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Center for Excellence

Identification of Factors Related to Violation Propensity

Mining the Data of the Franklin Intersections

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Lighting | Technology
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LIST OF ABBREVIATIONS AND SYMBOLS

ADT	Average daily traffic
CICAS-V	Cooperative Intersection Collision Avoidance Systems for Violations
DART	Data Analysis and Reduction Tool
DAS	Data acquisition system
DF	Depot by Franklin Intersection
DiffSpeed	Difference between actual speed and the posted speed limit
DOW	Day of the week
FAV	Forward adjacent vehicle
FAVCB	Forward adjacent vehicle crossing behavior
FAVCT	Forward adjacent vehicle crossing type
GES	General Estimates System
GPS	Global Positioning System
HOD	Hour of day
IF	Independence by Franklin Intersection
LD	lateral direction
LTAP	Left turn across path
LTIP	Left turn in path
LV	Lead vehicle
LVCB	Lead vehicle crossing behavior
LVCT	Lead vehicle crossing type
OD	Opposite direction
OR	Odds Ratio
PF	Peppers Ferry by Franklin Intersection
RTIP	Right turn in path
SCP	Straight crossing path
TAR	Time after red
TTIyp	Time-to-intersection at the yellow phase change
Tvol	Traffic Volume
VDOT	Virginia Department of Transportation
VL	Violators Left Turns
VLCLD	Violators Left Turns Cloudy Weather
VLCLR	Violators Left Turns Clear Weather

VS	Violators Straight Crossings
VSCLD	Violators Straight Crossings Cloudy Weather
VSCLR	Violators Straight Crossings Clear Weather
VTTI	Virginia Tech Transportation Institute
Vtype	Vehicle type

CHAPTER 1. INTRODUCTION

As a subtask within the Cooperative Intersection Collision Avoidance Systems for Violations (CICAS-V) study, a large volume of data was collected at three signalized intersections in the New River Valley region of Southwest Virginia. Across the equipped intersections, over five million intersection approaches were collected via a high-resolution radar and camera system. The resulting database was utilized for a specific algorithm development purpose during the CICAS-V project; however, an investigation of factors related to the prevalence of violations was not performed. The effort described in this report focused on identifying and exploring causal factors with the aim of assisting efforts to identify potential strategies for mitigation.

BACKGROUND

It is estimated that 260,000 red-light running crashes occur annually in the United States, resulting in 750 fatalities.(1) Furthermore, 30 percent of intersection-related fatalities are associated with signalized intersections; this is significant considering that only 10 percent of the nation's intersections are signalized.(2) Federal, state, and local agencies recognize the importance of intersection safety.(3,4) The primary objective of the following effort was to identify risk factors that are related to the likelihood of red-light running violations, with the ultimate goal of developing strategies to reduce intersection crashes.

An intersection is a type of junction that does not include a driveway or alley access. Approximately 60 percent of the crashes in the United States occur in the presence of a junction, and 44 percent of these crashes are attributed to intersections. Other crashes at junctions include driveway/alley access (10.6 percent), entrance/exit ramp (2.6 percent), rail grade crossing (1.7 percent), and others (1.2 percent).(5)

Crash incidence data, segregated by the type of maneuver, indicate that the largest proportion of intersection crashes are classified as a straight-crossing path (SCP).(6) General Estimates System (GES) data from 1998 also indicated the high relative prevalence of SCP crashes as shown below.(7,8) Based on these data, 80% of the intersection crashes are occurring during SCP and left turn across path (LTAP) maneuvers. As discussed further in a subsequent section, it was decided to focus the resources of this project on the SCP and LTAP maneuvers, where the majority of crashes occur.

- Straight-crossing path (SCP) 36.6%
- Left turn across path/opposite direction (LTAP/OD) 27.3%
- Left turn across path/lateral direction (LTAP/LD) 15.9%
- Left turn in path (LTIP) 4.7%
- Right turn in path (RTIP) 4.7%

Violation-related crashes tend to occur when the driver of a vehicle fails to yield while a conflicting vehicle is present. Therefore, reducing the prevalence of violations will result in a reduction in intersection crashes. Understanding the factors that contribute to the likelihood of intersection violations will assist engineers in the development of strategies designed to enhance intersection safety.

Direct observation of violations at signalized intersections provides insight into their causes. Low-speed "rolling stop" violations exceed "at speed" violations at signalized intersections. An in-depth analysis of violators at stop-controlled and signalized intersections has been conducted by Sudweeks et al.(9) using the data of the 100-Car Naturalistic Driving Study. In this study, violations and near-violations of 77 drivers at 168 signalized intersections were analyzed. The study showed that 96 percent of the violations at signalized intersections occurred during right-turn maneuvers. The authors concluded that nearly all of these violations were performed by attentive drivers at speeds less than 11 mi/h. This finding, combined with the relatively low frequency of right-turn crashes, suggests that violations performed during a right-turn maneuver are not as risky as straight-crossing and left-turn maneuvers.

The literature indicates that red-light running violations are influenced by a number of factors. First, the frequency of violations tends to increase as the traffic volume increases.(10,11) Furthermore, the presence of adjacent vehicles also influences the prevalence of violations.(12) Researchers observed that the probability of violation increases if the subject vehicle was closely following a vehicle that also violated. Similarly, the frequency of violation increases if the subject vehicle is being followed closely or if vehicles in the left lanes also violated the red light.

Gates and Noyce conducted a study that evaluated the stopping characteristics of vehicles at signalized intersections at the beginning of a yellow interval.(13) The study concluded that heavy vehicles (trucks, buses, recreational vehicles, etc.) were more likely to violate than passenger vehicles.

Vehicle speed is an indicator for violation likelihood. For vehicles with a similar time-to-intersection, the vehicle with a higher speed is more likely to violate.(12) Furthermore, the probability that a driver runs a red light depends on the time taken by the driver to reach the intersection when the light changes to yellow;(14) as the time-to-intersection increases, the probability of violation decreases. Finally, time of day may also influence red-light running behavior.(10) It has been observed that decreased numbers of violations have been reported between the hours of 8 p.m. and 5 a.m.(15)

Overall, much of the past research is based on relatively small samples collected primarily by observers along the side of roadways or through limited video reduction efforts. None of the projects obtained a large sample of detailed intersection approaches throughout all times of the day over an extended period. The project described in this report used the largest known database of continuous vehicle intersection approaches. This permitted the researchers to validate previous studies as well as extend the findings to cover a larger set of potential factors. This effort is intended to contribute to the body of knowledge regarding signalized intersection violations by identifying new risk factors and validating previous factors using the case-control study design with a large data sample.

CHAPTER 2. METHOD

The following chapter describes the methods implemented during this project. Although the data collection was not performed as part of this project, this chapter opens by providing a brief description of the data collection sites and equipment in order to provide the reader with appropriate contextual background. Data reduction is then described, which represented a significant proportion of the effort within this project since a reduction of compliant (non-violating) approaches had not been performed previously. This reduction was performed over a carefully selected sample that provided the complete data set required for a case-control analysis. Finally, this chapter closes with a discussion of the primary statistical analysis tool implemented during the investigation: the logistic regression model.

DATA COLLECTION SITE OVERVIEW

Located in the New River Valley area of southwest Virginia, three 4-way signalized intersections were selected for data collection during the CICAS-V project. While considering the literature, the sites were selected based on intersection characteristics (e.g., roadway design speed, number of lanes, protected and unprotected turn lanes, intersection box size, and geometry of approaches), crash statistics, traffic volume, and recommendations by the Virginia Department of Transportation (VDOT).

Table 1 provides a list of the selected intersections and the corresponding posted speed limits. The following pages provide images depicting a map that details measurements of each of the selected stop-controlled intersections, an aerial view, and ground images of each site. Ground images were captured from site visits and aerial images were later extracted from http://maps.live.com (Microsoft®, 2008).

Table 1. Signalized intersections.

Intersection	Posted Speed Limit
Franklin & Elm & Independence	25 mi/h, 35 mi/h, & 45 mi/h
Depot & Franklin	25 mi/h, 35 mi/h, & 45 mi/h
Bus 460 & VA-114	35 mi/h, & 45 mi/h

Independence by Franklin

The intersection of Franklin Street, Elm Street, and Independence Boulevard is a signalized intersection. The posted speed limits for Franklin, Independence, and Elm are 45 mi/h, 35 mi/h, and 25 mi/h, respectively. VDOT records show the entering average daily traffic (ADT) at 25,975. There has been an average of 21 annual crashes reported at this intersection.

Figure 1. Illustration. Diagram of Franklin, Elm & Independence intersection.

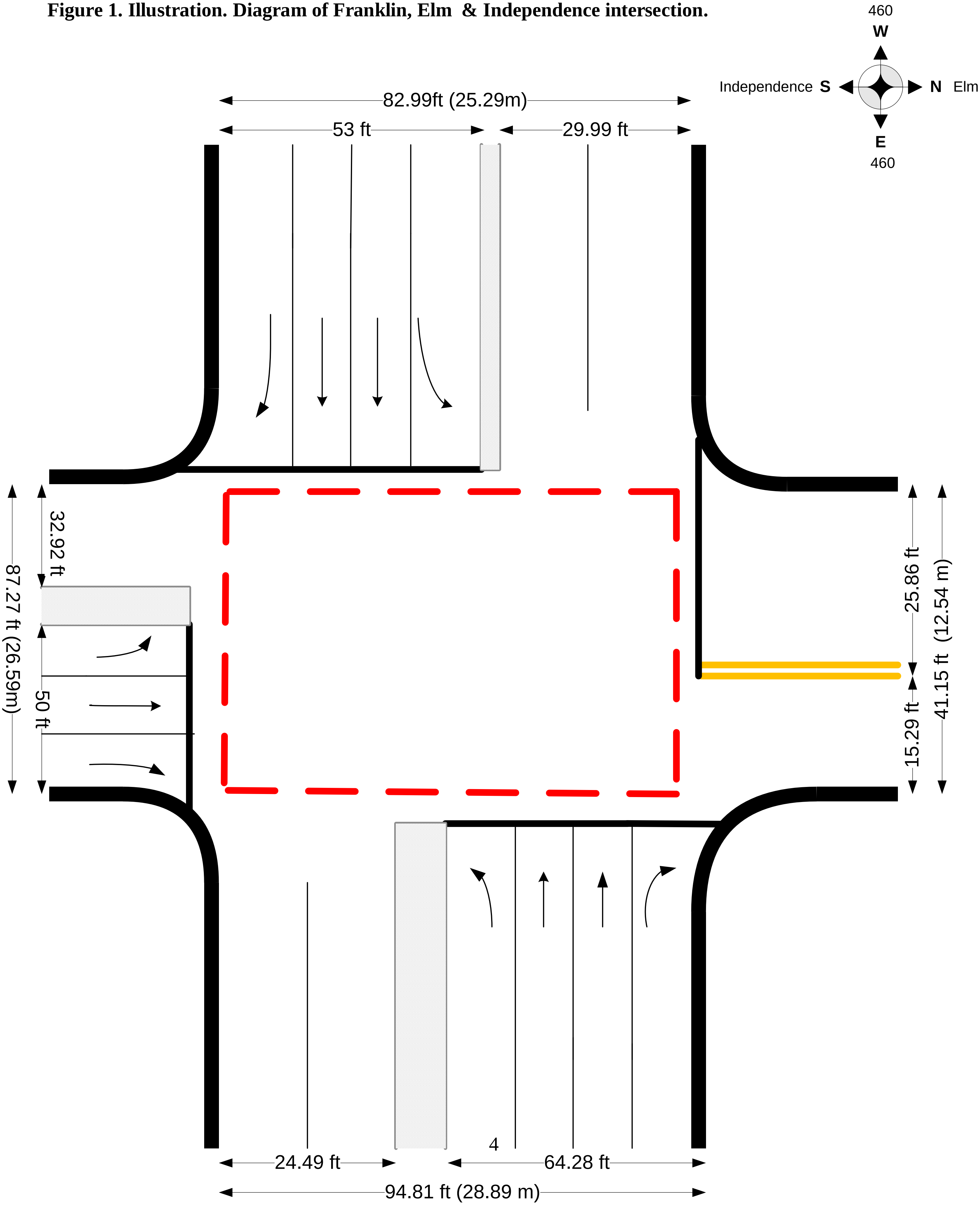

Figure 2. Photo. Aerial view of Franklin, Elm & Independence intersection.

Figure 3. Photo. Ground images from Franklin, Elm & Independence intersection.

Franklin by Depot Intersection

The intersection of Franklin Street and Depot Street is a signalized intersection. The Franklin Street eastbound intersection approach has a 35 mi/h posted speed limit, while the westbound intersection approach has a 25 mi/h posted speed limit. The Depot Street intersection approach has a 25 mi/h posted speed limit going southbound and a 35 mi/h posted speed limit going northbound. The entering ADT for this intersection is 26,671 and an average of 11 accidents per year has been reported at this intersection.

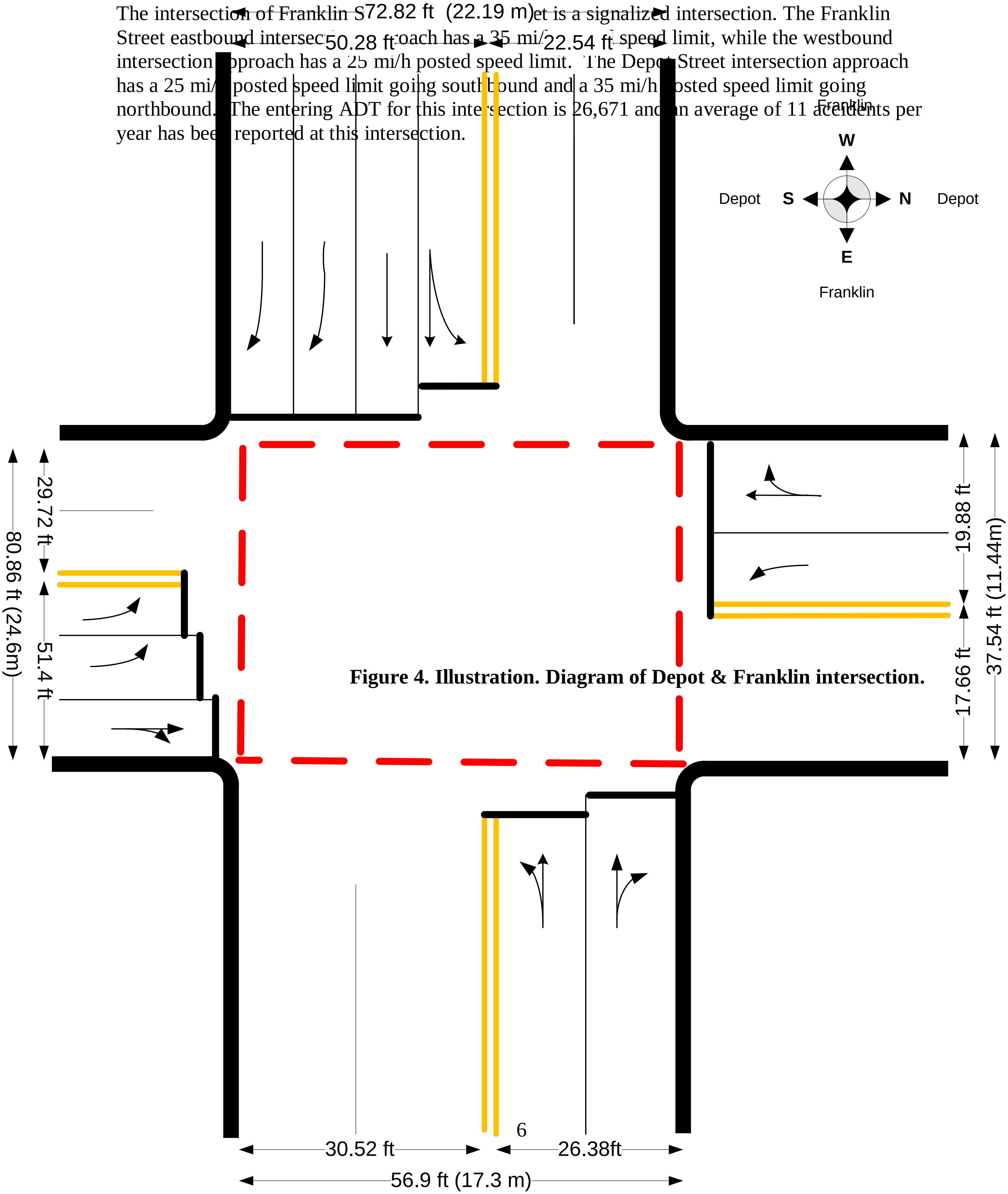

Figure 4. Illustration. Diagram of Depot & Franklin intersection.

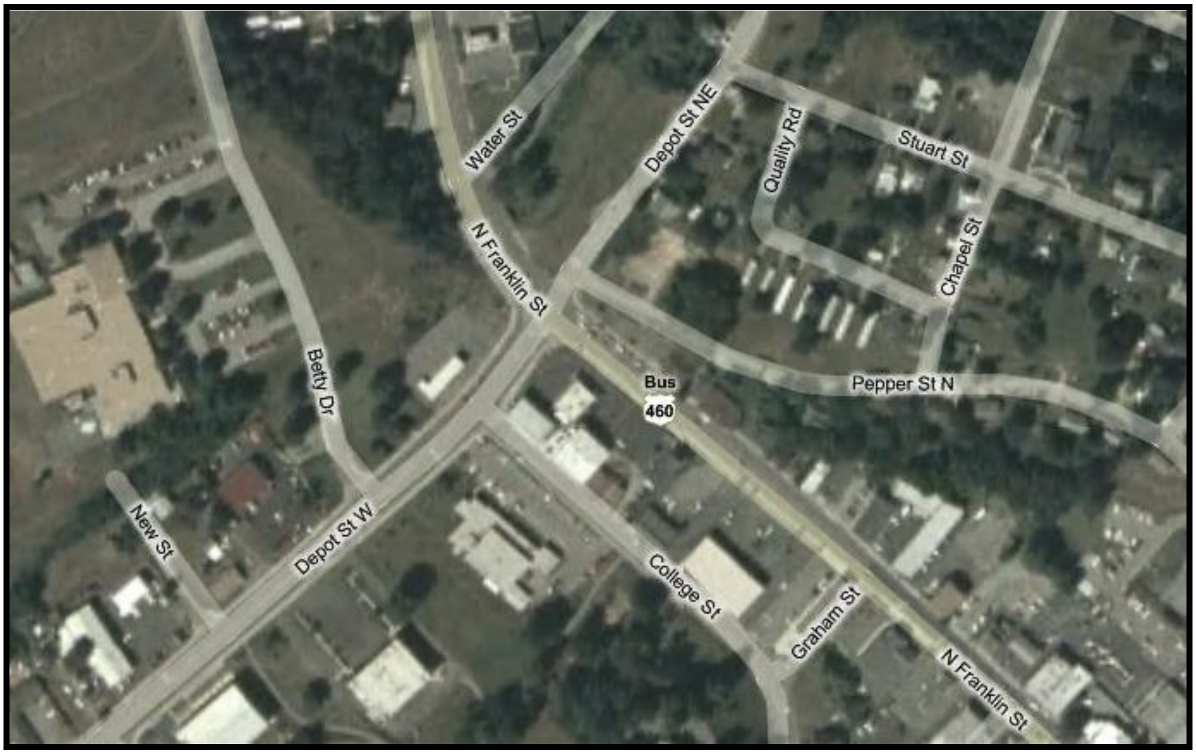

Figure 5. Photo. Aerial view of Depot & Franklin intersection.

Figure 6. Photo. Ground images from Depot & Franklin intersection.

Peppers Ferry by Franklin Intersection

The intersection of Peppers Ferry (VA-114) and Franklin (HW-460) is a signalized intersection. The Peppers Ferry intersection approach has a 35 mi/h posted speed limit in both directions. On Franklin there is a 45 mi/h posted speed limit in both westbound and eastbound directions. The entering ADT for this intersection is 31,905 and an average of 23 accidents per year has been reported at this intersection.

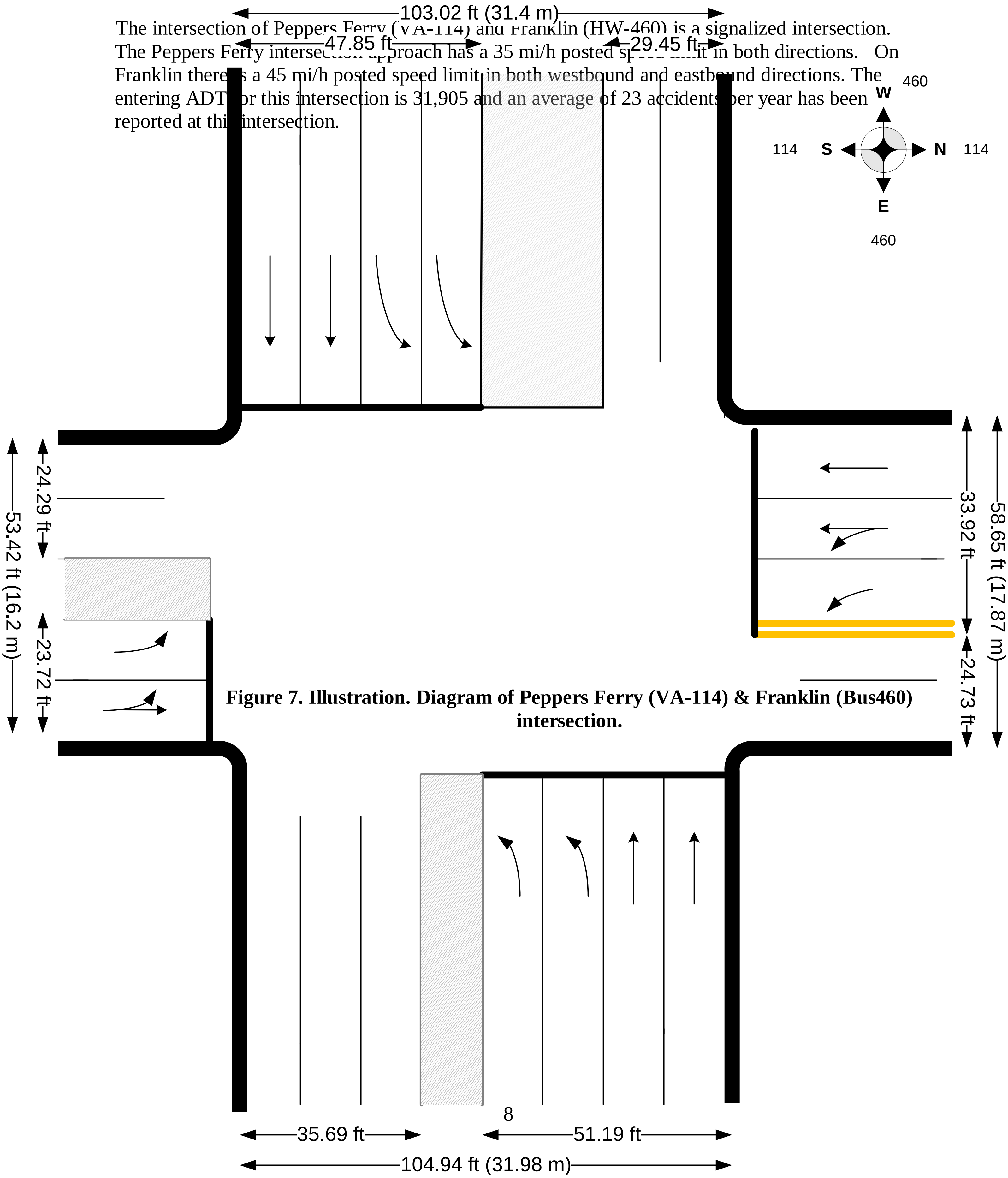

Figure 7. Illustration. Diagram of Peppers Ferry (VA-114) & Franklin (Bus460) intersection.

Figure 8. Photo. Aerial view of Peppers Ferry (VA-114) & Franklin (Bus460) intersection.

Figure 9. Photo. Ground images from Peppers Ferry (VA-114) & Franklin (Bus460) intersection.

DATA ACQUISITION SYSTEM OVERVIEW

The Center for Technology Development at the Virginia Tech Transportation Institute (VTTI) designed, developed, and installed the data acquisition systems (DAS) as part of the CICAS-V effort. This section contains a brief overview of the DAS; however, the interested reader should refer to the Subtask 3.2 report of the CICAS-V project for additional details.[16]

The DAS was responsible for sensing, pre-processing, and recording data. This system was completely contained at the intersection site and virtually invisible to drivers. A sensing network was distributed throughout the intersection with equipment located on all four-signal mast-arms, as well as inside the traffic signal controller cabinet. The sensing network consisted of five major components: a Global Positioning System (GPS), a weather station, a signal phase sniffer, a video array, and a radar array.

The first component, a GPS, acquired an accurate global time. This global time allowed the various intersections to be synchronized for analysis with respect to the time of day.

The second component of the sensing network was the weather station. This station provided weather information, including rainfall, wind speed and direction, temperature, and barometric pressure per minute. These weather-related data allowed researchers to investigate weather-related changes in traffic patterns without employing manual reduction techniques.

The third component of the sensing network was a device referred to as the signal phase sniffer. The signal sniffer was a custom-designed digital signal processor. The sniffer used inductive loops to measure the electrical current flowing to the traffic signal heads. The sniffer monitored the phase of every signal at the intersection. This method resulted in a completely unobtrusive system for monitoring the signal phase and timing.

The fourth element, a video camera, was installed on each of the four traffic signal mast-arms to provide an image of the entire intersection environment (Figure 10). The selected cameras are intended for outdoor use and have special features designed for vehicle environments, including headlight bloom reduction and a wide-range iris. The cameras were housed inside heated, power-vented, water-resistant enclosures to ensure consistently high quality video.

Figure 10. Photo. Video quadrants from camera units mounted on intersection mast-arms.

The final component in the sensing network was the high performance radar designed and developed specifically for the intersection data collection application by Smart Micro Systems. Prior to this study there was no commercially available sensor that could provide coverage for more than 150 m on a four-lane roadway. The custom radar underwent extensive lab testing and on-site tuning to ensure a high level of data quality. A radar unit was mounted on each of the four mast-arms below the camera and aimed directly at approaching traffic (Figure 11).

Figure 11. Photo. Camera and radar unit mounted on a single intersection mast-arm, along with instrumentation inside of the traffic signal controller cabinet.

The processing stack installed at the intersections was a high performance computational subsystem developed by VTTI. The system is built on a PC104 backbone with a custom interface capable of accepting and transmitting information to a variety of sensing components. The parametric data and video are choreographed via a proprietary VTTI software package running on the real-time Linux operating system. The software time stamps and aligns the various incoming messages and compresses them into a binary file, which is then written to a removable hard drive in real time.

Data were retrieved from each site every few days and transported to VTTI's secure data servers where it was uploaded to a relational database for post-processing and analyses. The post-processing consisted of a number of steps covered in detail within the Subtask 3.2 report.(16) These post-processing methods included the filtering out of erroneous data, radar data smoothing, and derivation of additional measures such as unique vehicle identifiers, lane position, brake status, time to intersection, and acceleration.

EPOCH VALIDATION AND REDUCTION

The data collected for this study were obtained primarily from an infrastructure-mounted radar sensor. Radar has some limitations relative to in-vehicle sensors. While the measurements of speed and range are accurate, the association of those measures with a particular vehicle is prone to error. This means that a vehicle reported by the radar is not necessarily a valid vehicle. A common example of this behavior occurs with large vehicles and trailers. The radar used for this study would frequently treat a large vehicle as two separate targets, particularly if a trailer was in tow. As a result, the subject vehicle may have crossed the stop bar during the yellow phase; however, the secondary false target located at the rear of the vehicle would appear to violate as it was pulled through the intersection after the presentation of the red phase.

One purpose of the video reduction was to validate the events of interest. It was important to ensure that false targets were not inadvertently being included in the sample of the driver approaches that were under study. In addition to false triggers, other invalid events also needed to be removed from the data set. These included violations that were a result of atypical scenarios such as a funeral procession and the crossing of in-service emergency vehicles. Therefore, it was necessary to mark and remove invalid events from the analysis.

Discussed in the next section, a strategy was devised to methodically select approaches of interest for reduction. Automated triggers swept through the parametric data and flagged events for which the data suggested a violation or compliant approach meeting the selection criteria was identified. The flagged events were automatically collected for easy retrieval and accessible to the data analysts.

The validation process required an analyst to view each event. Once the event was opened and viewed, a number of measures were coded by the analyst to better characterize the nature of the epoch. These measures included environmental data (such as surface condition) as well as information about the adjacent and conflicting vehicles.

The Data Analysis and Reduction Tool (DART) software package was used by data reductionists to validate the events. DART is the result of more than six years of software development at

VTTI. DART provides a user interface for the viewing and reduction of digital data (Figure 12). It contains user-configurable video and graphical interfaces to aid in manual reduction, and allows users to simultaneously view synchronized video and graphical data streams frame by frame.

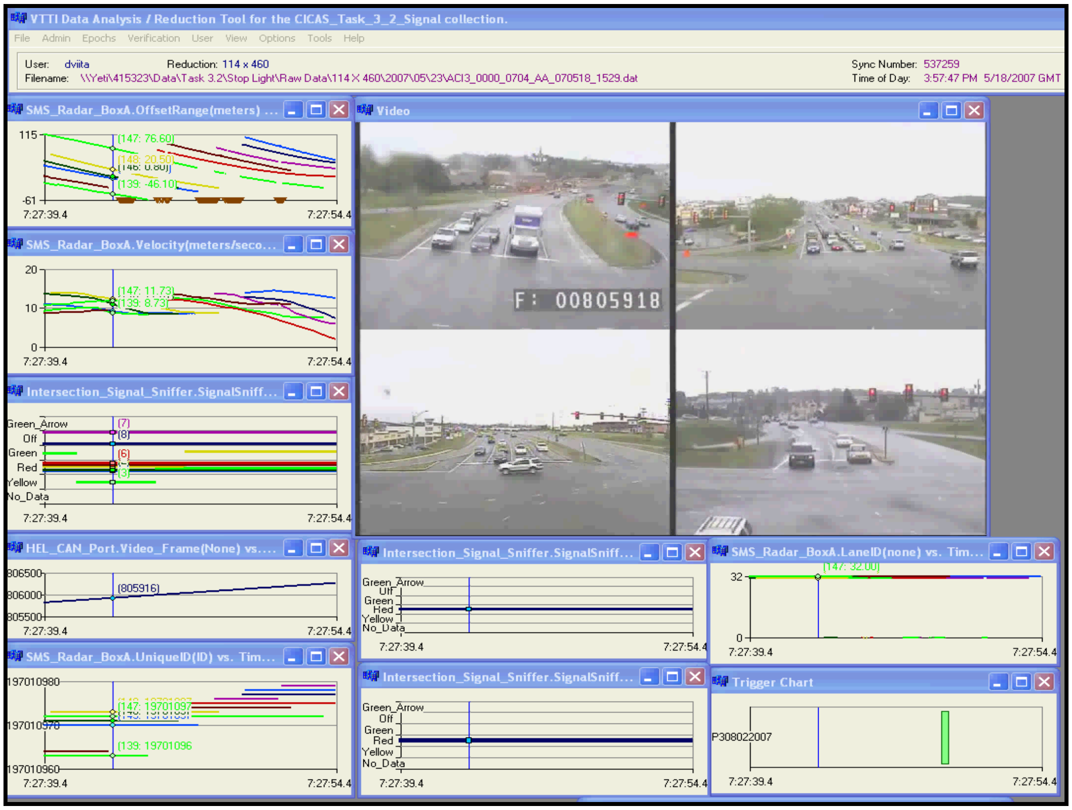

Figure 12. Screenshot. Data analysis and reduction software developed by VTTI.

To streamline the reduction process, DART provided the analysts with a question-and-answer prompting format. When an epoch of interest was viewed, the reductionist was provided with a form that included a list of questions and associated menus from which to select responses. For example, one question asked what the roadway surface condition was; this allowed the reductionist to select the appropriate response such as dry, wet, icy, etc. A complete list of the prompting questions and answers are provided within Appendix A.

Two measures of rater reliability were conducted on the trigger validations. First, reductionists performed 30 minutes of spot-checking (of their own or other reductionists' work) during each 4-hour shift. Any disagreements were flagged for review by the data reduction manager. Approximately 20 percent of all events were spot-checked. Any errors were addressed during regular meetings with the data reductionists.

The second measure was an inter-rater reliability test administered to each reductionist. The test contained 30 stop-controlled and 13 signalized triggers representing a variety of scenarios and a range of interpretation complexity. The test included valid and invalid events, as well as violations, near-violations, and non-violations. Triggers were first evaluated by the project manager, and a gold standard was developed against which rater tests were scored. Test scores for raters ranged from a low of 77 percent to a high of 98 percent. The average score across raters was 92 percent agreement with a standard deviation of 0.05 percent.

SAMPLE SELECTION

Overall, the data collected during CICAS-V included a total of 5,520,174 vehicles crossing the three intersections. Of these approaches, a total of 16,998 potential violations were identified through an automated algorithm. The algorithm operationally defined a violation as a vehicle that crossed over the stop bar after the presentation of red and continuing into the intersection for at least 3 m within 500 milliseconds. This definition was required to reduce the number of false alerts triggered by vehicles that stopped over the stop bar as well as those that made a slow "rolling stop" during a right turn maneuver.

The potential violations were manually validated to remove invalid observations such as in-service emergency vehicles and false triggers (e.g., trailers appearing as a lead vehicle and vehicles stopping over the stop bar). The manual validation resulted in a total of 8,089 violations across the three intersections.

From these violations, a sample was selected to acquire a feasible number of observations for performing manual data reduction. As discussed previously, the right-turn maneuvers are not as risky relative to the straight-crossing and left-turn maneuvers. Therefore, it was decided to focus this analysis on the straight and left-turn maneuvers by removing all violations that occurred while the vehicle was performing a right turn, thus reducing the sample to 3,746. Next, only the vehicle approaches that contained continuous data from 100 m through the stop bar were selected. This reduced the probability of missing data at the assessment locations due to incomplete radar tracks. The final number of violations was then randomly down-selected to 3,000 which provided a monetarily feasible number of epochs to reduce.

A corresponding sample of baseline approaches was next selected as a comparison group. The baseline group represented compliant drivers who did not violate the traffic control device. To permit a case-control sampling strategy, the goal was to obtain a sample of vehicles that were presented with the yellow phase at a comparable location relative to the violations. As such, the compliant drivers were faced with a similar situation as the violating drivers; however, they were able to either pass through the intersection prior to the presentation of red or stopped their vehicle in response to the signal change.

To obtain the comparable sample of baseline vehicles, the time-to-intersection at the yellow phase change (TTIyp) was extracted for the sample of violating drivers. The TTIyp is operationally defined as the time taken for the front of the vehicle to cross the stop bar, assuming constant velocity, evaluated at the instant when the signal phase changes from green to yellow. The use of TTIyp temporally represents a combination of distance and speed, therefore permitting application across the approaches with differing posted speed limits. The 90th percentile TTIyp of the violating group (3.55 s to 5.81 s) was used to limit the range over which the samples were extracted. All other variables (time of day, weather, etc.) were not controlled. It is important to note, this method excludes all drivers who pass through the signal on the green phase and is thus limited to only the drivers who approached the signal when it was changing phases. This permitted a direct comparison of measures between the drivers who violated and drivers that experienced a very similar scenario; yet did not violate (ether successfully completing a stop or driving through the intersection). The final samples selected for analysis included 3,000 vehicle approaches from the baseline and violating groups for a total of 6,000 observations. Each of these observations underwent the complete reduction and data analysis process.

LOGISTIC REGRESSION MODEL

The centerpiece of this effort was the application of a logistic regression model. The logistic regression model is a non-parametric statistic that, when paired with a case-control method, provides robust estimates of risk. The red-light violation behavior was modeled by a logistic regression model. First, a binary random variable Y_i is defined:

$$Y_i = \begin{cases} 1 & Red-light\,Violation \\ 0 & Baseline \end{cases}, \quad i = 1, \ldots, I$$

Where I is the sample size for violations and baselines. Assume Y_i follows a Bernoulli distribution, i.e.,

$$Y_i = Bernoullie(p_i) \tag{1}$$

The model coefficient p_i represents the probability of violation for observation i . It is assumed that this violation probability will be influenced by factors such as weather, traffic condition, adjacent vehicles, etc. This connection between the potential risk factors and the crash p_i can be mathematically modeled through a logit link function with the following form:

$$logit(p_i) = \log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_K X_{Ki} \tag{2}$$

Where X_{ki} is the variable based on independent variable k and β_k is the corresponding regression coefficient. With proper parameterization, the exponential of the regression coefficient β_k is corresponding to the odds ratio (OR) for the k^{th} factor. For example, for a binary variable X_i, the OR can be calculated as:

$$OR_k = \exp(\beta_k).$$

The OR_k indicates the relative risk of violation for the two levels. For a continuous variable, the OR indicates the relative risk increase/decrease for every one unit of change in the independent variable. The neutral value of OR is 1. The factor is statistically significant if the 95 percent confidence interval does not include 1.

Another merit of the OR estimated from the logistic regression is that the OR for a specific factor can be considered as an averaged value over all the levels of other factors included in the same model. Thus, the confounding effect can be effectively addressed by simply including multiple factors that might confound with each other simultaneously in the model.

CHAPTER 3. RESULTS AND DISCUSSION

An initial descriptive analysis was performed to characterize the violation and crash prevalence at the three signalized intersections (Table 2). Overall, a total of 8,089 violations occurred across 5.5 million intersection crossings. As discussed previously, only LTAP and SCP maneuvers were considered for the case-control analysis (3,746 violations). Note that the Independence intersection has a violation rate nearly three times higher than Depot and over five times higher than Peppers Ferry. The large discrepancy in violation rates between sites was a key motivator for this project as it indicated the potential to identify differences in the intersections that increase violation rate.

Table 2. Prevalence of violations and the targeted (LTAP and SCP) sample of violations.

Location	Approaches	All Violations		Only LTAP and SCP Violations	
		Frequency	per 100k crossings	Frequency	per 100k crossings
Depot	1,159,846	2,077	179	713	61
Independence	1,341,872	5,098	380	2,162	161
Peppers Ferry	3,018,456	914	30	871	29
Overall	**5,520,174**	**8,089**	**147**	**3,746**	**68**

The ultimate goal of investigating the violations was to gain insights that could lead to strategies for alleviating intersection crashes. Data on the prevalence of crossing path crashes and ADT were obtained from VDOT in the three years prior to the data collection (Table 3). The ADT from the collected sample was similar to the VDOT-reported ADT. The slightly lower traffic volumes reported at Depot and Independence may be due to seasonal differences in traffic flow that existed during the three months of data collection. In general, the following table indicates that the sample analyzed is compatible with past data collections and suggests that approximately one crash will occur for every 200,000 vehicles that cross the intersection.

Table 3. Prevalence of crashes and ADT reported by VDOT, compared to the sample.

Location	VDOT Data			Data Collection Period		
	Crashes Per year	Average Daily Traffic	Crashes Per 100k	Days of Collection	Average Daily Traffic	Predicted Crashes Per 100k
Depot	11	26,671	0.11	54	21,595	0.09
Independence	21	25,975	0.22	60	22,303	0.20
Peppers Ferry	23	31,905	0.20	93	32,515	0.20
Overall	**55**	**84,551**	**0.18**	**207**	**76,413**	**0.16**

It is of interest to compare the crash and violation trends at each location. At the onset of this effort it was assumed these two rates would be directly proportional. Notice that a high rate of violations occurs at Independence relative to Peppers Ferry; however, the crash rates are nearly equivalent. This trend suggests that violations at Peppers Ferry may have a higher probability of resulting in a crash than at Independence. Similarly, Depot Street has a considerably lower crash rate than Peppers Ferry while reporting double the violation rate. Although there were not sufficient resources to investigate this finding further, it appears that violations are not directly related to crashes. During a future assessment, it would be interesting to investigate the nature of the intersection crashes and violations further to understand why it appears that violations at Peppers Ferry are more likely to result in a collision.

LOGISTIC REGRESSION

A series of logistic regressions were performed to investigate the violations that were captured during data collection. The first set of regressions was performed on the overall database with the aim of looking at factors that affect the risk of a violation. The second set of regressions was performed to look at differences between the sites with the aim of determining which factors might be leading to the non-equivalent violation rates between intersections as described previously.

Regression across Location

The logistic regression model was applied to traffic light violations for straight-crossing and left-turn maneuvers. The factors of interest were parsed and combined from the reduction data based on the contingency table (Appendix B) and success of the logistic regression model convergence. Results of the regression are presented in ORs for easier interpretation. The straight-crossing results are shown below in Table 4. Some factors are abbreviated with full descriptions available in the list of abbreviations at the beginning of this report.

Table 4. The odds ratio estimation for straight-crossing red-light violation.

Odds Ratio Estimates			
Effect	Point Estimate	95% Wald Confidence Limits	
location df vs if	**0.233**	**0.186**	**0.291**
location pf vs if	**0.203**	**0.166**	**0.248**
vtype bus-truck-trailer vs car-van	**3.069**	**2.116**	**4.453**
vtype pickup-suv vs car-van	0.921	0.799	1.062
lvcb LV Near Violation vs LV Compliant	3.175	0.964	10.459
lvcb LV Violation vs LV Compliant	1.269	0.298	5.398
lvcb No LV vs LV Compliant	**1.301**	**1.014**	**1.669**
favcb FAV Near Violation vs FAV Compliant	0.686	0.346	1.358
favcb FAV Stopped vs FAV Compliant	**0.550**	**0.375**	**0.805**
favcb FAV Violation vs FAV Compliant	0.638	0.317	1.286
favcb No FAV vs FAV Compliant	1.209	0.901	1.621
weather cloudy vs clear	**6.235**	**4.496**	**8.647**
weather rain & fog vs clear	1.098	0.743	1.623
Time to intersection @ yellow onset	**0.741**	**0.676**	**0.813**
HOD 1 vs 10	**7.316**	**1.402**	**38.193**
HOD 2 vs 10	**5.278**	**1.338**	**20.824**
HOD 3 vs 10	**3.238**	**1.449**	**7.236**
HOD 4 vs 10	1.499	0.883	2.543
HOD 5 vs 10	1.001	0.640	1.565
HOD 6 vs 10	1.220	0.804	1.850
HOD 7 vs 10	1.060	0.703	1.597
HOD 8 vs 10	1.252	0.851	1.843
HOD 9 vs 10	0.738	0.500	1.089
HOD 11 vs 10	1.036	0.709	1.514
HOD 12 vs 10	1.190	0.798	1.776
HOD 13 vs 10	1.038	0.707	1.523
HOD 14 vs 10	1.201	0.823	1.754
HOD 15 vs 10	1.009	0.681	1.496
HOD 16 vs 10	1.166	0.797	1.707
HOD 17 vs 10	1.049	0.708	1.553
HOD 18 vs 10	1.193	0.796	1.788
HOD 19 vs 10	1.494	0.958	2.328
HOD 20 vs 10	**2.982**	**1.719**	**5.173**
HOD 21 vs 10	**2.805**	**1.392**	**5.652**
HOD 22 vs 10	**2.741**	**1.168**	**6.436**
HOD 23 vs 10	**11.311**	**2.711**	**47.193**
HOD 24 vs 10	**13.060**	**2.494**	**68.387**
DOW Fri vs Sun	0.915	0.686	1.219
DOW Mon vs Sun	1.052	0.787	1.407
DOW Sat vs Sun	0.945	0.714	1.251
DOW Thu vs Sun	1.008	0.752	1.352
DOW Tue vs Sun	0.993	0.748	1.317
DOW Wed vs Sun	1.043	0.788	1.380
Tvol	1.002	1.000	1.003
Diffspeed	**1.088**	**1.064**	**1.112**

***Descriptions of abbreviated words can be found in the list of abbreviations at beginning of document.**

The Independence intersection demonstrated roughly five times the risk for violation when compared to the other two sites. This result was expected based on the rates demonstrated in

Table 3. All three locations contained similar intersection geometry, speed limits, and sufficient site distances. The differences in frequency between sites motivated a second logistic regression within each site to further investigate the differences in factors between sites (presented in the next section).

Heavy vehicles (e.g., buses and tractor trailers) are three times more likely to violate a red light than are light vehicles. This may be caused by longer stopping distances required by the heavy vehicles which motivate the driver to pass through the intersection rather than stop. The longer time and increased effort needed for heavier vehicles to accelerate after stopping for a red light may also motivate a heavy-vehicle driver to "beat the light."

Although the crossing type of the lead vehicles did not have an unexpected influence on the subject, vehicles in adjacent lanes demonstrated an interesting influence. The presence of a forward adjacent vehicle that stops decreases the likelihood of violation by approximately half. It appears the driver is influenced by a vehicle nearby that decides to stop by demonstrating a higher tendency to follow suit and stop as well. This example of group-think suggests that if a few drivers can be convinced to stop through an intersection treatment, a number of adjacent drivers may be influenced to make the same decision even though it is not directly a result of the treatment.

Weather conditions have a particularly notable effect on violation propensity. Drivers were over six times more likely to violate on cloudy days than on clear days. Glare from direct sunlight may reduce the distance at which the signal phase is clearly perceived; this could result in drivers who are more attentive to the signal and, as such, are better prepared to respond. Additional research with in-vehicle and/or lab data is required to determine whether higher visibility of the signal head can actually increase the probability of a violation; particularly in consideration of the hour-of-day factor which demonstrated increased violation risk at certain nighttime hours.

Interestingly, there is a spike in the risk of violation starting at 10:00 pm and extending through 3:00 a.m. The peak risk of a violation is 13 times higher at midnight than it is at 10:00 a.m. As there are significant amounts of darkness on either side of the elevated window, this effect does not appear to be due to lighting conditions. It is possible that the spike in violation risk during these late night and early morning hours is due to either fatigue or impairment. It may be reasonable to assume impairment is a larger factor given that the rate rapidly decreases after most local establishments close (2:00 a.m.).

The OR for the time to intersection of the vehicle at the onset of the yellow phase (TTIyp) indicates that for every 1-second increase, the probability of violation will drop by 14 percent. This is an expected result as it demonstrates that drivers who are further from the intersection when the signal changes are more likely to stop.

As discussed in the literature review, past research has indicated an effect due to the day of the week. An unexpected finding is demonstrated by the risk of violation relative to the day of the week which did not confirm this earlier finding. Traffic volume also did not show a significant impact on the violation probability. As the previous studies were performed in larger cities, perhaps the difference is due to a weekday congestion effect that is less prevalent on the corridor tested in this study (which does not have significant congestion).

Finally, vehicle speed significantly affects the probability of violation. For every 1 m/s (2.2 mi/h) increase in the vehicle speed over the posted speed limit, the probability of a violation increases by nearly 10 percent. This implies that drivers exceeding the speed limit are more likely to violate which may be a measure of the drivers' desire to reach their destination quickly or their general risk tolerance.

The left-turn violation results are shown in Table 5. In general, fewer factors had a significant impact on violation risk than during straight-crossing maneuvers. In several cases this may be due to the change in vehicle velocity required in preparation for turning. For example, larger vehicles did not demonstrate a significant increase in violation risk as they did during straight-crossing maneuvers. This is likely due to the requirement for all vehicles to slow in advance of performing a turn, because slowing the vehicle to a stop is less challenging.

Table 5. The odds ratio estimation for left-turn red-light violation.

Odds Ratio Estimates			
Effect	Point Estimate	95% Wald Confidence Limits	
location df vs if	1.274	0.772	2.104
location pf vs if	0.844	0.506	1.406
vtype bus-truck-trailer vs car-van-ev	1.554	0.808	2.992
vtype pickup-suv vs car-van-ev	0.831	0.641	1.078
lvcb LV Near Violation vs LV Compliant	2.451	0.736	8.165
lvcb LV Violation vs LV Compliant	2.917	0.290	29.344
lvcb No LV vs LV Compliant	1.104	0.709	1.718
favcb FAV Near Violation vs FAV Compliant	0.119	0.011	1.320
favcb FAV Stopped vs FAV Compliant	**0.230**	**0.109**	**0.489**
favcb FAV Violation vs FAV Compliant	<0.001	<0.001	>999.999
favcb No FAV vs FAV Compliant	0.814	0.495	1.338
weather cloudy vs clear	**6.409**	**3.894**	**10.547**
weather rain & fog vs clear	0.586	0.315	1.089
Time to intersection @ yellow onset	1.000	0.995	1.005
HOD 1 vs 10	**15.332**	**1.675**	**140.373**
HOD 2 vs 10	>999.999	<0.001	>999.999
HOD 3 vs 10	1.640	0.438	6.144
HOD 4 vs 10	0.353	0.142	0.880
HOD 5 vs 10	0.678	0.317	1.454
HOD 6 vs 10	0.531	0.246	1.147
HOD 7 vs 10	0.554	0.257	1.193
HOD 8 vs 10	0.733	0.357	1.505
HOD 9 vs 10	0.882	0.432	1.798
HOD 11 vs 10	0.833	0.390	1.783
HOD 12 vs 10	0.938	0.456	1.932
HOD 13 vs 10	0.607	0.296	1.242
HOD 14 vs 10	0.846	0.417	1.717
HOD 15 vs 10	0.849	0.417	1.732
HOD 16 vs 10	1.028	0.489	2.161
HOD 17 vs 10	0.455	0.210	0.990
HOD 18 vs 10	0.634	0.281	1.430
HOD 19 vs 10	0.498	0.198	1.254
HOD 20 vs 10	0.992	0.349	2.820
HOD 21 vs 10	1.281	0.395	4.162
HOD 22 vs 10	1.223	0.301	4.961
HOD 23 vs 10	1.372	0.297	6.341
HOD 24 vs 10	4.835	0.484	48.274
DOW Fri vs Sun	1.387	0.818	2.351
DOW Mon vs Sun	**1.675**	**1.003**	**2.797**
DOW Sat vs Sun	**1.806**	**1.073**	**3.042**
DOW Thu vs Sun	1.668	0.979	2.842
DOW Tue vs Sun	0.934	0.542	1.608
DOW Wed vs Sun	**1.854**	**1.105**	**3.112**
Tvol	0.998	0.996	1.000
Diffspeed	**1.038**	**1.005**	**1.071**

Most significant risk factors are similar to straight-crossing maneuvers. In particular, the forward adjacent-vehicle crossing behavior and the weather conditions are nearly the same as the straight crossing. The hour-of-day effect followed a similar pattern; however, the pattern was not consistently significant, which may be due to lower sample size as indicated by contingency table (Appendix B).

Unlike the straight-crossing maneuver, traffic volume and TTIyp also did not demonstrate a significant impact on the risk of a violation. A subject vehicle exceeding the posted speed limit continued to affect the likelihood of a violation, albeit to a reduced degree. The remaining results are similar to SCP maneuvers. Of particular interest, however, is the increased (more than six times) likelihood of violation when the sky is cloudy versus clear. This finding continues to be one of the most unexpected results of this investigation.

Regression within Location

To investigate the contribution of violation risk by the different locations, a series of logistic regressions were also performed within each intersection for both straight-crossing and left-turn maneuvers. Contingency tables for these logistic regression procedures are provided in Appendix B. Unfortunately, the models for the left-turn maneuvers failed to converge due to insufficient sample sizes within a number of test cells, making examination infeasible. The results for the straight-crossing maneuvers are presented in Table 6.

Table 6. The odds ratio estimates for straight-crossing maneuvers at each of the three test sites.

Odds Ratio Estimates									
	Peppers Ferry			Depot			Independence		
Effect	Point Estimate	95% Wald Confidence Limits		Point Estimate	95% Wald Confidence Limits		Point Estimate	95% Wald Confidence Limits	
vtype bus-truck-trailer vs car-van	**3.183**	**1.529**	**6.629**	0.642	0.169	2.439	**5.350**	**3.123**	**9.165**
vtype pickup-suv vs car-van	0.941	0.698	1.268	1.011	0.652	1.566	0.938	0.779	1.129
lvcb LV Near Violation vs LV Compliant	9.584	0.738	124.375	1.043	0.032	33.947	2.358	0.511	10.886
lvcb LV Violation vs LV Compliant	>999.999	<0.001	>999.999				0.839	0.172	4.101
lvcb No LV vs LV Compliant	1.746	0.932	3.270	0.752	0.320	1.764	1.080	0.785	1.487
favcb FAV Near Violation vs FAV Compliant	1.011	0.059	17.176	<0.001	<0.001	>999.999	0.811	0.382	1.719
favcb FAV Stopped vs FAV Compliant	0.757	0.262	2.187	1.140	0.262	4.964	0.507	0.322	0.799
favcb FAV Violation vs FAV Compliant	4.683	0.213	103.034				0.586	0.280	1.227
favcb No FAV vs FAV Compliant	1.614	0.649	4.013	1.299	0.376	4.489	1.238	0.882	1.738
weather cloudy vs clear	**3.601**	**2.149**	**6.036**	**25.418**	**8.123**	**79.538**	**7.927**	**4.479**	**14.030**
weather rain & fog vs clear	1.293	0.691	2.421	0.513	0.119	2.202	1.093	0.610	1.958
Time to intersection @ yellow onset	1.100	0.958	1.264	**0.521**	**0.372**	**0.731**	**0.593**	**0.516**	**0.680**
HOD 1 vs 10	2.012	0.255	15.858						
HOD 2 vs 10	0.862	0.089	8.321	22.252	0.813	609.061	1.025	0.055	19.217
HOD 3 vs 10	0.443	0.095	2.061	**16.352**	**1.891**	**141.396**	1.511	0.399	5.725
HOD 4 vs 10	0.408	0.124	1.344	4.207	0.796	22.223	1.325	0.653	2.688
HOD 5 vs 10	0.370	0.126	1.088	2.004	0.434	9.251	0.848	0.482	1.492
HOD 6 vs 10	0.493	0.180	1.354	**10.074**	**2.495**	**40.684**	0.953	0.565	1.608
HOD 7 vs 10	**0.342**	**0.118**	**0.992**	**4.211**	**1.151**	**15.401**	1.007	0.600	1.690
HOD 8 vs 10	0.982	0.412	2.340	**4.428**	**1.206**	**16.259**	1.015	0.618	1.666
HOD 9 vs 10	0.594	0.242	1.455	1.531	0.395	5.933	0.645	0.395	1.054
HOD 11 vs 10	1.139	0.463	2.798	3.280	0.872	12.337	0.792	0.495	1.267
HOD 12 vs 10	0.841	0.359	1.971	3.765	0.899	15.769	1.075	0.637	1.815
HOD 13 vs 10	1.252	0.510	3.075	3.174	0.858	11.740	0.856	0.528	1.390
HOD 14 vs 10	2.016	0.882	4.609	**4.904**	**1.409**	**17.067**	0.838	0.515	1.362
HOD 15 vs 10	0.990	0.407	2.406	1.983	0.404	9.740	0.912	0.556	1.497
HOD 16 vs 10	1.082	0.470	2.491	3.565	0.946	13.433	0.990	0.607	1.614
HOD 17 vs 10	0.609	0.250	1.481	2.611	0.707	9.639	1.064	0.637	1.777
HOD 18 vs 10	0.470	0.178	1.238	2.438	0.616	9.650	1.456	0.860	2.467
HOD 19 vs 10	0.615	0.213	1.772	**7.452**	**1.788**	**31.059**	1.539	0.865	2.739
HOD 20 vs 10	0.776	0.242	2.488	**18.208**	**3.234**	**102.511**	**3.876**	**1.697**	**8.855**
HOD 21 vs 10	0.716	0.184	2.782	5.073	0.597	43.135	**6.368**	**1.891**	**21.439**
HOD 22 vs 10	0.688	0.147	3.214	>999.999	<0.001	>999.999	1.286	0.289	5.729

Odds Ratio Estimates									
	Peppers Ferry			Depot			Independence		
Effect	Point Estimate	95% Wald Confidence Limits		Point Estimate	95% Wald Confidence Limits		Point Estimate	95% Wald Confidence Limits	
HOD 23 vs 10	1.531	0.207	11.333	>999.999	<0.001	>999.999	>999.999	<0.001	>999.999
HOD 24 vs 10	1.735	0.206	14.609	>999.999	<0.001	>999.999	>999.999	<0.001	>999.999
DOW Mon vs Sun	**1.879**	**1.034**	**3.413**	1.038	0.469	2.299	0.877	0.587	1.309
DOW Tue vs Sun	1.297	0.692	2.434	1.313	0.564	3.056	0.948	0.649	1.385
DOW Wed vs Sun	1.498	0.822	2.727	0.844	0.377	1.888	0.974	0.665	1.425
DOW Thu vs Sun	**2.083**	**1.132**	**3.832**	0.619	0.246	1.563	0.813	0.548	1.207
DOW Fri vs Sun	**2.103**	**1.082**	**4.087**	0.625	0.277	1.410	0.848	0.575	1.250
DOW Sat vs Sun	1.343	0.715	2.524	0.888	0.410	1.923	0.903	0.621	1.314
Tvol	0.999	0.996	1.002	0.997	0.993	1.001	**1.003**	**1.001**	**1.005**
Approach 2 vs 1	**0.395**	**0.251**	**0.622**	**0.060**	**0.006**	**0.643**	<0.001	<0.001	>999.999
Approach 3 vs 1	1.244	0.841	1.841	0.513	0.236	1.114	0.991	0.819	1.200
Approach 4 vs 1	**0.123**	**0.069**	**0.220**	4.758	1.148	19.718			
Diffspeed	**1.229**	**1.160**	**1.302**	1.117	0.992	1.257	**1.128**	**1.090**	**1.167**

The vehicle type demonstrated a notable difference in violation risk for the Depot location. At this intersection, the heavy-vehicle category demonstrated a tendency for protective effect unlike the significant increase in violation risk (three to five times) found at the other two locations. It is possible this difference is due to the region of the intersection. Of the three intersections, Depot is the only location that lies at the entrance of a town and in which the major approach transitions from a higher speed (45 mi/h) to a lower speed (25 mi/h) roadway. As such, the heavy vehicles are primarily on either a low-speed approach or are transitioning to one, and are thus moving slower than at the other sites, therefore permitting a stop with reduced braking requirements and negating the risk found at the other sites.

Furthermore, the risk associated with vehicle type may also be related to vehicle weight and roadway incline. The Depot intersection has nearly flat approaches whereas the Peppers Ferry intersection has a grade ranging from 1% to 3% (depending on the approach) while the Independence intersection has minor approaches with a 1% grade but main approaches with a 6% grade. In general, the risk of violation appears to increase directly proportional to the grade found at the intersection. This may explain one of the reasons why an increased rate of violations is found at the Independence intersection where the two main approaches have the 6% grade. Unfortunately, there were an insufficient number of intersections in this data set to make a statistical conclusion regarding the influence of grade on violation likelihood (the model failed to converge). Continuing research that directly considers grade could validate this possible relationship.

Cloudy weather conditions continue to create an elevated risk relative to clear conditions. In fact, Depot has over 25 times the risk of violation when the weather conditions are cloudy; highlighting a potential area to make a safety improvement at that intersection. Additional research, from a visibility perspective, is likely required to identify precisely what is causing drivers to violate under cloudy conditions.

The TTIyp had similar risk for Depot and Independence; however, there was no significant difference in risk at Peppers Ferry. This could indicate that yellow time programmed into the controller at Peppers Ferry is better matched to its corresponding drivers than the timing at Depot and Independence. Alternatively, it was also noted by analysts during reduction that more drivers opted to violate very late at Peppers Ferry after completing a stop, these drivers may be influencing the model.

The hour of day at which the risk of violation is significant is inconsistent across location and is somewhat erratic due to low cell sizes at certain times. In general, it appears that late night and early morning carry the highest risk. For an unknown reason, Depot demonstrated a tenfold increase in violation risk at 6:00 a.m. as compared to 10:00 a.m. Perhaps there is a group of commuters who consistently violated the traffic control device at the same time each day. Further data reduction would be required to determine if repeated offenses by the same vehicle(s) are impacting the violation frequency as related to the time of day.

Finally, Peppers Ferry demonstrated the only instance in which the day of the week had an influence. The influence occurred at the beginning and end of the week, which is consistent with the previous findings described in the literature review. It is unclear from this analysis what differences between the intersections resulted in the discrepancy between the data location sites.

ADDITIONAL EXPLORATORY ANALYSES

In light of the logistic regression results, additional exploratory analyses were performed to gain further insights toward explaining a few of the most interesting trends. Box plots were selected as the statistical tool since they provide an easily interpreted graphical representation of data trends.

A box plot is a statistical method that visually depicts the empirical distributions of different populations without any assumptions of the underlying distribution. Most of the data within a group are contained inside a box which bounds the first and third quartile. The line within the box represents the median. The whiskers depict the regions that lie within 1.5 times the corresponding quartile. Values outside the whiskers are unusual observations and may be treated as outliers. In general, it is likely that an effect is significant if the boxes of two groups do not overlap.

The first box plots were drawn to investigate the relationship between the time of day and violation likelihood that was identified in the overall logistic regression. Specifically, an elevated risk of a violation occurred during the late night and early morning hours, particularly for straight-crossing violations. The analysts performing data reduction noted that during night events it appeared relatively common for drivers to stop their vehicle at a signal and then subsequently violate. These events appeared to be the result of a driver who stopped at a red light and subsequently grew impatient, leading to a decision to violate rather than wait for the signal to cycle. It was hypothesized that such a maneuver would lead to a lower minimum stop-bar speed during the hours with elevated violation risk.

The velocity at the stop bar was computed as a function of the hour of day for both straight-crossing (Figure 13) and left-turn violations (Figure 14). For straight crossings, the stop-bar speed at violation tends to decrease between the hours of 23:00 and 03:00. This time window corresponds to the significant effects found in the logistic regression. The average stop bar velocity was as low as 5 m/s (11 mi/h), which is substantially lower than the average speed limit of approximately 16 m/s (35 mi/h).

This low average stop-bar speed indicates that drivers either stopped or nearly stopped their vehicle prior to violating. Such behavior suggests a driver who is cognizant of the intersection and the red state of the signal, yet performs a purposeful violation. This driver is essentially treating the signalized intersection as an un-signalized intersection by approaching, slowing/stopping, and then proceeding when conflicting traffic is not present. Such a driver may not pose a significant crash risk, particularly considering the low traffic volumes present during the times at which this effect is prevalent.

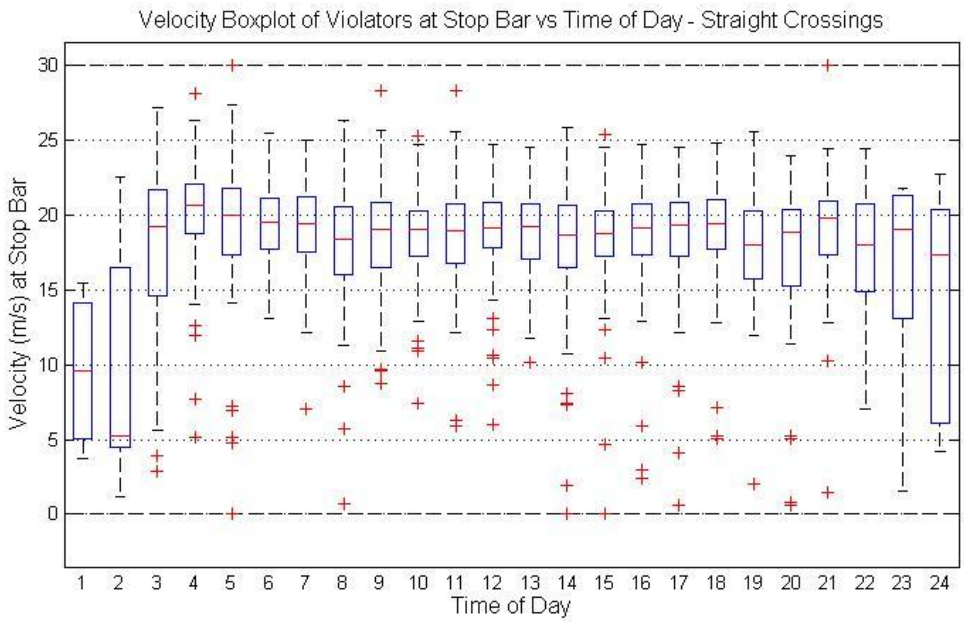

Figure 13. Graph. Vehicle velocity at the stop bar plotted as a function of the Time of Day at which a violation occurs for straight-crossing-path violations.

A similar trend is noted in left-turn maneuvers; however, as with the logistic regression, the effect size is smaller and generally fails to achieve a statistically significant level. The trend is exhibited over the hours of 21:00-03:00; which is a longer period of time than identified in straight crossings. This could indicate that drivers are somewhat more willing to treat the left turn signal like a stop sign; however, it may also simply indicate that drivers making left turns are more likely to encounter a red light during times of low traffic density (most signals are programmed to “rest” with the green in the straight-crossing direction). Further research is required to tease out differences between the straight-crossing and left-turn maneuvers since an analysis comparing the two maneuver types was not performed.

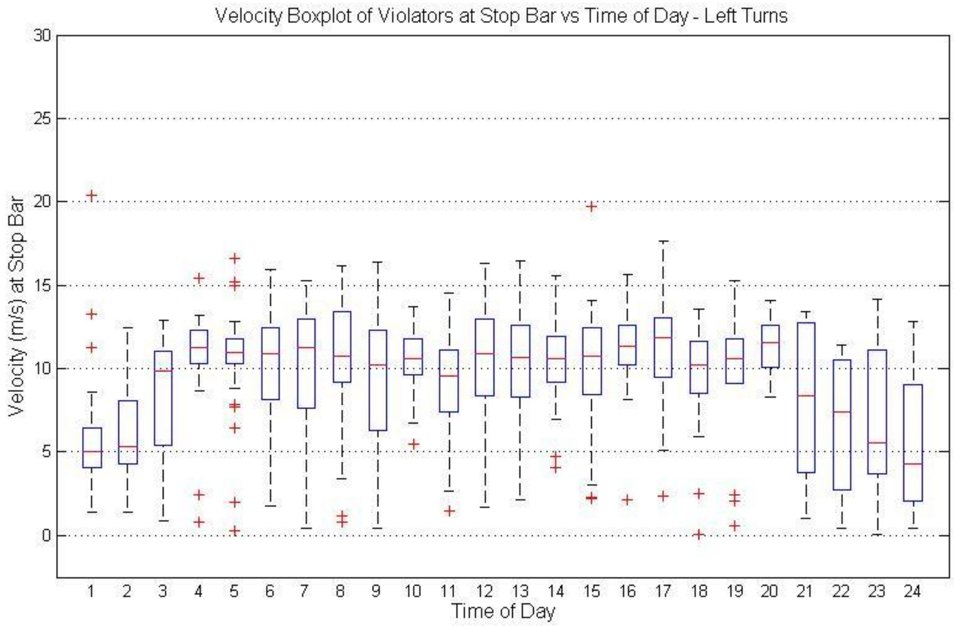

Figure 14. Graph. Vehicle velocity at the stop-bar plotted as a function of the Time of Day at which a violation occurs for left turn violations.

A second interesting result noted during the logistic regression was a large increase in violation risk associated with crossing the intersection during cloudy versus clear conditions. To investigate, a box plot of the time after red (TAR) at which the violating vehicle crossed the stop-bar was plotted (Figure 15). The premise of this analysis was to determine if the visibility of the signal played a role in increasing violation risk. It was hypothesized that under lower visibility conditions drivers might fail to perceive the signal, which could lead to violations that occur later in the red cycle (i.e., un-willful violations rather than drivers who slightly misjudged the length of the yellow state).

Results indicate that mean TAR remains largely unchanged across the cloudy and clear conditions. There is less variability in TAR for cloudy versus clear conditions, particularly for left-turn violations. The differences in variability are interesting given the increased risk of a violation during cloudy weather. Cloudy weather seems to result in a more consistently timed intersection approach; however, an increased proportion of approaches during cloudy weather will result in a violation.

Perhaps the increased violation risk can be attributed to better visual contrast of the traffic signal when it is viewed against a cloudy sky, rather than a clear sky in which glare from the sun may also be present. Drivers approaching a traffic signal under cloudy conditions are more likely to perceive the initial signal change from a further distance which allows them to make a more informed decision. This may result in a larger number of drivers who are sufficiently confident in the amount of remaining yellow cycle time to attempt “beating the light.” In contrast, drivers approaching the signal under clear skies may not perceive the signal until it is too late to stop. This occurs regardless of the signal state, which is why a larger number of drivers cross through the intersection well after the presentation of red.

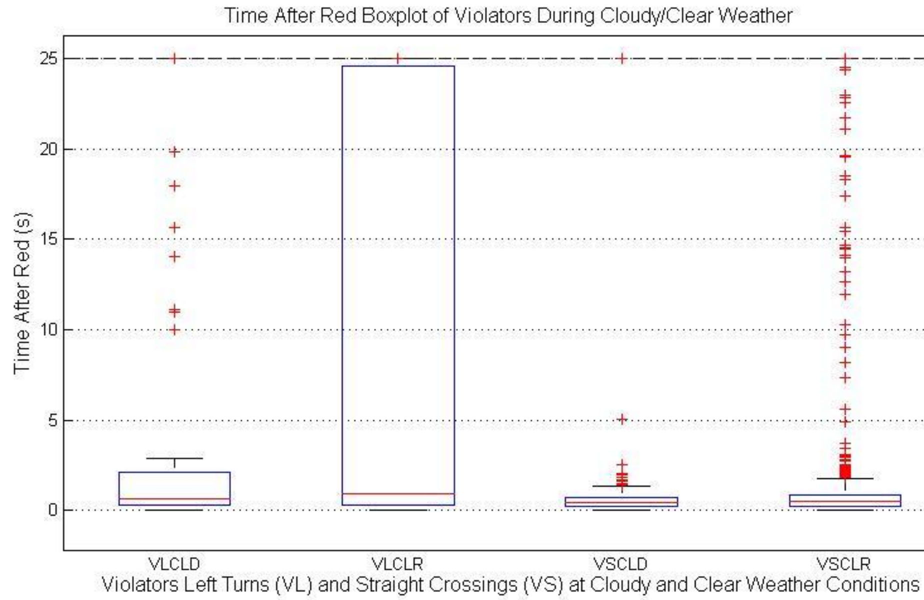

Figure 15. Graph. Time after red (TAR) when the violating vehicle crosses the stop bar, grouped by maneuver and cloudy versus clear weather conditions.

The above box plot fails to fully explain the impact of the weather condition on violation likelihood. It does, however, make an interesting statement about the potential dangers associated with performing a left turn during clear conditions. A large proportion of the drivers making left turns in clear conditions are doing so several seconds after the presentation of red. Since a late violation increases the chance that conflicting traffic will be present, these data suggest that left-turn violations committed in clear conditions pose a particularly high risk of collision. As with the weather impact itself, this finding also needs further investigation to be fully characterized.

CHAPTER 4. CONCLUSIONS

The discussion contained within the results chapter conveyed a number of interesting findings that are worth further consideration during this conclusion. Many of the results validate the published findings of previous research for the straight-crossing maneuvers; i.e., the risk of a violation increases for heavy vehicles, higher initial speed, and adjacent vehicle presence. Interestingly, with the exception of the initial speed, none of these factors influenced the likelihood of a left-turn violation, which may be due to the requirement for the driver to slow the vehicle in preparation for turning.

Some previously published results that were not confirmed include the relationship of traffic volume and day of the week to violation risk. It was suggested that this discrepancy could be related to the urban nature of the other intersections previously studied. Unlike those intersections, the collection sites of this study were not exposed to highly congested levels of traffic. Perhaps the influence of traffic volume does not become apparent until traffic begins to have significant queue lengths. Likewise, the day of the week effect may be related to these long queue lengths when drivers are motivated to start their weekend.

A few results considered in parallel may suggest that grade is a significant contributor to the differences found between intersections. While the Independence and Peppers Ferry intersections have an inclined grade on most of their approaches, Depot is nearly flat in all directions. Accordingly, Depot did not exhibit an increased risk for violations from heavy vehicles as the other two sites did. Depot was also the only intersection that did not exhibit an increased violation risk as a function of the initial vehicle speed. Since faster and heavier vehicles will be increasingly difficult to stop with increased incline, it is suggested that grade might play a role in the underlying cause of the increased violation risk.

It was not within the scope of this project to accurately measure and evaluate the approach grade of the intersections. An attempt was made to further assess the influence of grade through inclusion of intersection approach as a factor in the logistic regression. Unfortunately, due to a few small cell sizes, the models failed to converge when approach was included. Obtaining an accurate measure of grade and including that measure as a continuous variable into the logistic regression model is a potentially productive extension of the work performed during this effort.

There was an interesting trend that was investigated for the time-of-day factor. The risk of violation increased from the late evening into the early morning. Based on some informal comments from analysis regarding the nature of these violations, it became apparent that in some instances the violations were likely willful. These comments were supported, though not confirmed, through the box plot of stop bar speed as a function of the time of day. These plots showed that drivers did have a much lower speed during the same time periods in which the violation risk increased. It appears that these drivers were slowing or stopping their vehicle at a red light and then crossing the intersection prior to receiving the green signal.

If these violations were indeed willfully performed due to impatient drivers, there may be a potential treatment. It is possible that during the late evening/early morning hours the traffic volume is very low such that a driver who stops at a red is not stopping for conflicting traffic. This unnecessary stop may aggravate the driver and motivate a violation. Some potential mitigation strategies may include decreasing the time required to switch phases when a presence detector is triggered or to simply place the signals into a flash mode so that drivers only need to perform a brief stop.

Perhaps the most intriguing result of this research is finding that the likelihood of a violation is six times greater when the sky is cloudy than when it is clear. These findings should be further investigated to identify the underlying causes. A theory was presented that a greater visibility of the signal in cloudy conditions could lead drivers to become more aware of the signal from longer distances which motivates them to attempt to use the entire yellow phase.

Considering the relatively large contribution of weather to violation risk, teasing out the underlying mechanisms could lead to effective intersection crash mitigation strategies. To further investigate this finding it is likely necessary to collect data inside the vehicle to allow direct assessment of driver information. The upcoming SHRP2 naturalistic driving study may be a potential data source that will be large enough to capture a sufficient number of crossings under differing weather conditions to make a robust assessment.

An additional suggestion is to focus future research on the subset of violations that are dangerous from a crash-risk perspective. This is a difficult link to create; however, during this effort it became clear that a large number of violations in the models were simply not very dangerous. That is, the risk of a crash was quite low. Since the ultimate goal of transportation safety research is decreasing crashes and the resulting injuries, analysis of benign violations should be avoided when possible. Some examples from this analysis included the large number of violations that occurred immediately after the presentation of red. Violations that occur within the first few seconds after the red phase are unlikely to result in a crash as the conflicting traffic is not present.

Violations which occur later in the red phase should be the focus of projects such as this. The authors believe that the characteristics of the more egregious violations are likely significantly different than those that were assessed in this research. Many of the results, such as the time-of-day factor, are likely due to violations that do not carry a high risk of collision. The box plot of the time after red (Figure 15) demonstrated a factor (i.e., weather) that may have a large influence on the more dangerous (well into the red phase) violations. Focusing on findings of this nature would ensure that more meaningful results are obtained from the perspective of identifying treatments that could have a direct impact on saving lives.

APPENDIX A.

Table 7. List of questions that were addressed by data reductionists during the event annotation.

Q_ID	Q_Text	A_ID	A_Text
1	Is the video operational?	1	Yes, present and usable
1	Is the video operational?	2	Yes, poor video quality
1	Is the video operational?	3	No, no video present
2	Is video aligned?	4	Yes
2	Is video aligned?	5	No
2	Is video aligned?	6	Uncertain
3	Has the event been spot-checked?	7	Yes
3	Has the event been spot-checked?	8	No
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	9	Yes, Event is valid
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	10	No, Lead vehicle stopped in front of subject
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	11	No, Subject turned right
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	12	No, Insufficient radar/video data
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	13	No, Alternative traffic control
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	14	No, False trigger
4	Is the Event Valid? (If NOT, answer this question and skip to the end)	15	No, Incorrect radar vehicle position prediction
5	Vehicle Type	16	Car
5	Vehicle Type	17	Van (minivan or standard)
5	Vehicle Type	18	Pickup truck
5	Vehicle Type	19	SUV (includes Jeep)
5	Vehicle Type	20	Bus (transit or motor coach)
5	Vehicle Type	21	School Bus
5	Vehicle Type	22	Single-unit straight truck (includes panel truck Uhaul)
5	Vehicle Type	23	Tractor Trailer
5	Vehicle Type	24	Motorcycle or moped
5	Vehicle Type	25	Emergency vehicle (police, fire, ems - inservice)
5	Vehicle Type	26	Emergency vehicle (police, fire, ems - not in service)
5	Vehicle Type	27	Vehicle pulling trailer
5	Vehicle Type	28	Other/Unknown vehicle type
6	Turn Intent	29	Right turn
6	Turn Intent	30	Left turn
6	Turn Intent	31	Straight crossing
6	Turn Intent	32	U-turn
6	Turn Intent	33	Unable to determine

7	Was Turn Intent Permitted by Lane Restrictions?	34	Yes
7	Was Turn Intent Permitted by Lane Restrictions?	35	No + Original travel phase is NOT red; new travel IS red
7	Was Turn Intent Permitted by Lane Restrictions?	36	No + Original travel phase IS red; new travel phase is NOT red
7	Was Turn Intent Permitted by Lane Restrictions?	37	No + Both travel phases are red.
7	Was Turn Intent Permitted by Lane Restrictions?	38	No + Both travel phases are green.
8	Crossing Behavior	39	Not Applicable (Vehicle Stopped)
8	Crossing Behavior	40	Compliant (Yellow through Stop Bar)
8	Crossing Behavior	41	Near Violation (Red ON Stop Bar)
8	Crossing Behavior	42	Violation (Red before Stop Bar)
8	Crossing Behavior	43	Unable to determine
9	Stopping Behavior	44	Not Applicable (Vehicle did NOT stop)
9	Stopping Behavior	45	Stopped in Compliant Zone (Behind stop bar)
9	Stopping Behavior	46	Stopped in Protrusion Zone (<50% Over stop bar)
9	Stopping Behavior	47	Stopped in Intrusion Zone (>50% Over stop bar AND not in conflicting traffic)
9	Stopping Behavior	48	Stopped in Collision Zone (In conflicting traffic)
9	Stopping Behavior	49	Unable to determine
10	Is a lead vehicle present?	50	Yes
10	Is a lead vehicle present?	51	No
10	Is a lead vehicle present?	52	Unable to Determine
11	Lead vehicle's Crossing Behavior	53	Not Applicable (No Lead Vehicle)
11	Lead vehicle's Crossing Behavior	54	Lead Vehicle Stopped
11	Lead vehicle's Crossing Behavior	55	Compliant (Yellow through Stop Bar)
11	Lead vehicle's Crossing Behavior	56	Near Violation (Red ON Stop Bar)
11	Lead vehicle's Crossing Behavior	57	Violation (Red before Stop Bar)
11	Lead vehicle's Crossing Behavior	58	Unable to determine
12	Lead vehicle's Stopping Behavior	59	Not Applicable (No Lead Vehicle)
12	Lead vehicle's Stopping Behavior	60	Lead Vehicle did NOT stop
12	Lead vehicle's Stopping Behavior	61	Stopped in Compliant Zone (behind stop bar)
12	Lead vehicle's Stopping Behavior	62	Stopped in Protrusion Zone (<50% over stop bar)
12	Lead vehicle's Stopping Behavior	63	Stopped in Intrusion Zone (>50% over stop bar AND not in conflicting traffic)
12	Lead vehicle's Stopping Behavior	64	Stopped in Collision Zone (in conflicting traffic)
12	Lead vehicle's Stopping Behavior	65	Unable to determine
13	Is a following vehicle present?	66	Yes
13	Is a following vehicle present?	67	No
13	Is a following vehicle present?	68	Unable to determine
14	Following vehicle's Crossing Behavior	69	Not Applicable (No Following Vehicle)
14	Following vehicle's Crossing Behavior	70	Following Vehicle Stopped
14	Following vehicle's Crossing Behavior	71	Compliant (Yellow through Intersection)

14	Following vehicle's Crossing Behavior	72	Near Violation (Red ON Stop Bar)
14	Following vehicle's Crossing Behavior	73	Violation (Red before Stop Bar)
14	Following vehicle's Crossing Behavior	74	Unable to determine
15	Following vehicle's Stopping Behavior	75	Not Applicable (No Following Vehicle)
15	Following vehicle's Stopping Behavior	76	Following Vehicle did NOT stop
15	Following vehicle's Stopping Behavior	77	Stopped in Compliant Zone (behind stop bar)
15	Following vehicle's Stopping Behavior	78	Stopped in Protrusion Zone (<50% over stop bar)
15	Following vehicle's Stopping Behavior	79	Stopped in Intrusion Zone (>50% over stop bar AND not in conflicting traffic)
15	Following vehicle's Stopping Behavior	80	Stopped in Collision Zone (in conflicting traffic)
15	Following vehicle's Stopping Behavior	81	Unable to determine
16	Is a Forward Adjacent Vehicle present?	82	Yes
16	Is a Forward Adjacent Vehicle present?	83	No
16	Is a Forward Adjacent Vehicle present?	84	Unable to determine
17	Forward Adjacent Vehicle's crossing behavior	85	Not applicable (No Forward Adjacent Vehicle)
17	Forward Adjacent Vehicle's crossing behavior	86	Forward Adjacent Vehicle stopped
17	Forward Adjacent Vehicle's crossing behavior	87	Compliant (Yellow through stop bar)
17	Forward Adjacent Vehicle's crossing behavior	88	Near Violation (Red ON stop bar)
17	Forward Adjacent Vehicle's crossing behavior	89	Violation (Red before stop bar)
17	Forward Adjacent Vehicle's crossing behavior	90	Unable to determine
18	Forward Adjacent Vehicle's stopping behavior	91	Not Applicable (No Forward Adjacent Vehicle)
18	Forward Adjacent Vehicle's stopping behavior	92	Forward Adjacent Vehicle did NOT stop
18	Forward Adjacent Vehicle's stopping behavior	93	Stopped in Compliant Zone (behind stop bar)
18	Forward Adjacent Vehicle's stopping behavior	94	Stopped in Protrusion Zone (<50% over stop bar)
18	Forward Adjacent Vehicle's stopping behavior	95	Stopped in Intrusion Zone (>50% over stop bar AND not in conflicting traffic)
18	Forward Adjacent Vehicle's stopping behavior	96	Stopped in Collision Zone (in conflicting traffic)
18	Forward Adjacent Vehicle's stopping behavior	97	Unable to determine
19	Is a Rearward Adjacent Vehicle present?	98	Yes
19	Is a Rearward Adjacent Vehicle present?	99	No
19	Is a Rearward Adjacent Vehicle present?	100	Unable to determine
20	Rear Adjacent Vehicle's crossing behavior	101	Not applicable (No Rear Adjacent Vehicle)
20	Rear Adjacent Vehicle's crossing behavior	102	Rear Adjacent Vehicle stopped
20	Rear Adjacent Vehicle's crossing behavior	103	Compliant (Yellow through stop bar)
20	Rear Adjacent Vehicle's crossing behavior	104	Near Violation (Red ON stop bar)
20	Rear Adjacent Vehicle's crossing behavior	105	Violation (Red before stop bar)
20	Rear Adjacent Vehicle's crossing behavior	106	Unable to determine
21	Rear Adjacent Vehicle's stopping behavior	107	Not Applicable (No Rear Adjacent Vehicle)
21	Rear Adjacent Vehicle's stopping behavior	108	Rear Adjacent Vehicle did NOT stop
21	Rear Adjacent Vehicle's stopping behavior	109	Stopped in Compliant Zone (behind stop bar)
21	Rear Adjacent Vehicle's stopping behavior	110	Stopped in Protrusion Zone (<50% over stop bar)
21	Rear Adjacent Vehicle's stopping behavior	111	Stopped in Intrusion Zone (>50% over stop bar AND not in conflicting traffic)
21	Rear Adjacent Vehicle's stopping behavior	112	Stopped in Collision Zone (in conflicting traffic)

21	Rear Adjacent Vehicle's stopping behavior	113	Unable to determine
22	Conflicting Traffic Behavior	114	Not Applicable (No conflicting traffic OR Subject stopped prior to Collision Zone)
22	Conflicting Traffic Behavior	115	No movement
22	Conflicting Traffic Behavior	116	Movement begun
22	Conflicting Traffic Behavior	117	Entered intersection
22	Conflicting Traffic Behavior	118	Crossing intersection
23	Event classification	119	Not Applicable (No conflicting traffic OR Subject stopped prior to Collision Zone)
23	Event classification	120	Non-conflict (Conflicting traffic does not enter intersection box)
23	Event classification	121	Conflict (Conflicting traffic enters intersection but no change in trajectory required)
23	Event classification	122	Potential Crash (Did not require sudden evasive action)
23	Event classification	123	Near Crash (Sudden evasive maneuver performed)
23	Event classification	124	Crash
23	Event classification	125	Unable to determine
24	Weather	126	Clear
24	Weather	127	Cloudy
24	Weather	128	Rain
24	Weather	129	Sleet
24	Weather	130	Snow
24	Weather	131	Fog
24	Weather	132	Rain &Fog
24	Weather	133	Sleet & Fog
24	Weather	134	Other (sand, smoke, smog, dust)
24	Weather	135	Unknown
25	Roadway surface Condition	136	Dry
25	Roadway surface Condition	137	Wet
25	Roadway surface Condition	138	Snow or Slush
25	Roadway surface Condition	139	Ice
25	Roadway surface Condition	140	Mud Sand Oil Dirt
25	Roadway surface Condition	141	Other
25	Roadway surface Condition	142	Unknown
26	Daytime or Nighttime?	143	Daylight
26	Daytime or Nighttime?	144	Dawn/Dusk
26	Daytime or Nighttime?	145	Nighttime
26	Daytime or Nighttime?	146	Unable to determine
27	Does this event need to be reviewed by the project manager?	147	Yes
27	Does this event need to be reviewed by the project manager?	148	No

APPENDIX B.

Table 8. Contingency table across all locations.

Independent Variables		Straight Crossing		Left /U-Turn	
		Non Violators	Violators	Non Violators	Violators
V Type	Car-Van	1087	1171	386	308
	Pickup-SUV	812	821	338	214
	Bus-Truck	50	144	25	43
LVCT	No LV	1675	1962	625	499
	LV Compliant	182	159	63	52
	LV Near Violation	5	9	6	8
	LV Violation	4	4	1	6
FAVCT	No FAV	1605	1846	623	505
	FAV Stopped	195	111	77	15
	FAV Compliant	103	139	42	43
	FAV Near Violation	24	20	5	1
	FAV Violation	22	20	2	1
Weather	Clear	1823	1808	679	454
	Cloudy	57	267	28	90
	Rain & Fog	69	61	42	21
Day of Week	Sunday	239	229	93	52
	Monday	249	284	105	91
	Tuesday	307	355	126	62
	Wednesday	289	341	105	92
	Thursday	265	290	103	85
	Friday	326	359	127	99
	Saturday	274	278	90	84
Hour of Day	1	3	4	1	23
	2	4	7	0	14
	3	17	26	5	16
	4	62	80	40	19
	5	89	89	47	35
	6	101	120	51	27
	7	113	114	48	26
	8	130	137	49	34
	9	142	110	49	38
	10	131	133	46	31
	11	123	138	40	27
	12	110	123	46	32
	13	124	132	57	29
	14	120	154	46	35
	15	121	114	50	34
	16	128	143	36	30
	17	123	127	44	26
	18	116	135	32	23
	19	93	100	29	14
	20	49	77	15	13
	21	26	36	8	13
	22	19	17	5	11
	23	3	11	4	8
	24	2	9	1	7

Table 9. Contingency table for the Peppers Ferry intersection.

Independent Variables		Straight Crossing		Left /U-Turn	
		Non Violators	Violators	Non Violators	Violators
V Type	Car-Van	396	198	231	132
	Pickup-SUV	295	136	185	94
	Bus-Truck	19	23	12	30
LVCT	No LV	591	337	372	239
	LV Compliant	74	17	31	15
	LV Near Violation	1	2	3	2
	LV Violation	0	1	0	0
FAVCT	No FAV	629	328	354	238
	FAV Stopped	55	19	41	7
	FAV Compliant	22	8	29	10
	FAV Near Violation	3	1	4	1
	FAV Violation	1	1	0	0
Weather	Clear	633	282	393	202
	Cloudy	39	53	12	38
	Rain & Fog	38	22	23	16
Day of Week	Sunday	100	36	62	29
	Monday	88	48	55	40
	Tuesday	105	47	66	22
	Wednesday	109	62	66	39
	Thursday	98	71	65	44
	Friday	115	59	65	49
	Saturday	95	34	49	33
Hour of Day	1	3	4	0	20
	2	2	3	0	12
	3	10	9	1	8
	4	31	19	22	10
	5	32	16	19	16
	6	40	20	34	15
	7	36	10	23	10
	8	47	25	22	14
	9	43	15	35	15
	10	37	17	27	11
	11	29	20	24	6
	12	49	20	19	16
	13	34	20	34	12
	14	36	33	24	11
	15	46	17	35	8
	16	45	23	23	16
	17	45	18	23	11
	18	40	16	21	8
	19	34	13	18	6
	20	32	14	13	8
	21	19	9	6	6
	22	15	6	2	6
	23	3	5	3	6
	24	2	5	0	5
Approach	P1	267	186	49	44
	P2	162	39	134	58
	P3	126	82	107	93
	P4	155	50	138	61

Table 10. Contingency table for the Independence intersection.

Independent Variables		Straight Crossing		Left /U-Turn	
		Non Violators	Violators	Non Violators	Violators
V Type	Car-Van	491	853	24	24
	Pickup-SUV	378	603	27	16
	Bus-Truck	22	115	2	2
LVCT	No LV	768	1437	49	37
	LV Compliant	88	126	1	5
	LV Near Violation	3	6	0	0
	LV Violation	4	3	0	0
FAVCT	No FAV	671	1328	51	41
	FAV Stopped	114	81	1	0
	FAV Compliant	69	126	0	1
	FAV Near Violation	19	19	0	0
	FAV Violation	21	19	1	0
Weather	Clear	859	1358	52	37
	Cloudy	14	180	1	5
	Rain & Fog	21	35	0	0
Day of Week	Sunday	90	162	6	2
	Monday	113	200	6	7
	Tuesday	158	273	7	8
	Wednesday	131	250	12	12
	Thursday	123	203	9	4
	Friday	152	273	7	5
	Saturday	127	212	6	4
Hour of Day	1	0	0	0	0
	2	1	1	0	0
	3	5	8	0	1
	4	22	52	1	2
	5	42	65	6	6
	6	49	87	6	1
	7	51	91	3	4
	8	61	98	6	2
	9	69	86	0	1
	10	61	109	2	3
	11	73	110	3	6
	12	44	95	6	2
	13	67	101	1	0
	14	61	105	7	2
	15	60	93	5	4
	16	62	109	3	2
	17	49	96	4	1
	18	51	110	0	3
	19	45	72	0	1
	20	12	49	0	0
	21	5	24	0	1
	22	4	5	0	0
	23	0	5	0	0
	24	0	2	0	0
Approach	I1	546	891	4	0
	I2	4	0	47	42
	I3	344	682	2	0
	I4	0	0	0	0

Table 11. Contingency table for the Depot intersection.

Independent Variables		Straight Crossing		Left /U-Turn	
		Non Violators	Violators	Non Violators	Violators
V Type	Car-Van	200	120	131	152
	Pickup-SUV	139	82	126	104
	Bus-Truck	9	6	11	11
LVCT	No LV	319	190	204	223
	LV Compliant	8	1	31	32
	LV Near Violation	20	16	3	6
	LV Violation	1	1	1	6
FAVCT	No FAV	308	192	218	226
	FAV Stopped	26	11	35	8
	FAV Compliant	12	5	13	32
	FAV Near Violation	2	0	1	0
	FAV Violation	0	0	1	1
Weather	Clear	334	170	234	215
	Cloudy	4	34	15	47
	Rain & Fog	10	4	19	5
Day of Week	Sunday	49	31	25	21
	Monday	48	36	44	44
	Tuesday	44	35	53	32
	Wednesday	49	30	27	41
	Thursday	44	16	29	37
	Friday	60	28	55	45
	Saturday	54	32	35	47
Hour of Day	1	0	0	1	3
	2	1	3	0	2
	3	2	9	4	7
	4	9	9	17	7
	5	15	8	22	13
	6	12	13	11	11
	7	26	13	22	12
	8	22	14	21	18
	9	31	9	14	22
	10	33	7	17	17
	11	21	10	13	15
	12	17	8	21	14
	13	24	11	22	17
	14	23	16	15	22
	15	15	4	10	22
	16	21	11	10	12
	17	29	13	17	14
	18	25	9	11	12
	19	14	15	11	7
	20	5	14	2	5
	21	3	3	2	6
	22	0	6	3	5
	23	0	1	1	2
	24	0	2	1	2
Approach	D1	53	33	4	6
	D2	16	1	245	180
	D3	275	156	12	19
	D4	4	18	7	62

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