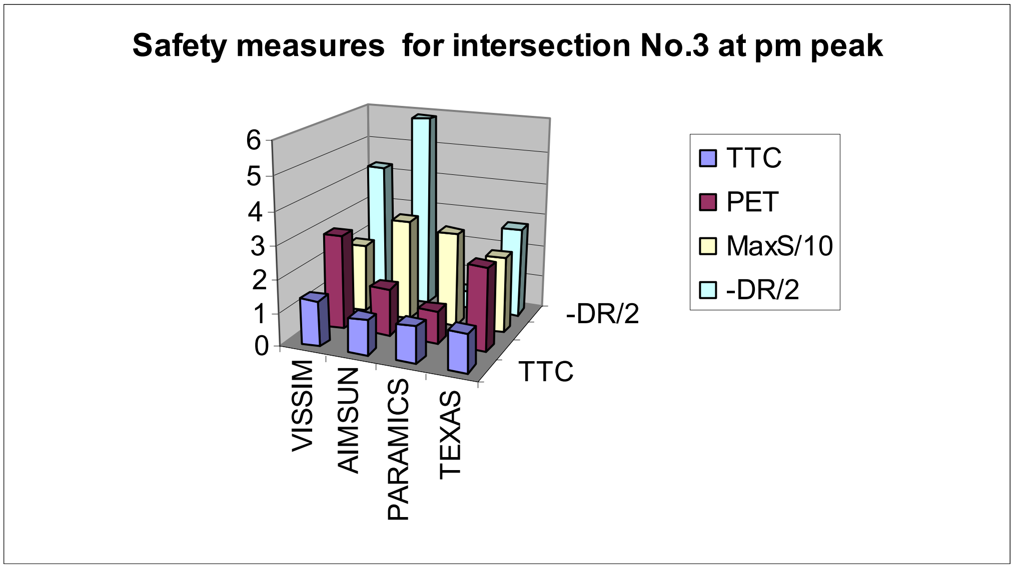


Figure 238. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 3 at PM Peak.

Intersection 4: Ryan Ave & Davison Ave, Detroit, MI:

Table 113 and table 114 list the surrogate safety measures generated from running the four simulation models for intersection 4. Corresponding figures provide 3-D views of the comparison for some of the measures among the four simulation models.

Table 113. Safety Measures under AM Peak Hour for Intersection 4.

Volume: 2,613 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.36	1.01	1.06	1.05
PET (s)	2.78	1.36	1.38	2.21
MaxS (feet/s)	21.52	32.27	33.75	24.67
DeltaS (feet/s)	15.25	28.20	24.70	21.63
DR (feet/s^2)	-8.92	-11.27	-7.87	-4.71
MaxD (feet/s^2)	-10.33	-12.05	-11.02	-9.72
MaxDeltaV (feet/s)	8.07	14.93	12.66	12.54
Crossing				
TTC (s)	n/a	0.87	0.75	0.58
PET (s)	n/a	1.89	0.85	0.84
MaxS (feet/s)	n/a	28.86	40.93	34.18
DeltaS (feet/s)	n/a	38.46	48.35	44.61
DR (feet/s^2)	n/a	-8.46	-8.50	-0.55
MaxD (feet/s^2)	n/a	-12.40	-9.77	-1.44
MaxDeltaV (feet/s)	n/a	22.56	-24.96	28.95
Rear End				
TTC (s)	1.41	1.01	1.11	1.1
PET (s)	2.94	1.4	1.48	2.32
MaxS (feet/s)	20.40	32.33	31.68	23.76
DeltaS (feet/s)	15.22	28.06	17.29	19.79
DR (feet/s^2)	-8.17	-11.18	-6.86	-5.04
MaxD (feet/s^2)	-8.95	-11.87	-10.53	-10.30
MaxDeltaV (feet/s)	7.97	14.84	8.76	11.19
Lane Change				
TTC (s)	0.97	1.06	1.27	0.89
PET (s)	1.6	1.11	1.64	2.06
MaxS (feet/s)	29.55	32.27	33.55	27.76
DeltaS (feet/s)	14.60	28.04	27.58	23.44
DR (feet/s^2)	-14.79	-11.96	-11.78	-4.35
MaxD (feet/s^2)	-20.47	-12.88	-14.99	-10.27
MaxDeltaV (feet/s)	8.33	14.78	14.20	14.41

1 ft = 0.305 m

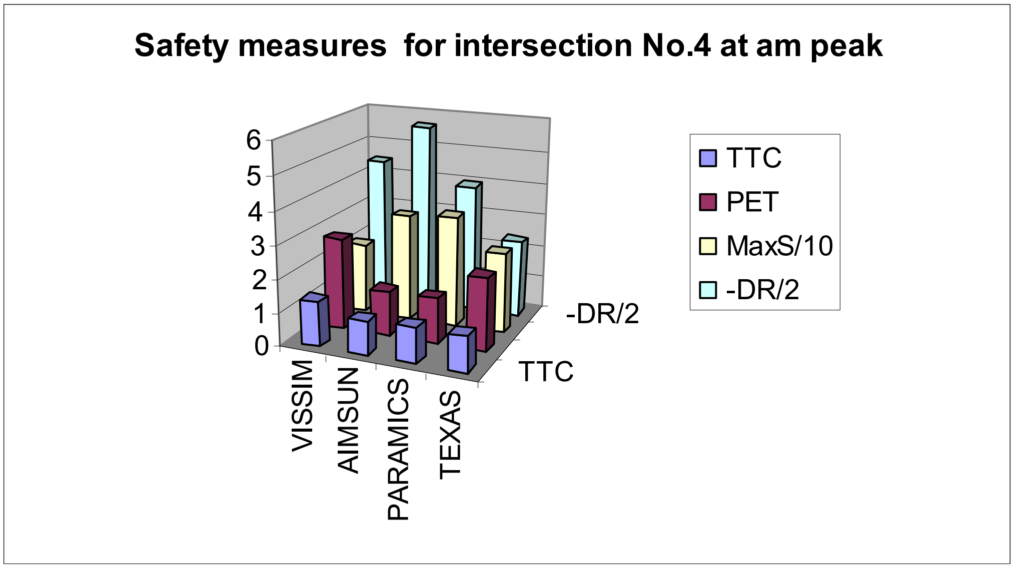


Figure 239. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 4 at AM Peak.

Table 114. Safety Measures Under PM Peak Hour for Intersection 4.

Volume: 3,017 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.34	1.02	1.07	0.89
PET (s)	2.87	1.37	1.32	1.72
MaxS (feet/s)	20.76	31.74	33.26	24.56
DeltaS (feet/s)	13.22	27.60	20.30	18.38
DR (feet/s^2)	-7.58	-11.20	-7.45	-3.20
MaxD (feet/s^2)	-10.46	-12.26	-11.94	-7.13
MaxDeltaV (feet/s)	6.92	14.66	10.33	10.60
Crossing				
TTC (s)	0.52	0.97	0.79	0.52
PET (s)	1.02	2.41	0.82	1.14
MaxS (feet/s)	7.71	21.81	40.28	33.77
DeltaS (feet/s)	9.32	30.84	46.94	43.21
DR (feet/s^2)	-1.27	-8.25	-9.48	-0.39
MaxD (feet/s^2)	-2.80	-11.31	-11.18	-0.96
MaxDeltaV (feet/s)	5.91	17.04	23.45	28.31
Rear End				
TTC (s)	1.39	1.01	1.05	0.95
PET (s)	3	1.41	1.31	1.86
MaxS (feet/s)	20.17	32.11	32.47	24.26
DeltaS (feet/s)	12.82	27.65	16.83	17.75
DR (feet/s^2)	-7.48	-11.18	-6.46	-3.71
MaxD (feet/s^2)	-9.18	-12.10	-11.32	-7.92
MaxDeltaV (feet/s)	6.66	14.68	8.50	10.02
Lane Change				
TTC (s)	1.12	1.05	1.24	0.64
PET (s)	2.24	1.13	1.48	1.03
MaxS (feet/s)	24.01	31.11	34.37	24.25
DeltaS (feet/s)	14.07	27.20	26.37	16.43
DR (feet/s^2)	-8.56	-11.48	-10.73	-0.70
MaxD (feet/s^2)	-18.63	-12.92	-14.43	-3.61
MaxDeltaV (feet/s)	7.38	14.42	13.71	10.04

1 ft = 0.305 m

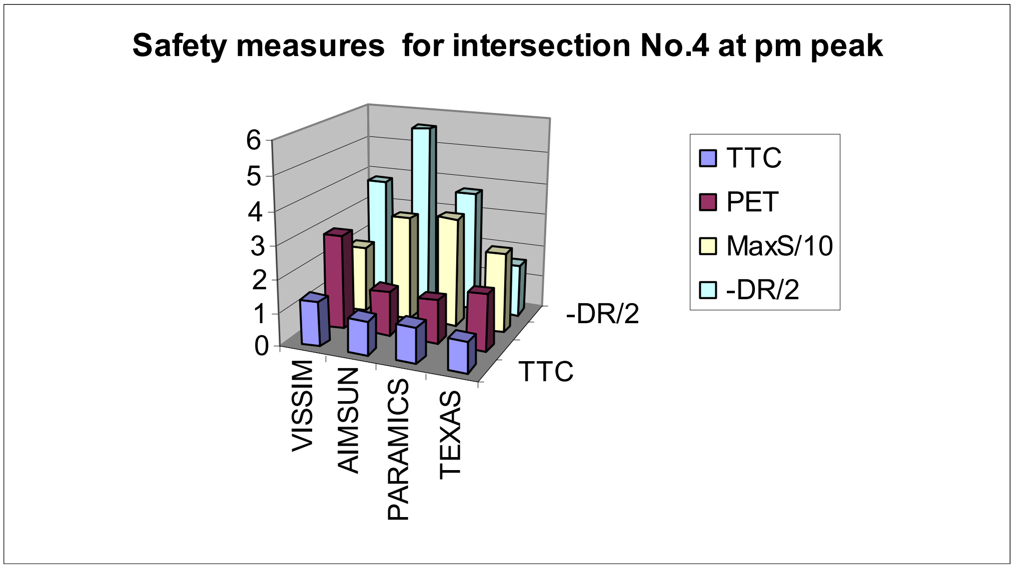


Figure 240. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 4 at PM Peak.

Intersection 5: Howe Ave & Fair Oaks Boulevard, Sacramento, CA:

Table 115 and table 116 list the surrogate safety measures generated from running the four simulation models for intersection 5. Corresponding figures provide 3-D views of the comparison for some of the measures among the four simulation models.

Table 115. Safety Measures Under AM Peak Hour for Intersection 5.

Volume: 6,425 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.28	0.98	1.13	1
PET (s)	2.7	1.13	1.60	2.27
MaxS (feet/s)	24.01	33.6	23.71	24.21
DeltaS (feet/s)	12.33	23.71	12.40	18.72
DR (feet/s^2)	-8.27	-10.69	-7.41	-5.2
MaxD (feet/s^2)	-11.35	-12.07	-13.91	-11.04
MaxDeltaV (feet/s)	6.46	12.57	6.26	10.6
Crossing				
TTC (s)	n/a	0.89	n/a	n/a
PET (s)	n/a	0.89	n/a	n/a
MaxS (feet/s)	n/a	34.89	n/a	n/a
DeltaS (feet/s)	n/a	34.92	n/a	n/a
DR (feet/s^2)	n/a	-12.38	n/a	n/a
MaxD (feet/s^2)	n/a	-12.41	n/a	n/a
MaxDeltaV (feet/s)	n/a	18.2	n/a	n/a
Rear End				
TTC (s)	1..36	0.95	1.14	1.01
PET (s)	3.04	1.17	1.67	2.3
MaxS (feet/s)	22.80	34.24	23.06	24.22
DeltaS (feet/s)	12.10	22.67	11.41	18.93
DR (feet/s^2)	-6.99	-10.32	-7.12	-5.28
MaxD (feet/s^2)	-9.25	-11.67	-13.94	-11.16
MaxDeltaV (feet/s)	6.33	12.03	5.74	10.71
Lane Change				
TTC (s)	1	1.05	1.04	0.89
PET (s)	1.51	1.03	1.13	1.69
MaxS (feet/s)	28.24	31.71	28.44	24.06
DeltaS (feet/s)	13.19	25.97	19.25	15.20
DR (feet/s^2)	-12.76	-11.63	-9.48	-3.86
MaxD (feet/s^2)	-18.76	-13.21	-13.64	-9.10
MaxDeltaV (feet/s)	6.92	13.76	9.74	8.84

1 ft = 0.305 m

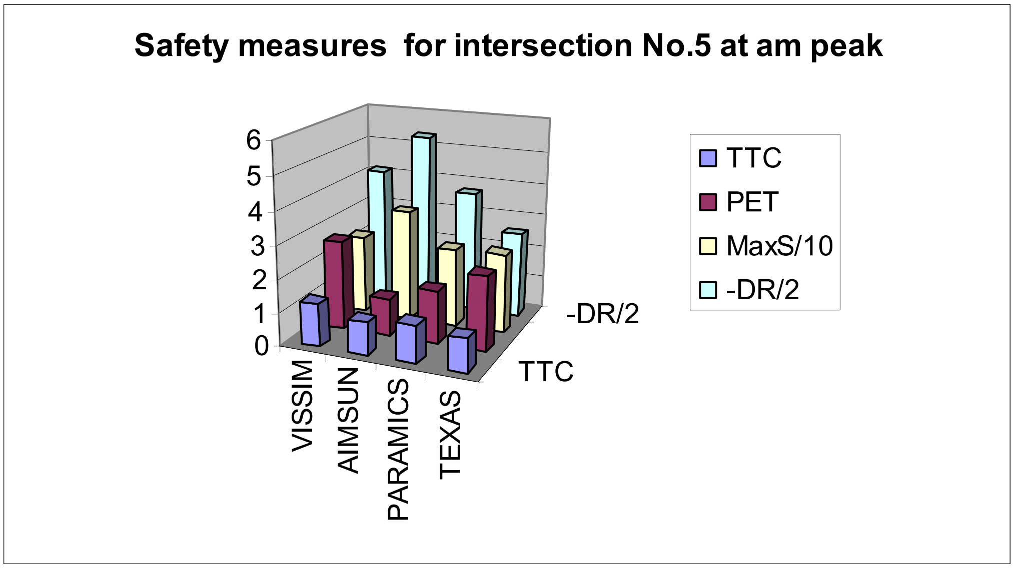


Figure 241. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 5 at AM Peak.

Table 116. Safety Measures Under PM Peak Hour for Intersection 5.

Volume: 8,815 v/hr	VISSIM	AIMSUN	PARAMICS	TEXAS
All Conflicts				
TTC (s)	1.24	1	1.10	0.97
PET (s)	2.71	1.17	1.54	2.19
MaxS (feet/s)	23.91	31.82	23.78	24.17
DeltaS (feet/s)	10.82	22.25	12.27	17.75
DR (feet/s^2)	-8.36	-10.41	-6.69	-5.04
MaxD (feet/s^2)	-12.82	-12.06	-13.45	-10.61
MaxDeltaV (feet/s)	5.74	11.82	6.17	10.08
Crossing				
TTC (s)	n/a	0.82	n/a	n/a
PET (s)	n/a	0.87	n/a	n/a
MaxS (feet/s)	n/a	33.03	n/a	n/a
DeltaS (feet/s)	n/a	33.33	n/a	n/a
DR (feet/s^2)	n/a	-11.18	n/a	n/a
MaxD (feet/s^2)	n/a	-12.14	n/a	n/a
MaxDeltaV (feet/s)	n/a	17.48	n/a	n/a
Rear End				
TTC (s)	1.33	0.98	1.14	0.98
PET (s)	3.16	1.22	1.63	2.24
MaxS (feet/s)	22.93	32.20	23.12	24.08
DeltaS (feet/s)	9.74	21.12	11.02	17.95
DR (feet/s^2)	-6.43	-10.11	-6.33	-5.15
MaxD (feet/s^2)	-10.17	-11.74	-13.58	-10.80
MaxDeltaV (feet/s)	5.15	11.24	5.54	10.17
Lane Change				
TTC (s)	1.02	1.06	0.91	0.87
PET (s)	1.66	1.03	1.06	1.61
MaxS (feet/s)	26.14	30.55	27.03	25.33
DeltaS (feet/s)	13.38	25.25	18.47	15.39
DR (feet/s^2)	-12.82	-11.34	-8.46	-3.70
MaxD (feet/s^2)	-19.02	-13.08	-12.66	-8.31
MaxDeltaV (feet/s)	7.15	13.38	9.28	8.96

1 ft = 0.305 m

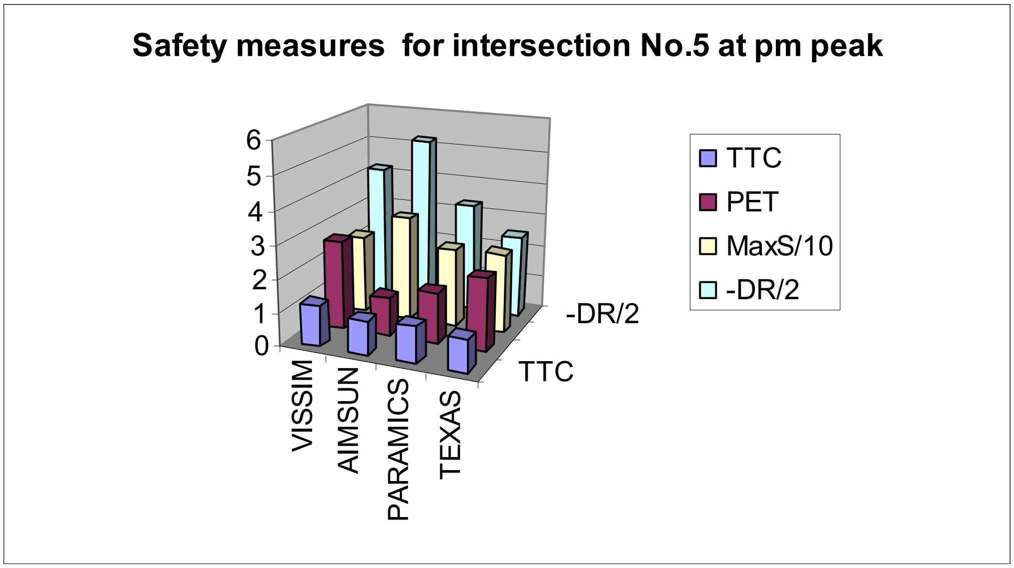


Figure 242. Graph. 3-D View of the Comparison on Major Surrogate Safety Measures for Intersection 5 at PM Peak.

In general, safety measures from VISSIM were consistently safer than those from the other three simulation platforms, while AIMSUN was the least safe among all of the simulation platforms. Some measures (TTC, PET, DeltaS, and MaxS) in VISSIM showed safer conflicts than in TEXAS, while others (DR, MaxD) showed the opposite results. There were no strong differences among these simulation platforms with all of the surrogate safety measures.

Simulation MOEs

MOEs from running the simulations for each intersection are recorded and tabulated, as shown in table 117 through table 121.

Table 117. MOEs for Intersection 1.

	VISSIM	AIMSUN	PARAMICS	TEXAS
AM PEAK HOUR: Volume: 4,365 v/hr				
Travel time(s)	121.71	102.80		146.20
Average delay(s)	87.03	66.00		110.60
# of vehicle	3,690	4,088	3,872	3,252
Mean speed(mi/h)	9.12	17.89	5.7	10.50
MID PEAK HOUR: Volume: 4,640 v/hr				
Travel time(s)	105.53	115.7		155.30
Average delay(s)	70.38	79		119.30
# of vehicle	3,539	3,520	3,460	2,633
Mean speed(mi/h)	10.62	18.23	5.15	12.90
PM PEAK HOUR: Volume: 4,790 v/hr				
Travel time(s)	96.61	122.80		134.10
Average delay(s)	61.36	86.30		97.90
# of vehicle	2,873	2,901	2,310	2,413
Mean speed(mi/h)	11.65	19.80	2.66	15.30

Table 118. MOEs for Intersection 2.

	VISSIM	AIMSUN	PARAMICS	TEXAS
AM PEAK HOUR: Volume: 5,260 v/hr				
Travel time(s)	140.45	131.30		173.30
Average delay(s)	106.89	9,4.70		137.60
# of vehicle	3,723	4,881	3,750	3,031
Mean speed(mph)	7.91	15.49	3.65	9.00
MID PEAK HOUR: Volume: 5,685 v/hr				
Travel time(s)	157.08	115.60		217.30
Average delay(s)	122.69	78.90		181.70
# of vehicle	4,267	5,417	4,402	3,500
Mean speed(mi/h)	7.03	16.83	3.32	6.90
PM PEAK HOUR: Volume: 5,585 v/hr				
Travel time(s)	161.24	126.00		202.10
Average delay(s)	126.82	89.20		166.60
# of vehicle	4,068	5,287	3,908	3,430
Mean speed(mi/h)	6.87	15.84	2.49	6.70

Table 119. MOEs for Intersection 3.

	VISSIM	AIMSUN	PARAMICS	TEXAS
AM PEAK HOUR: Volume: 1,975 v/hr				
Travel time(s)	52.27	60.00		67.80
Average delay(s)	17.41	17.30		28.20
# of vehicle	1,969	1,933	1,959	1,803
Mean speed(mi/h)	21.32	25.27	19.31	20.40
PM PEAK HOUR: Volume: 2,400 v/hr				
Travel time(s)	61.74	63.30		113.90
Average delay(s)	27.08	20.60		74.30
# of vehicle	2,384	2,367	2,326	2,110
Mean speed(mi/h)	18.06	24.33	17.58	18.20

Table 120. MOEs for Intersection 4.

	VISSIM	AIMSUN	PARAMICS	TEXAS
AM PEAK HOUR: Volume: 2,613 v/hr				
Travel time(s)	62.97	60.90		66.40
Average delay(s)	26.31	19.80		25.30
# of vehicle	2,593	2,581	2,601	2,399
Mean speed(mi/h)	17.73	25.46	21.8	19.70
PM PEAK HOUR: Volume: 3,017 v/hr				
Travel time(s)	76.26	61.70		69.60
Average delay(s)	40.21	20.40		28.90
# of vehicle	2,990	3,003	3,030	2,765
Mean speed(mi/h)	14.78	24.94	20.65	18.10

Table 121. MOEs for Intersection 5.

	VISSIM	AIMSUN	PARAMICS	TEXAS
AM PEAK HOUR: Volume: 6,425 v/hr				
Travel time(s)	114.11	79.80		161.10
Average delay(s)	75.19	49.70		129.30
# of vehicle	5,501	6,309	5,257	3,662
Mean speed(mi/h)	10.99	22.13	3.8	13.00
PM PEAK HOUR: Volume: 8,815 v/hr				
Travel time(s)	125.12	115.00		185.8
Average delay(s)	97.09	84.50		155
# of vehicle	7,319	8,447	5,960	4,942
Mean speed(mi/h)	9.06	17.34	2.2	8.9

In general, the performance MOE results indicated the following:

- The number of vehicles processed through the system by AIMSUN was closest to the input volume. This is consistent with AIMSUN's higher average speeds and lower delay times.
- TEXAS always generated the lowest number of vehicle throughput.
- When traffic volume was low or medium, VISSIM and PARAMICS also generated appropriate vehicle throughput.
- The definition of average delay in PARAMICS was different from the other simulation systems, and thus, the average delays from the models could not be compared.
- Networks modeled in PARAMICS had the highest travel times and lowest mean speeds, implying heavier blockages in the simulation during high input volumes.

SUMMARY

The sensitivity analysis exercise was performed to identify differences between the SSAM-related outputs of each simulation model vendor's system on the same traffic facility designs. Five intersections were selected for modeling from the same source as the 83 intersections used in the field validation study. As much as possible, the intersections were modeled identically in each of the four simulation systems. The goal of this exercise was not to calibrate the models to field data but rather to assess the ability of each model to produce reasonable estimates of both traditional performance MOEs (delay, throughput, average vehicle speed, etc.) and the new surrogate measures of safety developed in this project (total conflicts, average TTC, PET, etc.).

The sensitivity analysis activity indicated that there was a fairly wide range of results that could be obtained from applying different simulation models to the same facility designs. In general, intersections modeled in VISSIM had the lowest total number of conflicts, and intersections modeled in TEXAS had the highest total number of conflicts occurring, with frequency of approximately 10 times higher than VISSIM. Conflict totals from AIMSUN and Paramics simulation systems fell within those two. Modifications made to the TEXAS model after this analysis is completed, as communicated to the project team by Rioux Engineering, should reduce the total numbers as well as eliminate many of the crossing "crashes" that occur in TEXAS. The abnormally high number of conflicts in TEXAS reflected that (somewhat paradoxically) the driver behavior modeling in TEXAS included active conflict avoidance, where the other models had a more "reactive" driver behavior approach to conflict avoidance. This was particularly manifested in the extreme braking/deceleration events observed in the AIMSUN and Paramics simulation systems.

In all of the simulation systems, rear-end conflict events made up the bulk of the total conflicts at all levels of critical TTC (0.5s, 1.0s, and 1.5s), even after eliminating low-speed events from the analysis (i.e., vehicles interacting in queues at close-proximity TTC may be below critical threshold but no reasonable human observer would count these events as conflicts). There were no strong differences in the average values of the TTC across all of the models, although AIMSUN and Paramics did exhibit higher average values for DR and lower values for PET, indicating that vehicles in Paramics and AIMSUN drive “less safely” than in VISSIM or TEXAS (still considering the paradox noted above). In general, the traffic performance measures such as throughput and delay were fairly variable but vaguely comparable from all systems during relatively light traffic, but the differences in the default driving behaviors and modeling assumptions became more pronounced as reflected in these measures when congestion levels increased. In the case of high traffic input volumes (as is true in the real world as well), some of the simulation systems rapidly broke down into the congested flow regime, thus causing the average performance results to diverge significantly.

All of the simulation systems exhibit modeling inaccuracies that lead SSAM to identify conflict events with TTC = 0 (“crashes”). The operating assumption at the beginning of this project was that none of the simulation systems would have any crashes during the simulation because the vehicles were avoiding each other at all times. In some cases, modeling inaccuracies had been explained by simulation system developers as being an artifact of the animation process but not due to the underlying driver and vehicle behavior logic. The level of “nanoscopic” analysis applied by SSAM revealed that this was not true—the driver and vehicle behavior logic in the simulation systems did not reflect crash avoidance under all vehicle-to-vehicle interaction scenarios. In hindsight, this is not surprising because the logical rules necessary to ensure this level of detailed crash avoidance would add additional processing burden to the systems, resulting in much poorer computational performance, particularly for traffic facility networks. It is generally assumed that very detailed collision avoidance behavior (or misbehavior) is of minor significance when simulation analysis is focused on the accurate (and perhaps only *relative*) assessment of measures such as throughput and delay. This study does not suggest that such measures may be inaccurate; however, the non-negligible occurrence of conspicuous and questionable behavior found in this analysis does raise some concern. These virtual crashes represent a serious issue that, as shown in the field validation study of the previous chapter, can seriously confound the ability of the models to produce justifiable metrics for safety analysis.

In some simulation systems, these crashes could be filtered out by appropriate identification of the analysis area. In AIMSUN and VISSIM, crashes occur at entry and exit areas of links. It can easily be argued that these events do not represent the area of interest for safety analysis, and any maneuvering happening in these areas should be ignored. A geographic extent filter has been added to SSAM for this purpose. In the future, however, as additional analysts gain experience in using and analyzing safety with these measures, the responsibility should be shifted from the analyst to the models. The TRJ output should probably be provided starting some point significantly after the link entrance and stop significantly before the link exit. This will add processing logic to the systems that could further decrease computational performance.

In some of the simulation systems, conspicuous vehicle behavior problems were not localized to areas away from the intersection that could easily be filtered out. Crashes from vehicles driving through each other should be eliminated (or at least limited to very rare events) by the simulation system vendors by adding processing logic to their models in the future. Efforts are already underway to improve TEXAS and VISSIM based on findings from SSAM analysis. However, in some cases, the user configuration plays a significant role as well. Interestingly, SSAM is useful in identifying modeling inaccuracies in each of the systems. For example, in VISSIM, the placement and orientation of connectors and links can significantly influence the occurrence of these virtual crashes. Using SSAM, the placement can be refined to remove the virtual crashes. However, in the case of lane-changing events, the logic of the simulation models must be enhanced to address these virtual crashes to enhance the credibility of safety analysis using the vendors' tools. Additional collaborative research and development work is suggested for the future to continue to improve the safety measures from the simulation models as the technique still holds major promise.

CHAPTER 6. CONCLUSION

SUMMARY

This project evaluated a method of safety assessment utilizing a traffic conflicts analysis technique applied to simulation models of intersections, interchanges, and roundabouts. The high-level scope of project was two-fold:

- Develop a software application to automate the task of traffic conflicts analysis.
- Conduct validation testing to gauge the efficacy of the assessment method.

Model Development

The safety assessment approach in this project is grounded in the discussion of surrogate safety assessment methodology and recommendations outlined in report FHWA-RD-3-050: *Surrogate Safety Measures from Traffic Simulation*.(6) The current project fleshed out the algorithmic proposals outlined in that preceding project, and the method was codified into a software utility, referred to as the Surrogate Safety Assessment Model (SSAM). SSAM identifies conflict events by processing detailed vehicle trajectory data, which can be exported from the following traffic simulation software of four corresponding vendors who collaborated on the project:

- AIMSUN
- Paramics
- TEXAS
- VISSIM

Conflicts are identified when the trajectories of two vehicles (headings and velocities) indicate an imminent collision with a TTC of less than 1.5 seconds. Although the evaluation focus of this project was oriented toward intersections, interchanges, and roundabouts, the SSAM algorithms can identify conflicts on any type of roadway where two vehicles travel in close proximity (e.g., a section of freeway). The conflict events are classified by maneuver type (path-crossing, rear-end, and lane-change events), and SSAM computes corresponding surrogate safety measures (TTC, PET) and hypothetical collision severity measures (Delta-V). It was hypothesized that the measures such as the relative frequency of conflicts of two traffic facilities may be used to distinguish the relatively frequency of crashes, and thus, the relative safety of the two traffic facilities.

Model Validation

Validation of SSAM was a three-part undertaking, consisting of the following:

- Theoretical validation.
- Field validation.
- Sensitivity analysis.

These three validation activities are summarized along with their corresponding findings in the next section.

FINDINGS

Theoretical Validation

The theoretical validation effort assessed the use of SSAM to discern the relative safety of a pairs of intersection/interchange design alternatives in a series of eleven case studies as follows:

- Signalized, four-leg intersection with permitted left turn versus protected left turn.
- Signalized, four-leg intersection with and without left-turn bay.
- Signalized, four-leg intersection with and without right-turn bay.
- Signalized, four-leg intersection with leading left turns versus lagging left turns.
- Signalized, four-leg intersection versus a pair of offset T-intersections.
- Diamond interchange with three-phase timing versus four-phase timing.
- SPUI versus diamond interchange.
- Signalized, four-leg intersection with left turns versus no left turns with median U-turn bays.
- Signalized, four-leg intersection versus roundabout.
- Signalized, three-leg, T-intersection versus roundabout with three legs.
- Diamond interchange versus double roundabout.

It was found that under equivalent traffic conditions (e.g., traffic volumes and turning percentages), for both intersection design alternatives, SSAM could discern statistically significant differences in the total number of conflicts, the number of conflicts by type (i.e., crossing, lane-change, or rear-end events), and conflict severity indicators (e.g., average TTC, PET, Delta-V values). However, in most cases the comparison of the two alternatives did not reveal a clearly preferable design but rather a trade-off of surrogate safety measures. It was typical, for example, that one design exhibited a higher frequency of conflicts, but those conflicts exhibited lower severity ratings than the alternative design. This type of assessment outcome hinders unequivocal decision-making about which design is the safer of the two.

These results clearly point to the need for future research to develop a “conflict index” or “safety index”. This might be accomplished by computing appropriate weightings of observed conflicts of different types, frequencies and severities, and aggregating results observed from a distribution of daily traffic conditions to form a composite safety assessment of a traffic facility. This would facilitate safety assessment efforts, alleviating analysts from the need to undertake their own series of complex calculations and judgments.

Field Validation

The field validation effort was concerned with the direct accuracy of surrogate safety assessment, as opposed to the relative safety assessment of the theoretical validation. A set of 83 field sites were selected—all four-leg, urban, signalized intersections—and were modeled in VISSIM, simulated, and assessed with SSAM. The conflict analysis results of these intersections were compared to actual crash histories (based on corresponding insurance claims records), using five statistical tests. This effort also provided an opportunity for benchmark comparison of surrogate safety estimates versus traditional crash prediction models based on ADT volumes.

It was found that the simulation-based intersection conflicts data provided by SSAM were significantly correlated with the crash data collected in the field, with the exception in particular of conflicts during path-crossing maneuvers, which were under-represented in the simulation. The relationship between total conflicts and total crashes exhibited a correlation (R-squared) value of 0.41, which is consistent with the typical performance reported in several studies using traditional crash prediction models on urban, signalized intersections. However, it was notable that in this study, the traditional (volume-based) crash prediction models were better correlated with the crash data than the surrogate measures in all test cases. For example, ADT-based crash prediction models exhibited a correlation (R-squared) value of 0.68 with actual crash frequencies.

It is well-established that as traffic volume increases, so does the occurrence of crashes and conflicts. Thus, some correlation of conflicts frequencies and crash frequencies is to be expected. This effort did find a significant correlation between simulated conflicts and actual crashes; however, a good correlation between intersections with abnormally high conflicts and abnormally high crashes was not found. This finding does not suggest that such a relationship can be definitively rejected, as tests conducted to that end proved somewhat unsuitable to the task. Thus, while the SSAM approach shows significant potential, the validation results did not reach a definitive conclusion.

Sensitivity Analysis

The sensitivity analysis effort complemented the field validation study, which was limited solely to intersection modeling with the VISSIM simulation. The sensitivity analysis reassessed 5 intersections—of the 83 considered in the field validation—with each of 4 simulation systems: AIMSUN, Paramics, TEXAS, and VISSIM. A series of comparisons were employed to characterize the sensitivity and/or bias of the surrogate safety measures, as they differed when obtained from each of the four simulations.

It was found that a fairly wide range of results can be obtained from applying different simulation models to the same traffic facility designs. In general, intersections modeled in VISSIM exhibited the fewest total conflicts, and intersections modeled in TEXAS had the highest conflict frequency—approximately 10 times higher than VISSIM. Conflict totals from AIMSUN and Paramics fell between these extremes. The abnormally high number of conflicts in TEXAS seems to stem (somewhat paradoxically) from the explicit inclusion of active conflict avoidance in the driver behavior model of TEXAS, whereas other simulations employ more reactive driver behavior modeling. An example of reactive behavior manifested in the form of particularly extreme braking/deceleration events observed in the AIMSUN and Paramics simulations.

In all of the simulation systems, rear-end conflict events made up the bulk of the total conflicts at all evaluated TTC thresholds (0.5s, 1.0s, and 1.5s). This bias persisted even after eliminating low-speed events from the analysis (i.e., events occurring at speeds less than 16.1 km/h (10 mi/h)). There were no major differences in the average TTC values across the models, although AIMSUN and Paramics did exhibit higher average deceleration rates (DR) and lower PET, consistent with their relatively reactive driver behavior modeling. In general, the traffic performance measures such as throughput and delay were variable but vaguely comparable from all systems under light traffic; however, the differences in the default driving behaviors and modeling assumptions pronounced differences in results at higher congestion levels. Also, SSAM identified questionable scenarios in all simulations where vehicles were driving directly through one another (i.e., crashes or conflicts with a TTC of 0).

RECOMMENDATIONS

The SSAM approach demonstrated significant correlations with actual crash data, consistent with the range of correlations reported in several studies with traditional (primarily volume-based) crash prediction models; although, in direct comparison, volume-based prediction models provided better correlation to field data (crash records) than simulated conflicts.[8] SSAM also demonstrated a capability to distinguish safety differences between different intersection design features under the same traffic volumes, though differences were often a trade-off, improving one measure with degrading another. Additionally, SSAM is applicable to the analysis of traffic facilities that have not yet been constructed and traffic control policies not yet enacted in the field. Thus, the SSAM approach exhibits promise, while at the same time the validation results are not definitive.

SSAM and corresponding documentation is available to the public at no cost and can be obtained from the FHWA.[9] It may well serve as a useful assessment tool in capable hands where analysts are cognizant of the underlying limitations discussed in this report.

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[8] It was noted in the Field Validation chapter that simulated volumes were differed somewhat from the ADT volumes used for traditional crash prediction.

[9] Please direct also inquiries regarding SSAM to the FHWA Office of Safety R&D.

There were indeed a number of limitations, which motivate the recommendation of certain directions in future research:

- Improve driver behavior modeling in simulations.
- Develop a composite "safety index".
- Study the underlying nature of conflicts in real-world data.
- Collect adequate vehicle trajectory data sets from the real world.
- Investigate conflict classification criteria.

Improve Driver Behavior Modeling in Simulations

As discussed in the report, SSAM analysis was often confounded by occurrences of unintended crashes in the model that could not be removed completely without modeling techniques that resulted in unrealistic driver behaviors and unrealistic facility performance (e.g., reduced approach capacity and throughput). Notably, ongoing simulation enhancements have already been reported to the project team which may enhance the quality of analysis results possible with SSAM in the coming months and years:

- VISSIM has added the notion of "conflict areas" to version 4.3, which incorporates the notion of explicit conflict avoidance logic as an alternative/adjunct to priority rules.
- TEXAS has undergone revisions that have substantially reduced unintended crashes in benchmark test models.

Develop a Composite "Safety Index"

It is evident from the validation effort that modification of the intersection design or traffic control policy may lead to a trade-off in surrogate safety measures where, for example, there is a significant increase in rear-end conflicts but a significant decrease in crossing conflicts, or, as another example, a decrease in total conflicts but an increase in severity measures. Thus, there is a need to research the development of a composite index scheme that could factor in the multitude of often contradictory surrogate safety indicators. This could facilitate easier and more accurate safety comparisons and decision-making.

Study the Underlying Nature of Conflicts in Real-World Data

The field validation and sensitivity analysis efforts both exhibited a distribution of conflicts by type and severity that lean more heavily toward less dangerous events than the distribution of events found in actual crash records. For example, the conflict-to-crash ratio is higher for rear-end conflicts than it is for lane-change conflicts and crossing conflicts. However, in digesting this finding, it is difficult to discern whether this discrepancy is due to flaws in the underlying simulations models or the conflict identification scheme or if the conflict occurrence in the field does indeed differ from crash occurrence. Thus, there is a need to study real-world data to quantify the shortcomings of simulated conflict data versus real-world conflict data and to learn any potential shortcomings of the current analysis method. Manual (human observer) field studies are not capable of collecting the rich surrogate safety information that SSAM can glean from detailed vehicle trajectory data. Thus, using SSAM to study real-world vehicle trajectory data and conflict phenomena could yield new understanding. Additionally, efforts to develop an appropriate composite would benefit from real-world data for calibration.

Collect Adequate Vehicle Trajectory Datasets from the Real World

Aside from studying real-world data, that data must actually be collected. Manual (human observer) studies are not capable of recording detailed vehicle trajectory data. Efforts to collect data from video image processing are improving, though additional research and development effort is warranted. This is an ambitious task unto its own and thus is listed as separate research direction.

Investigate Conflict Classification Criteria

This study classified vehicle conflicts as one of three types: rear end, lane changing, or crossing. The classification logic was initially based only the angle of two converging vehicles and then was revised for more accurate capture of rear-end and lane-changing events, utilizing knowledge of underlying lanes and links where possible. However, link and lane information is often not applicable (which is the subject of a protracted conversation not included here). For example, in potentially applying SSAM to process real-world data, an underlying link/lane model might not be available. As a concrete example, perhaps the most conspicuous case where the "lines" of classification are blurred is where a vehicle entering a roundabout conflicts with a vehicle within the traffic circle. Supposing the vehicle traveling within the traffic circle crashes into the rear of the entering vehicle—can it be said clearly where/how a lane-change event is differentiated from a rear-end event in this case? Is there a precise angle at which the entering vehicle should be classified as crossing rather than lane changing? This topic warrants further investigation into appropriate angles and additional criteria/logic for classification. It would also be useful to document the underlying value and motivation of classifying conflicts. Perhaps more conflict types or subtypes should be considered, and perhaps a conflict should be allowed to have multiple classifications with either binary or partial memberships in those classes. Aside from classification by movement types, perhaps there are also useful classifications by severity type that (like movement type classification) are properly identified only with multidimensional considerations rather than imposing threshold ranges on a single measure. Such investigation should include consideration of field data and provide guidance on effective and useful classification.

RESOURCES

As mentioned previously, SSAM and corresponding documentation is available to the public at no cost and can be obtained from the FHWA. As more analysts gain experience with the technique and analyze additional types of traffic facilities, additional directions for development and research will likely be identified. It is recommended that FHWA continue to collect experiences of analysts and form a committee of experts to discuss issues of surrogate measures in further determining the needs for future research.

APPENDIX A. DESCRIPTION OF CANADIAN INTERSECTIONS

Table 122 provides a summary description of the geometry and traffic control variations in the 83-interection test set used for validation testing. The rightmost column is labeled *K*. In the Highway Capacity Manual, *K* (or the K-factor) represents a ratio of ADT (average daily traffic in vehicles per day) to PHV (peak hour volume in vehicles per hour). This was a conveniently short label for this column; however, it is not entirely accurate. The denominators used to calculate the ratios in the *K* column are actually AM-peak volumes that were simulated for all 83 intersections. When inspecting these *K* factors for these intersections, note that many were greater than 24, indicating that the peak morning hourly volume was less than 1/24th of the daily volume. Thus, the AM peak was evidently not the actual peak hour for many of these intersections.

Table 122. Canadian Intersections Geometry and Traffic Flow Data.

ID	Intersections	Lane Counts				Intersection Design	Signal Type	Approach Volume (ADT veh/day)				Simulated AM Peak Hour Volume (PHV in vph)								K
		NB	SB	EB	WB			Major	Minor	Total	PEV	NB	SB	EB	WB	N+S	E+W	Total	PEV	
1	Gilley & Kingsway	2	2	3	3	60 Degrees	Semi Actuated	57,450	15,750	73,200	30,081	310	305	685	1,710	615	2,395	3,010	1,214	24
2	Coast Meridian & Prairie	4	3	3	3	90 Degrees	Fully Actuated	21,500	20,600	42,100	21,045	290	530	150	545	820	695	1,515	755	28
3	Coast Meridian & Robertson	1	2	1	1	90 Degrees	Predefined	25,350	10,950	36,300	16,661	365	800	55	520	1,165	575	1,740	818	21
4	Oxford & Prairie	1	1	1	1	90 Degrees	Fully Actuated	22,950	6,750	29,700	12,446	85	130	225	615	215	840	1,055	425	28
5	128 & 96	3	3	3	3	90 Degrees	Semi Actuated	51,500	33,800	85,300	41,722	225	350	435	650	575	1,085	1,660	790	51
6	Griffiths & Kingsway	2	2	3	3	90 Degrees	Semi Actuated	50,850	16,900	67,750	29,315	620	320	690	1,315	940	2,005	2,945	1,373	23
7	Willingdon & Moscrop	4	4	3	3	WB-Skew	Semi Actuated	57,450	30,150	87,600	41,619	1,495	1,030	765	910	2,525	1,675	4,200	2,057	21
8	Edmonds & Canada	3	4	3	3	90 Degrees	Semi Actuated	55,620	32,920	88,540	42,790	345	1,005	735	1,231	1,350	1,966	3,316	1,629	27
9	Sprott & Douglas	1	1	1	1	10 Degrees	Semi Actuated	20,040	10,640	30,680	14,602	165	335	187	685	500	872	1,372	660	22
10	132 & 88	2	2	3	3	90 Degrees	Semi Actuated	41,450	27,450	68,900	33,731	390	575	720	1,155	965	1,875	2,840	1,345	24
11	128 & 88	3	3	3	3	90 Degrees	Semi Actuated	40,300	33,700	74,000	36,853	425	695	665	1,065	1,120	1,730	2,850	1,392	26
12	Coast Meridian & Lougheed	2	2	4	4	Skewed	Predefined	58,250	15,450	73,700	29,999	30	765	895	1,575	795	2,470	3,265	1,401	23
13	Mariner & Como Lake	3	4	3	3	SB-Skew	Predefined	32,850	24,050	56,900	28,108	560	1,225	645	260	1,785	905	2,690	1,271	21
14	Johnson & Guildford	3	4	3	3	90 Degrees	Predefined	43,850	35,250	79,100	39,316	605	645	645	875	1,250	1,520	2,770	1,378	29
15	Johnson & Barnet	5	4	6	6	25 Degrees	Predefined	72,950	45,050	118,000	57,327	705	1,320	815	1,970	2,025	2,785	4,810	2,375	25
16	Johnson & David	4	4	3	3	25 Degrees	Predefined	38,180	5,320	43,500	14,252	655	1,190	272	58	1,845	330	2,175	780	20
17	McCallum & Marshall	4	4	4	3	90 Degrees	Semi Actuated	45,150	31,750	76,900	37,862	890	795	725	705	1,685	1,430	3,115	1,552	25
18	Mariner & Dewdney Trunk	4	4	4	3	EB Skew	Predefined	38,200	21,150	59,350	28,424	845	280	490	1,165	1,125	1,655	2,780	1,365	21
19	128 & 76	3	3	2	2	90 Degrees	Semi Actuated	28,300	22,000	50,300	24,952	525	560	410	340	1,085	750	1,835	902	27
20	Yale & Airport	4	4	2	2	WB Skew	Fully Actuated	52,650	10,390	63,040	23,389	1,460	1,175	125	392	2,635	517	3,152	1,167	20

Table 122. Canadian Intersections Geometry and Traffic Flow Data—continued.

ID	Intersections	**Lane Counts**				Intersection Design	Signal Type	**Approach Volume** (ADT veh/day)				**Simulated AM Peak Hour Volume** (PHV in vph)								K
		NB	SB	EB	WB			Major	Minor	Total	PEV	NB	SB	EB	WB	N+S	E+W	Total	PEV	
21	152 & 104	4	4	4	4	90 Degrees	Semi Actuated	46,750	43,150	89,900	44,914	790	935	675	855	1,725	1,530	3,255	1,625	28
22	Glover & Logan	3	3	3	3	45 Degrees	Semi Actuated	21,200	18,700	39,900	19,911	185	335	190	335	520	525	1,045	522	38
23	Yale & Hodgins	3	3	2	3	NB,EB,WB Skew	Fully Actuated	35,300	19,300	54,600	26,102	1,145	545	585	455	1,690	1,040	2,730	1,326	20
24	Yale & Hocking	3	3	2	2	SB Skew	Fully Actuated	54,950	13,550	68,500	27,287	1,270	1,430	370	355	2,700	725	3,425	1,399	20
25	Borden & McKenzie	2	2	3	3	90 Degrees	Semi Actuated	61,600	18,700	80,300	33,940	255	585	1,340	1,175	840	2,515	3,355	1,453	24
26	152 & 56	4	4	2	3	90 Degrees	Semi Actuated	43,150	33,950	77,100	38,275	750	790	750	1,305	1,540	2,055	3,595	1,779	21
27	152 & 88	3	3	3	3	90 Degrees	Semi Actuated	39,800	38,700	78,500	39,246	1,120	810	735	797	1,930	1,532	3,462	1,720	23
28	Quadra & McKenzie	3	3	3	4	SB Skew	Predefined	47,850	37,050	84,900	42,105	620	910	1,140	825	1,530	1,965	3,495	1,734	24
29	Saanich & MckKenzie	2	2	2	2	90 Degrees	Predefined	46,100	9,600	55,700	21,037	175	180	1,085	960	355	2,045	2,400	852	23
30	Shelbourne & McKenzie	4	3	3	3	90 Degrees	Semi Actuated	41,750	38,250	80,000	39,962	635	1,000	915	760	1,635	1,675	3,310	1,655	24
31	Glanford & McKenzie	3	3	4	4	90 Degrees	Semi Actuated	52,950	22,150	75,100	34,247	450	625	1,203	1,255	1,075	2,458	3,533	1,626	21
32	Douglas & Kelvin	3	3	2	2	WB-EB Skew	Semi Actuated	61,850	16,100	77,950	31,556	855	2,025	170	600	2,880	770	3,650	1,489	21
33	Douglas & Saanich	4	3	3	4	WB Skew	Semi Actuated	58,400	34,900	93,300	45,146	930	1,765	595	785	2,695	1,380	4,075	1,928	23
34	Gordon & Harvey	4	4	5	5	90 Degrees	Semi Actuated	98,950	44,250	143,200	66,171	575	775	1,820	1,305	1,350	3,125	4,475	2,054	32
35	Gordon & Springfield	3	3	3	3	90 Degrees	Semi Actuated	37,500	35,800	73,300	36,640	625	720	355	780	1,345	1,135	2,480	1,236	30
36	Gordon & Bernard	3	3	3	3	90 Degrees	Semi Actuated	34,300	25,300	59,600	29,458	555	735	290	520	1,290	810	2,100	1,022	28
37	Wharf & Dolphin	2	2	2	2	90 Degrees	Semi Actuated	22,350	20,850	43,200	21,587	630	440	335	755	1,070	1,090	2,160	1,080	20
38	Boundary & Lougheed	5	4	4	4	35 Degrees	Semi Actuated	69,050	50,950	120,000	59,314	805	1,465	1,260	1,330	2,270	2,590	4,860	2,425	25
39	Gatensbury & Como Lake	1	1	2	2	90 Degrees	Fully Actuated	47,350	6,950	54,300	18,141	80	150	685	1,345	230	2,030	2,260	683	24
40	Poirier & Como Lake	1	1	2	2	90 Degrees	Fully Actuated	47,650	6,050	53,700	16,979	120	145	633	1,400	265	2,033	2,298	734	23
41	Harris & Hammond	3	3	1	2	90 Degrees	Semi Actuated	13,900	10,550	24,450	12,110	205	475	90	415	680	505	1,185	586	21
42	Bryne & Marine	2	3	3	3	90 Degrees	Predefined	66,450	23,450	89,900	39,475	70	1,460	1,315	1,650	1,530	2,965	4,495	2,130	20
43	Patterson & Kingsway	2	1	3	3	WB-EB Skew	Semi Actuated	61,400	9,500	70,900	24,152	905	1,225	85	190	2,130	275	2,405	765	29
44	Brooke & Nordel	2	2	2	2	45 Degrees	Semi Actuated	59,950	6,350	66,300	19,511	40	105	655	1,740	145	2,395	2,540	589	26
45	56 & 12	3	3	2	3	90 Degrees	Predefined	30,250	15,150	45,400	21,408	570	415	230	305	985	535	1,520	726	30
46	No. 5 & Steveston	3	2	4	3	90 Degrees	Semi Actuated	48,900	20,200	69,100	31,429	290	460	1,145	1,020	750	2,165	2,915	1,274	24
47	No. 5 & Westminster	4	3	4	4	90 Degrees	Semi Actuated	60,200	25,600	85,800	39,257	720	325	1,010	1,450	1,045	2,460	3,505	1,603	24
48	Garden City & Westminster	4	3	3	4	90 Degrees	Semi Actuated	35,650	35,150	70,800	35,399	1,260	600	595	1,085	1,860	1,680	3,540	1,768	20
49	Garden City & Alderbridge	4	4	4	3	90 Degrees	Semi Actuated	45,200	45,000	90,200	45,100	1,250	525	490	1,220	1,775	1,710	3,485	1,742	26
50	No. 4 & Alderbridge	3	3	4	3	90 Degrees	Semi Actuated	57,400	21,600	79,000	35,211	745	295	795	1,345	1,040	2,140	3,180	1,492	25
51	Shell & Alderbridge	4	4	4	4	90 Degrees	Semi Actuated	53,000	17,250	70,250	30,237	420	315	1,245	1,530	735	2,775	3,510	1,428	20
52	Fraser & 96	3	2	4	4	EB WB Skew	Semi Actuated	36,970	35,570	72,540	36,263	1,001	462	561	896	1,463	1,457	2,920	1,460	25
53	King George & 72	4	4	4	4	90 Degrees	Semi Actuated	53,350	44,850	98,200	48,916	1,395	915	785	985	2,310	1,770	4,080	2,022	24
54	140 & 72	1	2	3	3	90 Degrees	Semi Actuated	46,530	11,530	58,060	23,162	157	430	745	970	587	1,715	2,302	1,003	25
55	184 & Fraser	3	3	2	1	45 Degrees	Predefined	35,570	15,650	51,220	23,594	356	395	904	906	751	1,810	2,561	1,166	20

Table 122. Canadian Intersections Geometry and Traffic Flow Data—continued.

ID	Intersections	Lane Counts				Intersection Design	Signal Type	**Approach Volume** (ADT veh/day)				**Simulated AM Peak Hour Volume** (PHV in vph)								K
		NB	SB	EB	WB			Major	Minor	Total	PEV	NB	SB	EB	WB	N+S	E+W	Total	PEV	
56	64 & Fraser	4	3	3	3	90 Degrees	Predefined	36,400	33,940	70,340	35,148	1,099	794	918	706	1,893	1,624	3,517	1,753	20
57	Willowbrook & Fraser	1	3	4	4	NB-SB Skew	Predefined	43,130	30,630	73,760	36,347	443	1,234	948	1,063	1,677	2,011	3,688	1,836	20
58	Scott & 72	3	3	3	4	90 Degrees	Semi Actuated	46,650	37,050	83,700	41,574	400	495	455	520	895	975	1,870	934	45
59	Scott & 80	3	3	3	3	90 Degrees	Semi Actuated	49,050	24,650	73,700	34,772	830	550	430	380	1,380	810	2,190	1,057	34
60	Scott & 64	3	3	3	3	90 Degrees	Semi Actuated	41,350	36,300	77,650	38,743	650	770	445	960	1,420	1,405	2,825	1,412	27
61	Scott & 58	3	3	4	4	EB Skew	Semi Actuated	43,450	15,200	58,650	25,699	270	590	790	1,015	860	1,805	2,665	1,246	22
62	Shaw & Hwy 101	1	2	2	2	90 Degrees	Semi Actuated	24,400	5,200	29,600	11,264	95	205	535	645	300	1,180	1,480	595	20
63	Schoolhouse & Austin	1	1	2	2	90 Degrees	Semi Actuated	37,050	8,450	45,500	17,694	140	235	405	1,235	375	1,640	2,015	784	23
64	Marmont & Austin	2	1	3	3	90 Degrees	Semi Actuated	36,050	13,950	50,000	22,425	260	205	495	1,270	465	1,765	2,230	906	22
65	Rupert & 22	2	2	1	1	90 Degrees	Semi Actuated	37,700	23,700	61,400	29,891	780	770	480	410	1,550	890	2,440	1,175	25
66	Rupert & 1	3	4	3	2	NB Skew	Predefined	80,820	20,840	101,660	41,040	387	815	1,596	1,575	1,202	3,171	4,373	1,952	23
67	Rupert & Grandview	3	4	4	4	90 Degrees	Semi Actuated	69,050	44,250	113,300	55,276	990	760	1,630	1,615	1,750	3,245	4,995	2,383	23
68	Kerr & 49	3	3	3	3	90 Degrees	Predefined	37,950	35,250	73,200	36,575	820	700	730	930	1,520	1,660	3,180	1,588	23
69	Shaughnessy & Lions	4	3	1	2	90 Degrees	Semi Actuated	36,200	10,100	46,300	19,121	860	585	25	395	1,445	420	1,865	779	25
70	Shaughnessy & Pitt River	2	3	2	2	90 Degrees	Semi Actuated	21,000	17,950	38,950	19,415	160	620	330	480	780	810	1,590	795	24
71	Spall & Springfield	1	3	3	3	EB Skew	Predefined	59,400	15,350	74,750	30,196	80	440	650	1,095	520	1,745	2,265	953	33
72	272 & Fraser	2	2	2	2	80 Degrees	Semi Actuated	20,600	9,400	30,000	13,915	290	220	530	445	510	975	1,485	705	20
73	240 & Fraser	2	2	2	2	45 Degrees	Semi Actuated	29,050	8,750	37,800	15,943	365	120	550	810	485	1,360	1,845	812	20
74	216 & Fraser	4	4	4	3	35 Degrees	Semi Actuated	39,900	21,300	61,200	29,153	720	375	600	825	1,095	1,425	2,520	1,249	24
75	Bradner & Fraser	2	1	2	2	90 Degrees	Semi Actuated	26,900	7,150	34,050	13,868	230	135	560	590	365	1,150	1,515	648	22
76	Vedder & Spruce	3	3	1	3	Skewed	Semi Actuated	42,000	6,600	48,600	16,649	800	1,345	145	140	2,145	285	2,430	782	20
77	Vedder & Watson	3	3	2	3	80 Degrees	Semi Actuated	29,650	18,950	48,600	23,704	635	910	305	580	1,545	885	2,430	1,169	20
78	Vedder & Knight	3	3	2	2	NB Skew	Semi Actuated	44,800	11,200	56,000	22,400	885	1,275	415	225	2,160	640	2,800	1,176	20
79	Vedder & Luckakuck	4	4	4	4	45 Degrees	Semi Actuated	46,300	30,800	77,100	37,763	945	1,200	955	755	2,145	1,710	3,855	1,915	20
80	34 & 25	3	3	3	3	NB Skew	Semi Actuated	28,500	15,050	43,550	20,711	335	165	570	530	500	1,100	1,600	742	27
81	William & lynn	3	2	4	3	45 Degrees	Semi Actuated	50,850	12,250	63,100	24,958	275	278	185	925	553	1,110	1,663	783	38
82	Mountain & Lynn	2	2	3	2	45 Degrees	Semi Actuated	27,700	20,700	48,400	23,946	530	605	325	580	1,135	905	2,040	1,013	24
83	227 & Dewdney	2	2	3	3	90 Degrees	Semi Actuated	34,650	12,950	47,600	21,183	145	295	470	910	440	1,380	1,820	779	26
	Average (per intersection)	2.8	2.8	2.9	2.9			43,963	22,525	66,488	30,375	571	669	634	879	1,239	1,513	2,752	1,261	25
	Min (over all intersections)	1	1	1	1			13,900	5,200	24,450	11,264	30	105	25	58	145	275	1,045	425	20
	Max (over all intersections)	5	4	6	6			98,950	50,950	143,200	66,171	1,495	2,025	1,820	1,970	2,880	3,245	4,995	2,425	51

Table 123 provides the average yearly crash information for all 83 intersections in the field validation study. At least 3 years of data were available for all intersections, though some intersections had more data. The longest data record was 8.25 years. The crash information includes yearly crash counts, crashes counts by maneuver type, and crash counts by severity type.

Table 123. Average Yearly Crashes per Intersection.

ID	Intersections	Average Yearly Crash Count				Average Yearly Crash Count by Severity				
		Crossing	Rear End	Lane Change	Total	Fatalities	Injuries	Damage $ ≤ 1K	Damage $ > 1K	Total
1	Gilley & Kingsway	12.4	33.1	11.7	57.1	0.0	29.4	11.7	16.0	57.1
2	Coast Meridian & Prairie	5.3	12.0	2.3	19.7	0.0	9.7	6.7	3.3	19.7
3	Coast Meridian & Robertson	3.3	3.7	1.0	8.0	0.0	2.7	1.3	4.0	8.0
4	Oxford & Prairie	5.2	5.8	1.2	12.2	0.0	6.6	2.4	3.2	12.2
5	128 & 96	16.3	30.4	8.0	54.7	0.0	29.0	15.7	10.0	54.7
6	Griffiths & Kingsway	13.0	20.4	7.7	41.1	0.0	20.4	9.3	11.4	41.1
7	Willingdon & Moscrop	12.4	46.7	6.7	65.8	0.0	27.0	22.0	16.7	65.8
8	Edmonds & Canada	16.4	49.4	15.4	81.1	0.0	33.1	27.7	20.4	81.1
9	Sprott & Douglas	4.0	3.3	0.7	8.0	0.0	4.7	1.0	2.3	8.0
10	132 & 88	11.4	38.4	5.0	54.8	0.0	27.7	16.4	10.7	54.8
11	128 & 88	20.7	49.4	9.0	79.1	0.0	40.4	19.4	19.4	79.1
12	Coast Meridian & Lougheed	1.3	35.1	2.3	38.7	0.0	12.0	16.0	10.7	38.7
13	Mariner & Como Lake	3.0	17.2	4.4	24.6	0.0	8.6	9.2	6.8	24.6
14	Johnson & Guildford	11.0	20.8	2.8	34.6	0.0	15.6	11.8	7.2	34.6
15	Johnson & Barnet	8.4	62.0	8.0	78.4	0.0	33.6	24.8	20.0	78.4
16	Johnson & David	1.8	4.2	1.8	7.8	0.0	1.8	2.4	3.6	7.8
17	McCallum & Marshall	13.7	29.0	6.3	49.0	0.0	21.7	14.0	13.3	49.0
18	Mariner & Dewdney Trunk	10.8	14.2	2.4	27.4	0.0	14.6	6.6	6.2	27.4
19	128 & 76	10.7	17.0	4.3	32.1	0.3	15.0	8.7	8.0	32.1
20	Yale & Airport	5.7	24.4	2.3	32.4	0.0	16.3	7.0	9.0	32.4
21	152 & 104	16.0	55.0	17.0	88.1	0.0	36.0	28.4	23.7	88.1
22	Glover & Logan	5.3	2.0	1.3	8.7	0.0	5.3	1.3	2.0	8.7
23	Yale & Hodgins	2.3	7.7	2.3	12.3	0.0	5.0	3.0	4.3	12.3
24	Yale & Hocking	3.3	18.7	1.7	23.7	0.0	12.3	5.0	6.3	23.7
25	Borden & McKenzie	3.3	12.0	1.7	17.0	0.0	8.0	5.7	3.3	17.0
26	152 & 56	9.0	40.0	8.3	57.4	0.0	25.0	13.7	18.7	57.4

Table 123. Average Yearly Crashes per Intersection—continued.

ID	Intersections	Average Yearly Crash Count				Average Yearly Crash Count by Severity				
		Crossing	Rear End	Lane Change	Total	Fatalities	Injuries	Damage $ ≤ 1K	Damage $ > 1K	Total
27	152 & 88	15.0	44.0	6.0	65.0	0.0	35.4	16.7	13.0	65.0
28	Quadra & McKenzie	3.0	29.7	6.0	38.7	0.0	16.3	13.3	9.0	38.7
29	Saanich & MckKenzie	7.7	9.0	1.7	18.3	0.0	10.3	4.3	3.7	18.3
30	Shelbourne & McKenzie	1.3	16.7	4.7	22.7	0.0	7.7	10.0	5.0	22.7
31	Glanford & McKenzie	4.7	19.7	1.3	25.7	0.0	12.3	8.3	5.0	25.7
32	Douglas & Kelvin	2.7	24.7	2.7	30.0	0.0	15.0	8.0	7.0	30.0
33	Douglas & Saanich	4.3	15.7	5.3	25.4	0.0	15.0	5.3	5.0	25.4
34	Gordon & Harvey	12.7	29.7	4.3	46.7	0.0	22.0	12.0	12.7	46.7
35	Gordon & Springfield	3.7	10.0	2.3	16.0	0.0	7.3	5.3	3.3	16.0
36	Gordon & Bernard	4.3	8.7	1.0	14.0	0.0	5.7	5.3	3.0	14.0
37	Wharf & Dolphin	1.3	2.3	0.3	4.0	0.0	1.3	1.3	1.3	4.0
38	Boundary & Lougheed	13.7	52.4	16.7	82.7	0.0	30.7	26.7	25.4	82.7
39	Gatensbury & Como Lake	9.6	5.6	1.8	17.0	0.0	9.4	3.2	4.4	17.0
40	Poirier & Como Lake	2.8	6.8	2.2	11.8	0.0	5.2	4.0	2.6	11.8
41	Harris & Hammond	1.1	2.1	0.4	3.5	0.0	1.2	1.0	1.3	3.5
42	Bryne & Marine	6.3	46.4	6.7	59.4	0.0	25.0	17.0	17.4	59.4
43	Patterson & Kingsway	6.0	44.4	5.3	55.8	0.0	21.7	20.4	13.7	55.8
44	Brooke & Nordel	5.3	14.4	2.3	22.0	0.0	13.7	3.3	5.0	22.0
45	56 & 12	3.3	7.3	2.0	12.7	0.0	4.3	4.0	4.3	12.7
46	No. 5 & Steveston	6.7	51.7	15.7	74.1	0.0	28.7	22.4	23.0	74.1
47	No. 5 & Westminster	10.3	44.7	3.3	58.4	0.3	21.7	18.7	17.7	58.4
48	Garden City & Westminster	4.0	59.1	7.0	70.1	0.3	21.0	31.0	17.7	70.1
49	Garden City & Alderbridge	12.4	58.4	7.3	78.1	0.0	26.7	31.7	19.7	78.1
50	No. 4 & Alderbridge	9.0	46.1	2.0	57.1	0.0	22.4	20.0	14.7	57.1
51	Shell & Alderbridge	7.3	36.7	2.3	46.4	0.0	20.4	13.7	12.4	46.4
52	Fraser & 96	8.3	48.7	1.3	58.4	0.3	31.4	14.0	12.7	58.4
53	King George & 72	20.7	82.1	15.7	118.5	0.0	47.1	40.4	31.0	118.5
54	140 & 72	10.3	15.0	3.0	28.4	0.0	13.4	8.7	6.3	28.4
55	184 & Fraser	5.0	18.5	1.3	24.8	0.0	11.0	6.3	7.5	24.8
56	64 & Fraser	7.8	54.3	2.0	64.0	0.0	26.3	21.5	16.3	64.0
57	Willowbrook & Fraser	7.5	21.8	5.0	34.3	0.0	10.5	13.3	10.5	34.3

Table 123. Average Yearly Crashes per Intersection—continued.

ID	Intersections	Average Yearly Crash Count				Average Yearly Crash Count by Severity				
		Crossing	Rear End	Lane Change	Total	Fatalities	Injuries	Damage $ ≤ 1K	Damage $ > 1K	Total
58	Scott & 72	20.3	81.4	14.0	115.7	0.3	48.7	42.4	24.4	115.7
59	Scott & 80	18.3	44.4	6.7	69.4	0.0	35.7	19.7	14.0	69.4
60	Scott & 64	9.7	24.0	3.0	36.7	0.0	15.7	11.0	10.0	36.7
61	Scott & 58	3.7	43.4	6.3	53.4	0.0	21.0	20.3	12.0	53.4
62	Shaw & Hwy 101	1.7	0.7	1.0	3.3	0.0	1.3	0.7	1.3	3.3
63	Schoolhouse & Austin	8.8	7.4	4.0	20.2	0.0	9.8	3.6	6.8	20.2
64	Marmont & Austin	2.8	12.4	4.2	19.4	0.0	8.6	7.0	3.8	19.4
65	Rupert & 22	5.5	19.0	3.0	27.5	0.0	10.0	12.0	5.5	27.5
66	Rupert & 1	8.8	43.0	11.5	63.3	0.0	24.8	23.5	15.0	63.3
67	Rupert & Grandview	19.3	72.3	20.3	111.8	0.3	48.0	36.3	27.3	111.8
68	Kerr & 49	7.8	28.5	10.0	46.3	0.0	20.8	11.8	13.8	46.3
69	Shaughnessy & Lions	6.0	8.7	2.0	16.7	0.0	8.7	4.0	4.0	16.7
70	Shaughnessy & Pitt River	11.7	11.3	1.3	24.4	0.0	12.0	6.3	6.0	24.4
71	Spall & Springfield	4.7	15.8	2.2	22.7	0.0	11.3	5.7	5.7	22.7
72	272 & Fraser	4.0	13.0	1.3	18.3	0.3	8.0	4.7	5.3	18.3
73	240 & Fraser	2.3	11.0	1.0	14.3	0.0	5.7	3.7	5.0	14.3
74	216 & Fraser	8.0	19.7	2.7	30.4	0.0	15.3	7.3	7.7	30.4
75	Bradner & Fraser	3.0	13.0	1.0	17.0	0.0	8.7	4.0	4.3	17.0
76	Vedder & Spruce	2.3	6.0	1.2	9.5	0.0	4.0	2.7	2.8	9.5
77	Vedder & Watson	10.7	10.0	4.8	25.5	0.0	10.0	6.2	9.3	25.5
78	Vedder & Knight	5.5	9.3	3.7	18.5	0.2	8.3	4.5	5.5	18.5
79	Vedder & Luckakuck	4.0	33.3	8.7	46.0	0.0	20.5	16.0	9.5	46.0
80	34 & 25	4.7	5.2	0.8	10.7	0.0	6.5	1.7	2.5	10.7
81	William & lynn	1.7	7.8	1.5	11.0	0.0	3.3	4.0	3.7	11.0
82	Mountain & Lynn	3.5	12.3	3.0	18.8	0.0	6.7	6.8	5.3	18.8
83	227 & Dewdney	9.0	9.7	2.8	21.5	0.0	11.3	4.8	5.3	21.5
	SUM (over all intersections)	**632**	**2141**	**397**	**3170**	**2.4**	**1387**	**973**	**808**	**3170**
	AVERAGE (per intersection)	**7.6**	**25.8**	**4.8**	**38.2**	**0.0**	**16.7**	**11.7**	**9.7**	**38.2**
	PERCENTAGE (by type)	**19.9%**	**67.5%**	**12.5%**	**100%**	**0.1%**	**43.7%**	**30.7%**	**25.5%**	**100%**

Table 124 provides the average hourly conflict information for all 83 intersections in the field validation study. All intersection were simulated for five replications, each of 1 hour in duration. The counts in table 124 represent the average hourly values, in terms of total conflicts and conflicts by maneuver type.

Table 124. Average Hourly Conflicts per Intersection.

ID	Intersections	Average Hourly Conflict Counts			
		Crossing	Rear End	Lane Change	Total
1	Gilley & Kingsway	0.0	63.4	6.2	69.6
2	Coast Meridian & Prairie	0.0	40.8	1.6	42.4
3	Coast Meridian & Robertson	0.0	50.8	2.8	53.6
4	Oxford & Prairie	0.0	32.8	0.4	33.2
5	128 & 96	0.0	36.8	1.0	37.8
6	Griffiths & Kingsway	0.2	56.2	5.2	61.6
7	Willingdon & Moscrop	0.0	60.0	2.6	62.6
8	Edmonds & Canada	0.0	59.0	5.0	64.0
9	Sprott & Douglas	0.4	40.6	4.6	45.6
10	132 & 88	0.0	62.4	1.6	64.0
11	128 & 88	0.0	59.2	3.2	62.4
12	Coast Meridian & Lougheed	0.0	43.8	2.8	46.6
13	Mariner & Como Lake	0.0	42.8	0.6	43.4
14	Johnson & Guildford	0.0	47.8	2.8	50.6
15	Johnson & Barnet	0.2	83.8	5.0	89.0
16	Johnson & David	0.0	42.8	3.2	46.0
17	McCallum & Marshall	0.0	66.2	3.4	69.6
18	Mariner & Dewdney Trunk	0.2	60.8	1.8	62.8
19	128 & 76	0.2	49.2	3.0	52.4
20	Yale & Airport	0.0	77.2	3.2	80.4
21	152 & 104	0.0	53.6	4.8	58.4
22	Glover & Logan	0.0	13.4	0.2	13.6
23	Yale & Hodgins	0.4	82.6	6.6	89.6
24	Yale & Hocking	0.8	85.6	6.8	93.2
25	Borden & McKenzie	0.8	78.8	4.4	84.0
26	152 & 56	0.0	78.0	7.8	85.8

Table 124. Average Hourly Conflicts per Intersection—continued.

ID	Intersections	Average Hourly Conflict Counts			
		Crossing	Rear End	Lane Change	Total
27	152 & 88	0.0	69.0	3.4	72.4
28	Quadra & McKenzie	0.2	47.2	3.2	50.6
29	Saanich & MckKenzie	0.0	49.4	2.2	51.6
30	Shelbourne & McKenzie	0.0	52.4	3.0	55.4
31	Glanford & McKenzie	0.0	65.0	2.8	67.8
32	Douglas & Kelvin	0.0	56.6	2.2	58.8
33	Douglas & Saanich	0.0	60.4	4.6	65.0
34	Gordon & Harvey	0.0	72.0	3.4	75.4
35	Gordon & Springfield	0.0	45.6	1.4	47.0
36	Gordon & Bernard	0.2	51.0	2.4	53.6
37	Wharf & Dolphin	0.0	52.2	1.2	53.4
38	Boundary & Lougheed	0.0	73.0	3.2	76.2
39	Gatensbury & Como Lake	0.0	47.4	3.0	50.4
40	Poirier & Como Lake	0.2	62.0	5.2	67.4
41	Harris & Hammond	0.0	14.4	3.0	17.4
42	Bryne & Marine	0.6	68.0	3.2	71.8
43	Patterson & Kingsway	0.0	40.4	4.2	44.6
44	Brooke & Nordel	0.0	55.0	1.4	56.4
45	56 & 12	0.2	24.0	1.6	25.8
46	No. 5 & Steveston	0.0	42.2	2.6	44.8
47	No. 5 & Westminster	0.0	58.2	5.2	63.4
48	Garden City & Westminster	0.0	61.4	7.6	69.0
49	Garden City & Alderbridge	0.0	80.2	3.6	83.8
50	No. 4 & Alderbridge	0.6	58.0	4.8	63.4
51	Shell & Alderbridge	0.0	61.4	4.2	65.6
52	Fraser & 96	0.0	56.6	1.0	57.6
53	King George & 72	0.2	78.6	4.8	83.6
54	140 & 72	0.0	37.6	5.0	42.6
55	184 & Fraser	0.0	53.4	0.0	53.4
56	64 & Fraser	0.0	41.0	1.6	42.6
57	Willowbrook & Fraser	0.0	67.6	2.6	70.2

Table 124. Average Hourly Conflicts per Intersection—continued.

ID	Intersections	Average Hourly Conflict Counts			
		Crossing	Rear End	Lane Change	Total
58	Scott & 72	0.0	37.6	2.2	39.8
59	Scott & 80	0.2	35.4	1.6	37.2
60	Scott & 64	0.2	85.8	5.6	91.6
61	Scott & 58	0.0	45.6	3.0	48.6
62	Shaw & Hwy 101	0.0	20.4	1.8	22.2
63	Schoolhouse & Austin	1.4	39.8	6.4	47.6
64	Marmont & Austin	0.0	40.0	3.4	43.4
65	Rupert & 22	0.0	77.6	1.8	79.4
66	Rupert & 1	0.0	84.2	4.6	88.8
67	Rupert & Grandview	0.0	83.0	5.0	88.0
68	Kerr & 49	0.0	77.6	4.2	81.8
69	Shaughnessy & Lions	0.0	24.0	1.2	25.2
70	Shaughnessy & Pitt River	0.2	32.4	1.0	33.6
71	Spall & Springfield	0.0	33.4	2.2	35.6
72	272 & Fraser	0.0	36.8	2.2	39.0
73	240 & Fraser	0.4	37.4	3.4	41.2
74	216 & Fraser	0.0	43.2	1.8	45.0
75	Bradner & Fraser	0.0	38.0	2.8	40.8
76	Vedder & Spruce	0.0	48.2	1.2	49.4
77	Vedder & Watson	0.2	58.0	3.2	61.4
78	Vedder & Knight	0.4	66.0	6.8	73.2
79	Vedder & Luckakuck	0.0	46.6	3.4	50.0
80	34 & 25	0.2	28.6	2.0	30.8
81	William & lynn	0.0	36.6	0.6	37.2
82	Mountain & Lynn	0.2	51.6	0.6	52.4
83	227 & Dewdney	0.0	33.4	1.0	34.4
	SUM (over all intersections)	8.8	4410.8	261.2	4680.8
	AVERAGE (per intersection)	0.1	53.1	3.1	56.4
	PERCENTAGE (by type)	0.2%	94.2%	5.6%	100.0%

APPENDIX B. ABRUPT LANE-CHANGE BEHAVIOR

This section provides an example of the abrupt lane-changing behavior experienced in VISSIM using version 4.1. Figure 243 shows two vehicles stopped at the red light on the eastbound approach to the intersection, with two more vehicles approaching. The first vehicle is the approaching vehicle that is closer to the downstream stop line, while the second vehicle is the furthest from the stop line.

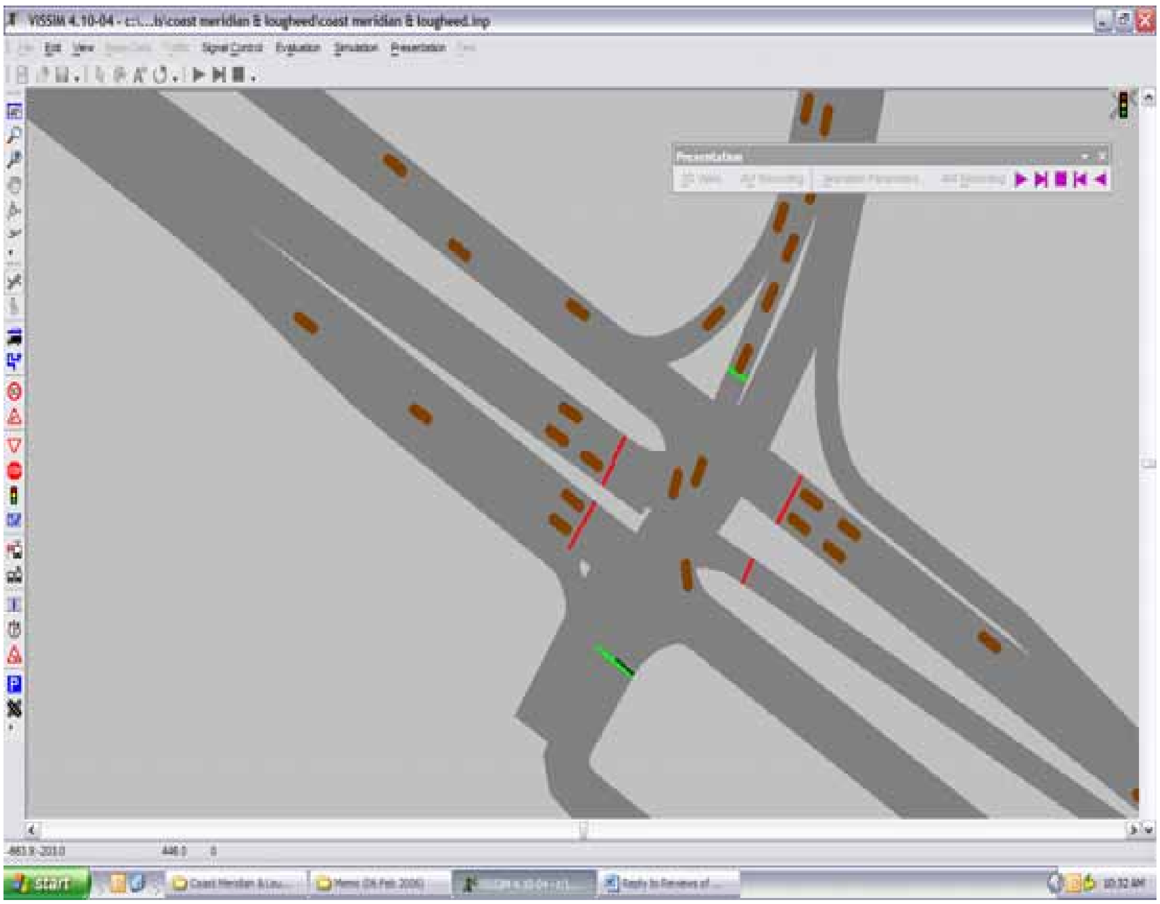

Figure 243. Screen Capture. First and Second Vehicles Arriving.

In figure 244, the first vehicle has come to a complete stop, while the second vehicle has decided to change lanes and queue up on the outer left lane of the eastbound approach.

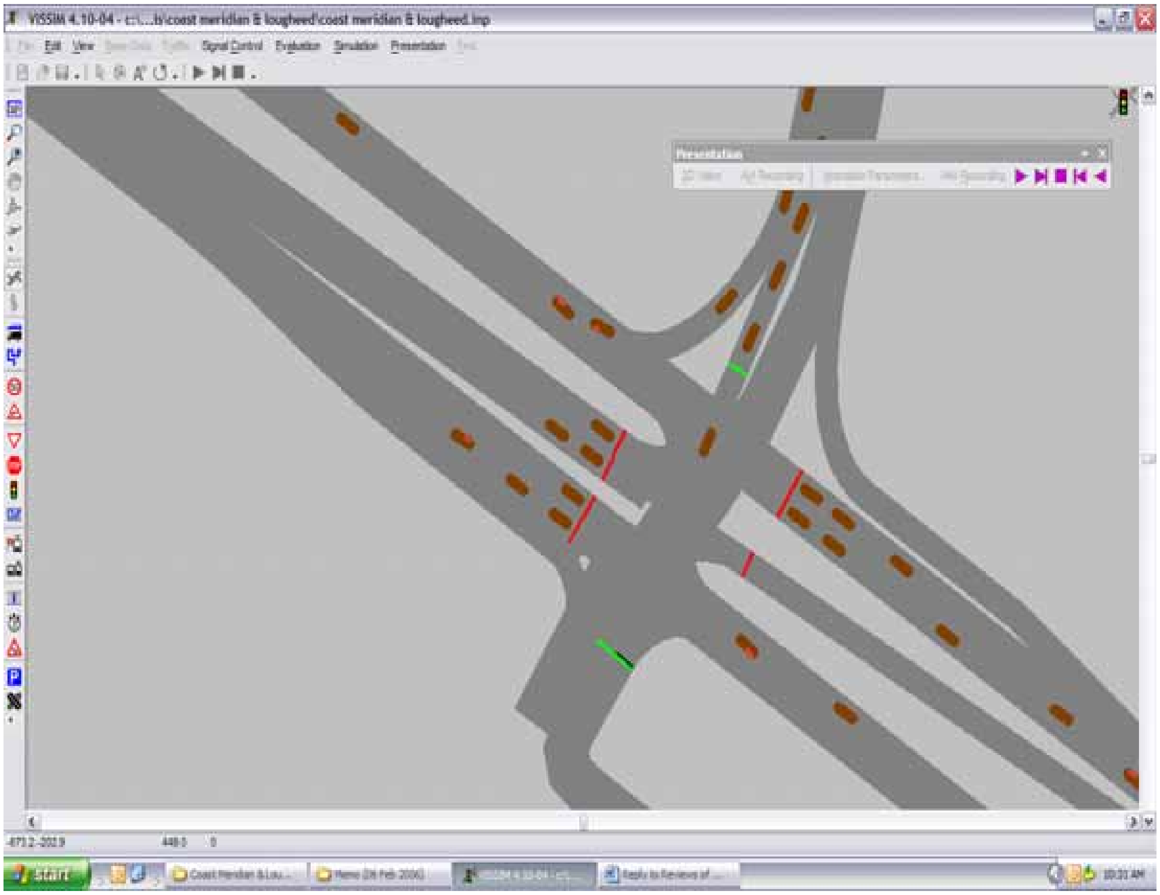

Figure 244. Screen Capture. First Vehicle Stops and Second Vehicle Decides to Change Lanes.

In figure 245, the second vehicle changes lanes and stops diagonally.

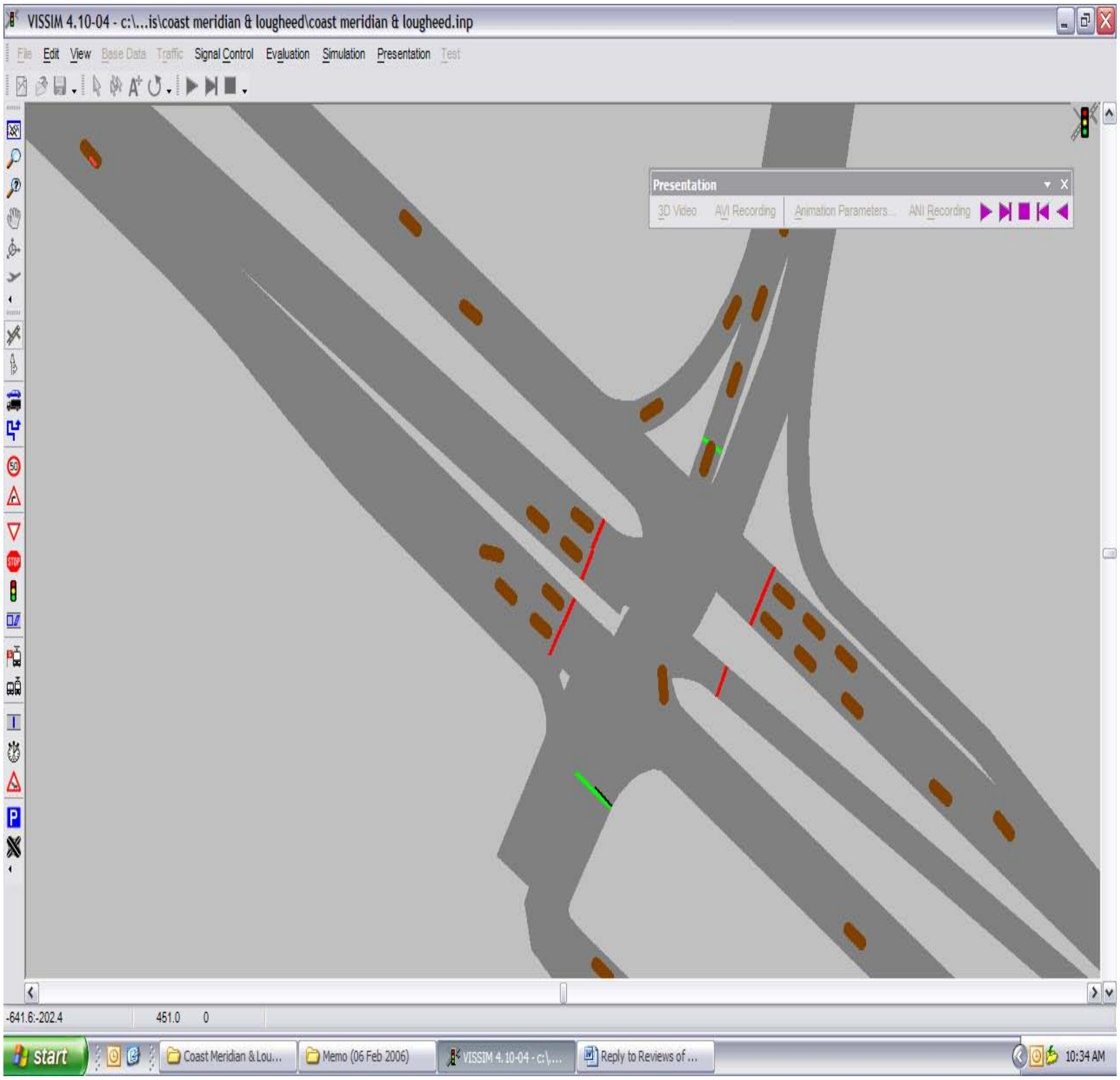

Figure 245. Screen Capture. Second Vehicle Changes Lanes and Stops.

In figure 246, a third vehicle is approaching the intersection, also traveling eastbound.

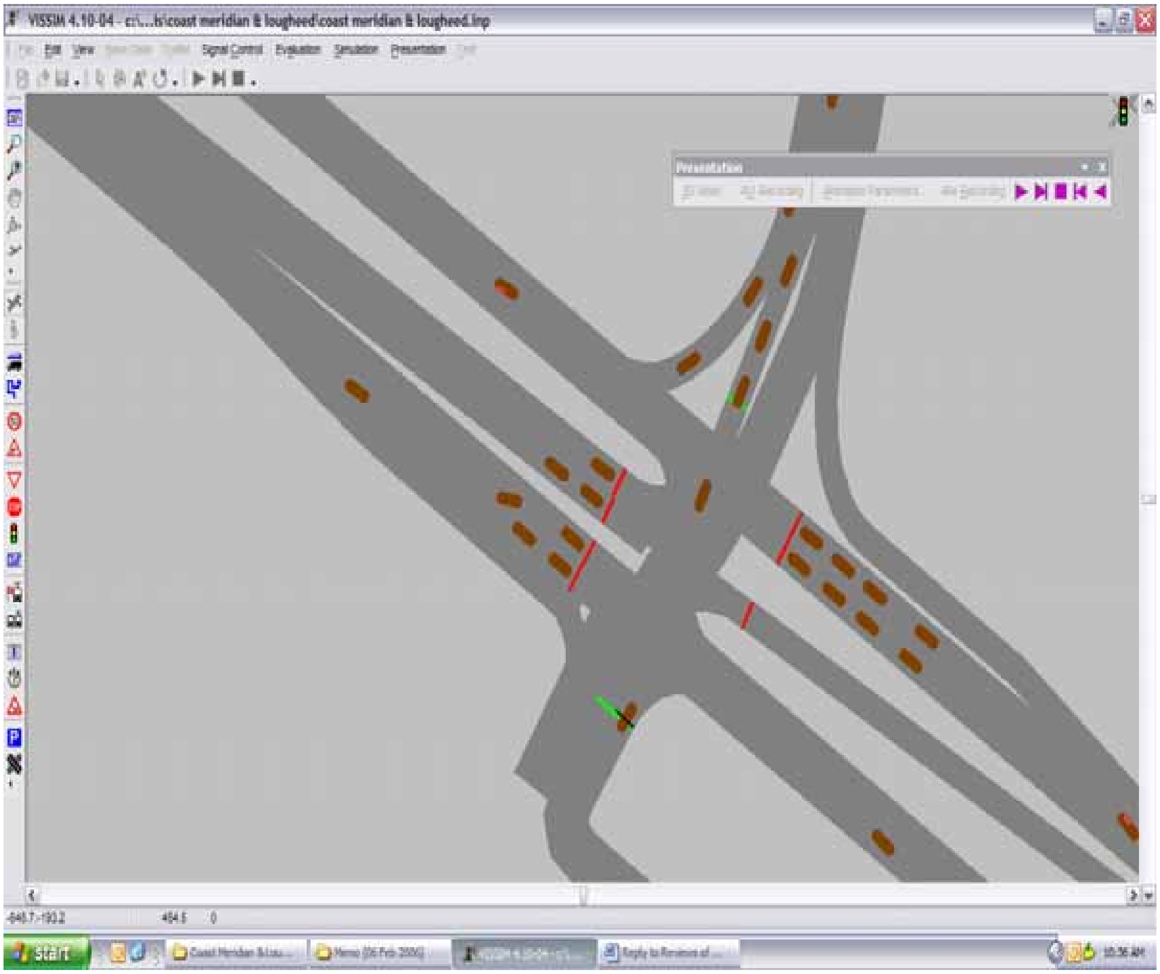

Figure 246. Screen Capture. Third Vehicle Arriving.

As shown in figure 247, the third vehicle fails to recognize the presence of the second vehicle (only partially in the lane) and passes right through it. In occupying the same physical location at the same time, SSAM regards this event as a crash (i.e., as a conflict event with a minimum TTC of 0 seconds). This behavior was observed in VISSIM 4.1 and in all other simulation systems. However, this represents a problematic issue in the field validation effort, correlating simulated conflicts to actual crash data.

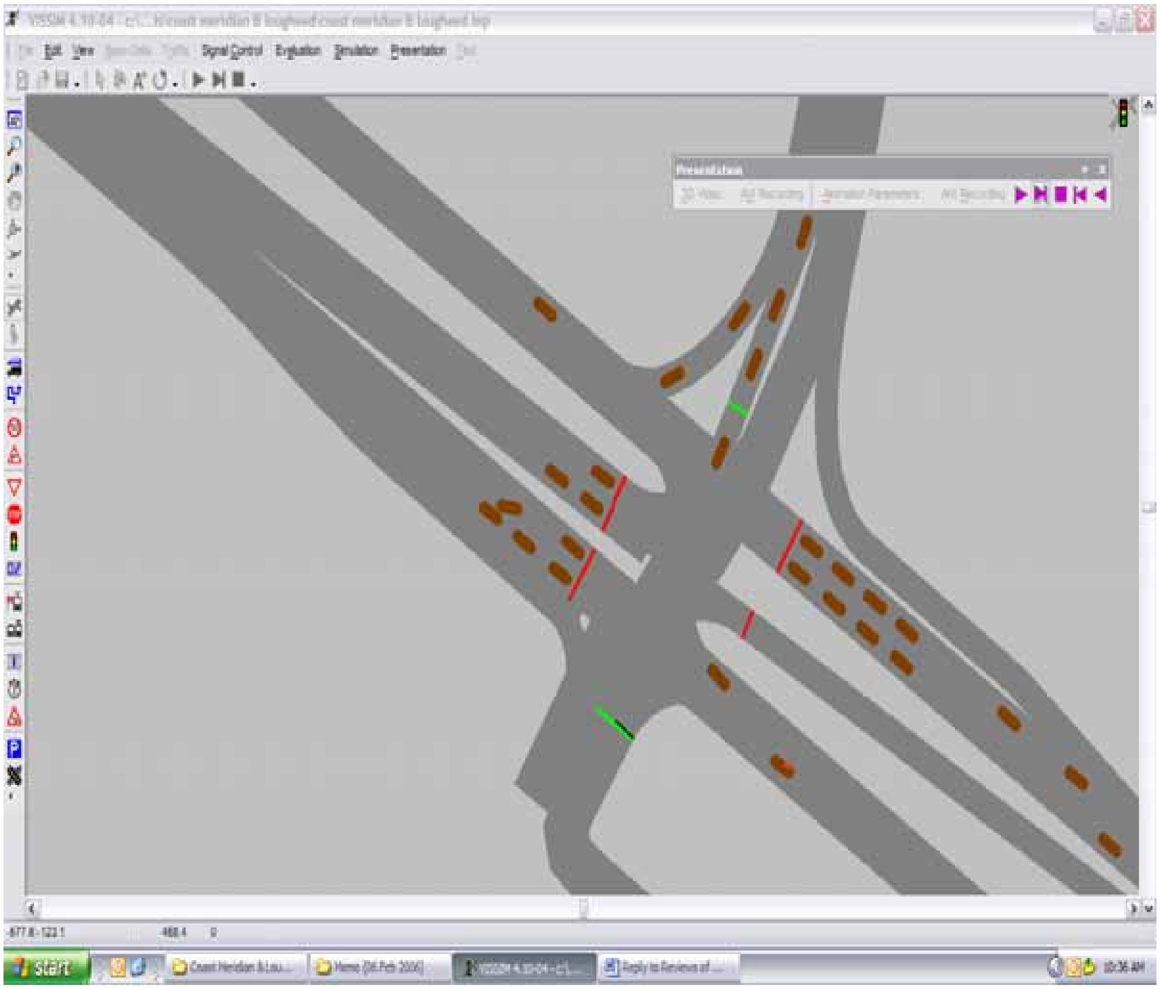

Figure 247. Screen Capture. Third Vehicle Crashing into Second Vehicle.

APPENDIX C. CONFLICTS ANALYSIS RESULTS

Table 125 provides the average hourly conflict counts for all 83 intersections in the field validation study, based on five, 1-hour simulation runs. The counts in table 125 represent the average hourly values in terms of total conflicts and conflicts by maneuver type. Average values (taken over all intersections) are listed at the bottom of the table.

Table 125. Average Hourly Conflicts per Intersection.

ID	Intersections	Average Hourly Conflict Counts			
		Crossing	Rear End	Lane Change	Total
1	Gilley & Kingsway	0.0	63.4	6.2	69.6
2	Coast Meridian & Prairie	0.0	40.8	1.6	42.4
3	Coast Meridian & Robertson	0.0	50.8	2.8	53.6
4	Oxford & Prairie	0.0	32.8	0.4	33.2
5	128 & 96	0.0	36.8	1.0	37.8
6	Griffiths & Kingsway	0.2	56.2	5.2	61.6
7	Willingdon & Moscrop	0.0	60.0	2.6	62.6
8	Edmonds & Canada	0.0	59.0	5.0	64.0
9	Sprott & Douglas	0.4	40.6	4.6	45.6
10	132 & 88	0.0	62.4	1.6	64.0
11	128 & 88	0.0	59.2	3.2	62.4
12	Coast Meridian & Lougheed	0.0	43.8	2.8	46.6
13	Mariner & Como Lake	0.0	42.8	0.6	43.4
14	Johnson & Guildford	0.0	47.8	2.8	50.6
15	Johnson & Barnet	0.2	83.8	5.0	89.0
16	Johnson & David	0.0	42.8	3.2	46.0
17	McCallum & Marshall	0.0	66.2	3.4	69.6
18	Mariner & Dewdney Trunk	0.2	60.8	1.8	62.8
19	128 & 76	0.2	49.2	3.0	52.4
20	Yale & Airport	0.0	77.2	3.2	80.4
21	152 & 104	0.0	53.6	4.8	58.4
22	Glover & Logan	0.0	13.4	0.2	13.6
23	Yale & Hodgins	0.4	82.6	6.6	89.6
24	Yale & Hocking	0.8	85.6	6.8	93.2
25	Borden & McKenzie	0.8	78.8	4.4	84.0
26	152 & 56	0.0	78.0	7.8	85.8
27	152 & 88	0.0	69.0	3.4	72.4
28	Quadra & McKenzie	0.2	47.2	3.2	50.6
29	Saanich & MckKenzie	0.0	49.4	2.2	51.6
30	Shelbourne & McKenzie	0.0	52.4	3.0	55.4
31	Glanford & McKenzie	0.0	65.0	2.8	67.8
32	Douglas & Kelvin	0.0	56.6	2.2	58.8
33	Douglas & Saanich	0.0	60.4	4.6	65.0
34	Gordon & Harvey	0.0	72.0	3.4	75.4
35	Gordon & Springfield	0.0	45.6	1.4	47.0
36	Gordon & Bernard	0.2	51.0	2.4	53.6
37	Wharf & Dolphin	0.0	52.2	1.2	53.4
38	Boundary & Lougheed	0.0	73.0	3.2	76.2

Table 125. Average Hourly Conflicts per Intersection—continued.

ID	Intersections	Average Hourly Conflict Counts			
		Crossing	Rear End	Lane Change	Total
39	Gatensbury & Como Lake	0.0	47.4	3.0	50.4
40	Poirier & Como Lake	0.2	62.0	5.2	67.4
41	Harris & Hammond	0.0	14.4	3.0	17.4
42	Bryne & Marine	0.6	68.0	3.2	71.8
43	Patterson & Kingsway	0.0	40.4	4.2	44.6
44	Brooke & Nordel	0.0	55.0	1.4	56.4
45	56 & 12	0.2	24.0	1.6	25.8
46	No. 5 & Steveston	0.0	42.2	2.6	44.8
47	No. 5 & Westminster	0.0	58.2	5.2	63.4
48	Garden City & Westminster	0.0	61.4	7.6	69.0
49	Garden City & Alderbridge	0.0	80.2	3.6	83.8
50	No. 4 & Alderbridge	0.6	58.0	4.8	63.4
51	Shell & Alderbridge	0.0	61.4	4.2	65.6
52	Fraser & 96	0.0	56.6	1.0	57.6
53	King George & 72	0.2	78.6	4.8	83.6
54	140 & 72	0.0	37.6	5.0	42.6
55	184 & Fraser	0.0	53.4	0.0	53.4
56	64 & Fraser	0.0	41.0	1.6	42.6
57	Willowbrook & Fraser	0.0	67.6	2.6	70.2
58	Scott & 72	0.0	37.6	2.2	39.8
59	Scott & 80	0.2	35.4	1.6	37.2
60	Scott & 64	0.2	85.8	5.6	91.6
61	Scott & 58	0.0	45.6	3.0	48.6
62	Shaw & Hwy 101	0.0	20.4	1.8	22.2
63	Schoolhouse & Austin	1.4	39.8	6.4	47.6
64	Marmont & Austin	0.0	40.0	3.4	43.4
65	Rupert & 22	0.0	77.6	1.8	79.4
66	Rupert & 1	0.0	84.2	4.6	88.8
67	Rupert & Grandview	0.0	83.0	5.0	88.0
68	Kerr & 49	0.0	77.6	4.2	81.8
69	Shaughnessy & Lions	0.0	24.0	1.2	25.2
70	Shaughnessy & Pitt River	0.2	32.4	1.0	33.6
71	Spall & Springfield	0.0	33.4	2.2	35.6
72	272 & Fraser	0.0	36.8	2.2	39.0
73	240 & Fraser	0.4	37.4	3.4	41.2
74	216 & Fraser	0.0	43.2	1.8	45.0
75	Bradner & Fraser	0.0	38.0	2.8	40.8
76	Vedder & Spruce	0.0	48.2	1.2	49.4
77	Vedder & Watson	0.2	58.0	3.2	61.4
78	Vedder & Knight	0.4	66.0	6.8	73.2
79	Vedder & Luckakuck	0.0	46.6	3.4	50.0
80	34 & 25	0.2	28.6	2.0	30.8
81	William & lynn	0.0	36.6	0.6	37.2
82	Mountain & Lynn	0.2	51.6	0.6	52.4
83	227 & Dewdney	0.0	33.4	1.0	34.4
	SUM (over all intersections)	8.8	4410.8	261.2	4680.8
	AVERAGE (per intersection)	0.1	53.1	3.1	56.4
	PERCENTAGE (by type)	0.2%	94.2%	5.6%	100.0%

APPENDIX D. GAP CONFIGURATION AND CONFLICT FREQUENCY

Table 126 provides total conflict counts observed (both including and excluding simulated crashes) for three different minimum gap settings in VISSIM. These results are based on a single 1-hour simulation run with the same seed number.

Table 126. Gap Sizes of 4, 5, and 6 Seconds and Their Corresponding Conflict Counts.

ID	Gap Size 4 sec		Gap Size 5 sec		Gap Size 6 sec	
	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes
1	96	76	92	80	122	97
2	41	38	36	34	38	35
3	76	70	80	79	74	72
4	47	45	22	21	52	49
5	42	41	42	42	42	38
6	206	106	217	122	201	125
7	122	90	121	90	130	107
8	88	77	95	85	95	79
9	54	53	66	64	57	57
10	84	80	79	70	81	71
11	77	72	72	67	74	68
12	205	130	181	115	176	126
13	55	53	59	58	65	64
14	77	68	76	65	84	76
15	158	87	153	88	151	83
16	55	54	59	58	56	55
17	122	102	120	102	140	101
18	147	119	158	124	152	122
19	70	65	65	60	70	62
20	81	68	114	100	100	91
21	84	67	70	58	71	62
22	25	23	28	26	23	21
23	121	99	89	76	115	99
24	88	71	134	114	158	131
25	128	108	118	100	95	89
26	152	124	168	126	175	139
27	91	82	88	76	92	82
28	70	56	74	65	71	60
29	76	68	81	69	77	67
30	82	69	83	69	83	69
31	79	73	100	94	94	84
32	87	71	99	81	131	93
33	99	65	109	80	114	88
34	110	89	106	93	100	89
35	47	46	45	44	45	44

Table 126. Gap Sizes of 4, 5, and 6 Seconds and Their Corresponding Conflict Counts—continued.

ID	Gap Size 4 sec		Gap Size 5 sec		Gap Size 6 sec	
	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes
36	84	77	85	82	85	76
37	56	56	52	51	73	71
38	111	86	137	102	165	120
39	75	64	62	59	77	69
40	93	77	109	86	97	73
41	19	16	24	23	22	21
42	141	112	187	146	155	119
43	52	50	42	38	63	61
44	64	63	67	63	75	69
45	30	27	33	31	34	32
46	54	52	53	48	61	52
47	73	64	73	67	72	64
48	101	85	22	20	102	92
49	98	92	81	75	88	83
50	74	71	63	57	67	62
51	79	62	86	70	85	73
52	84	79	72	69	70	66
53	114	107	122	100	108	93
54	59	52	63	53	83	75
55	196	141	238	159	172	131
56	134	103	124	100	98	91
57	289	128	287	134	286	146
58	51	50	54	53	55	54
59	51	47	51	45	51	45
60	130	120	134	125	143	131
61	61	56	64	57	66	61
62	37	32	36	32	35	31
63	58	40	76	58	93	58
64	46	43	48	45	58	53
65	103	101	84	82	96	96
66	143	117	132	107	162	134
67	103	78	101	90	119	99
68	115	106	94	89	106	95
69	33	32	34	34	38	36
70	34	34	36	35	35	34
71	43	38	42	36	50	43
72	43	43	47	47	64	64
73	51	50	61	60	61	59
74	83	67	83	67	82	68
75	45	45	48	48	54	53
76	52	48	68	62	76	71
77	70	65	63	61	66	61
78	94	74	79	59	85	70
79	87	65	92	72	87	67

Table 126. Gap Sizes of 4, 5, and 6 Seconds and Their Corresponding Conflict Counts—continued.

ID	Gap Size 4 sec		Gap Size 5 sec		Gap Size 6 sec	
	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes	Including Simulated Crashes	Excluding Simulated Crashes
80	30	25	35	32	36	30
81	26	23	24	23	32	32
82	61	56	57	54	59	58
83	44	43	39	38	30	30

REFERENCES

1. NHTSA, *Motor Vehicle Traffic Crashes as a Leading Cause of Death in the U.S., 2002—A Demographic Perspective*. DOT HS 809 843. National Highway Transportation Safety Administration (NHTSA), 2005.
2. Evans, L., *Traffic Safety and the Driver*. New York: Van Nostrand Reinhold. p. 92–93, 1991.
3. NHTSA, *Traffic Safety Facts 2005*. DOT HS 810 631. National Highway Transportation Safety Administration (NHTSA), 2006.
4. Vogt, A., *Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop Controlled and Two-Lane by Tow-Lane Signalized*. Report No. FHWA-RD-99-128. Federal Highway Administration (FHWA): Washington, D.C., 182 pp., 1999.
5. Hauer, E. and Persaud, B., *A Common Bias in Before-and-After Accident Comparisons and Its Elimination.* Transportation Research Record 905, pp. 164–174, 1983.
6. Gettman, D. and Head, L., *Surrogate Measures of Safety from Traffic Simulation Models*. Report No. FHWA-RD-03-050. Federal Highway Administration (FHWA): Washington, D.C., 2003.
7. Amundsen, F. and Hyden, C. *Proceedings of first workshop on traffic conflicts*. 1977. Oslo: Institute of Transport Economics,
8. Parker, M.R. and Zegeer, C.V., *Traffic Conflict Techniques for Safety and Operations--Observers Manual*. Report No. FHWA-IP-88-027. Federal Highway Administration (FHWA): Washington D.C., 40 pp., 1989.
9. Perkins, S.R., *GMR Traffic Conflicts Technique—Procedures Manual*. General Motors Research Laboratories: Warren, Michigan, 1969.
10. Sayed, T., Brown, G., and Navis, F., *Simulation of Traffic Conflicts at Unsignalized Intersections with TSC-Sim.* Accident Analysis and Prevention, Vol. 26, No. 5, pp. 593–607, 1994.
11. Hayward, J.C., *Near-Miss Determination Through Use of a Scale of Danger*. Report No. HRR 384. Highway Research Board, pp. 24–35, 1972.
12. Hyden, C., *The development of a method for traffic safety evaluation: The Swedish Conflicts Technique*. Department of Traffic Planning and Engineering, Lund University: Sweden, 1987.
13. Hardwood, D.W. and Council, F.M., *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*. Report No. FHWA-RD-99-207. Federal Highway Administration (FHWA): Washington, D.C., 2000.
14. Bared, J.G. and Kaiser, E.I. *Advantages of Offset T-Intersections with Guidelines*. in *Road Safety on Three Continents*. 2001. Moscow, Russia: Swedish National Road and Transport Research Institute,
15. Wolshon, B., *Chapter 1*, in *Toolbox on Intersection Safety and Design*. Institute of Transportation Engineers (ITE): Washington, D.C., 2004.
16. Robinson, B.W., Rodegerdts, L., and Scarborough, W., *Roundabouts: An Informational Guide*. Report No. FHWA-RD-00-067. Federal Highway Administration (FHWA): Washington, D.C., 2000.

17. *Highway Capacity Manual 2000*. Washington, D.C.: Transportation Research Board, National Research Council, 2000.
18. Engelbrecht, R. and Barnes, K. *Advanced Traffic Signal Control for Diamond Interchanges*. in *Annual Meeting of the Transportation Research Board*. 2003. Washington, D.C.,
19. Martin, D., *Single Point Urban Interchanges*. URL: http://www.donovanmartin.com/roads/spui.html, accessed 2007.
20. Bared, J., Powell, A., Kaisar, E., and Jagannathan, R., *Crash Comparison of Single Point and Tight Diamond Interchanges.* Journal of Transportation Engineering, Vol. 131, Issue 5, pp. 379-381, May 2005.
21. Vogt, A. and Bared, J.G., *Crash Models for Two-Lane Rural Roads: Segments and Intersections*. Report No. FHWA-RD-98-133. Federal Highway Administration (FHWA): Washington, D.C., 1998.
22. Jacquemart, G., *Modern Roundabout Practice in the United States*. NCHRP Synthesis of Highway Practice No. 264. Transportation Research Board: Washinton, D.C., 1998.
23. Hummer, J.E., *Chapter 14: Intersection and Interchange Design*, in *Handbook of Transportation Engineer*. p. pp. 14.1–14.27, 2004.
24. Hauer, E., *Observational Before-After Studies in Road Safety*. Pergamon Press, 1997.
25. Sayed, T. and Rodriguez, F., *Accident Prediction Models for Urban Unsignalized Intersections in British Columbia.* Transportation Research Record 1665, pp. 93–99, 1999.
26. Miaou, S.P., *Measuring the Goodness-of-Fit of Accident Prediction Models*. Report No. FHWA-RD-96-040. Federal Highway Adminstration (FHWA): McLean, VA, 1996.
27. Hauer, E., *Bias-by-Selection.* Accident Analysis and Prevention, Vol. 12, pp. 113–117, 1980.
28. DeLeur, P. and Sayed, T., *Using claims prediction model for road safety evaluation.* Canadian Journal of Civil Engineering, Vol. 28, Issue 5, pp. 804–812, 2001.
29. *VISSIM 4.10 User Manual*. Karlsruhe, Germany: PTV Planung Transport Verker AG, 2005.
30. Bauer, K.M. and Harwood, D.W., *Statistical Models of At-Grade Intersection Accidents—Addendum*. Federal Highway Adminstration: McLean, VA, pp. 46–47, 1998.
31. Zegeer, C.V. and Deen, R.C., *Traffic conflict as a diagnostic tool in highway safety.* Transportation Research Record 667, pp. 48–55, 1978.
32. McDowell, M.R.C., Wennell, J., Storr, P.A., and Darzentas, J., *Gap acceptance and traffic conflict simulation as a measure of risk.* Special Report 776. Transport and Road Research Laboratory (TRRL), pp. 1–27, 1983.
33. *Special Service Vehicles*. Michigan State Police, https://www.michigan.gov/documents/msp/VehicleEvaluation2007_MSP-SpecialDesigned_182664_7.pdf, accessed 2007.

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