Virtual Road Safety Audits: Recommended Procedures for Using Driving Simulation and Technology to Expand Existing Practices

SAFETY RESEARCH USING SIMULATION

UNIVERSITY TRANSPORTATION CENTER

David A. Noyce
Director and Chair, PI
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Madhav V. Chitturi
Assistant Scientist, Co-PI
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

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David A. Noyce
Director and Chair
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Madhav V. Chitturi
Assistant Scientist
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Lingqiao Qin
Research Assistant
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Kelvin R. Santiago
Assistant Researcher
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

Andrea R. Bill
Associate Researcher
Traffic Operations and Safety Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

A Report on Research Sponsored by SAFER-SIM

February 2018

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Abstract

One approach that has been proposed to address the limitations of the current reactive safety-monitoring approaches is the use of road safety audits (RSAs). As part of an RSA, the existing or expected characteristics and traffic conditions of a location are evaluated using multiple points of view to identify what could be the factors causing the safety issues identified. The potentially proactive nature of the RSA approach is the ability to conduct an RSA regardless of sufficient crash history at a location. The goal of the RSA process is to obtain better insights into the behaviors that drivers exhibit (or could exhibit) at a location. Unfortunately, there is a limited amount of information that can be obtained through field visits or assumed by analyzing the design documents of a proposed project.

If the geometry and operational characteristics of an existing or proposed design are converted into a virtual scenario, an experiment can be conducted to obtain detailed driver behavior measurements that can be used to characterize potential safety problems and identify the corresponding solutions. This idea is known as a Virtual Road Safety Audit (VRSA). A VRSA allows engineers to focus on understanding specific driver behaviors in a controlled laboratory environment. VRSAs can be conducted with different levels of fidelity, ranging from a full-scale driving simulator experiment to a dynamic survey that simulates driving scenarios. This report summarizes steps followed in the selection of a signalized intersection for a VRSA and steps involved in the creation of a virtual scenario required for a VRSA. An alternative approach to the identification of candidate intersections, based on objective measurements, is introduced to address the limitations of relying on feedback from users to identify potentially unsafe locations within the transportation network.

1 Introduction

The safety of our transportation system is constantly mentioned as a key target pursued by transportation engineers. However, when safety is discussed, an unfortunate misconception commonly accepted is that a safe location is one without crashes. This unfortunate but prevalent view in practice illustrates the reactive nature of most safety evaluations conducted today. Since crashes are rare events, a reactive safety-monitoring approach could lead to long periods of unsafe conditions that go unaddressed until an unfortunate event takes place. Therefore, proactive safety approaches to manage the transportation system are important.

1.1 Existing Proactive Safety Approaches

Often, feedback from drivers or the personal experiences of those in charge of the transportation system can lead to the identification of sites with potential safety problems even when there is no crash history. Identification of a safety problem is only the first step to improving safety. Therefore, once a potentially unsafe location is identified, a formal method to identify the potential causes for the perceived safety problem is needed. One method that has been proposed to address the limitations of the current reactive safety-monitoring approaches is the use of road safety audits (RSAs) on locations that do not exhibit a crash history or that are in the design stage.

As part of an RSA, the existing or expected characteristics and traffic conditions of a location are evaluated using multiple points of view to identify factors that could be causing the safety issues identified. In the case of existing sites, the safety assessment could involve site visits as well as a review of the design plans. For a proposed design, the process primarily involves a review of the proposed design plans, but visits to similar sites could be used to better understand the expected conditions and behavior. In the case of the review of design plans for a proposed project, the approach is certainly proactive since potential problems can be addressed before construction. In the case of already-built sites, there is also a level of proactiveness since the review can take place before the availability of multiple years of crash data.

Regardless of when an RSA is conducted, the goal of the process is to obtain better insights into the behaviors that drivers exhibit (or could exhibit) at a location. Unfortunately, there is a limited amount of information that can be obtained through field visits or assumed by analyzing the design plans of a proposed design. This limitation is caused by the lack of objective measurements that describe driver behavior since observations made during an RSA are often qualitative in nature and limited as far as time and conditions.

1.2 The Case for a VRSA

If the geometry and operational characteristics of an existing or proposed design are converted into a driving simulator scenario, an experiment can be conducted to obtain detailed driver behavior measurements that can be used to characterize potential safety problems and identify the corresponding solutions. This idea of bringing an existing or proposed design into a driving simulator environment is known as a virtual road safety audit (VRSA). A VRSA allows engineers to focus on understanding specific driver behaviors in a controlled laboratory environment. A laboratory environment is ideal for isolating and controlling factors associated with a potential (or identified) safety problem and for testing potential solutions. The experiment in the laboratory can be conducted by building 3D models of a site and asking subjects to conduct a virtual drive through the virtual site. Figure 1.1 shows an example of 2D design plans converted into a 3D model suitable for driving simulation.

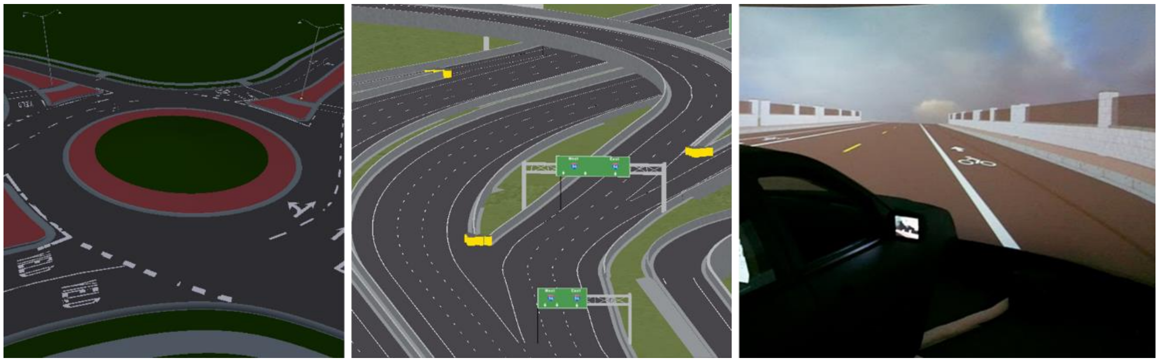

Figure 1.1. Example of Designs Converted to Driving Simulator-Environment Scenarios

The repeatability of the process is also a benefit of the VRSA process. For example, if safety problems are detected on the left-turn movement of an intersection approach, an experiment can be conducted using eye-tracking equipment during a simulated left turn with multiple subjects exposed to the same conditions. By exposing multiple subjects to similar conditions, an insight into driver behavior (not possible with a traditional RSA approach) is a possibility.

1.2.1 Levels of Fidelity for a VRSA

Depending on the complexity of the project for which a VRSA is conducted, different levels of driving simulation fidelity can be used. For example, small projects with simpler requirements might be more suitable for a low-fidelity single-screen driving simulator environment, while larger projects with complex requirements could benefit from the use of high-fidelity multi-screen driving simulators. However, the selection of the driving simulator environment's fidelity needs to also take into consideration the project timelines and budget constraints. Additionally, the needs and expectations of the VRSA project should also drive the fidelity required for the simulation. For example, it should not be assumed that a high-fidelity simulation always provides a better solution than a low-fidelity one for identifying specific safety problems on a complex project. As one can imagine, the cost associated with the different levels of fidelity, project complexity, and timelines will be a key consideration in the process.

1.2.2 Cost Feasibility Considerations

Project costs can make or break a project. Therefore, the cost-feasibility of conducting a VRSA is an important aspect that will drive the decision of whether to move forward with a VRSA experiment. The main question that needs to be asked during the decision-making process is if the marginal costs of performing a VRSA can be justified with the safety improvements that could result from the experimental findings. Moreover, while the cost-benefit evaluation process when the benefits are unknown is not a straightforward one, there needs to be recognition that crashes are rare events and that a lack of crash data does not mean that a safety benefit cannot be calculated. Therefore, identifying the expected benefit-cost of a VRSA project might require using engineering judgment to estimate expected benefits that are not clear by following traditional procedures.

1.3 Report Objectives and Goals

The goal of this report is to provide guidance in the planning of experiments that involve a VRSA by summarizing steps involved in the identification of a VRSA candidate site and highlighting concerns that should be addressed during the scenario creation process. In addition to the site identification example and a scenario creation example, a summary of results from an actual VRSA conducted in a proposed interchange design are presented. Concepts discussed in the report can be used by readers to better plan a VRSA and to understand the potential limitations. Finally, the report also identifies a potential evolution of a safety-monitoring technique based on existing vehicle-detection technology that can be used to identify sites that are a candidate for a VRSA.

1.4 Report Structure

A review of literature associated with the RSA process is presented in Chapter 2 of this report. The literature review was conducted from the perspective of supporting a VRSA process, and findings were taken into consideration when preparing the presented guidelines. Chapter 3 presents a discussion on the recommended workflow that a VRSA should follow, including guidance on the selection of the appropriate experiment. In addition to the guidance, Chapter 3 also presents a summary of a previously conducted VRSA experiment for a proposed interchange design.

Chapter 4 summarizes the characteristics of a site that the research team identified as a potential candidate for a VRSA and includes a summary of the crash information that led to the selection of the site. Chapter 5 presents a summary of steps involved in the creation of a scenario and concerns that should be addressed as part of the VRSA planning process. Steps are presented as the foundation for a VRSA regardless of the fidelity of the driving simulation experiment used. Finally, Chapter 6 presents conclusions as well as recommendations for alternative procedures to conduct a VRSA by focusing on the analysis of driver-behavior data.

2 Background

2.1 Road Safety Audits

The sections ahead summarize the concept of RSAs, a concept that has been around for decades and for which plenty of scientific literature is available. Numerous reports have been published by the Federal Highway Administration (FHWA). Therefore, the goal of the summaries presented is to provide only a brief introduction of the concept.

2.1.1 History

The concept of safety audits was initially developed by British railway engineers as a tool to examine safety issues on railways. Railway engineers practiced safety audits to investigate frequent incidents before any scheme was implemented at the location of the incident. In 1987, the UK government claimed its first casualty reduction goal, expecting to achieve a one-third reduction in fatal collisions by 2000 [1]. Soon after, the UK enacted the Road Traffic Act 1988, stating that in constructing any new road, local authorities must take such measures to reduce the possibilities of roadway crashes before the roadway facilities come into use. RSAs became mandatory on motorway schemes and trunk roads in the United Kingdom in 1991. In 2000, the Highways Agency in the United Kingdom started a review of the UK Safety Audit practice [2].

The safety benefits of such systematic examination of roadway facilities were later recognized by many road traffic engineers in other countries, such as Denmark, Norway, Ireland, Australia, and New Zealand. For example, RSAs were introduced in Denmark in 1997 as a recommended practice on roadways. By 2007, RSAs had become common throughout much of Western Europe, North America, Australasia, and South-East Asia, and on major highway schemes [1, 2]. In 2008, the European Union stated that RSAs should be implemented in member states by December 2010 [3]. The early activities of RSAs in the United States started with the 1994 FHWA safety management scanning tour and the 1996 FHWA RSA scanning tour in Australia and New Zealand. The FHWA then contacted all state DOTs to investigate their interest in applying the RSA concepts they had learned. FHWA later organized a road safety audit workshop in St. Louis to develop procedures to be used in the pilot program of RSAs. The first pilot program included thirteen states and marked the beginning of RSAs in the United States [4].

2.1.2 Practice

In the United States, RSAs are practiced as a tool with which the safety performance, design, and operations of roadways and intersections are examined by an independent, multidisciplinary team. In 2006, the FHWA published the guidelines for RSA practices in the United States [5]. Seven prompt lists were developed to help RSA teams identify potential safety issues and to ensure that anything important is not missed. Seven case studies demonstrated that RSAs can be implemented at various stages (e.g., preliminary design, construction, and in-service roadway) and on different types (e.g., intersections, interchanges, rural roads, and highways) of projects. The detailed process of a typical RSA includes the following eight steps [5]:

Step 1: Identify project or existing road to be audited;

Step 2: Select RSA team members;

Step 3: Conduct a pre-audit meeting to review project information;

Step 4: Perform field observations under various conditions;

Step 5: Conduct audit analysis and prepare a report of findings;

Step 6: Present audit findings to Project Owner/Design Team;

Step 7: Prepare formal response; and

Step 8: Incorporate findings into the project when appropriate.

There are many successful completed RSA projects in the United States. The first RSA conducted for a mega-project in the United States was at the Marquette Interchange in Milwaukee, Wisconsin, in 2003, where four-level left-side system ramps were replaced by five-level all-right-side system ramps [6]. In 2007, an RSA was conducted along Bullhead Parkway, a four-lane, divided, rural roadway with a posted speed limit of 50 mph for the entire length that covered 4 signalized intersections and 13 un-signalized intersections in Bullhead City, Arizona. The RSA cost was $30,000, the implementation cost was $839,478, and it led to a crash reduction of 54% [7]. Due to high motorcycle collision rates and the high severity of crashes along NC 28 and NC 143, the North Carolina Department of Transportation conducted several motorcycle RSAs at seven locations from 2012 to 2014 [8]. This region is widely known among motorcyclist communities as the “Tail of the Dragon” because of its extensive horizontal and vertical curves. The RSA organizers invited representatives from the Motorcycle Safety Foundation to gain insight on behavioral issues affecting the safety of the motorcyclists in the study area. Motorcyclists’ participation was critical for the RSA team to understand their behavior, needs, and concerns.

Besides the traditional field-review-based RSAs, the Office of Safety at FHWA also conducted a study on the application of 3D visualization to assist the RSA process [9]. Proposed concepts and designs of RSAs were demonstrated through 3D models exported in PDF files, enabling the RSA team to visualize the safety improvement ideas and identify elements that may pose safety concerns to drivers. Four case studies, which included early-stage field review, procedures, and results of 3D visualizations, were presented in this study. Through these case studies, it was recommended that the 3D visualization continue to be incorporated within RSAs of future/potential construction projects [9].

2.1.3 Risk Assessment on Roadways

Risk assessment is the process of identifying and quantifying risk events and can be utilized in Step 5 of the RSA process. Risk assessment for transportation facilities is a complex process and can be qualitative or quantitative. In qualitative assessments, the risk characterization produces qualitative estimates of risk, while in quantitative assessments, numeric estimates of risks are provided.

Qualitative assessments in RSAs are based on the review teams’ view of the risks associated with each safety issue. Previous RSAs have used qualitative measures such as such as high, medium, and low to indicate the potential effectiveness of the treatments [10]. Crash frequency and severity are two primary characteristics used to screen risks that require the audit team’s attention. One common method is to use a two-dimensional matrix that classifies risks into six categories based on the frequency rating and the severity rating. Table 2.1 shows an example of a qualitative crash risk assessment used by an RSA team to prioritize the safety issues of road facilities under audit [11].

Table 2.1. Crash Risk Assessment

Frequency Rating	**Severity Rating**			
	Low	Moderate	High	Extreme
Frequent	C	D	E	F
Occasional	B	C	D	E
Infrequent	A	B	C	D
Rare	A	A	B	C

* Crash Risk Ratings

A: lowest risk level
B: low-risk level
C: moderate-low risk level
D: moderate-high risk level
E: high-risk level
F: highest risk level

While the qualitative assessment is instrumental for screening risks and for developing appropriate risk mitigation strategies, the quantitative one is useful for estimating the numerical and statistical nature of the risks. Quantifying safety will help decision-makers to better understand the safety impacts and to identify opportunities for improvement. Numeric risks can be determined using Equation 2.1.

$$\text{Risk} = \text{Severity} \times \text{Probability} \times \text{Exposure} \quad \text{Equation 2.1}$$

In Equation 2.1, the value of risk is calculated using numerical inputs, including severity, probability, and exposure. One method to estimate a numerical value for crash frequency and the probability is to use crash modification factors (CMFs). A CMF is a multiplicative factor that can be used to estimate the expected number of crashes after implementing a given treatment at a specific site. The FHWA has developed CMFs that can be applied to measure the safety effectiveness of a treatment or to compare the relative safety effectiveness of multiple treatments and determine the potential costs or benefits. CMFs have been applied by Michigan DOT in an RSA in the operational and preliminary design stage along M-26 in Houghton County. Six potential safety issues at the study location were identified. Several potential countermeasures were also developed by the RSA team to address the identified issues. In this case, the RSA team also provided additional information in the final report regarding the application of CMFs, which included the crash estimation without treatment, the computation of the safety benefits, the estimation of countermeasure costs, and the computation of benefit-cost ratio [1010]. A guidebook prepared for the National Cooperative Highway Research Program (NCHRP) presented the procedures for evaluating the safety impact of alternative intersection configurations and traffic control types [12]. The reference manual for crash reduction factors published by FHWA includes tables of intersection crash reduction factors for roadway departure crash reduction factors and for pedestrian crash reduction factors [13].

2.1.4 Driving Simulator

The 3D representation of visual information (along with other information) in VRSAs can be used to examine driving performance. Specifically, based on the 3D scene, dynamic surveys or a driving simulator can be employed as the tools to take the current RSA process to the next level by measuring driver performances and using the performance measures as the feedback about what might be contributing factors to a crash and what corresponding changes are needed to improve the safety of the road facility. A driving simulator provides auditors opportunities to look into driver behaviors and driver errors in a virtual but forgiving environment. In addition, fixing a design error or improving a design plan in a virtual 3D modeling world is relatively fast and inexpensive compared to repairing an error in the real-world setting. Driving simulators enable studies that could never be realized due to cost or time limitations on roadway designs and safety evaluations.

Extensive studies in the literature have used driving simulators to test the impact of traffic control devices, pavement markings, and geometric designs on driving safety and driver performance. Driving simulators have allowed researchers to develop repeatable experiments to study new types of traffic signal head design and signal phasing arrangement. For example, based on driver's eye movement data and data collected from the driving experiment, driver performance and comprehension were analyzed in relation to retrofitting existing traffic signal displays by installing a flashing yellow arrow in a bimodal traffic signal section [14]. The highly controllable setting of driving simulators has also allowed the design and development of new types of traffic control devices. For example, the validity of using virtual traffic control devices (TCDs) was studied using a driving simulator experiment [15]. An in-vehicle head-up display was implemented to communicate existing TCD information to drivers. The potential that these virtual TCDs have was examined by studying how subjects travel on a sign-less roadway.

A driving simulator is also an ideal test bed for new concepts or standards in roadway designs. Various roadway features such as pavement markings and geometrics were studied using simulators. For example, elongated pavement marking letters and arrows were studied in a driving simulator, and it was shown that recognition distance increases quadratically as the elongation ratio increases [16]. A driving simulator was also used to evaluate the impact of different alternatives of tunnel lighting systems on driving safety. Through a driving simulator experiment, a statistically significant difference was revealed as a function of the type of lighting [17]. Driving-simulator-based studies were also conducted to investigate the safety impact of the curvatures of horizontal and vertical curves, lane widths, and terrain types on driving safety and driving speed [18, 19].

2.2 Surrogate Safety Measures

Surrogate safety measures (SSM) have been proposed as a proactive approach to evaluate the safety of transportation system elements. As the name suggests, these are, in fact, measurements from traffic. SSM can supplement existing safety evaluation approaches due to their known capacity to act as indicators of conflict severity. In fact, the term *conflict severity measure* has been used in the literature [20] to refer to measurements such as time to collision (TTC). The sections ahead introduce two of these measurements: TTC and post-encroachment time (PET). The use of PET values obtained from a radar-based vehicle detection system is introduced in this report as an alternative to objectively identify intersections that are candidates for a VRSA once the technology required is widely available.

2.2.1 Time to Collision

Hayward [21] introduced the TTC concept, originally named time-measured-to-collision (TMCT) as a measure of the danger of near-miss situations. A near-miss situation can be considered an event where the danger to which the vehicle occupants, the second vehicle occupants, and/or pedestrians are exposed is higher than the danger under normal conditions. TTC is defined as "the time required for two vehicles to collide if they continue at their present speeds and on the same path." TTC values can be used as a scale for traffic conflicts defined by the application of the brake lights. As expected, a low value of TTC indicates a higher level of danger than a high value. When values of TTC reach high levels, the severity of a conflict is simply non-existent. The reason is that, under common driving conditions, vehicles are always on a collision course with either another vehicle or an object on the road; collisions don't occur is because drivers constantly make adjustments to their speed and trajectory [21]. These simple constant adjustments allow the drivers to keep TTC values at the aforementioned high levels, thus achieving safe driving conditions.

2.2.2 Gap Time in a Left-Turn Scenario

The concept of TTC can be applied to the situation shown in Figure 2.1 where the vehicle *i* is the one performing the left turn and vehicle *i-1* is the vehicle in the opposing flow. In Figure 2.1, POC indicates the point of conflict, i.e., the point where both vehicle paths intercept. A collision between the two vehicles will take place only if the speed profile maintained by both vehicles will cause them to arrive at the POC at the same time.

The similarities between this surrogate safety measure and TTC are obvious. Both measures provide an indication of how close two vehicles are to reaching a point. In the definition of TTC, the point to be reached is mostly shown as the rear end of a second vehicle; however, in this measurement, the time in question is the time it will take both vehicles to reach the point of conflict after a particular moment in time. Both measurements also depend on the speed of both vehicles; however, this one depends on two different distances from the vehicles to the POC.

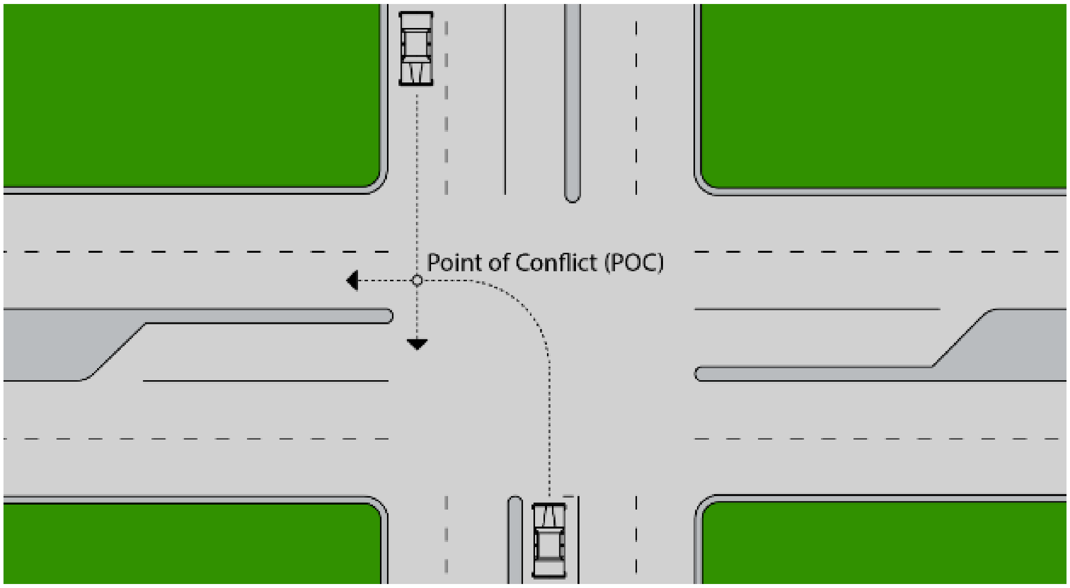

Figure 2.1. Time to collision in a left turn with an opposing vehicle.

In the scenario shown in Figure 2.1, the TTC for a left-turn scenario is defined as the combination of the term values in Equation 2.2 that causes the G_{OL} value to be zero. Therefore, a crash only takes place if both terms are equal; more importantly, the G_{OL} variable defines how close the two vehicles were, in terms of time, to being involved in a crash. This means that lower absolute values of G_{OL} can indicate higher levels of risk. The structure of the equation allows taking into account a situation in which left-turning vehicles arrive first at the point of conflict as well as one in which the left-turn vehicles arrive after the opposing vehicle to that point of conflict. The former is clearly a more dangerous situation than the latter since it is an indicator of being close to a head-on crash.

$$G_{OL} = \frac{d_1}{v_1} - \frac{d_{i-1}}{v_{i-1}} \qquad \text{Equation 2.2}$$

The G_{OL} term is crucial in understanding how a conflict between the left-turning vehicles and the opposing through vehicles occurs. Furthermore, from a driver's perspective, the motivation to proceed when approaching an intersection is based on the assessment of how safe or unsafe the estimated value of G_{OL} is.

2.2.3 Post-Encroachment Time

The SSM discussed in the section above can be expanded into a more formal measure that has been around for years. The corresponding measure is called post-encroachment time (PET) and is defined by Allen [22] as "the time from the end of encroachment to the time that the through vehicle arrives at the potential point of collision." The measurement is perhaps one of the most obvious for how close the two vehicles were from being in an actual crash, and it is a special case of Equation 2.2 with the left-turn vehicle arriving at the POC before the opposing vehicle. A more down-to-earth definition of PET can be "the time by which a crash is avoided, a definition that relies on the value of time, and that is analog to the TTC definition. In the cases of both TTC and PET, as the value of the measurement increases, the safety of the situation characterized by the values increases.

3 Proposed VRSA Workflow

A traditional RSA for an already-built project involves a field review of the site conditions by a group of experts. One of the challenges associated with field reviews is the inherent difficulty of collecting quantitative data about the behavior of drivers at the location. Besides obtaining speed, volume, gap acceptance, headway, and other derived measurements, obtaining more precise measurements such as detailed trajectory information is a challenge. Furthermore, while the obtainable measurements are certainly valuable, the limited time period during which the measurements can be collected is a limitation of data available for a traditional RSA process. For example, the aforementioned traffic performance measurements can't be obtained over long periods of time using existing technologies, which limits the traffic conditions that can be covered as part of the data reviewed during a traditional RSA process. Given the variability in the behavior as a function of volume, time of day, and weather conditions, there is a chance for a traditional RSA to miss key driver behavior that could be used to explain the root cause of a detected safety problem.

3.1 A Search for Alternative Approaches to RSAs

The limitations of the traditional RSA process represent one of the driving forces that have prompted the transportation engineering community to search for alternative approaches to better understand safety without having to rely entirely on crash data. For decades, researchers have identified SSM as an objective method to understand the safety of the transportation system without the need to wait for crash history to become available. However, obtaining the necessary data to perform a safety evaluation of a site based on an SSM approach can be a time-consuming and labor-intensive process. For example, identifying issues that could eventually result in rear-end crashes requires constant monitoring of braking activity, which is infeasible over extended periods of time. As a result, and regardless of the inherent limitations, RSAs remain a valuable tool for identifying the cause of safety problems or uncovering problems not previously considered.

3.2 The Virtual Road Safety Audit Approach

The concept of a virtual road safety audit (VRSA) has been proposed as an alternative to a traditional RSA since it involves a controlled laboratory environment that allows obtaining insight into what may be the cause of safety problems. With the advances in 3D modeling and rendering technologies, the use of a VRSA to identify and address potential safety problems is now a possibility. Two extremes (in terms of fidelity) can be successfully used to conduct a VRSA. These extremes are defined by a full-scale driving simulator experiment (on the higher end of fidelity spectrum) and by a dynamic survey (on the low end of the fidelity spectrum). Regardless of the position within the fidelity spectrum, as long as the VRSA intends to expose subjects to a virtual representation of the conditions at a proposed or existing site, the same set of 3D modeling tools can be used as a starting point in the VRSA process.

3.3 Recommended Approach to Conduct a VRSA

Sections 3.4 through 3.6 present guidance on the steps that can be followed to move forward with a VRSA. Steps presented provide only a summary; therefore, it is important to recognize that engineering judgment will play a key role in deciding the details of steps followed throughout a VRSA process.

3.4 Identify a Candidate Site

Selecting a site that is a candidate for a VRSA could involve two potential sources of information. The first source is crash data, and the second is feedback about behaviors experienced on a site. When crash data is used, sites with a crash history that is not consistent with the safety performance expected can be flagged for evaluation. If a safety problem detected on the flagged site can't be addressed through traditional methods, the site can be considered a candidate for a VRSA. For example, a typical candidate site is one with a safety problem for which countermeasures have been tried and deemed unsuccessful. When the second source is used to identify a potential candidate site, the feedback about the potential safety issues could be received in the form of complaints from commuters and direct observations by those in charge of the transportation system. As in the case of sites identified using crash data, if the safety issues identified can be addressed through alternative means, then there is no need for a VRSA. Chapter 4 summarizes the process used to identify a candidate site for a VRSA in the City of Madison by considering crash data as well as local knowledge.

3.4.1 Collection of Supplemental Data

Once a site is deemed a candidate for a VRSA and a decision to proceed is made, then additional data about the site needs to be collected. The additional data collected can include performance measures that describe the behavior of traffic. The measurements can be used to make the VRSA scenario a more realistic one. In addition to the performance measures that describe the behavior of traffic, the collection of supplemental data involves obtaining design documents that can help with the creation of the VRSA scenario.

3.4.2 Creation of the Scenario

Regardless of the level of driving simulator fidelity used to conduct the VRSA, a 3D model representing the candidate site needs to be created. The model can be created by using the supplemental site data collected. Advances in 3D modeling technologies have made possible the creation of 3D scenarios that can be used as part of a VRSA. Chapter 5 describes steps taken to create a 3D model of the site in the City of Madison identified as a candidate for a VRSA. The 3D model created from the site could undergo further refinements depending on the fidelity of the experiment used, but most of the work conducted during the scenario creation step will be similar across locations.

3.5 Selecting Experiment Fidelity

Once a 3D model that represents the conditions on the field and that can be used as the foundation for a driving simulator experiment is created, a decision needs to be made about the fidelity of the experiment that will support the VRSA. Furthermore, the experimental requirements for the experiments should be outlined. Outlining the experimental requirements involves identifying or modifying components of a scenario that can support the evaluation of potential safety issues. By considering the experimental requirements as well as factors such as project timelines and budget constraints, the fidelity of the experiment can be selected. The benefits of two levels of fidelity are presented in the sections ahead.

3.5.1 Dynamic Survey

A VRSA conducted using a dynamic survey involves the rendering of 3D models into videos that represent typical conditions on a site and that expose a subject to a set of controlled conditions. The video (or sequence of videos) that subjects watch can be viewed on different platforms, thus the use of the term *dynamic survey*. The survey component of the experiment involves asking subjects to respond to events shown on the video using a data collection device that can be used to measure the response of the subject. The controlled conditions shown in the video should support the assessment of driver behavior during conditions that could contribute to the potentially unsafe conditions identified for the site. In other words, the situations shown in the rendered video should help to better understand driver behavior, and when the derived data is analyzed, the results should help to understand the underlying causes of a potential safety problem. Additional details about the characteristics of a dynamic survey environment such as the details of the equipment that can be used to collect driver responses are presented in Chapter 5.

3.5.2 Full-Scale Driving Simulator

A VRSA that relies on a higher-fidelity environment such as that provided by a full-scale driving simulator has additional benefits over those provided by a dynamic survey environment. If an experiment that takes place on a simulator with a full vehicle cabin, subjects participating in the experiment will be tested in a more realistic environment that simulates physical obstructions to the line of sight introduced by the design of the vehicle cabin. A VRSA experiment on a full-scale driving simulator is similar to other experiments commonly conducted but focuses on gaining a better insight into the potential safety problems identified. A summary of the procedures followed as part of a previously conducted RSA for a proposed project is presented in Section 3.7 to help understand the nature of a VRSA using the full-scale driving simulator shown in Figure 3.1.

Figure 3.1. Full-scale driving simulator.

3.6 Experimental Procedures and Iteration

Once a scenario is created for a location that can support the evaluation of the potential safety problems identified, testing of the experimental procedures should start. Testing provides opportunities for improving the scenario and for collecting pilot data. Pilot data from the perspective of a VRSA refers to data that can be used to test the analysis procedures. For example, the research team can run an experiment in the selected fidelity and attempt to generate data by emulating the expected behavior of subjects. If the data obtained is found to support the planned analysis, then no changes to the scenario are required. If the pilot data reveals that the analysis procedures are not properly supported, modifications should be made to the scenario as part of an iterative process until the scenario is found to support the analysis procedures.

It should be noted that during pilot data collection it is possible that the fidelity selected for the experiment will be deemed not optimal or inadequate. If this is the case, researchers need to decide whether or not to move ahead with the planned experiment. This can be avoided by better planning the scenario and by understanding the limitations of a platform ahead of time. However, for experiments that attempt to measure a unique behavior that is not often measured using driving simulation technologies, the risk for a trial-and-error process that causes iterations is likely unavoidable.

Once the experiment that will make the VRSA possible moves forward, data describing the behavior of subjects is collected. An analysis of the data is then performed to search for possible explanations for a safety problem. For example, if an unusual number of pedestrian crashes occur downstream of an intersection, eye-tracking data from subjects can be analyzed to see if there appear to be design elements or conditions that are causing drivers to look away from a pedestrian crossing point.

3.7 Example of a VRSA Experiment Conducted Using a Full-Scale Driving Simulator

A VRSA of the proposed design of the US Highway 45 and Watertown Plank Road interchange near Milwaukee, WI, was conducted [23] in a full-scale driving simulator as part of a project for the Wisconsin Department of Transportation (WisDOT). Using design drawings, a research team from the University of Wisconsin-Madison Traffic Operations and Safety Laboratory (TOPS Lab) created a 3D model of the proposed interchange design compatible with a full-scale driving simulator. The scenario was created using a combination of proprietary and open source technologies. For example, the 3D model of the proposed roadway was created using Blender (an open source 3D modeling software), while the assembled version of the model was finalized using Internet Scene Assembler and SimVista (proprietary software tools required to finalize the models for the driving simulator platform used).

The resulting simulation enabled the VRSA experiment participants to experience a simulated drive along different components of the proposed interchange prior to construction. The driving simulator used for the experiment was the one shown in Figure 3.1. The simulator environment allowed the collection of driver behavior data 60 times per second along the drive. Data collected includes speed, gas pedal position, brake pedal position, and steering position. The vehicle-derived driver behavior measurements, along with eye-tracking data, were used by the research team to understand the performance of drivers during the experiment.

3.7.1 Experimental Procedure

As part of the VRSA experiment, 24 subjects were recruited to participate in the study. The approximate average driving experience of the subjects was 15 years. Gender was evenly distributed (11 female subjects and 13 male subjects). Upon arrival to the simulation laboratory, subjects were provided with a brief explanation of the experiment and were asked to go through a signed-consent process. Subjects that decided to proceed with the experiment were then asked to wear an eye-tracking device and to participate in a practice drive to become familiar with the simulator. After the practice drive, the VRSA experiment started, and subjects virtually drove through the proposed interchange design. Figure 3.2 shows a top view of the different components (Items 1 through 4) of interest that were studied as part of the previously conducted VRSA experiment [23].

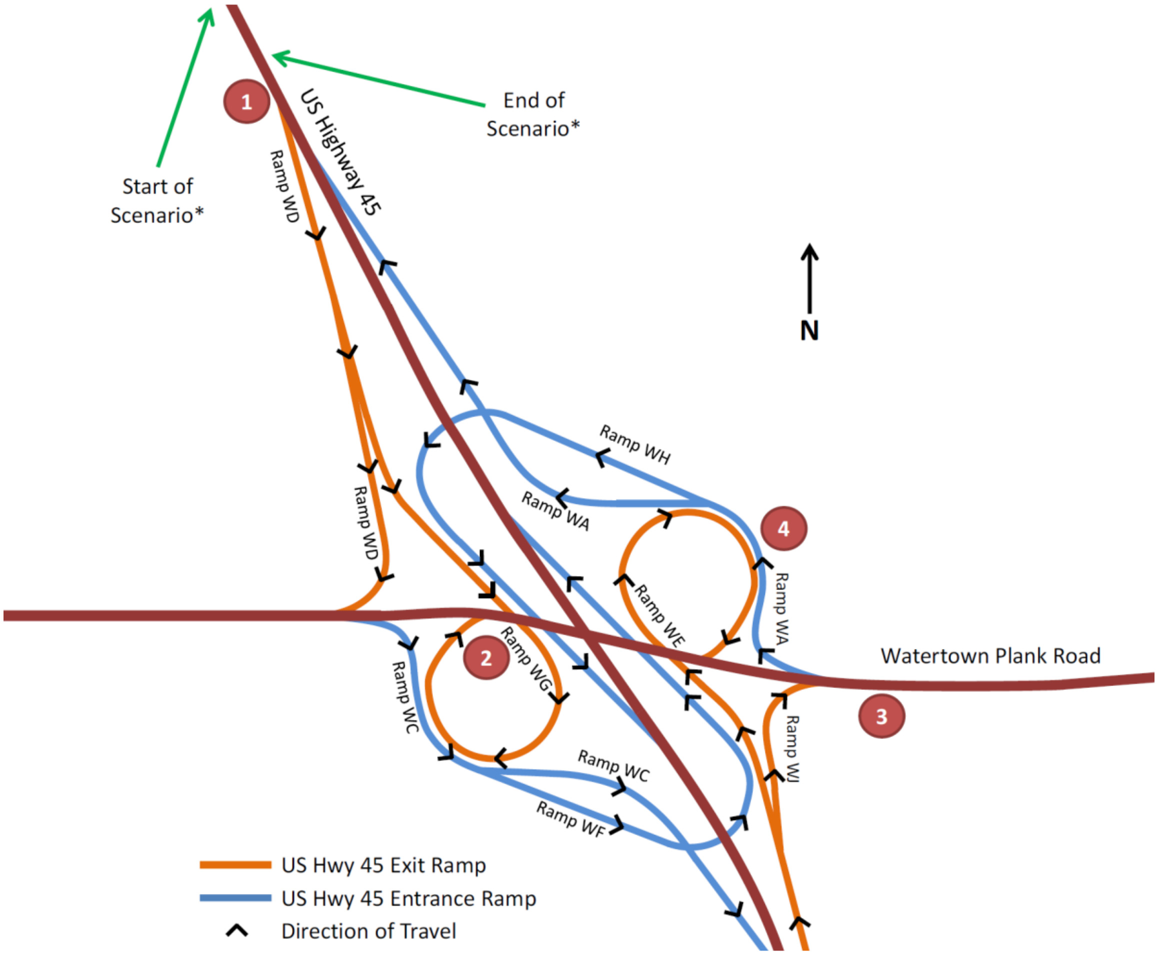

Figure 3.2. Top view schematic of VRSA experiment.

The full results from the experiments can be found in the corresponding project report [23]. However, a summary of one of the findings and supporting analysis is presented here for Item 2: Behavior of drivers when approaching a pedestrian crossing at the end of a ramp.

3.7.2 Findings Summary for Pedestrian Crossing Location

One reason for studying the behavior of drivers approaching a pedestrian crosswalk at the end of a "cloverleaf-style" exit ramp is that concerns were raised that drivers would not be fully aware of the presence of the pedestrian crossing at the end of the ramp due to the nature of the control tasks required to navigate the ramp successfully. During the VRSA experiment, eye-tracking data was collected while the subjects navigated through the ramp. Figure 3.3 shows eye-tracking data collected at different points of the ramp navigation process for one subject.

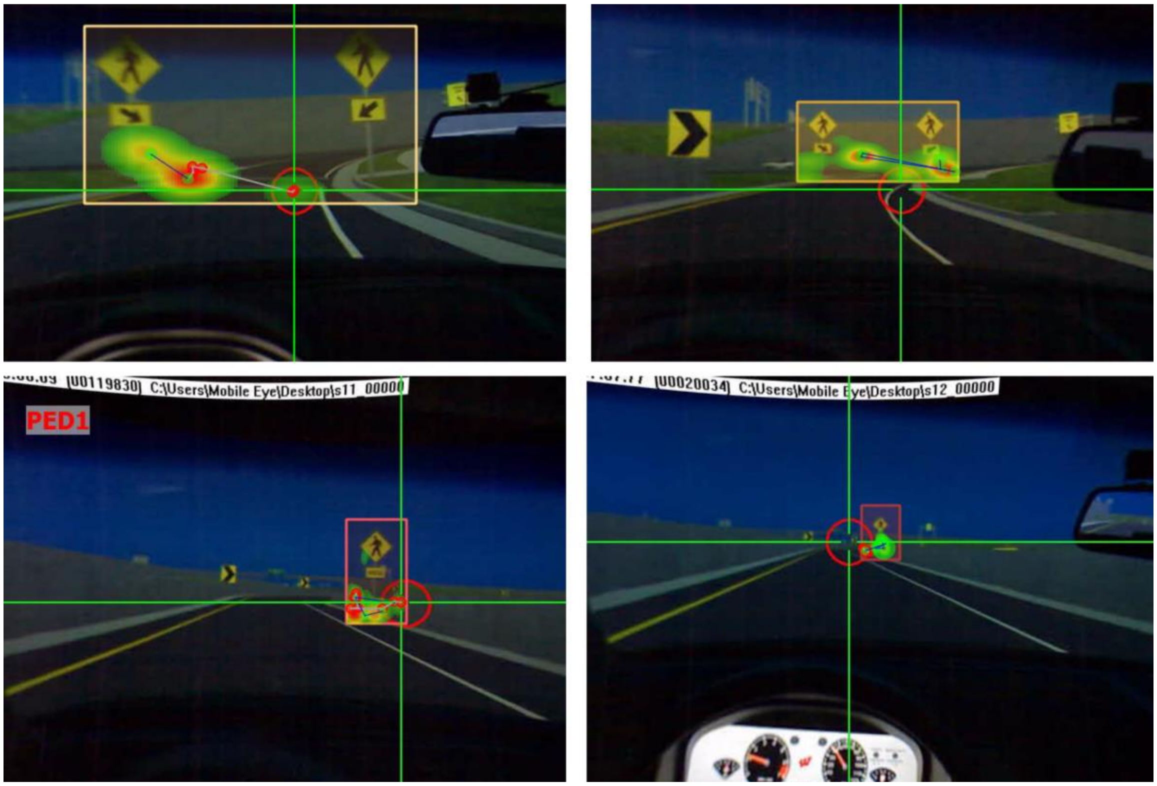

Figure 3.3. Example of eye-tracking data for the ramp.

Data obtained from the eye-tracking equipment suggest that, upon entering the ramp, drivers correctly identify the location of an advanced warning sign indicating the presence of a pedestrian ahead. However, an analysis of the data also revealed that the geometry of the ramp caused drivers to constantly monitor the edge of the road, thus reducing the amount of time available for drivers to react to the presence of a pedestrian on the crosswalk located at the end of the ramp. Based on the findings, a recommendation was made for creating additional awareness about the crosswalk using a rectangular rapid flashing beacon (RRFB) upstream of the pedestrian crossing. The results demonstrate the potential for a VRSA to obtain data not possible through other methods and make recommendations to the engineers in charge of making design decisions.

4 Example of Site Selection

This chapter provides an example of the selection of a site in Madison, WI, that is a candidate for a VRSA. The site selection is based on historical crash data and considers local knowledge about the site. As previously mentioned, the absence or presence of crash data is not necessarily an indication of safety because crashes are rare events. Therefore, an objective approach is needed to identify sites with potential safety problems that don't have a crash history. If the trajectory data of vehicles for a site (e.g., a signalized intersection) is known, then SSM such as TTC can be continuously monitored and used as a mechanism to identify sites that exhibit concerning behavior. The feasibility of using field-obtained SSM to screen for locations that exhibit concerning behavior is demonstrated by showing the computation of TTC values from data collected using an existing radar-based data collection system.

4.1 Selection of a Candidate Site Based on Crash Data

To select a potential candidate site, the crash history of multiple intersections in Madison, WI, was screened to identify unsafe factors that caused crashes at those intersections. Historical crash data from January 2008 to December 2013 were used to identify the intersections in Madison with the highest number of crashes over a five-year period. The details of the crashes associated with each of the top intersections were reviewed to understand the underlying causes of the crash. Specifically, crash type, weather conditions, driver error, and travel direction were reviewed. Based on the crash history review and by considering the type of crashes as well as potentially contributing factors, the intersection at South Park Street and W Badger Street was selected as a site that could benefit from the use of a VRSA to understand the potential causes of crashes.

A summary of the crash history of the intersection, along with the details of a field visit, are presented in the sections ahead. From a VRSA planning perspective, the identification of the site through screening procedures that consider local knowledge and engineering judgment is an important step. Screening procedures based solely on crash data can lead to the identification of a site for which proven safety treatments are already known or for which a VRSA might not be able to provide additional answers. For example, a crash screening procedure might reveal a high-crash site with a high proportion of crashes for which alcohol was a contributing factor. Such a site might not benefit from a VRSA as much as another site for which an unusually high number of left-turn crashes exist (not related to alcohol) since a VRSA can't help address the underlying cause of alcohol crashes.

4.1.1 Crash History for Candidate Site

A comprehensive crash diagram for the intersection was created after reviewing all the crash reports from January 2008 through December 2013. In total, 87 crashes occurred at this intersection, and 77 crash reports were available for the researchers to create the crash diagram shown in Figure 4.1. As the crash diagram shows, more crashes occurred in the NE quadrant than in the other three quadrants. The most frequent crashes at the intersection were property-damage-only crashes followed by possible-injury crashes. Approximately 85% of the crashes shown in the diagram occurred within the intersection. The remaining percentage of crashes occurred right before entering the intersection. Supplemental information such as crash type, crash time, vehicle travel direction, and events prior to the crash are discussed in the sections ahead.

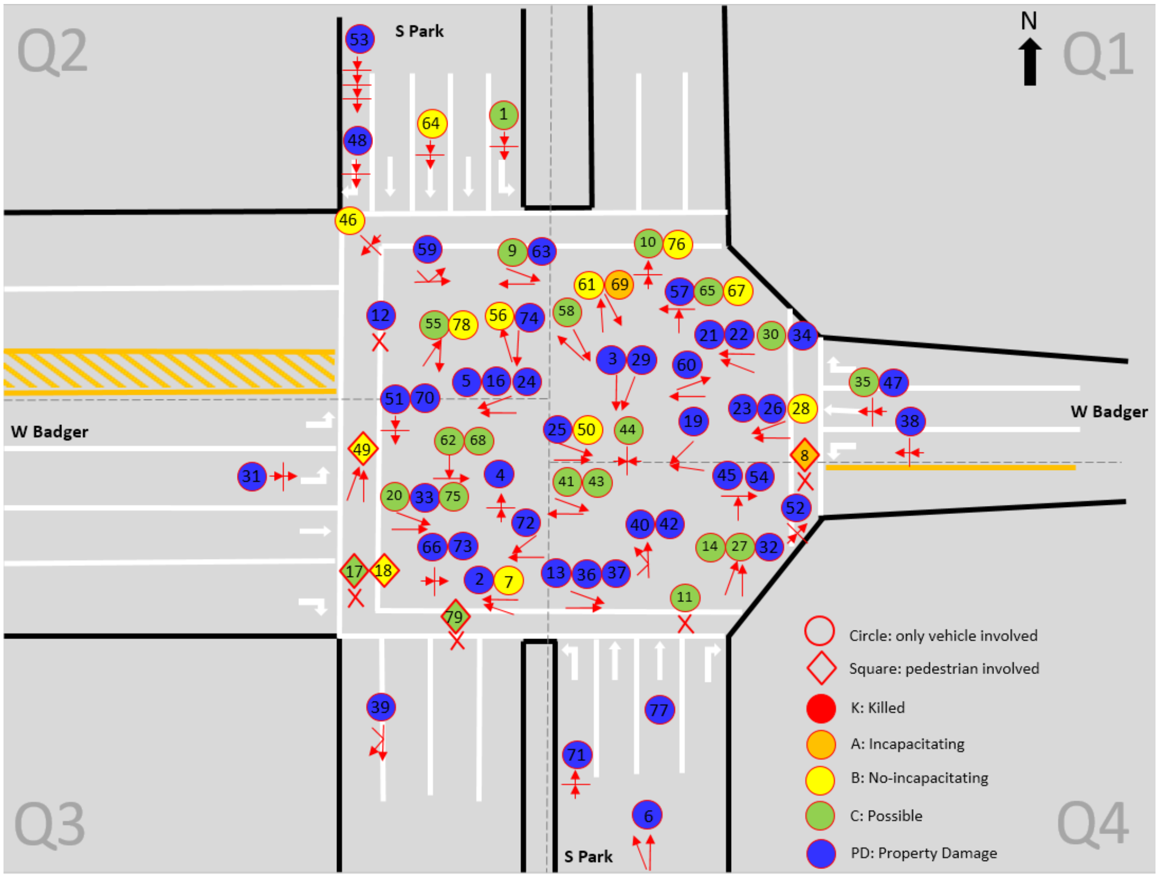

Figure 4.1. Crash diagram of the S Park and W Badger intersection.

4.1.2 Crash Type

Figure 4.2 shows the percentages of different crash types at S Park and W Badger. Angle crash and rear-end crash were the two most frequent types of crashes. In fact, combined, they represent 84% of the total number of crashes reported. From a VRSA planning perspective, the most common type of crash could be used to design the specific type of scenario studied in the VRSA experiment.

4.1.3 Crash Time

Figure 4.3 shows a crash histogram for the time of day when the reported crashes took place. The highest concentration of crashes appears to be in the middle of the afternoon. In fact, if the time data is treated as a continuous variable, the mean value for the reported crash time is 2:36 PM. From a VRSA planning perspective, the time of day experiencing the highest concentration of crashes could be used to identify the traffic conditions that should be replicated in the VRSA experiment.

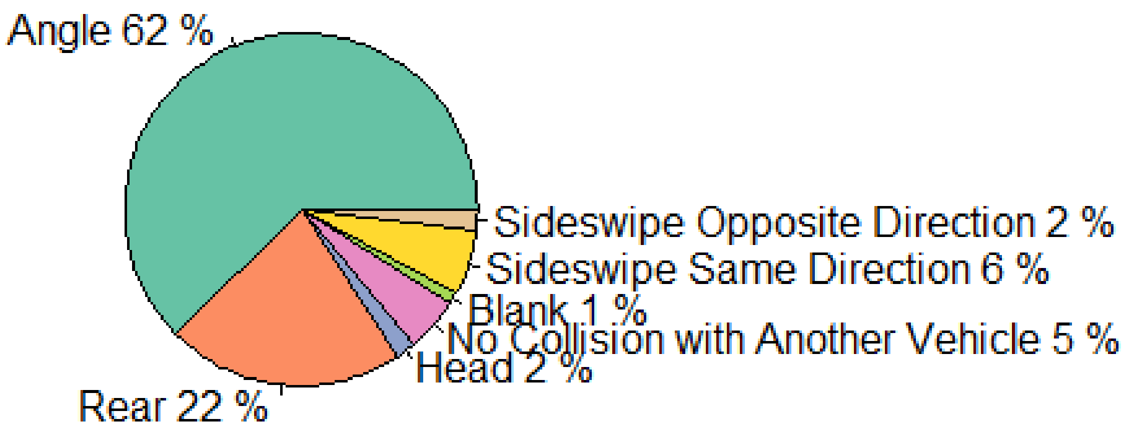

Figure 4.2. Crash types of the S Park and W Badger intersection.

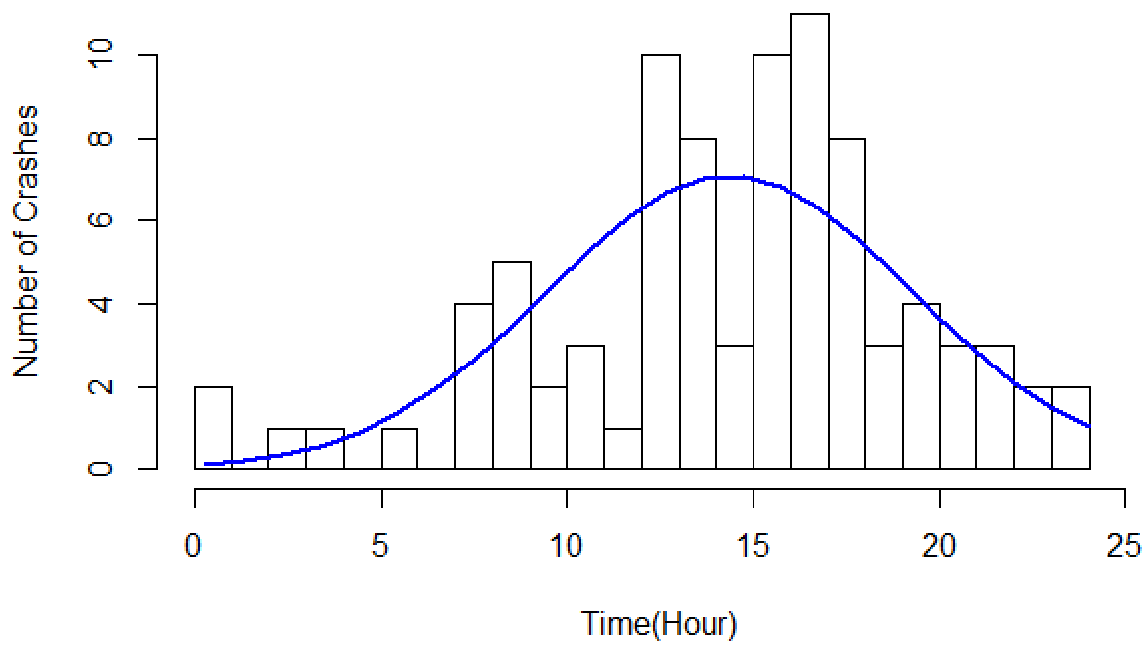

Figure 4.3. Crash time histogram with normal curve.

4.1.4 Vehicle Travel Direction

Crash reports filed by police officers typically refer to Driver 1 and Driver 2 to identify drivers involved in a two-vehicle crash. For multi-vehicle crashes, the numbers are simply increased accordingly. For each vehicle in a crash report, the travel direction when the crash took place is documented. A visual summary of the travel direction is shown in Figure 4.4. As expected, due to the direction of the primary roads, most drivers involved in a crash were traveling in the southbound or northbound direction. From a VRSA planning perspective, the most common direction of travel can be used to identify possible contributing factors such as sun glare that should be considered when analyzing the results of a VRSA experiment or when attempting to replicate field conditions in the virtual scenario.

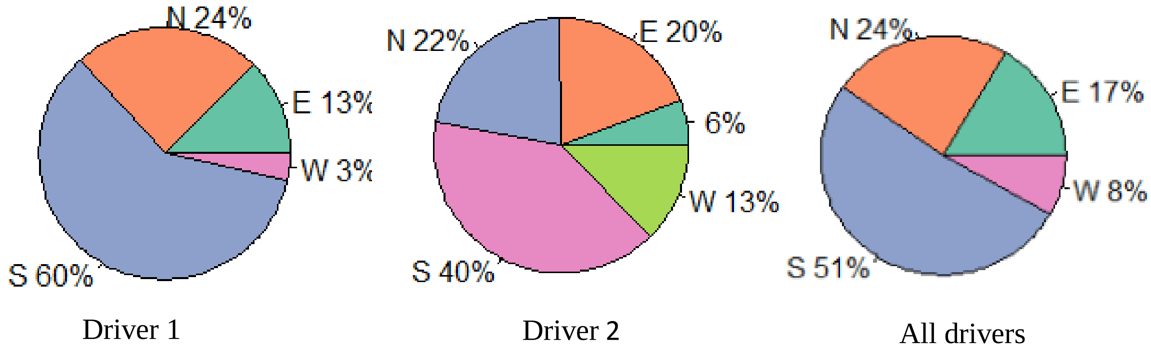

Figure 4.4. Traveling directions of all the drivers involved in a crash.

4.1.5 Event Prior to the Crash

The actions of drivers at the moment of the crash were reviewed and summarized in Table 4.1 and Table 4.2. Given that most reported crashes involved only two vehicles, only the actions of Driver 1 and Driver 2 are shown in the table. The data clearly shows that through and left-turning movements were the most common maneuvers, which is consistent with angle and rear-end crashes being the most common types. From a VRSA planning perspective, the maneuver type can be used to further narrow the type of scenario that needs to be studied and what factors need to be considered. For example, the scenario can target the identification of potential issues such as poor gap judgment, line-of-sight obstructions, and poor signal timing, among others. During an experiment, each of these issues should be tested and assessed with the corresponding scenario.

Table 4.1. Action of Driver 1.

Direction of Travel	Backing	Changing Lane	Going Trough	Turning Left	Turning Right	Slowing or Stopped	Stopped
East	0	0	7	4	0	0	0
North	0	0	12	6	0	1	2
South	1	2	35	6	1	6	1
West	0	0	2	1	0	0	0

Table 4.2. Actions of Driver 2

Direction of	Going	Turning	Merging	Other	Slowing or	Stopped

Travel	Straight	Left			Stopped	
East	15	3	0	1	0	0
North	12	8	0	0	0	1
South	23	2	1	0	3	8
West	8	4	2	0	0	0

4.2 Supplemental Site Information from Field Review

As previously mentioned, a decision about a candidate site for a VRSA should not rely only on crash data. Therefore, a site review was conducted of the potential site to observe driver behaviors and site characteristics. Photos and videos from the site were collected to better document the geometry, traffic signal timing, traffic signs, and pavement markings on the site. Additionally, the site visits allowed for observing the behavior around the site such as possible sources of conflicts and the interaction between vulnerable road users such as pedestrians and vehicles. From a VRSA planning perspective, a site visit allows for identifying scenario characteristics and details not easily available from design plans, especially after modifications are made to a site. By documenting the details of a site, a scenario that better replicates the conditions can be created. Figure 4.5 shows some of the traffic signals and signs found at the study site. The details from the figure are key in the 3D model creation process, which will be presented in Chapter 5.

Figure 4.5. Examples of traffic signals and signs found on site.

A field review of the site, combined with what was found through an analysis of crash data, revealed that there could be many contributing factors to the crashes that took place at the intersection. Some of the factors that contribute to the crashes could be related to the characteristics of the area. In fact, one of the characteristics of the intersection is the presence of a nearby freeway ramp that is one of two sources of traffic for the northbound approach of the intersection. From a VRSA planning perspective, the posted speed differential between the freeway and the intersection approach is an item of interest given the number of left-turn crashes at the location. A VRSA experiment could attempt to understand if there are problems in the negotiation of left-turn maneuvers at the intersection.

4.3 Site Selection Summary Using Crash Data and Local Knowledge

The site selection process identified a candidate location that could benefit from a VRSA by looking at the crash history from multiple sites in Madison, WI. By looking at the intersections with the highest number of crashes, a site was identified based on local knowledge about factors associated with crashes at other locations. The site identified was the intersection of West Badger Road and South Park Street. A review of the crash data for the site allowed the identification of factors that should be considered when planning a VRSA experiment. These factors, combined with observations from a field visit, allow for the creation of a detailed 3D model and corresponding scenario characteristics that can be used for a VRSA experiment.

4.4 Alternative to Standard Site Identification Practices

Continuously monitoring the safety performance of a signalized intersection (and other transportation infrastructure) using a proactive approach is a challenging process. Traditional approaches to safety monitoring such as the ones used to identify candidate sites for a VRSA involve the identification of crash history trends. The limitations of a reactive approach to safety are clear; as a result, multiple proactive safety monitoring approaches have emerged, such as the RSA and SSM. The challenges of existing RSA procedures have been previously discussed; however, one of the challenges of relying on the use of SSM is the inability to obtain the required measurements over long periods of time using traditional data collection procedures. As vehicle detection technology improves, software-based data collection tools can be used to obtain the necessary data to move away from reliance on crash data to screen sites for potential safety issues.

One of the vehicle detection technologies that have increased in use over the years is radar-based detection. Radar-based vehicle detection systems can monitor the trajectory of vehicles, but they only use that information to detect the presence of vehicles within pre-defined zones that emulate inductive loop detectors. Therefore, and regardless of its potential, valuable vehicle trajectory data is constantly discarded. If properly monitored and collected, the data ignored by radar-based vehicle detection systems can be used to constantly monitor SSMs such as PET to identify potential safety problems, regardless of the occurrence of crashes. In other words, properly collected vehicle trajectory data opens the door to a truly proactive safety monitoring approach that can identify sites that could benefit from a VRSA.

4.4.1 A Radar-Based Data Collection Tool

A novel software-based vehicle trajectory data collection system was developed at the University of Wisconsin-Madison. The data collection system monitors and logs the underlying trajectory data of a commercially available radar-based vehicle detection system used as an alternative to loop detectors. Logging of the trajectories is achieved without interfering with the primary vehicle detection function of the radar-based vehicle detection system and can be done without considering the type of signal controller used. The software-based nature of the vehicle trajectory data collection system allows deployment on numerous platforms, including single board computers, thus facilitating the installation of the system inside signal cabinets. Vehicle trajectory data has been successfully collected at an intersection in Appleton, WI, as shown in Figure 4.6. The data shown has been filtered using previously published techniques [24].

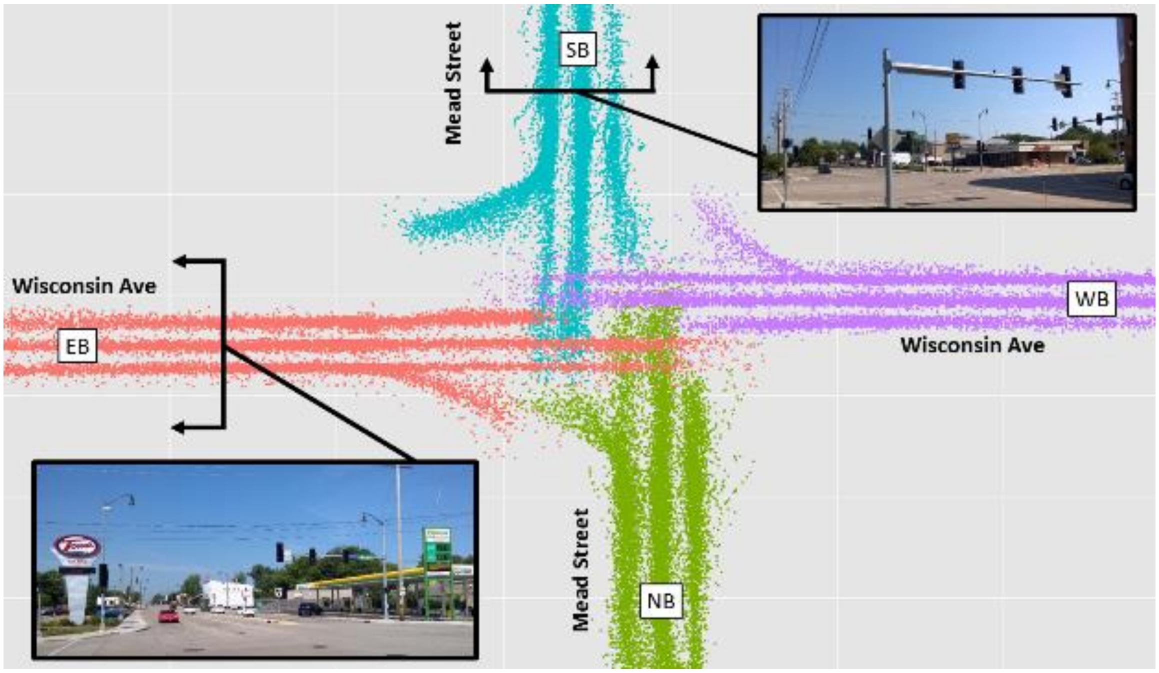

Figure 4.6. Visualization of data obtained using trajectory data collection tool.

4.4.2 Field Monitoring of Post Encroachment Time

The PET between two vehicles, considered a traditional SSM, indicates how close (measured in time) two vehicles are from a collision with each other at the location of a known conflict point. In theory, when two vehicles need to travel through the same point of the road, these two vehicles were in a near-collision scenario. Naturally, a PET value of 1 second between the two vehicles is more concerning than a PET value of 10 seconds. If PET values can be continuously monitored for all pairs of vehicles on the road, the exposure of the traffic to unsafe scenarios can be measured and used to proactively identify locations within the transportation system that need safety countermeasures or need further analysis through a VRSA.

4.4.3 PET Between Right Turning Vehicles and Thru-Traveling Vehicles

One scenario in which PET values can be used to describe how safe the interactions between vehicles are is that in which a right turn on red (RTOR) occurs. On a typical four-leg intersection, when a vehicle makes a right turn from the southbound approach, the next thru-traveling vehicle that crosses the stop bar on the westbound approach is likely on a theoretical collision course with the right-turning vehicle. The two vehicles are in a collision course if the thru-traveling vehicle will eventually occupy the same lane as the right-turning vehicle and if the speed of the thru-traveling vehicle is higher than the speed of the right-turning vehicle. Figure 4.7 shows an example of such a scenario. In the figure, the vehicles on a theoretical collision course are the vehicles making the right turn from the southbound approach (R_1) and the thru-traveling vehicles on the westbound approach (T_1).

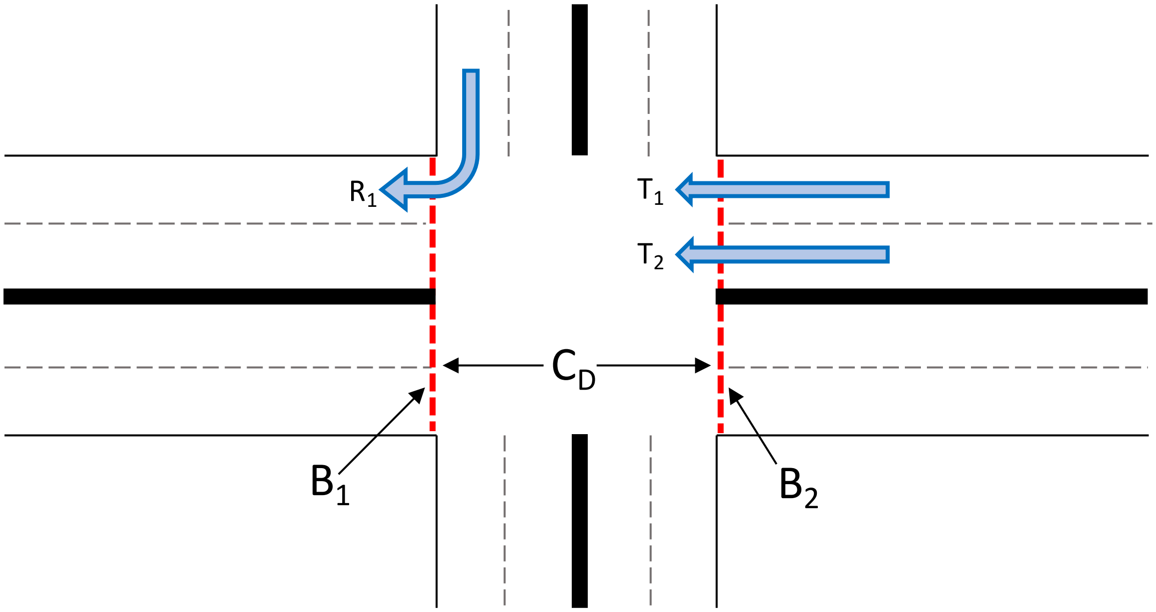

Figure 4.7. Vehicles involved in the computation of PET values.

The standard four-leg intersection shown in Figure 4.7 also shows points that are important for the computation of PET values between pairs of R_1 and T_1 vehicles. The B_1 line shown in the figure represents the theoretical conflict point between T_1 and R_1 vehicles. Therefore, the PET value between pairs of conflicting vehicles can be measured at the point where R_1 crosses the B_1 line.

4.4.4 PET Computational Procedures

Once vehicle trajectories from a radar-based vehicle detection system are classified into the corresponding turning movements using previously published procedures [24], the computation of PET values between pairs of T_1 and R_1 vehicles is possible. Due to the nature of the vehicle trajectory dataset used for analysis, the time at which T_1 vehicles cross the B_2 line (T_1^{B2}) can be obtained through interpolation as well as the corresponding vehicle speed. Using a similar process, the time at which R_1 vehicles cross the B_1 line (R_1^{B1}) can be determined by interpolation or extrapolation. Once T_1^{B2} and R_1^{B1} are known, Equation 3 can be used to compute PET values between a pair of T_1 and R_1 vehicles. PET value computations can be made using the speed of the T_1 vehicle at B_2 (S_1^{B2}). An assumption is made that once a vehicle crosses T_1 it will not change speed prior to crossing B_1. The assumption is certainly not valid for vehicles that stopped prior to crossing B_2. From a PET value computation perspective, these vehicles are unlikely to represent a safety concern given that T_1 vehicles would have had time to assess the presence of a potentially conflicting R_1 vehicle because of the acceleration process from a stopped or low-speed condition. Finally, in Equation 4.1, C_D represents the distance between B_1 and B_2.

$$PET_{T1}^{R1} = T_1^{B2} + \frac{C_D}{S_{B2}} - R_1^{B1} \quad \text{Equation 4.1}$$

4.4.5 Sample PET Results

Post-encroachment times were calculated over a 24-hour period using the procedures previously described as well as Equation 4.1. As expected, most of the PET values observed do not represent a safety concern. In fact, PET values measured were as high as 1,172 seconds at around 2 AM. As traffic for the intersections grows, the PET values measured become smaller. Figure 4.8 shows a distribution of PET values measured between westbound through and southbound right vehicles between 7 AM and 10 AM for the Wisconsin Avenue and North Meade Street intersection in Appleton, WI.

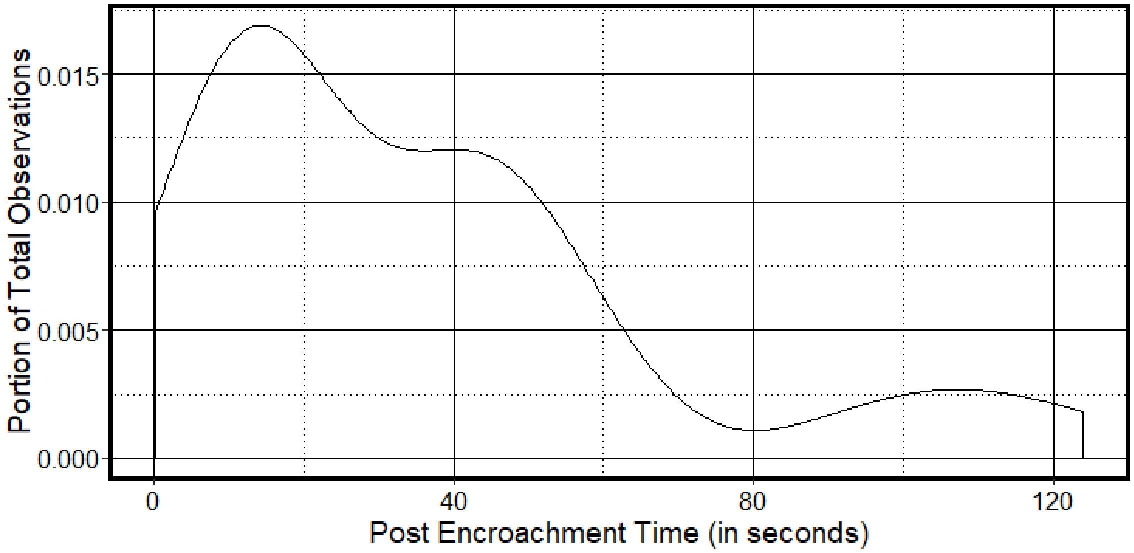

Figure 4.8. Histogram of PET values lower than 10 seconds over a 24-hour period.

As the figure shows, most of the PET values are within what could be considered a safe range. For example, in Figure 4.8, only 1 out of 62 PET values (representing 1.6% of observations) calculated for westbound thru-traveling vehicles was found to be under 1.0 seconds. A cumulative distribution representation of the PET values described in Figure 4.8 is shown in Figure 4.9. The results shown are similar to those from other time periods, thus showing the feasibility of moving away from microsimulation data to compute SSM such as PET values.

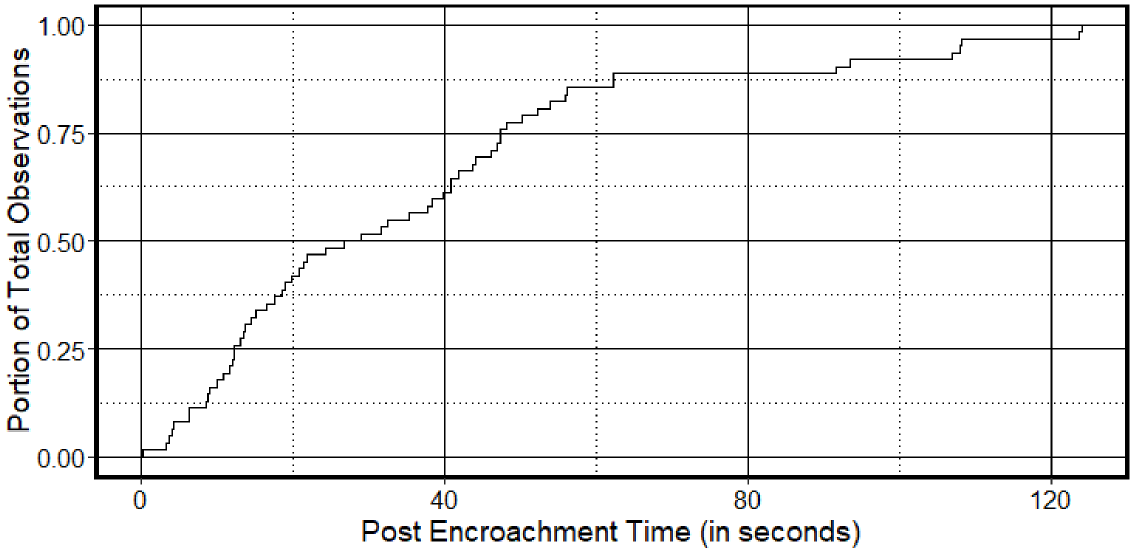

Figure 4.9. Histogram of PET values lower than 10 seconds over a 24-hour period.

Figure 4.10 shows a different representation of the PET dataset computed for the 24-hour period. In the figure, all PET values lower than 10 seconds over the entire 24-hour period are shown. During the period, only 38 PET observations under 10 seconds were identified, and of those, only 4 were lower than 1.0 seconds.

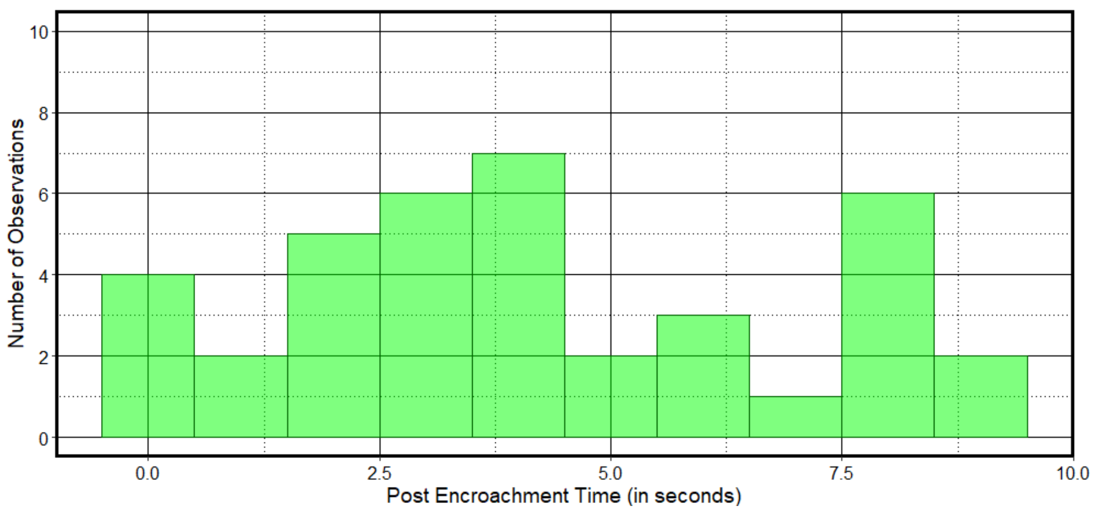

Figure 4.10. Histogram of PET values lower than 10 seconds over a 24-hour period.

The implication of the sample computations shown is two-fold. First, the results demonstrate the feasibility of obtaining the PET values from direct field observations. Second, the results demonstrate that ranking intersections based on objective safety measures is a possibility, thus allowing the identification of sites that are candidates for VRSA experiments. As technology advances, the approach demonstrated can be used in lieu of crash data (or to supplement crash data) when identifying sites that are candidates for a VRSA experiment.

5 Scenario Creation Procedure Guidance

To demonstrate the feasibility of conducting a VRSA experiment using a driving simulator environment, a 3D model of the candidate site identified in Chapter 4 was created. Procedures used to create the scenario are shown in the sections ahead. The steps are followed by a recommendation to use a low-fidelity experiment for the VRSA experiment and a discussion of how the 3D model created supports the recommended experimental procedures.

5.1 3D Model Creation

After a site is identified as a candidate for a VRSA experiment, the next step in the process is the creation of a 3D model that recreates the geometry of the site as much as possible. To create the 3D model, there are multiple tools that can be used. However, from a workflow perspective, there are certain steps that are common to most 3D model creation processes. These steps include the creation of a 2D drawing (top-view representation of the site), conversion of the 2D drawing into a 3D model, and conversion of the 3D model into the target environment that will be used to conduct the VRSA experiment.

5.1.1 Preparation of 2D Drawing of Candidate Site

Depending on the type of location identified as a candidate for a VRSA experiment, the process associated with the creation of 2D drawings for the site can vary. For locations that were built prior to the availability of CAD technology, creating a 2D drawing could involve the use of surveys or at the very least the use of CAD technology to trace over aerial photographs. For locations built more recently (and for which CAD drawings already exist), the electronic version of the drawings can be used as the 2D drawing of the candidate site. When creating (or using) 2D CAD drawings, an important consideration that must be kept in mind throughout the process is that the end goal of the 2D CAD drawings is the eventual creation of a 3D model.

For guidance and planning purposes, when creating or using 2D CAD drawings, the lines that define the drawings should be as long and continuous and possible. The continuity of the lines reduces the number of lines that define a model. Figure 5.1 shows a CAD drawing created for the West Badger Road and South Park Street site. As the figure shows, the CAD drawing is not limited to the single intersection. In fact, a number of nearby intersections were included in the drawing, along with the connecting roads. The inclusion of the nearby intersections and roadways is key to the experimental process since during a VRSA experiment the subjects are not only asked to perform a task at the site but also can approach the virtual representation of the site from an upstream location.

In the CAD drawing shown in Figure 5.1 there are four components that are key to the next step of the process (conversion into a 3D drawing). These components are driving surface (roadway), pedestrian/cycling surface (sidewalks and bike paths), pavement markings, and the outline of nearby buildings. During the creation of the 2D drawing, these elements should be isolated from each other as independent objects in the 3D model will be used to represent each one. Therefore, the guidance to pursue continuity in the lines should only be applied within each of the aforementioned key components of the 2D drawing. Finally, the guidance introduced assumes that there is no change in elevation along the road.

If elevation changes along the road need to be achieved on the VRSA scenario, more robust CAD tools than those typically used for 2D documents are required. The research team has successfully used Autodesk Civil 3D to create models that accurately represent 3D roadway alignments. These models can then be exported into a DXF file format that can be used to create a more generic 3D model for the VRSA experiment.

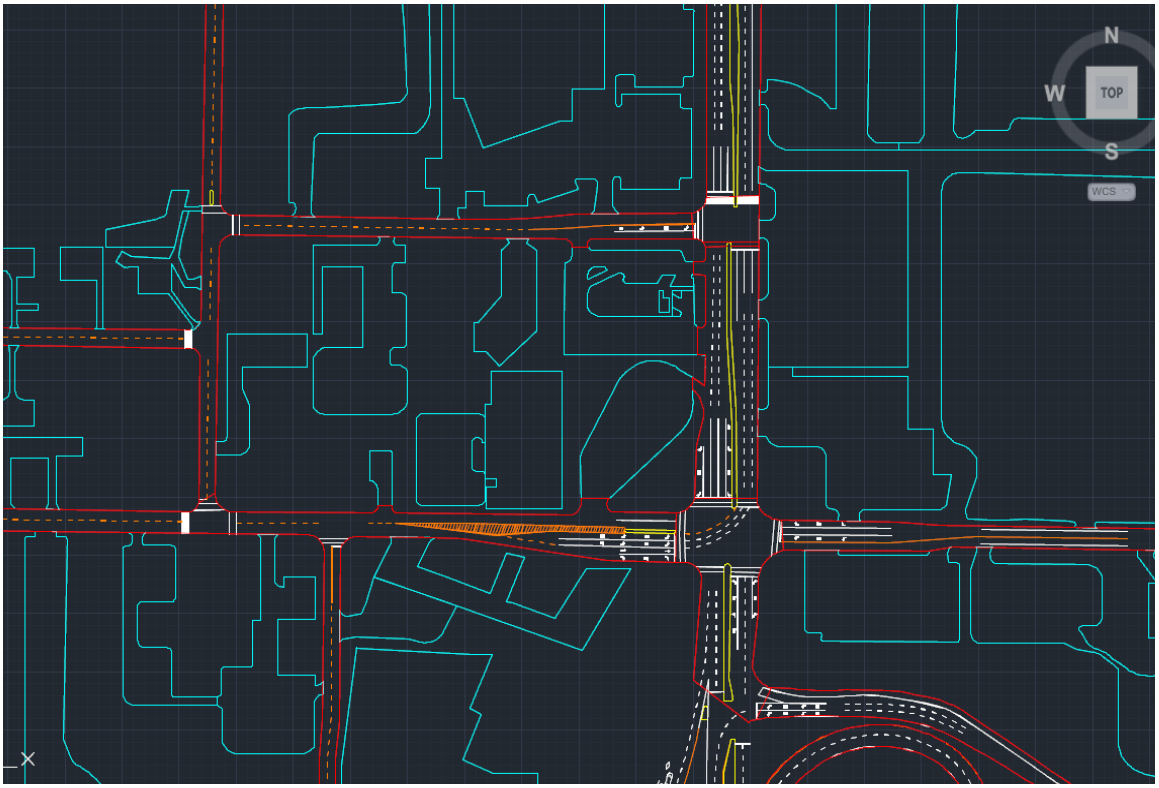

Figure 5.1. 2D network and land use drawing of the S Park and W Badger intersection.

5.1.2 Conversion of 2D Drawing to 3D Model

Once a 2D model that represents that site for the VRSA experiment is available, there are numerous tools that can be used to create a 3D representation of the site that can then be used to create different driving simulator experiments of varied fidelity. The tool used by the research team to convert the 2D drawing into a 3D model was Blender. Blender is an open source program widely used in the creation of 3D models and animation. The first step in the 3D model creation process is importing the 2D representation of the site into the 3D modeling software selected. In Blender, the program can import DWG and DXF file formats. Once a file is imported, the different components created in the 2D file will appear as objects in the 3D model; this is why it is important to have long, continuous lines to define the scenario in the 2D model.

Using standard 3D modeling procedures, the 2D model needs to be extruded into a 3D representation. The specifics of how to achieve the extrusion process not only vary by program but also by versions of a program. Therefore, manuals or tutorials for the corresponding program need to be consulted. Similarly, once a 3D model is created, the model needs to be textured accordingly to better represent the site conditions. Part of the 3D model created for the site selected as a candidate for a VRSA experiment is shown in Figure 5.2. When creating the 3D model, special considerations should be taken in the use of textures and in the inclusion of supplemental elements such as traffic control devices and buildings.

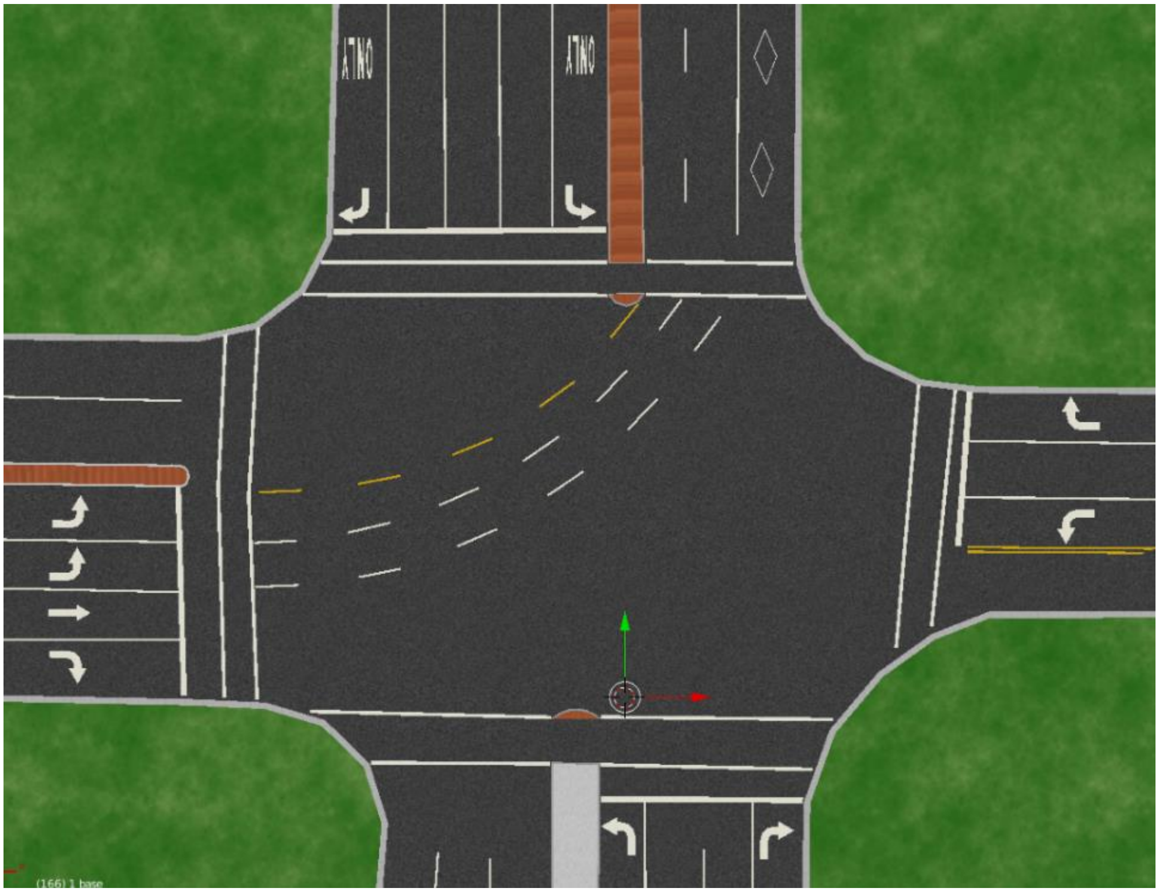

Figure 5.2. Snapshot of the 3D intersection model.

5.1.2.1 Considerations for texturing the model

Once the 2D representation of the site is created, the initial version of the 3D model does not have any textures assigned to the model. In other words, the initial version of the 3D model is associated with the default color of the 3D modeling program or no color at all. As one can imagine, such a model is not useful for experimental purposes and thus needs to be assigned textures to achieve a level of realism. Adding textures to a 3D model is a software-dependent process. However, there are universal principles that can help streamline the process. First, most driving simulators rely on game engines and hardware that is not as powerful as those used in console games, thus forcing the use of a lower number of textures and sizes of textures. Second, if compatibility across multiple simulator platforms is desired, the image format of the file that defines a texture needs to be selected accordingly. For example, some simulator platforms accept PNG image files as textures, while others might not.

Finally, the use of custom textures created by using the "paint" features of 3D modeling software should be avoided or limited as much as possible because the feature will result in the use of a large number of textures in the model and potentially trigger performance issues in the simulator. As a rule, to the extent possible, a narrow group of generic textures that can be used to define the appearance of the road will provide for the best performance. The ability to increase realism and rely on custom textures will be dependent on the platform used as well as on the needs of the VRSA experiment. For example, in the case of low-fidelity experiments that rely on the use of a rendered video of a site to study the reaction of subjects to events, a larger number of textures can be used to increase realism as these textures are not rendered in real time. However, in the case of a driving simulator environment that allows control of the scenario by the subject, the number of textures used and the realism provided by the textures should be a function of the requirements of the experiment and the capabilities of the system.

5.1.2.2 Inclusion of traffic control devices

Conversion of the 2D model into a textured 3D model typically will not include traffic control devices since the inclusion of these on a 2D representation of the site that can be extruded is often impractical. Libraries of traffic signs are available with software typically included with a driving simulator. Similarly, numerous traffic sign models can be found online. These sign models can be easily customized for the site selected for a VRSA. However, one TCD that can be difficult to obtain from an existing library in such a way that it matches those found on the VRSA site are traffic signals. Regardless of the uniformity of traffic signals in terms of lens position and coloring, finding the correct arrangement of signals in an existing library can be a challenge. Therefore, if an accurate representation of the signals found on the field is needed, then custom models need to be created. The creation of the models is not a challenging process, but it must be done in accordance with the requirements of the platform that will be used to conduct the VRSA experiment. For example, if the test environment allows the subject to control the scenario (i.e., a traditional driving simulator), the traffic signals added to the environment must be configured with the appropriate "switches" to allow modifying the indication shown during the simulation. Figure 5.3 shows custom traffic signals and signs that were created as part of the 3D model assembled for the West Badger Street and South Park Street intersection.

5.1.2.3 Inclusion of Buildings

The same considerations that drive the selection of textures should be applied to the inclusion of buildings in the 3D model. Including buildings that look and feel like those found near the site is key. However, the level of detail should be sufficient to provide subjects with a feeling similar to that experienced in the field rather than accurately representing each architectural detail of the building.

5.1.2.4 Inclusion of Additional Vehicles

When adding vehicles to the simulator scenario, to increase the accuracy of the experiment, they should represent vehicles that are typical of the country of the site. Software tools provided by simulator manufacturers often include a wide range of vehicles that might include vehicles not common to the country of the candidate VRSA site.

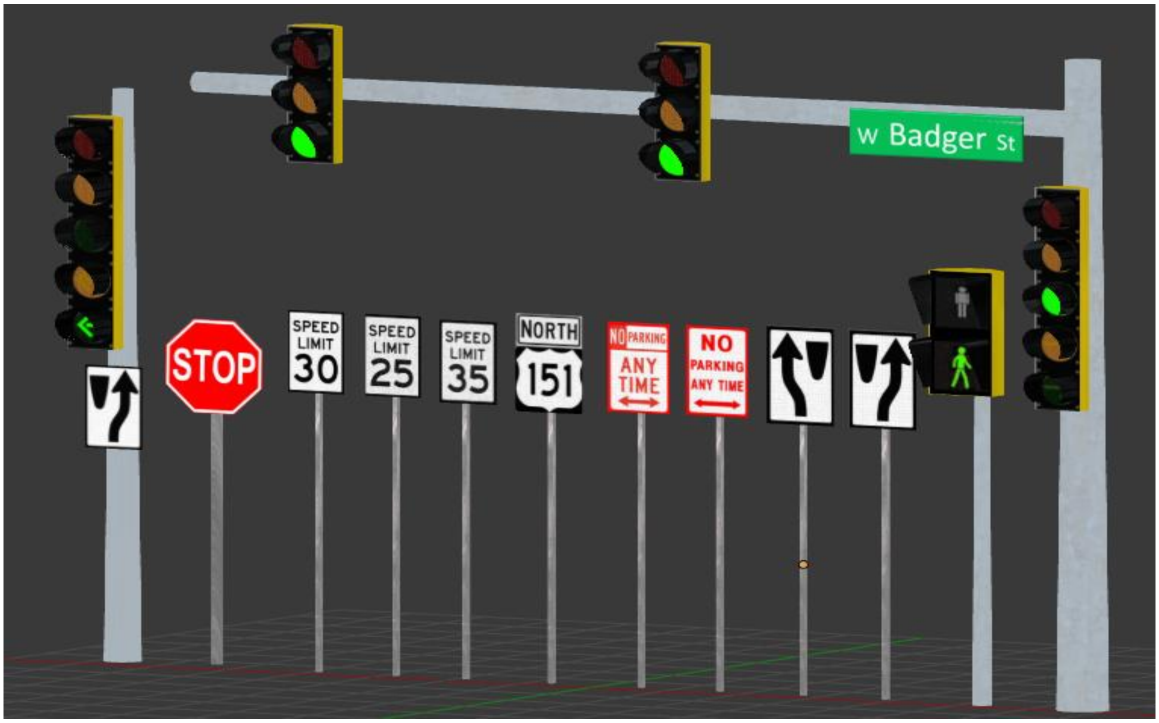

Figure 5.3. Traffic control devices and traffic signals used in the scenario.

5.2 Use of Scenario on a Full-Scale Driving Simulator

Once a textured 3D model is ready for the simulation, the steps for a typical full-scale driving simulator (or similar equipment) involve the conversion of the 3D model into a compatible scenario and the definition of roadway metadata. Depending on the type of experimental requirements, behaviors and events may need to be coded into the simulation. The summary outlined at the end of Chapter 3 describes the procedure used for a VRSA experiment in a full-scale driving simulator. From a guidance perspective, the site identified as a candidate for a VRSA should not be evaluated using a full-scale driving simulator since such an approach would be unfeasible. Many variables can be associated with the types of crashes observed at the intersection shown, and isolating the corresponding behaviors could be infeasible from an experimental design and cost perspective.

5.3 Use of Scenario on a Dynamic Survey

A dynamic survey to conduct a VRSA involves the rendering of videos from the 3D model that presents subjects participating in the experiment with conditions that are of interest. One big advantage that a dynamic survey provides over a full-scale simulator experiment is the feasibility of having a larger number of subjects without the complexities required for an experiment involving a full-scale simulator. Based on the characteristics of the site identified as a candidate for a VRSA and described in Chapter 4, a dynamic survey is the recommended approach for the VRSA experiment. The recommendation is based on the need to narrow the potential factors responsible for the safety issues identified. Narrowing the number of factors requires an experiment with a number of subjects that may be challenging in a full-scale simulator setting.

5.3.1 Data Collection Via a Dynamic Survey

During a dynamic survey, subjects can be presented with different scenarios, and their response times can be collected. Each scenario is produced by rendering a video displaying an event of interest and asking subjects to react to the event or indicate when something happens. Videos are displayed to subjects based on a planned experimental design. Instructions can be provided via images that are displayed to subjects prior to a video. To facilitate the process of displaying instructions to subjects, displaying the video of a scenario, and collecting data, a Python script that takes advantage of existing video playing libraries was created. The input for the script is shown in Figure 5.4. As shown in the figure, the input is a text file that outlines the sequence in which instructions (images) and scenarios (videos) are displayed to the subject.

Subject responses are measured by the script by monitoring the events reported by a mechanical trigger device connected to the computer that displays the scenarios. A photo of a mechanical device that has been tested and proven to work in related research is shown in Figure 5.5. On the device used, three buttons are available for the subject to press as a response to the scenario displayed on the screen. Each button on the trigger device is associated with an event code that is logged by the script handling the dynamic survey.

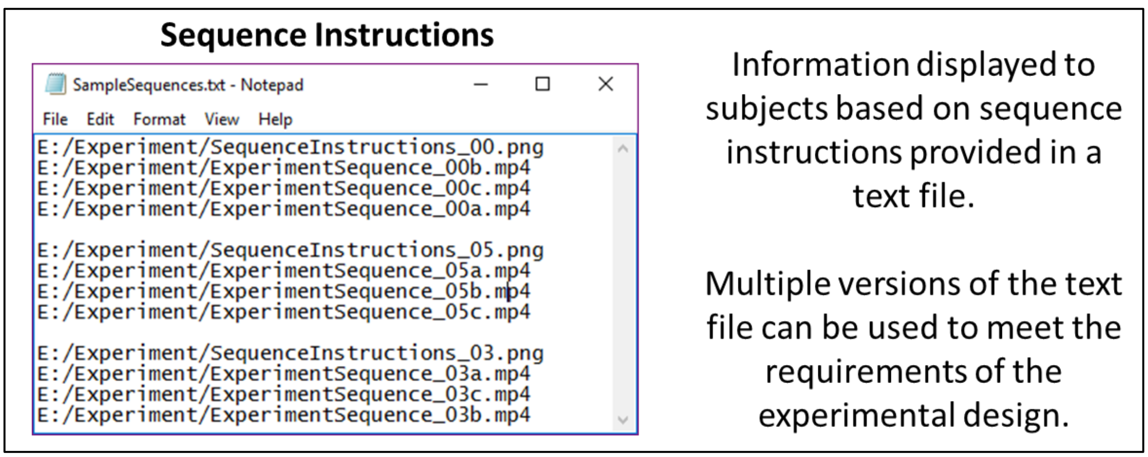

Figure 5.4. Example configuration file used to collect dynamic survey responses.

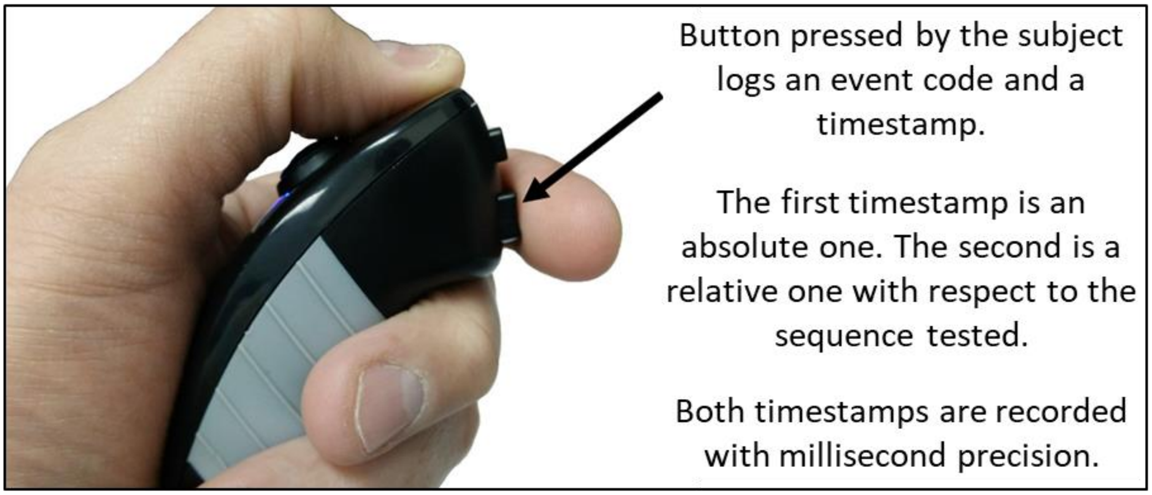

Figure 5.5. Device used to capture responses from the subject.

When a button is pressed, two timestamps and the corresponding event code are logged. The first timestamp represents the time associated with the start of the video sequence, e.g., *01-01-2017 14:35:22.497*. The second timestamp represents the time elapsed since a scenario, e.g., a video or image, is displayed on the screen. Therefore, the second timestamp can be used as a reaction time measurement. The analysis of the data collected for the experiment will depend on the needs of the experiments and the scenario presented. From a VRSA planning perspective, if using a dynamic survey, the experimental design should focus on creating scenarios that can provide insight into the cause of safety issues through simple responses. As the type of data that can be collected suggest, measurements that rely on reaction time observations or recognition tasks are the ideal candidates for a dynamic survey environment.

6 Conclusions

The virtual road safety audits (VRSA) approach described and proposed to assess the safety of a location is an alternative to traditional safety approaches that rely primarily on crash history data. A VRSA can provide insight into the behavior of drivers that is not possible through existing techniques. The insights are possible because of the introduction of a human behavior component into the safety evaluation. A VRSA can be conducted using primarily two approaches: a driving simulator experiment or a dynamic survey experiment. The driving simulator experiment can involve the use of a full-scale driving simulator (or similar device) to study the behavior of subjects as they navigate through a virtual world that resembles the site studied. A dynamic survey involves the use of rendered videos that are shown to subjects. Videos shown to subjects as part of a dynamic survey experiment represent conditions and scenarios that are of interest from a safety perspective. During the survey, subjects are asked to respond to events shown on those videos using a device that generates data to obtain reaction time and other derived measurements.

6.1 Guidance for Selecting a VRSA Site

In this report, guidance on the approach that should be followed to conduct a VRSA was provided. A site was identified as a candidate for a VRSA, and guidance for the creation of the necessary scenarios was provided. When selecting sites that could be a candidate for a VRSA, attention should be paid to the potential underlying causes of the safety problem. If the safety problem that a site exhibits can be addressed through well-established countermeasures or through a traditional RSA, the use of a VRSA is not warranted. On the other hand, there are situations in which countermeasures have been tried at a site and a safety problem remains. Under such a scenario, a VRSA can introduce a human behavior component into the safety evaluation process. By introducing a human behavior component, an insight into the behavior of drivers (from a perspective not obtained through traditional observations) can be obtained and used to identify the underlying causes of a safety problem. If the underlying causes can be identified, existing/new countermeasures that are not obvious can be applied or tested as a safety treatment.

A benefit of VRSAs, and RSAs in general, is the ability to identify potential problems prior to the availability of crash data. In other words, feedback from users of the system or the personal experiences of engineers can trigger a VRSA or RSA. The potential for evaluation prior to the occurrence of crashes makes the use of a VRSA or RSA a proactive safety approach. As the report shows, the ultimate proactive safety approach that involves a VRSA is conducting it prior to construction. An example of a VRSA conducted for a proposed interchange was introduced. When deciding to conduct a VRSA for a proposed project, one of the driving factors will be the identification of potential benefits that could result from the VRSA findings and determining if the benefits warrant moving forward with the evaluation. As the complexity of a project increases, the potential benefits of a VRSA increase as well, and the costs associated with the evaluation become a less significant part of the total project budget. Therefore, conducting a VRSA for a proposed project is something that will likely be justified from a benefit-cost perspective for large-scale projects where a mistake could be costly not only from the safety perspective but also from the financial one.

6.2 Moving Towards a Proactive and Objective Site Identification Approach

As discussed, there are generally two approaches to identifying a site that is a candidate for a VRSA: relying on crash-based screening procedures and local knowledge to identify a location for which traditional safety countermeasures do not provide a solution; or relying on feedback from users or experts about a location that, while not experiencing a crash problem, could be unsafe. The latter is a proactive approach to site identification if done prior to the identification of a crash trend, but it is subjective since it relies on feedback from users rather than on objective measurements. An objective approach to identifying signalized intersections with potential safety problems was introduced as an alternative to user feedback.

The objective approach relies on expanding the capabilities of an existing radar-based vehicle detection system to continuously collect vehicle trajectories. The availability of vehicle trajectories enables monitoring the values of surrogate safety measures (SSM) such as time-to-collision and post-encroachment time to identify those sites that show values approaching or below safe thresholds. If the data collection procedure can be deployed at a large number of intersections, SSM measurements can be obtained and used as an alternative to crash data. Such an approach to safety monitoring will be proactive as well as objective and can streamline the identification and prioritization of sites that are candidates for VRSAs. Judgments about which sites should be studied first can be made by considering the levels of severity observed at different sites.

6.3 Recommendations and Additional Considerations

The recommended approach to identifying a site that is a candidate for a VRSA involves the use of feedback from experts and users along with crash data. Ideally, if technology allows the monitoring of SSM across the transportation system, then these measurements should be used in lieu of crash data and subjective feedback. Regardless of the approach used to identify the site, there are considerations that should be kept in mind throughout a VRSA process. For example, when planning an experiment, the goals of the experiment should be clearly outlined, and existing literature (to the extent possible) should be used to identify the best platform to meet the goals of the experiment. A dynamic survey experiment might be better suited for certain tasks in the same way that a full-scale driving simulator experiment might be better suited for others. Finally, the need to change course during the evaluation needs to be planned for and included in the schedule. As experiments progress, preliminary data might suggest that changes to the scenario are needed. Similarly, assumptions about the validity of a particular level of fidelity to study a safety issue might be found to be incorrect, thus triggering the need for last-minute platform changes.

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