RITA Intelligent Transportation Systems
Joint Program Office

Macroscopic Review of Driver Gap Acceptance and Rejection Behavior at Rural Thru-Stop Intersections in the US – Data Collection Results for Eight States:

(CICAS-SSA Final Report # 3)

August 2010

U.S. Department of Transportation
Research and Innovative Technology Administration

Intelligent Transportation Systems Institute
Center for Transportation Studies
University of Minnesota
511 Washington Avenue SE, Suite 200
Minneapolis, Minnesota 55455

Intelligent Vehicles Laboratory
Department of Mechanical Engineering
University of Minnesota

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Macroscopic Review of Driver Gap Acceptance and Rejection Behavior at Rural Thru-Stop Intersections in the US – Data Collection Results in Eight States: CICAS-SSA Report #3		5. Report Date August 2010 6. Performing Organization Code:
7. Author(s) Alec Gorjestani, Arvind Menon, Pi-Ming Cheng, Bryan Newstrom, Craig Shankwitz, Max Donath		8. Performing Organization Report No. CTS Project #2006050
9. Performing Organization Name and Address Department of Mechanical Engineering University of Minnesota 111 Church Street S.E. Minneapolis, Minnesota 55455		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address United States Department of Transportation, Federal Highway Administration 1200 New Jersey Ave, S.E. Washington, DC 20590		13. Type of Report and Period Covered Work started March 2006. Draft report submitted to Mn/DOT: November 2008. 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Crashes at rural thru-stop intersections arise primarily from a driver attempting to cross or enter the mainline traffic stream after failing to recognize an unsafe gap condition.

Because the primary cause of these crashes is not failure to stop, but failure to recognize an unsafe condition, the US DOT FHWA, Mn/DOT, and the University of Minnesota ITS Institute undertook the CICAS-SSA program. CICAS-SSA uses roadside radar sensors, a computer processor and algorithms to determine unsafe conditions, and an active LED icon based sign to provide timely alerts and warnings which are designed to reduce the frequency of crashes at rural expressway intersections.

These rural, thru-stop crashes are problems in many states. In conjunction with the CICAS-SSA program, Mn/DOT and the University of Minnesota led a nine-state (CA, GA, IA, MI, MN, NC, NH, NV, and WI) pooled-fund study whereby driver behavior data at rural thru-stop intersections was collected by the Minnesota Mobile Intersection Surveillance System (MMISS).

The ultimate goal of the pooled fund study and the analysis of that data described here, was to identify whether drivers in different regions of the county exhibit different gap acceptance/rejection behavior, and if different driver behaviors are identified, determine whether they are different enough to inhibit the deployment of a common CICAS-SSA design throughout the US. The analysis of the data indicated that the system can indeed be deployed nationally.

17. Key Words	18. Distribution Statement
Rural highways, Unsignalized intersections, Highway safety, Collisions, Gap acceptance, Cooperative Intersection Collision Avoidance Systems-Stop Sign Assist (CICAS-SSA) program, Warning signs, Automobile drivers, Human factors, Driver behavior, Graphical user interfaces, Information display systems	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class if. (of this report)	20. Security Class if. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	49	

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

TECHNICAL REPORT DOCUMENTATION PAGE

Acknowledgements

We wish to thank Janet Creaser for providing a review of intersection gap analyses and Table 2 comparing the results of various critical gap estimation techniques.

Arvind Menon, Lee Alexander, and Bryan Newstrom of the IV Lab travelled to WI, MI, IA, NC, GA, NV, and CA to install and take down the system after data collection was complete. They were greatly assisted by personnel from each of the state DOTs. Without the DOT assistance, the data collection process would have never happened. Moreover, the states provided the fuel for the system, and also assisted when problems with the system arose. At the risk of omitting some names, special thanks go to:

WI	William Hallock, Morris Luke, Rebecca Yao
MI	Dale Lighthizer, Keith Skilton, Randy Neff
IA	Troy Jerman, Jeff Vander Zwaag, Kurtis Shackelford
NC	Allen Waddel, Drew Cox, Carrie Simpson, Kent Langdon, Renee Roach
GA	Norm Cressman, Dee Corson, Steve Sanders
NV	Andrew Souza, James Ceragioli
CA	Greg Weirick, Thomas Schriber, Gurprit Hansra
FHWA	Gene McHale, Greg Davis, Dave Kopacz

Gene McHale, Greg Davis, Dave Kopacz from the US DOT Federal Highway Administration attended all of the pooled fund meetings, and supported the project from the federal perspective. They want to see the system deployed, and have helped coordinate this effort.

This work is funded by US DOT FHWA and Mn/DOT through Cooperative Agreement DTFH61-07-H-00003, and by State Pooled Fund Project TPF-5(086).

Listed below are the currently available reports in the CICAS-SSA Report Series (as of August 2010):

Determination of the Alert and Warning Timing for the Cooperative Intersection Collision Avoidance System – Stop Sign Assist Using Macroscopic and Microscopic Data: CICAS-SSA Report #1
Prepared by: Alec Gorjestani, Arvind Menon, Pi-Ming Cheng, Craig Shankwitz, and Max Donath

The Design of a Minimal Sensor Configuration for a Cooperative Intersection Collision Avoidance System – Stop Sign Assist: CICAS-SSA Report #2
Prepared by: Alec Gorjestani, Arvind Menon, Pi-Ming Cheng, Craig Shankwitz, and Max Donath

Macroscopic Review of Driver Gap Acceptance and Rejection Behavior at Rural Thru-Stop Intersections in the U.S. – Data Collection Results in Eight States: CICAS-SSA Report #3
Prepared by: Alec Gorjestani, Arvind Menon, Pi-Ming Cheng, Bryan Newstrom, Craig Shankwitz, and Max Donath

Sign Comprehension, Considering Rotation and Location, Using Random Gap Simulation for Cooperative Intersection Collision Avoidance System – Stop Sign Assist: CICAS-SSA Report #4
Prepared by: Janet Creaser, Michael Manser, Michael Rakauskas, and Max Donath

Validation Study – On-Road Evaluation of the Cooperative Intersection Collision Avoidance System – Stop Sign Assist Sign: CICAS-SSA Report #5
Prepared by: Michael Rakauskas, Janet Creaser, Michael Manser, Justin Graving, and Max Donath

Additional reports will be added as they become available.

Table of Contents

List of Figures

List of Tables

Executive Summary

Crashes at rural thru-Stop intersections arise primarily from a driver, after stopping, attempting to either cross or enter the mainline traffic stream after failing to recognize an unsafe gap condition. The driver proceeds into the approaching traffic, and is hit by a vehicle travelling at high speed. Unfortunately, because of the high speeds involved, these crashes often produce serious injuries or fatalities.

Because the primary cause of these crashes is not failure to stop, but failure to recognize an unsafe condition, the United States Department of Transportation Federal Highway Administration (US DOT FHWA), the Minnesota Department of Transportation (Mn/DOT) and the University of Minnesota Intelligent Transportation Systems ITS Institute have initiated three programs designed to address crashes at thru-Stop rural intersections:

- The **Intersection Decision Support** (IDS) program developed an analysis technique to determine which rural thru-Stop intersections are most at risk, developed an intersection surveillance system which would determine the dynamic "state" of the intersection, including identifying and tracking gaps on the major road, and developed infrastructure-based dynamic signs designed to alert and warn drivers of dangerous conditions. (This study is complete.)
- The **Pooled Fund Study TPF-5(086**), "Reducing Crashes at Rural Intersections: Toward a Multi-State Consensus on Rural Intersection Decision Support" program developed a mobile intersection surveillance which was used to collect driver gap acceptance and rejection data at problematic intersections in seven different states throughout the United States. Characterizing driver behavior in these different states will lead to a nationally deployable system which will address gap related crashes at rural thru-Stop intersections. (This report concludes this study.)
- The **Cooperative Intersection Collision Avoidance System – Stop Sign Assist** (CICAS-SSA) program uses sensing technology, a computer processor and algorithms to determine unsafe conditions, and a driver interface to provide timely alerts and warnings which are designed to reduce the frequency of crashes at rural expressway intersections. Work previously undertaken under CICAS-SSA includes the design and test (in a driving simulator) of an infrastructure-based driver interface, the design of highway surveillance systems, and the collection and analysis of driver behavior and vehicle trajectory data with the infrastructure-based driver interface at the Minnesota research intersection, which is at US 52 and Goodhue County Road 9 in Goodhue County, MN.

The focus of this report is on quantifying driver gap rejection and acceptance behavior in a number of states to determine both

- the alert and warning timing used to provide a driver with assistance in recognizing and taking appropriate action when presented with a gap which could be considered unsafe, and
- whether gap acceptance and rejection behavior in different states is sufficiently similar to facilitate a single CICAS-SSA system design to be deployed throughout the United States.

If gap acceptance and rejection behavior is similar, then it follows that a basic system design should work throughout the United States.

The critical piece of the CICAS-SSA system is the alert and warning timing; if alerts and warnings are given prematurely, drivers will find the system to be overly conservative, and will be unlikely to use it. In contrast, if alerts and warnings are given too late, crashes could occur even if drivers follow the instructions provided by the system.

Three tenets are particularly germane to the determination of alert and warning timing for the CICAS-SSA system.

The CICAS-SSA system is designed to assist drivers to recognize and properly respond to unsafe gap conditions. The CICAS-SSA system does not help a driver choose a safe gap; it is designed to assist a driver with the rejection of unsafe gaps.

Prohibitive reference frame. The system indicates when it is unsafe to proceed. If a driver accepts the information provided by the driver interface, the driver will not enter or cross a traffic stream. This minimizes risk due to system failure.

The system must complement good decision making, and address those instances where poor decision making could lead to a crash. Because of the high speeds involved, rural expressway, thru-Stop intersection crashes often produce fatalities or life-changing injuries. Driver indifference to the system has potentially severe consequences.

Accurate alert and warning timing is critical from the driver acceptance point of view. For the system to be accepted and credible, the information conveyed to the driver and the time at which this information is conveyed must be well aligned with a safe driver's behavior at these thru-Stop intersections. The system should affirm a driver who makes a proper gap rejection decision, and at the same time provide adequate time for a driver who has not yet made a proper gap rejection decision to respond to the information provided by the driver interface. If the affirmation and decision processes can both be realized, the system is likely to reduce crash frequency at locations where it is deployed.

Gap rejection behavior is addressed from the macroscopic point of view. Conditions examined include effects due to maneuver type, time of day, average length of gap available to a waiting driver, time spent waiting for an acceptable gap, departure zone, and vehicle classification.

This state pooled fund also facilitated the opportunity to observe whether geographic or geometric differences affect driver behavior. Table 1 below indicates the geometric and geographic differences in the intersections at which driver gap acceptance and rejection data was collected. The original scope of the pooled fund was rural expressway thru-Stop intersections. Had only those intersections been instrumented, no geometric confounds would be present. However, partner states wanted different geometries tested. Data collection was done at geometrically different intersections; this led to confounds, but also provided a broader base of geometry to evaluate. As will be shown, driver gap acceptance and rejection behavior is reasonably consistent among the intersections studied.

Three important findings arose from this macroscopic study. First, drivers are consistent in gap rejection behavior, both in terms of geographic location and in terms of conditions associated with those gap rejection decisions. One explanation is that gap rejection is a threat assessment process, and much of human threat assessment is instinctual. Although variations do exist, the variations are slight, and amendable through a properly designed system.

Second, drivers do not appear to change their gap acceptance behavior in response to the time that drivers are required to wait for an acceptable gap. This indicates that if the alert and warning timing is on the conservative side (i.e., warnings provided earlier to give drivers more time to comprehend the sign and react accordingly), the frustration level of the driver is unlikely to increase to the point where the alerts and warnings are no longer obeyed.

Table 1. Intersection locations, geometry for the Pooled Fund Partner States. Although NV is a multi-lane, non-median separated highway, it is identified most closely and grouped with the two non-median separated highway, thru-Stop intersections (MI and GA).

Geometry	States	Locations
Median-Separated Expressway	MN, WI, NC	MN: US 52 and CSAH 9, Goodhue Co. WI: US 53 and County 77, Washburn Co. NC: US-74 and NC-1574, Columbus Co.
Median-Separated Expressway, "T" Intersection	IA, CA	IA: US-30 and T Ave., Boone Co. CA: US-395 and Gill Station Coso Road, Inyo Co.
Two Lane Rural Thru-Stop	MI, GA	MI: M-44 and Ramsdell Dr., Kent Co. GA: US-411 and GA-140, Bartow Co.
Four lane, non-median separated, w/left turn lanes	NV	NV: US-50 and Sheckler Cutoff, Churchill Co.

Third, and most surprising, is the finding that gap rejection is essentially *independent* of vehicle classification (i.e., size). The prevalent hypothesis prior to this analysis is that drivers of heavy and/or large vehicles will produce a higher gap rejection threshold when compared to drivers of lighter, faster vehicles because of the additional time required by heavy and long vehicles to clear an intersection. However, this hypothesis was found to be incorrect; drivers of heavy trucks reject gaps in a manner very consistent with drivers of smaller, faster vehicles. This finding has significant impact on the costs to deploy CICAS-SSA systems: the expensive vehicle classification equipment used on the minor road approaches is likely unnecessary. Because the vehicle classification subsystem represents approximately ½ of the cost of the CICAS-SSA system, significant cost savings can be realized.

Because of this surprising third result, two additional analyses were undertaken to ensure its correctness. The first analysis was to compare speed reductions for mainline vehicles when large and small vehicles were crossing the mainline traffic flow. Exposure to large minor road vehicles produced greater speed reductions in mainline traffic than did smaller vehicles, which is an expected result. The second analysis compared the time to cross mainline traffic for small and large vehicles departing the minor road. Using the location of the vehicle front bumper as a measure of time to cross, large vehicles took approximately 0.75 seconds more time to cross than did smaller vehicles. (Longer vehicles, of course, will take longer to completely clear the intersection.) This implies that drivers of large vehicles are aggressive once the decision to go has been made, and that they assume the same initial risk as drivers of smaller vehicles.

Because of the consistency of gap rejection behavior between conditions and between states, a standard alert and warning timing appears to be feasible. From the data presented herein, alerts have been determined to be provided in the 7.5-to-11 second gap/lag range. Alerts turn to warnings at the 7.5-second epoch.

In summary, although some geometric and geographic confounds exist, in general, gap acceptance and rejection behavior is shown to be consistent. Consistency does not imply that a single alert and warning timing will apply at each intersection at which the countermeasure is deployed. It does imply that the process to establish the alert and warning timing will be consistent among deployments and that the information provided by the DII can be consistent among the deployments.

1 Chapter 1 Introduction

Motivation

More than 30% of all vehicle crashes in the U.S. occur at intersections; these crashes result in nearly 9000 annual fatalities, or approximately 25% of all traffic fatalities. Moreover, these crashes lead to approximately 1.5 M injuries/year, accounting for approximately 50% of all traffic injuries.

In rural Minnesota, approximately one-third of all crashes occur at intersections. The American Association of State Highway and Transportation Officials (AASHTO) recognized the significance of rural intersection crashes in its 1998 Strategic Highway Safety Plan [1] and identified the development and use of new technologies as a key initiative to address the problem of intersection crashes in [2], Objective 17.1.4: "Assist drivers in judging gap sizes at Unsignalized Intersections."

To clearly define the rural intersection crash problem, an extensive review of both the Minnesota Crash Database and research reports quantifying the national problem was undertaken; the results are documented in [2]. This study of 3,700 Minnesota intersections shows that crashes at rural expressway thru-Stop intersections have similar crash and severity rates when compared to all rural thru-Stop intersections. However, right angle crashes (which are most often related to gap selection) were observed to account for 36 percent of all crashes at the rural expressway intersections. At rural expressway intersections that have higher than expected crash rates, approximately 50 percent of the crashes are right angle crashes. Further investigation also found that drivers' inability to recognize the intersection, and consequently run the "Stop" sign, was cause for only a small fraction of right angle crashes. *Gap selection is the predominant problem*.

This is consistent with other findings; Chovan et al. [2] found that the primary causal factors for drivers who stopped before entering the intersection were:

The driver looked but did not see the other vehicle (62.1 %)

The driver misjudged the gap size or velocity of the approaching vehicles (19.6 %),

The driver had an obstructed view (14.0 %), or

The roads were ice-covered (4.4 %).

Of these four driver errors, the first three can be described as either problems with gap detection or gap selection.

Crash analyses, including field visits and crash database reviews, for Michigan [4] North Carolina [5] and Wisconsin [6] have shown that in these states, poor gap acceptance on the part of the driver is the primary causal factor in approximately 60% of rural thru-Stop, right-angle intersection crashes. Analyses performed in the other states corroborate the findings of the median-separated, rural-expressway, thru-Stop intersections [7].

Prior to CICAS-SSA, and its predecessor Intersection Decision Support (IDS), high rural intersection crash rates were addressed through the use of either a traffic control device or increased conspicuity of the intersection itself. Improvements in conspicuity include additional and/or larger "Stop" signs, flashers, improved pavement markings, etc. However, neither of these approaches fully addresses the rural intersection crash problems. The addition of traffic control devices typically results in an exchange of right angle crashes (between major and minor road vehicles) for rear-end crashes (between vehicles on the major road). Improvements in intersection conspicuity failed to make an improvement in crash rates because conspicuity was never the problem. These two approaches represent the tools available to the traffic engineer to address the problem. Clearly, these two tools are insufficient to address the problem.

In order to improve rural intersection safety, new approaches are required. Responding to this need, CICAS-SSA is the manifestation of a technology-based approach to improving rural intersection safety. As was borne out in [2], the primary issue with rural expressway intersections exhibiting higher than expected crash rates is the poor *rejection* of unsafe lags or gaps in traffic. Although often described as a gap acceptance program, the ultimate goal of the CICAS-SSA program is assistance for drivers who may accept an unsafe gap. By providing assistance in the identification and rejection of unsafe gaps, rural intersection safety can be improved, while at the same time maintaining vehicular throughput on the major road. Safety improves without a capacity penalty.

2 Design Premise

Given the extent of the crash problem and the causal factors, the CICAS-SSA system design continues to develop under the following design factors:

In the majority of the rural thru-Stop crashes, the driver has obeyed the "Stop" sign. This implies that the driver is cognizant of his/her situation, and that it is likely that the driver interface used at the intersection is likely to capture the driver's attention. This is a significant departure from the signal/Stop sign violation problem, where the intervention system has to both capture the driver's attention and convey a timely message with substantial authority that a violation is imminent if a proper response is not executed.

With the premise that the driver's attention has been captured, CICAS-SSA system provides a driver timely, relevant information regarding *unsafe* conditions. The purpose of the system is to provide this information as a means to enable a driver to make a safer decision regarding gap rejection, but not make the decision for the driver. A prohibitive reference frame (i.e., indicating to a driver when *not* to go) is used to lessen liability issues as compared to indicating to a driver when it is "*safe*" to go. As will be borne out in the sequel, "*unsafe*" is much easier to quantify than is safe. This is a key concept which enables CICAS-SSA to be effectively deployed.

Given the increasing traffic volumes on rural expressways and the need of traffic engineers to maintain or increase capacity on these roads, the CICAS-SSA system should not stop traffic on the main road. It is hoped that the CICAS-SSA system will provide the safety benefits of a signal-controlled intersection without the adverse effects on mainline capacity, throughput, and congestion.

2.1 Surveillance System Description

Figure 1 below provides a plan view of the research version of the Minnesota Mobile Intersection Surveillance System (MMISS) as it was installed at the intersection of US 53 and County 77 in Washburn County, WI. For the research surveillance system, mainline sensing is provided by an array of radar sensors spaced 122m (400 ft) apart, and connected to the central processor through an IEEE 802.11b wireless local area network. A station adapter is associated

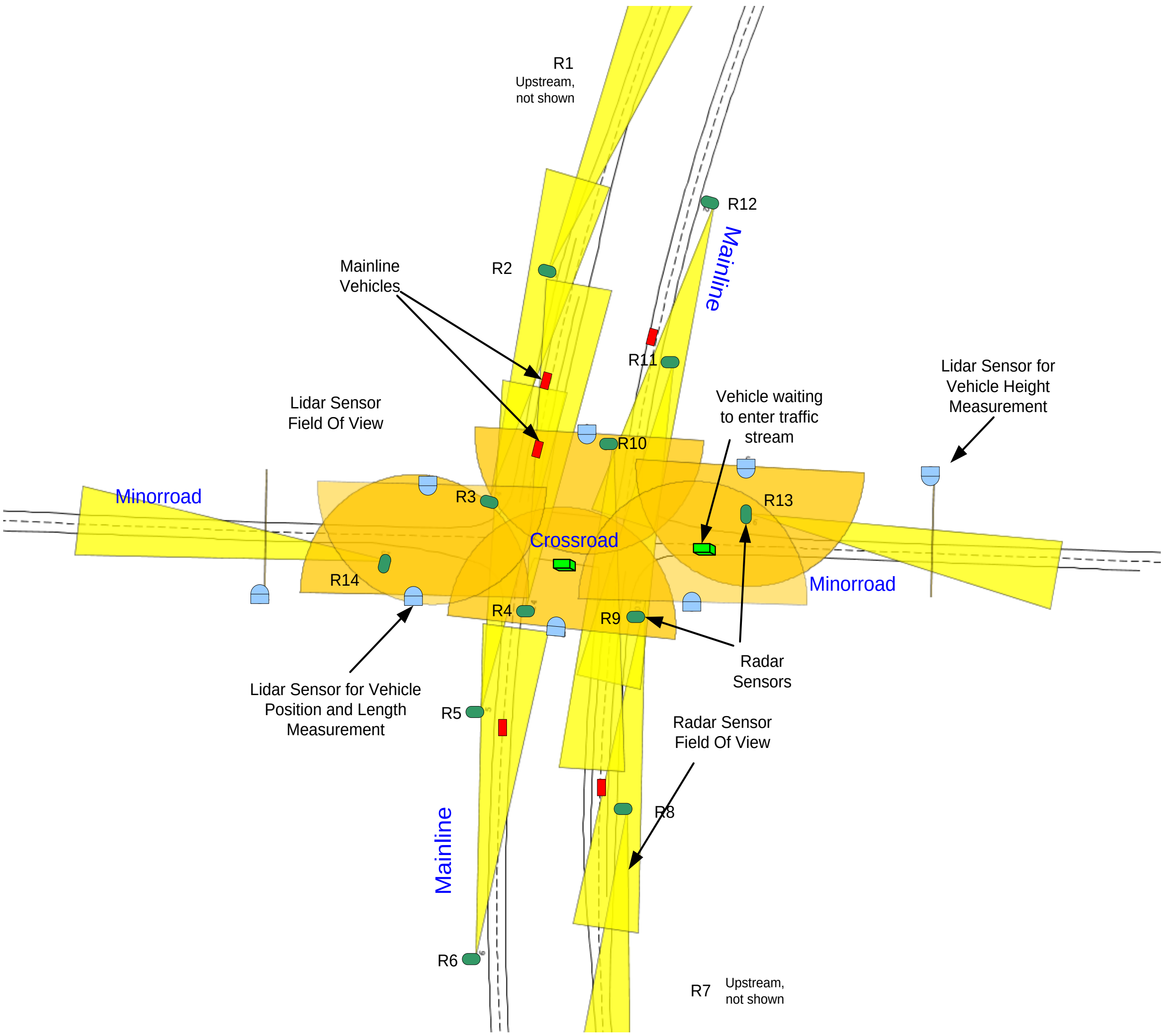


Figure 1. Plan view of the MMISS instrumented rural WI expressway intersection. Sensors are radar and scanning lidar; all data is broadcast wirelessly from sensor processors to the main data acquisition computer via 802.11b wireless devices. Of particular interest for driver behavior research is the crossroad surveillance area. Approximately eighty percent of crashes at rural expressway intersections having higher than expected crash rates occur on the "far" side of the intersection. Understanding of behavior in the median will facilitate the development of an effective rural Stop Sign Assist (SSA) system.

with each radar sensor, and transmits radar sensor data to the central processor. Minor road sensing is provided by a fusion of radar and scanning lidar sensors, also connected to the central processor through the local 802.11b local area network. Minor road sensing is designed to detect the presence, location, and speed of a vehicle approaching the major road, and to classify the vehicle into one of four categories. Median crossroads surveillance is accomplished using an array of scanning lidar sensors, also connected to the central processor via the local 802.11b wireless network. The purpose of the median sensor is to determine the presence and location of vehicles located in the median crossroads. The mainline sensor system, the minor road sensor system, the crossroad sensor system, central processor, and power distribution systems are discussed in detail in [9].

This surveillance system determines the dynamic “state” of the intersection. Mainline state information includes the position, speed, (derived) acceleration, and lane of travel of each vehicle within the surveillance zone. This state information, combined with known intersection geometry, facilitates the real time tracking of traffic gaps on the mainline. Minor road state information includes the position and speed of the vehicle on the minor road, and an estimate of the classification of the vehicle. Present classification separates vehicles into four categories: Motorcycle/passenger cars, SUV/light truck, medium duty truck/school bus, and heavy-duty truck/semi/motor coach/farm equipment. A central processor computes the state of the intersection at 10 Hz.

The state information provides the basis with which to assess threats to drivers waiting to cross or enter the mainline traffic stream. In addition to intersection state data, the threat assessment algorithms may utilize parameters including driver demographic information (potentially available wirelessly), road condition information (from weather/road sensors mounted at or near the intersection), and vehicle information (model, performance parameters, etc., potentially available wirelessly).

The system is designed so that should an unsafe condition be detected by the threat assessment algorithm, the central processor initiates the proper alert and warning sequence to the driver through either an infrastructure-based interface known as the Driver-Infrastructure Interface (DII) or an in-vehicle Driver-Vehicle Interface (DVI). Understanding of driver gap acceptance and rejection behavior allows the alert and warning timing for the DII and DVI to be properly determined.

The research surveillance system serves three purposes. First, it allows the collection of macroscopic data related to driver gap acceptance and rejection. This is done by recording the trajectories of vehicles entering and crossing the mainline traffic stream while simultaneously recording the trajectories of vehicles travelling on the mainline. Prior to the deployment of this system, driver gap rejection and acceptance behavior instrumentation was limited to video cameras and discrete pavement sensors [10]. Because of the demands associated with video processing, time and budget constraints limit the volume of data which can be analyzed. In contrast, the Minnesota system described above relies solely on sensor data. (Video is collected so that crashes and other unexpected behavior can be re-examined.) The macroscopic analyses found in this report are based on two months of data collected per intersection at the intersections listed in Table 1.

The system provides a basis with which to evaluate the prototype CICAS-SSA system before it is exposed to the general public. With the inclusion of the alert and warning timing algorithm presented herein, the driver interface can be tested *in-situ* at a research intersection, both with an instrumented vehicle (for system testing) and to the general public (for an extensive Field Operational Test). This allows a new traffic control device to be tested in a controlled manner before it is released fully to the public.

Field tests are planned in Minnesota under the CICAS-SSA program, and in Wisconsin under the Rural Safety Initiative Program (RSIP). Testing of the full system will begin in June of 2009 in Minnesota, and in November 2009 in Wisconsin.

Finally, it should be noted that the MMISS research instrumentation is designed to acquire an extensive set of vehicle trajectory and driver behavior data far beyond that what is needed to deploy a CICAS-SSA system. The CICAS-SSA system will be realized as a subset of the comprehensive research-based system; the realization of the optimized sensor and system configuration for a deployed system is described in [11].

2.2 Driver Interface

Through CICAS-SSA, a number of different architectures for providing information to the driver can be envisioned; at one end of the cooperative spectrum, full intersection information (i.e., the dynamic state, which includes geometric characteristics as well as the location, speed, heading, and classification (for minor road vehicles)) is provided to the vehicle waiting to cross or enter the traffic stream. This allows the vehicle's on-board system to assess the threat, and determine whether an alert or warning is warranted at that time. The result would be information communicated through a DVI. At the other end of the cooperative spectrum, driver demographic information or alert and warning timing preferences could be wirelessly transmitted from the vehicle to the intersection controller. This demographic information would be used by the alert and warning timing algorithm to modify the base algorithm to accommodate the specific needs of the driver at the minor road.

Under the IDS program, and presently under CICAS-SSA, the driver interface to be used to validate alert and warning timing will be a DII. A number of test procedures have been undertaken to determine the optimal design of the DII and validate the alert and warning timing presented herein. Testing includes

- Simulator testing to determine the optimal DII location, content, and alert and warning timing.
- On-site testing using both an instrumented passenger car and an instrumented heavy truck to measure human response to the system and to validate alert and warning timing.

The simulator testing was completed in March of 2008, and the on-site testing with the passenger car and the heavy truck was completed in October of 2008.

To give the reader context, photos of the DIIs used in the testing are shown below in Figure 2. Alerts are issued when conditions require vigilance from the driver; during an alert, a driver could successfully either enter the traffic stream, or cross it with sufficient safety margin. On the other hand, warnings are issued when conditions could lead to a crash, or when passage will result in a narrow or no safety margin.

2.3 State Pooled Fund Intersection Data Collection and Analysis and Report Organization

The prototype intersection for the CICAS-SSA system was a rural, median-separated, thru-Stop intersection. When this pooled fund study was proposed, the goal was to identify similar intersections in the partner states. However, of the seven states where data collection was performed, rural, median-separated, thru-Stop intersections were identified only in MN, WI, and NC. As is shown in Chapter 5, MN, WI, and NC showed remarkably similar driver gap rejection behavior. The results of the data collection and analysis from these three states provided the basis for the alert and warning timing for the live testing performed during the summer of 2008 at the Minnesota Research Intersection.

Table 1 indicated the geometries of the intersections selected as a result of a crash analysis performed in each of the partner states [7]. As a result of these crash analyses, a total of four intersection geometries were identified. Because geometry plays an important role in alert and warning timing, analyses of gap acceptance and rejection behavior are grouped by intersection geometry.


DIVIDED HIGHWAY
LOW SHOULDER

Figure 2. Prototype DIIs as tested at the Minnesota Research intersection at US 52 and CSAH 9 in Goodhue County, MN. The DIIs are 80x112 pixel, 20 mm pitch LED displays measuring 63in by 88in. In the left photo, traffic approaching from the left is more than 7.5 seconds from the crossroads; traffic from the right is less than 7.5 seconds from the crossroads. In the right photo, the nearest vehicle on the left is more than 11.5 seconds from the crossroads; the vehicle approaching from the right is less than 7.5 seconds from the crossroads.

The remainder of this report is organized as follows:

Chapter 2 addresses previous gap acceptance and rejection research.
Chapter 3 provides the background and framework for subsequent analyses.
Chapter 4 provides the rationale for the study of *rejected* gaps.
Chapter 5 addresses rural, median-separated, expressway thru-Stop intersections.
Chapter 6 addresses rural, median-separated, expressway thru-Stop “T” intersections.
Chapter 7 addresses rural, non-median separated highway thru-Stop intersections.
Chapter 8 provides conclusions and directions for additional work.

3 Chapter 2
Review of Prior Gap Acceptance Research

The literature regarding traffic gap acceptance and/or rejection is quite rich. Although the body of literature is extensive, little of what has been published pertains directly to the problem of providing a driver assistance in rejecting unsafe gaps or lags in traffic. Gap acceptance/rejection research began as a means to estimate highway capacity [12]. Highway capacity remains its primary application, but recent research involving safety and sightlines has also used gap acceptance/rejection models.

It is important to note that in previous work, the goal of driver modeling has been to *understand* driver behavior regarding gap acceptance/rejection and its effect on highway capacity and highway design policy. What differentiates what is done under CICAS-SSA to what has been done previously with gap acceptance/rejection is that while gap acceptance/rejection behavior still needs to be understood, the more important issue is to *modify* unsafe behavior as a means to improve intersection safety.

The primary motivation for estimating the critical gap is the estimation of the capacity of a road which intersects other roads. The critical gap, as defined in this context, is the value used to represent a "typical" gap accepted by drivers waiting to enter or cross a traffic stream.

If a model of traffic density (and therefore, a model of the distribution of gaps made available to a driver on the minor road from the traffic on the major road) is available, the fraction of available gaps which are acceptable to a driver can be computed, thereby facilitating an estimate of the rate at which vehicles can cross or enter the major road traffic stream.

An excellent overview on critical gap estimation is given in [13]. A thorough description of a number of approaches for computing/estimating a critical gap value from observational data is provided. These methods are well described, and their formulae presented, including the method of Seigloch for saturated conditions. For unsaturated conditions, the lag method, the Raff method, the Ashworth method, the Harder method, Logit procedures, Probit procedures, the Hewitt method, and maximum likelihood methods are presented. However, these critical gap estimation techniques are used to support highway capacity modeling, and are not intended for safety applications.

As a means to compare these different procedures to estimate the critical gap, a traffic simulation is used as the basis of computation for each of the critical gap estimation techniques provided above. In [13], a traffic simulation was run, whereby mainline traffic volume varied between 100 and 900 vehicles per hour, and the minor road traffic volume varied between 0 and its maximum capacity, *c*. To achieve a realistic pattern of headways, the hyper-Erlang distribution was applied to the major stream traffic flow generation where traffic on one single lane has been assumed. Using a two-hour period of simulated mainline traffic based on the hyper-Erlang distribution, critical gaps for each condition (100 to 900 vehicles per hour) for each estimation procedure were computed; the results are shown in Figure 3.

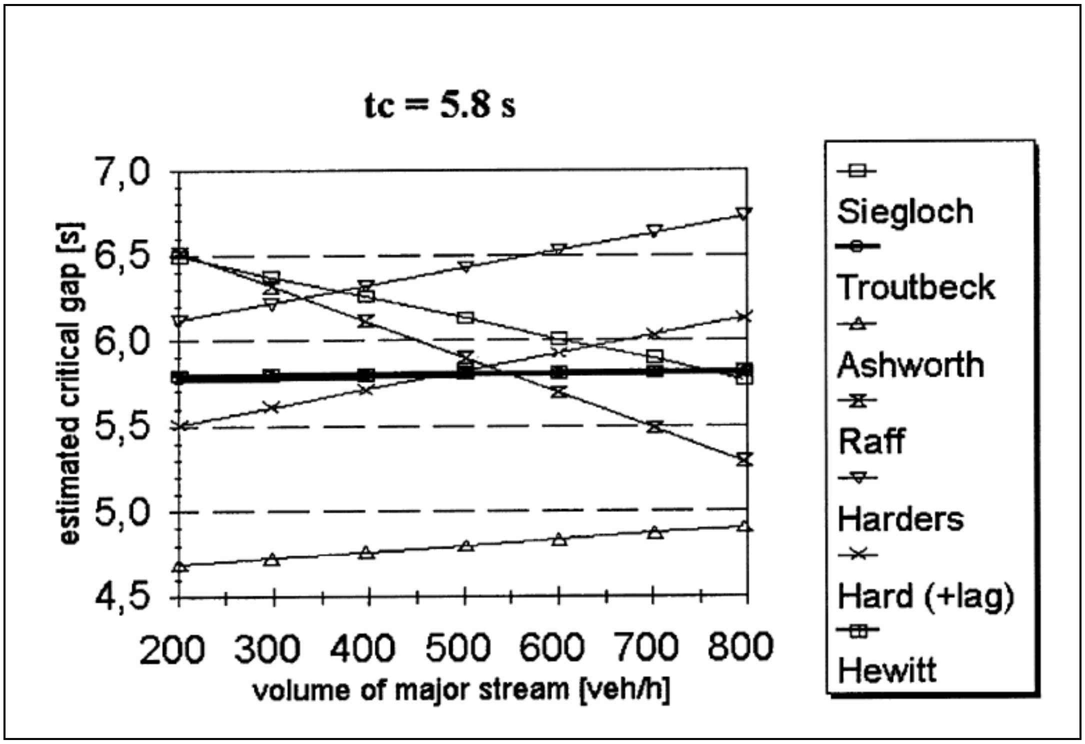


Figure 3. Comparison of critical gap values for a variety of critical gap estimation techniques; graph taken from [13]. Note that a considerable spread exists with differences approaching 40% in some cases.

Note that a considerable variability exists in the estimation of the critical gap among the various methods. In general, the Ashworth method provides the smallest estimate of the critical gap, and the Harders method provides the greatest estimate of the critical gap.

Field results also bear out a variance in the estimation of what is a "valid" critical gap or how critical gaps should be computed based on intersection geometry, traffic flow, etc. A review of a number of studies where field data was collected to determine a critical gap value is shown in Table 2.

Comparison of gap acceptance field study results with results from other studies [10],[14],[15] also indicates that the notion of a representative critical gap value fails to exist, and that even for the same intersection, different methods produce different values for that critical gap number. Traffic engineers and researchers have yet to produce a ubiquitous definition of the critical gap.

Table 2. Critical gap estimates for a variety of intersections.

Maneuver	Harwood et al., [10]		Lerner et al., [14]	Kyte et al., (1996) [15]
	Raff Method	Logistic Regression	Critical gap accepted by 50% of drivers	Maximum likelihood method
Right turn	6.3	6.5	7	6.2
Left turn	8.0	8.2	7.0	7.0

Although the critical gap has been defined primarily in the context of highway capacity estimation, it has also been used for some highway safety considerations. In [10], an effort was undertaken to determine sightline requirements for highway design policies. The critical gap was used with other parameters to determine minimal sight lines for safe highway design.

In conclusion, although the literature is rich with a variety of definitions and approaches to estimating critical gap, the context of critical gap lies primarily within the highway capacity context. The application of critical gap is well suited for *describing* driver behavior in terms of highway capacity, but it is not well suited as a point at which to *modify* driver gap acceptance/rejection behavior.

4 Chapter 3 Framework, Goals, and Context

The framework for the analysis leading to alert and warning timing is presented herein. The results from the data collection in the seven partner states are presented here. The analysis is focused on two areas:

1. Determination of the alert and warning timing used to provide a driver with assistance in recognizing and taking appropriate action when presented with a gap which could be considered unsafe, and
2. Judgment of whether gap acceptance and rejection behavior in different states is sufficiently similar to facilitate a single CICAS-SSA system design to be deployed throughout the US.

The analyses described here are solely macroscopic; no in-vehicle data was collected as part of the intersection pooled fund study.

4.1 Data Collection

The Minnesota Mobile Intersection Surveillance System (MMISS) was used to collect the macroscopic data used for the analyses presented herein. Data was collected in seven states; see Table 1: Intersections for which data was collected were selected because these intersections exhibited higher than expected crash rates, and were not scheduled for upgrades in the near future [2], [5], [6], and [7]. Data was collected for at least eight weeks in each location. Months of data collection are found in Table 3.

Table 3. Dates of data collection in pooled fund states.

State	Dates	State	Dates
WI	AP – JN 2006	GA	JN – AU 2007
MI	JL – SE 2006	NV	DE 2007– MR 2008
IA	SE – DE 2006	CA	AP 2008 – JN 2008
NC	MR – MY 2007		

Data collected by the MMISS is summarized in Table 4 for the mainline, minor road, median, and atmosphere.

Table 4. Raw data collected by the MMISS.

Mainline	Minor Road	Median Crossroads	Weather
Vehicle speed	Vehicle speed	Vehicle speed	Atmospheric temperature
Vehicle position	Vehicle position	Vehicle position	Precipitation type & rate
Lane of travel	Vehicle classification	Video recording	Relative Humidity
			Atmospheric Visibility

The mainline radar sensors provide 2000 feet of surveillance coverage in each direction of traffic; all vehicles approaching the intersection are tracked from this sensor data by the main system computer. Laser scanners located adjacent to the minor road near the crossroads classify vehicles on the minor road based on length and height. Laser scanners located in the highway median (at intersections where a median is present) track vehicles as they pass through or stop in the crossroads median. A video camera is present and designed to collect crossroad data so that in the event of crash, further analysis can be undertaken. Also present on site is a Vaisala PWD 12 present weather detector, which measures atmospheric conditions at the test site, allowing weather effects on gap rejection/acceptance behavior to be determined as well.

The technical capabilities offered by the MMISS facilitate the collection of extensive data over long periods of time. Because the vast majority of data collected by the MMISS is engineering data, analysis of the data can be automated, reducing the human effort necessary for analysis. This is in contrast to video-based systems, used in [10] which require huge data repositories for video data, and extensive human review of video to computer gap acceptance/rejection data.

Definitions.

Three primary definitions are associated with gap acceptance and rejection; these are shown in Figure 4 below. Gap is the time separating two consecutive vehicles approaching (or separated by) the minor road at the crossroads. The lag is the time separating the vehicle on the minor road from the vehicle first approaching from the left. The lead is the time from the vehicle at the minor road to the vehicle just passing the minor road.

For multi-lane roads, gaps are defined on a per-lane basis, as is shown in Figure 5.

The definition of “accepted lag” becomes problematic from a macroscopic point of view. Rejected gaps are easy to define; a pair of vehicles passes by, and if a vehicle fails to enter the intersection between those two vehicles, that gap has obviously been rejected.

Likewise, if a vehicle enters the traffic stream, the accepted gap was the time headway between the two vehicles between which the entering vehicle crossed. However, the definition of "accepted lag" becomes problematic from a macroscopic point of view. Definition of "accepted" for drivers who roll through the intersection without stopping becomes difficult, and adds noise to the measurements. Without in-vehicle equipment, it is difficult to determine the point at which the driver executed the decision to accept a lag. Without a repeatable measurement of the decision point, any quantification of the lag values becomes noisy.

To address this noisy situation, acceptance criteria from the macroscopic point of view could be the time at which a vehicle crosses a stop bar, the time the vehicle enters a particular geographic region, or the time at which a vehicle achieves a particular speed. For the microscopic point of view, throttle opening, acceleration level, or vehicle location can be used to define the point of acceptance for a lag.

From the macroscopic point of view presented here, the definition of "lag" is tied to intersection geometry. Using a geometric reference from which to measure lag acceptance ensures consistency throughout the analysis, and minimizes discrepancies associated with sensor readings, rolling stops, "inching" forward, etc. Associating lag acceptance with intersection geometry leads to an objective measurement; this is in contrast to human observers equipped with stop watches who subjectively determine when a driver begins entering or crossing a traffic stream. Because this definition is repeatable, and is not affected by "rolling stops" and other behavior, it provides a consistent definition regardless of the location of the instrumented intersection.

The concept of a "rejected lag" makes sense in only one instance: the first time a driver enters the specified geographic region and fails to proceed through the intersection. Anytime after that first opportunity, a rejected lag cannot be determined because the instant at which a driver decided not to proceed cannot be measured. Thus, the only measure of rejection beyond that first rejected lag is rejected gap. As is explained below, because of their physical manifestations, distributions of rejected gaps are significantly different than distributions of rejected lags.

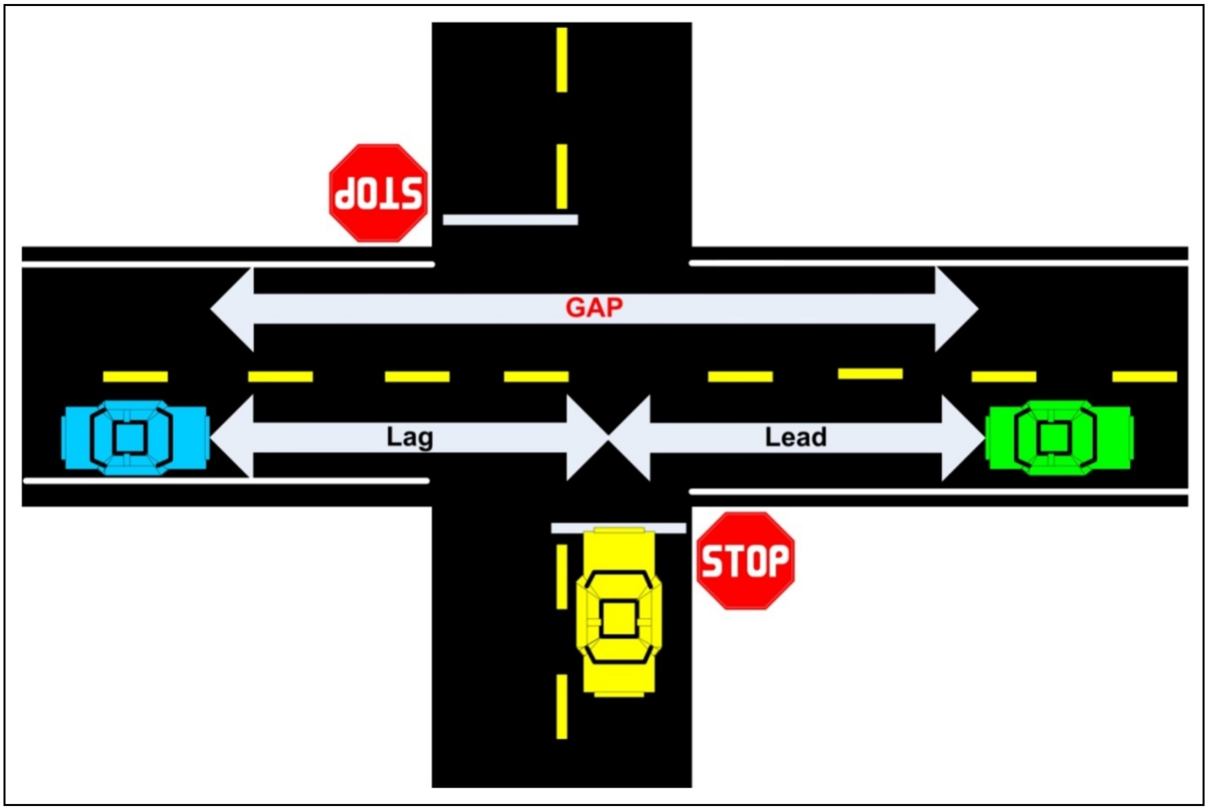


Figure 4. Geometrical definitions associated with gap acceptance and rejection.

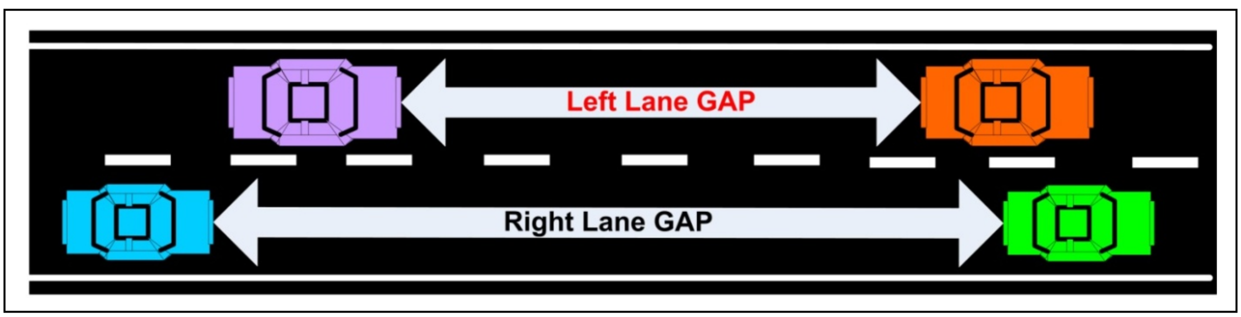


Figure 5. Gap definition for multi-lane roads. Gaps, leads, and lags are defined on a per-lane basis.

Because of the difficulties with precisely determining the point at which a lag has been accepted from the macroscopic point of view, the macroscopic analysis has focused on gap rejection behavior. This is consistent with assisting a driver with unsafe gap rejection, and does not suffer from ambiguities associated with lag acceptance estimation. Figure 6 illustrates the single lag acceptance/rejection opportunity for a driver approaching the intersection from the minor road.

Practical considerations when considering gaps and lags.

A number of practical considerations regarding gaps and lags affect the analysis, including relative frequency, distributions, and measurement biases. These considerations are discussed below.

Relative frequency. As a driver approaches a thru-Stop intersection, a driver makes the first (and only) lag rejection decision; the lag is either rejected, or accepted. Beyond that first instance, the ability to measure the instant at which a driver accepts or rejects a lag cannot be measured.

The data showed that there were more rejected lags than rejected gaps. Often times the driver rejects the initial lag and then proceeds, and therefore does not reject the next gap. There were few instances when a driver waited for multiple gaps.

Distributions. As a driver approaches a thru-Stop intersection, a driver makes the lag acceptance/rejection decision based on the location of the vehicle closest in time to the minor road. In this situation, the approaching vehicle could be any distance from the intersection, resulting in a *continuous* (and possibly uniform) distribution of available lags from which the driver can accept or reject.

In contrast, the gap is defined as the space between two vehicles in the same lane as they travel on the major road. Safety advocates recommend a two-second spacing between vehicles to ensure a sufficient safety margin. If drivers were to follow these recommendations, the distribution of available gaps on any road would show zero instances in the space between zero- and two-seconds. In practice, the lower limit in gap measurement appears to be approximately 1.5 seconds. Therefore, few instances of gap rejections of gaps less than 1.5 seconds will be recorded simply because the *opportunity* to reject gaps of 1.5 seconds or less are quite few. Although this phenomenon skews distributions a bit, it can be fully explained, so it causes no problems with any analyses.

Measurement biases due to left- and right-lane gap definitions. As the CICAS-SSA system will be deployed, the primary control input which governs the alert and warning timing is the time from the closest major road vehicle to the intersection crossroads. This closest major road vehicle poses the greatest threat to the minor road vehicle. The CICAS-SSA system will not distinguish between left and right lane traffic because major road driver intent cannot be determined (i.e., drivers can change lanes at any time).

Measuring gaps on a lane-by-lane basis rather than by measuring the space between the two closest vehicles travelling in adjacent lanes could lead to some measurement bias. The situation where bias could arise is shown and described in Figure 7.

Fortunately, the likelihood of this measurement bias is slight, based on the data used in this report. Examination of the history of rejected gaps and lags for the work presented in the sequel are summarized in Table 5 below. Drivers are generally not waiting for more than two gaps to arrive before departing the intersection.

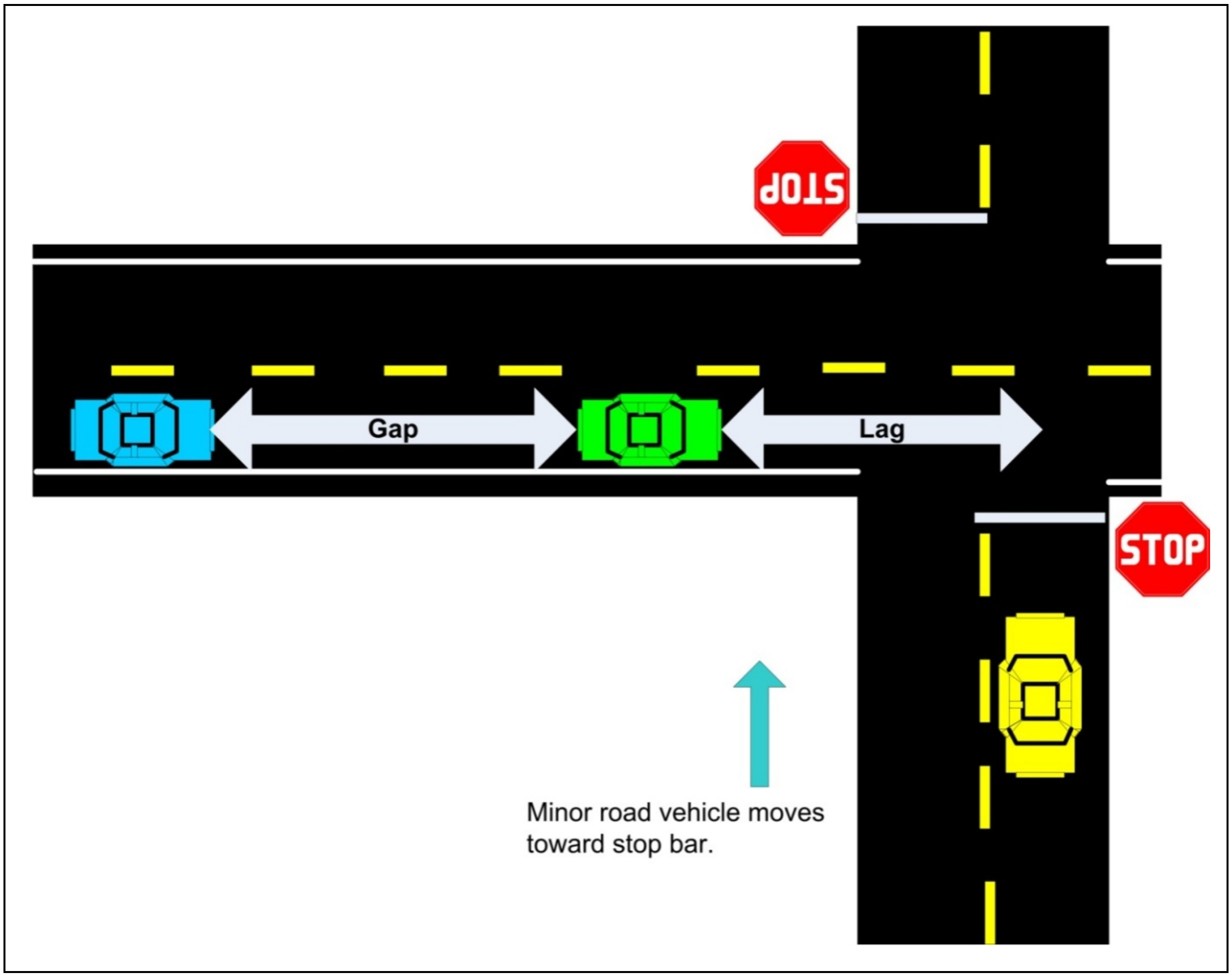


Figure 6. Single lag acceptance/rejection opportunity as a minor road vehicle approaches an intersection with a major road. The vehicle approaching the stop bar has only one opportunity to either accept or reject a lag; acceptance or rejection is noted at the time the minor road vehicle occupies the specified geographic region. After the first opportunity, only rejected or accepted gaps are defined.

Table 5. Relative frequency of gap acceptance for both single and multiple gap rejections; data from the Minnesota median-separated expressway intersection. Clearly, most drivers reject the initial lag, and then proceed through the intersection. The frequency of instances where a driver waits to reject more than one gap is small.

Summary of Gap and Lag Rejection Relative Frequency	
Only one gap needed to be rejected for maneuver	1603
Multiples gaps were rejected for maneuver	1915
No gaps were rejected. Only the initial lag was rejected	21735

In practice, the lane-by-lane gap definition accurately captures the decision process of the driver, and reflects the timing mechanism by which drivers will be provided alert and warnings by the CICAS-SSA system.

Macroscopic study goals.

As such, the data will be used to determine

- Regional differences in gap acceptance and rejection
- Sensitivities of gap rejection behavior to maneuver, time of day, sequence of previously available gaps, time waiting for a gap, departure point (either median or minor road), and vehicle classification.
- Alert and warning timing.

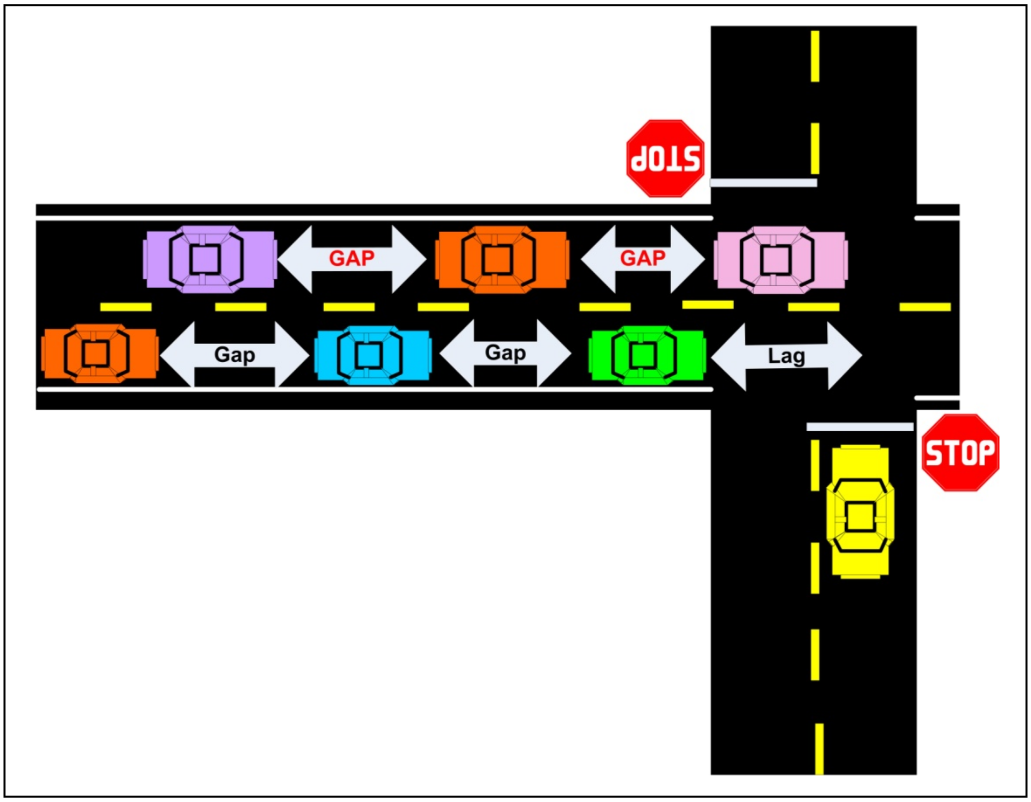


Figure 7. Example situation where lane-by-lane gap definition could produce rejected gap measurement bias. In this example, assume that each lane-by-lane gap for both the left and right lanes is ten seconds, and that the lag depicted above is five seconds. This puts the spacing between a vehicle on the right lane and its closest vehicle in the left lane at five seconds. If the minor road vehicle rejects the lag and subsequent gaps, the rejection history would reflect a 5 second rejected lag and a series of rejected 10 second gaps. However, if both lanes are considered, in essence, the minor road driver is really rejecting a sequence of five second lags. This discrepancy can lead to measurement bias.

5 Chapter 4
CICAS-SSA Tenets

Three tenets characterize the CICAS-SSA program; each tenet impacts the approach and the analysis regarding alert and warning timing.

1. **The system is to help drivers recognize and properly respond to unsafe gap conditions.** If a driver fails to recognize a safe gap, the driver's time waiting at the intersection increases. If a driver fails to recognize an unsafe gap and enters the intersection, a crash is likely. The primary objective of the CICAS-SSA system is to assist drivers in the *recognition of and appropriate response to* unsafe gaps.

   This point cannot be emphasized strongly enough. In fact, even some CICAS-SSA publications failed to adequately make this point. For instance, in [9], the primary result was that gap acceptance distributions follow log-normal distributions. Although the results were interesting and supported other claims that gap acceptance behavior exhibits log-normal distributions, CICAS-SSA is a gap *rejection decision support* tool. As such, gap rejection distributions are of greater concern to this project.

   The importance of a gap rejection frame of reference when determining alert and warning timing is manifest in the fact that humans are remarkably consistent in what is perceived as a threat. As is shown in the following chapter, drivers exhibit a threat assessment behavior which is remarkably consistent. When a threat is not present, human behavior varies widely. The fact that threat assessment in the presence of oncoming vehicles is consistent is the key to alert and warning timing likely to be acceptable to drivers in terms of affirming good gap rejection decisions and preventing bad gap rejection decisions.

2. **Prohibitive reference frame.** Since the inception of IDS, the predecessor of CICAS-SSA, the prohibitive reference frame has been specified. When IDS began, the prohibitive time frame was chosen primarily for liability protection. From the prohibitive frame, if a driver chooses to obey the system the driver will remain on the minor road, and a crash will not occur. On the other hand, from permissible point of view, if the system presents a "safe" message, and the driver obeys it, a possible outcome is a crash. The prohibitive reference frame protects not only the sponsoring agency, but the driver as well.

3. **The system must complement good decision making, and address those instances where poor decision making could lead to a crash.** Because of the high speeds involved, rural expressway, thru-Stop intersection crashes often produce fatalities or life-changing injuries. Driver indifference to the system has potentially severe consequences including those fatalities and life-changing injuries. As such, the CICAS-SSA system has to coexist with drivers who function capably by providing a safe, reassuring experience and with those drivers who are at risk and require timely information so that a crash can be avoided.

6 Chapter 5 Rural Expressway, Median-Separated, Thru-Stop Intersections

Three important findings arise from the study of rural, expressway, median-separated, thru-Stop intersections. First, drivers are extremely consistent in gap rejection behavior, both in terms of geographic location and in terms of conditions associated with those gap rejection decisions. One explanation is that gap rejection is a threat assessment process, and part of human threat assessment is instinctual. Although variations do exist, the variations are slight, and amendable through a properly designed system.

Second, drivers do not appear to change their gap rejection behavior in response to the time that drivers are required to wait for an acceptable gap. This indicates that if the alert and warning timing is on the conservative side (i.e., warnings provided earlier to give drivers more time to comprehend the sign and react accordingly), the frustration level of the driver is unlikely to increase to the point where the alerts and warnings are no longer obeyed.

Third, and most surprising, is the finding that gap rejection is essentially *independent* of vehicle classification (i.e., size). The prevalent hypothesis prior to this analysis is that drivers of heavy and/or large vehicles will produce a higher gap rejection threshold when compared to drivers of lighter, faster vehicles because of the additional time required by heavy and long vehicles to clear an intersection. However, this hypothesis was found to be incorrect; drivers of heavy trucks reject gaps in a manner very consistent with drivers of smaller, faster vehicles. This finding has significant impact on the costs to deploy CICAS-SSA systems: the expensive vehicle classification equipment used on the minor road approaches is likely unnecessary. Because the vehicle classification subsystem represents approximately ½ of the cost of the CICAS-SSA system, significant cost savings can be realized.

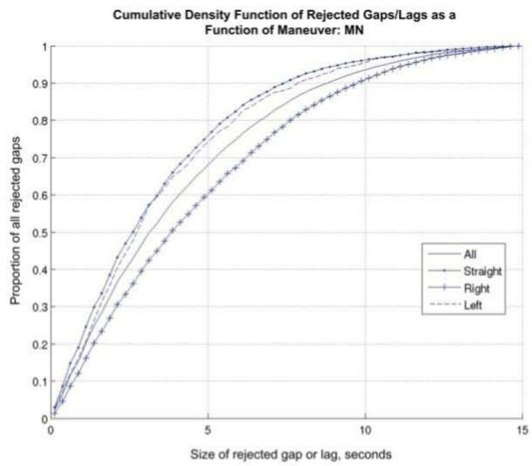
The sensitivities to gap rejection threshold as a function of

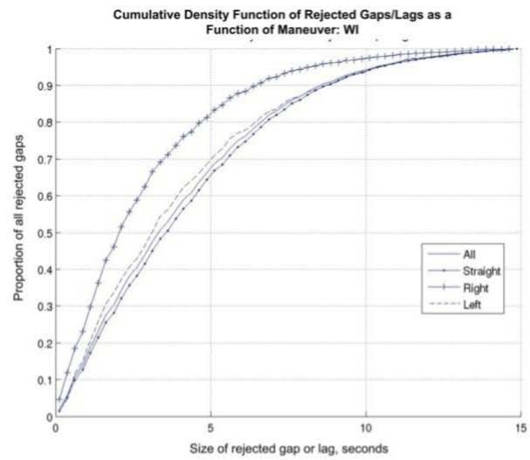
- Maneuver
- Time of day
- Time spent waiting for an acceptable gap
- Average size of previously available
- Departure zone (i.e., median or minor road departure point), and
- Vehicle classification,

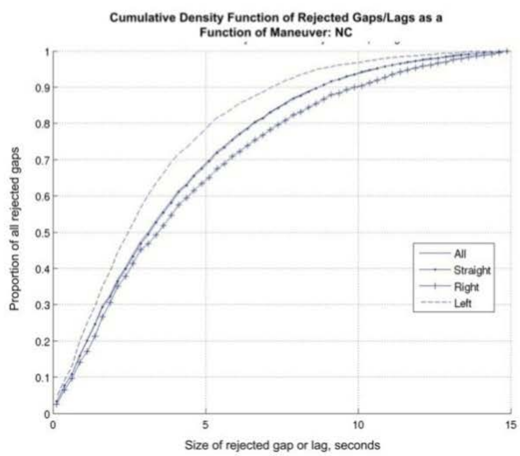
are described below.

6.1 Gap Rejection Threshold Sensitivity to Maneuver Type

We will use a Cumulative Density Function (CDF) is used to characterize gap rejection decisions made by stopped drivers. The CDFs for intersection entry maneuvers by type are shown in Figure 8. Each point on a curve represents the proportion of all *rejected* *gaps* (the ordinate axis) that are less than a particular gap (or lag), as measured in seconds (the abscissa).







80% Gap Rejection Threshold: Maneuver						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
ALL	6.67	23842	6.61	25902	6.56	26759
Straight	5.51	10860	6.78	21850	6.57	22708
Right turn	7.61	11967	4.67	2684	7.46	2097
Left turn	5.82	1015	6.44	1368	5.18	1954

Figure 8. Plots of driver gap rejection behavior at the MN, WI, and NC test intersections. These plots show the gap rejection behavior for the aggregation of the maneuvers, and for each individual maneuver. Table on lower right shows the gap corresponding to the 80th percentile of all rejected gaps.

When presented a lag fifteen-seconds or greater, every driver will enter or cross the traffic stream. As a result, any gaps or lags greater than 15 seconds are removed from the data pool. In the context of driver gap rejection assistance, the rejected gap curves for the "ALL" condition in Figure 8 can be interpreted as describing the percentage of *all rejected gaps* which were rejected of a *particular duration or less.* For the Minnesota Test Intersection, of "All" the rejected gaps recorded at the intersection of duration of 15 seconds or less, 80% of drivers rejected gaps of 6.67 seconds or less.

For a non-cooperative system, using the "ALL" warning level is reasonable because there is no good measure of driver intent. For cooperative systems, a partial measure of driver intent is provided by turn signal activation. If a turn signal activation has been detected, then the timing can be adjusted to accommodate the maneuver indicated by the turn signal.

Physical interpretation of the generic rejected gap cumulative distribution function.

It is important to note that the curves presented in this report are functions of the *gaps rejected by drivers;* they are *not* curves of gaps *accepted* by drivers. This is a key distinction from previous work which addresses gaps accepted by drivers.

The shape of the gap rejection curve warrants some extra attention. Free flowing traffic on a highway is comprised of both vehicles and the spaces between the vehicles. Safe driving practices dictate that the minimum separation between vehicles should be at least two seconds. Thus, if free flowing traffic is watched, few gaps shorter than 2 seconds would be observed; a relatively uniform distribution of gaps above 2 seconds will flow past the intersection. The frequency of gaps of a particular size will depend on traffic volume. If traffic volumes are low, the traffic stream will have a relatively uniform distribution of gaps. If traffic volumes are high, the relative proportion of small gaps passing by will be higher than that for low traffic volumes; moreover, the proportion of large gaps will be significantly smaller for higher traffic densities. This phenomenon is graphically illustrated in Figure 9 below.

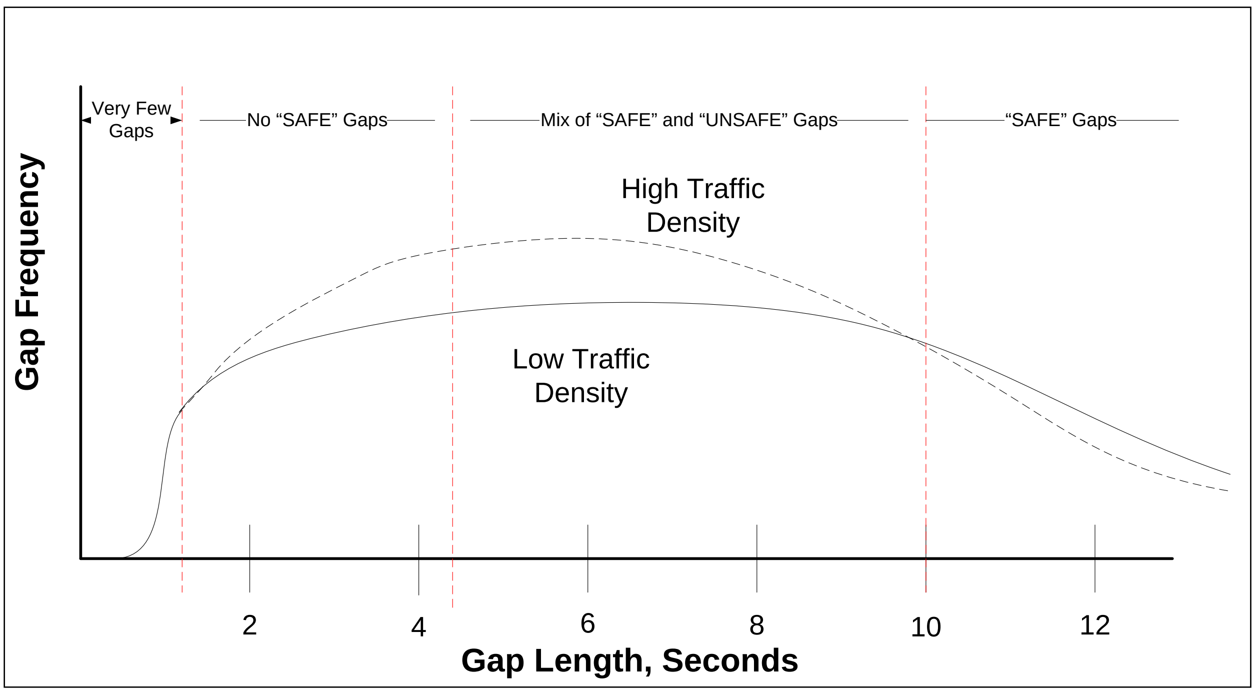


Figure 9. Illustration of the distribution of gap frequency as a function of gap length and traffic density for free flowing traffic. It is important to note that the graph above describes ALL gaps, not just rejected gaps.

The number of gaps expected to pass by a stopped driver (waiting to enter) with a length of x seconds or less is the integral of the traffic density curve from 0 to x seconds, or equivalently, the area under the traffic density curve measured from 0 to x seconds. Integrating the plots in Figure 9 produces the cumulative gap density (cumulative gap density plots the percentage of all gaps below a specific gap size) plot presented in Figure 10 below.

If a driver exhibits safe behavior, *all* gaps passing by a driver of a length less than *X* will be rejected by the driver. Crashes occur only when gaps of length less than *X* are (unsafely) accepted by the driver. (For illustrative purposes, *X* ~ 4.2 seconds in Figure 9 above.)

For the cumulative distribution functions presented herein, it is important to remember that the region on the left side of that curve will all generally assume the same shape. This is because the vast majority of drivers reject *all* small gaps presented to them in the traffic stream. The cumulative distribution curve deviates from linear (i.e., exhibits an inflection) at the point where drivers shift from rejecting *all* presented gaps to rejecting *some* of the gaps presented. The cumulative distribution function approaches its horizontal asymptote when the driver would accept *nearly all* gaps in the traffic stream of that size or larger which are presented.

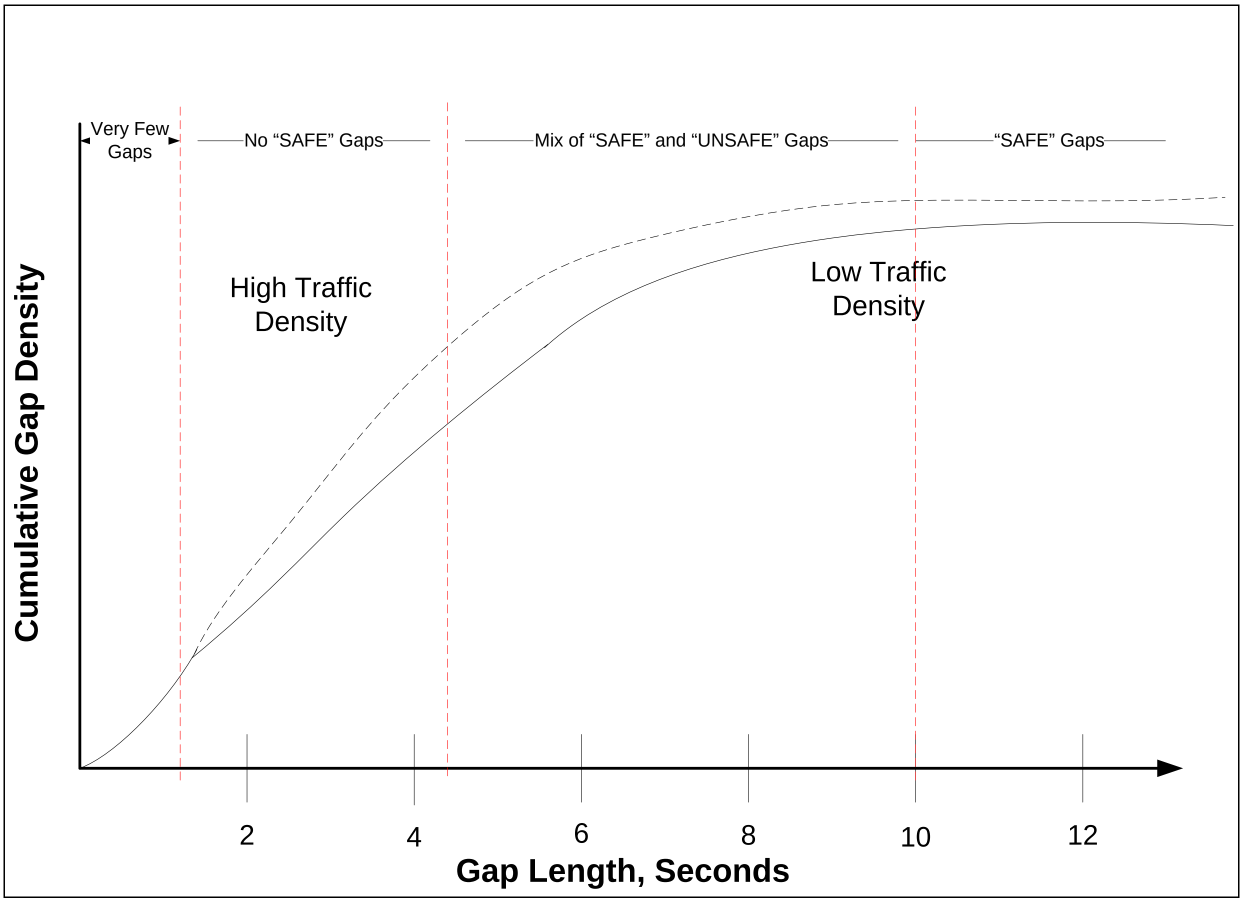


Figure 10. Cumulative distribution function for all available gaps for low and high density traffic flows. This again is for all gaps, not just rejected gaps.

It is also important to note that rejected lags are included in the rejected gap data. When a vehicle arrives at an intersection, the initial lag presented to the driver can range from very small (i.e., much less than one second in length) to small (less than six seconds) to large (more than six seconds). The small rejected lags contribute to the CDF, further explaining why the CDF plot is non-zero for small gap/lag lengths.

For any given intersection, the cumulative distribution of rejected gap plots will all take a similar shape. That is because drivers generally reject ALL gaps in the ‘No “SAFE” Gaps’ region in Figure 9 above. (Those who don’t are the ones involved in crashes.) Variations in the cumulative distribution plots occur in the region indicated by a “Mix of ‘SAFE’ and ‘UNSAFE’ Gaps” in Figure 9. Essential to proper alert and warning timing is the understanding of the “Mixed Gap” region and its effect on the cumulative distribution function.

Physical interpretation of gap rejection threshold and warning timing.

Warning timing for the driver interface is directly related to the gap rejection level for a particular intersection. For example, assume that the DII warning is activated at the 80% gap rejection level. At this level, on average, 80% of people who will reject a gap will a reject a gap of this duration or less. For drivers who have already decided to reject a gap, activation of the warning will affirm their decision to reject that gap. For the 20% of drivers who have not yet decided to reject a gap, activation of the warning will capture their attention, and prevent unsafe entry into the intersection.

The key to alert and warning timing is to choose values which both affirm a driver’s previous decision and warn a driver who has yet to decide that a gap is unsafe. As will be shown later, the distributions of gap rejections reviewed as a function of other factors (vehicle class, time of day, etc.) are remarkably consistent. Although guidelines will arise from this analysis, final numbers will have to be determined through on-site testing. Preliminary on-site testing corroborates this hypothesis of relatively low sensitivity, but that work is based on a small sample size. Additional testing will provide more insight into timing sensitivity.

Review of the table embedded in Figure 8 shows that in WI and NC, approximately 80% of the captured maneuvers are straight through the intersection, with left and right turns representing 5-7% and 7-10% of maneuvers, respectively. Left turns account for 5% of Minnesota maneuvers; right turns and straight-thrus are nearly equally represented. Even with the disparity in maneuver type distribution, gap rejection behavior at all three states is quite consistent.

The primary anomaly in the data is the extremely low 80% gap rejection threshold for WI right turns. The primary hypothesis for this short duration is that the WI research intersection is located on a large horizontal curve, and visibility is somewhat restricted from the east side of the intersection.

6.2 Gap Rejection Threshold Sensitivity to Time of Day

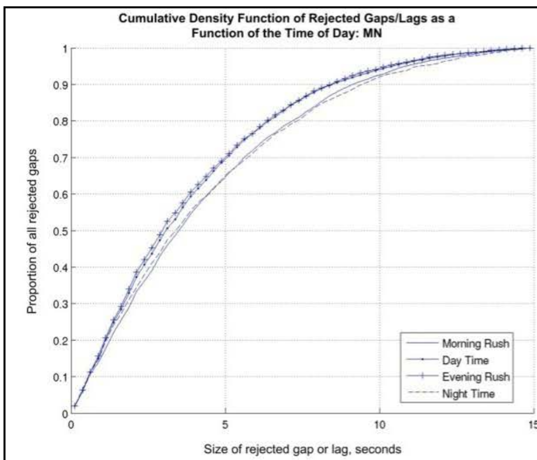
Gap rejection by time of day for each of the three states is shown in Figure 11 below.

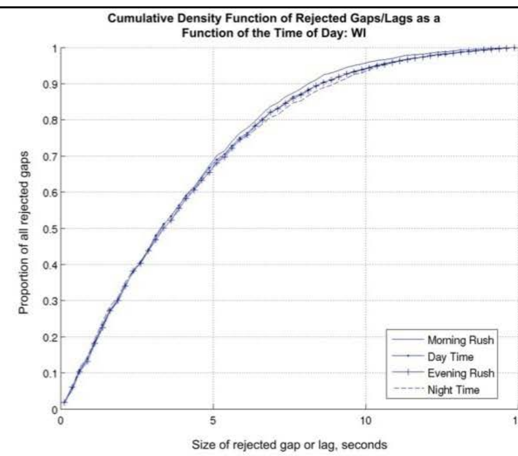
The spread of the curves in each of the states is small, and consistent between the states. Minnesota shows the highest variation in the 80% gap rejection level – a 0.8 second difference between AM and PM rush. It appears Minnesotans are in more of a hurry to return home than to go to work. The other states show no more than a 0.7 second variation. The largest 80% gap rejection threshold is for evening hours; during relatively low traffic volume periods, lower mainline traffic volumes result in fewer small gaps being presented to drivers. With less exposure to small gaps, the gap rejection threshold has no option other than to increase. Overall, the gap rejection threshold shows little sensitivity to time of day effects.

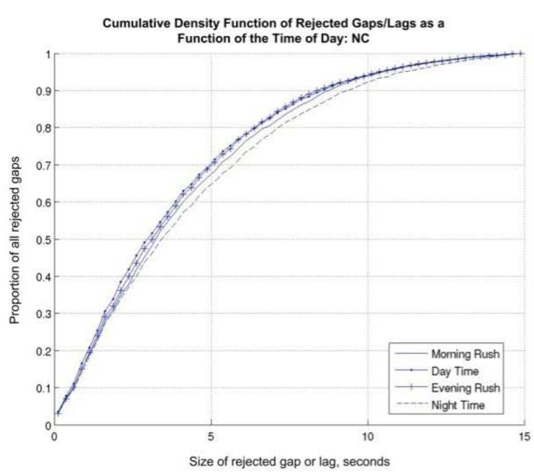
6.3 Gap Rejection Threshold Sensitivity to the Average Size of Previously Available Gaps

Figure 12 below shows the gap rejection behavior when drivers are faced with a "clustering" of gaps of a particular duration. This exercise tests the propensity of a driver to accept a smaller than expected gap when only smaller than expected gaps are presented.

For the data presented in Figure 12, the four categories of average gap length were based on a thirty second observation period by the driver on the minor road. The observation period began thirty seconds prior to the driver accepting a gap; the average gap for that thirty second period prior to gap acceptance had to lie within the specified ranges. The volume of data collected for the 0-5 second average gap is small because few instances of such heavy traffic on the tested minor roads were presented to the driver. In MN, fewer than 3% of rejected gaps correspond to an average exposure of 0 – 5 second gaps; in WI, fewer than 0.5% were exposed to such tight conditions, and for NC, the value is approximately 2.4%.







80% Gap Rejection Threshold: Time of Day

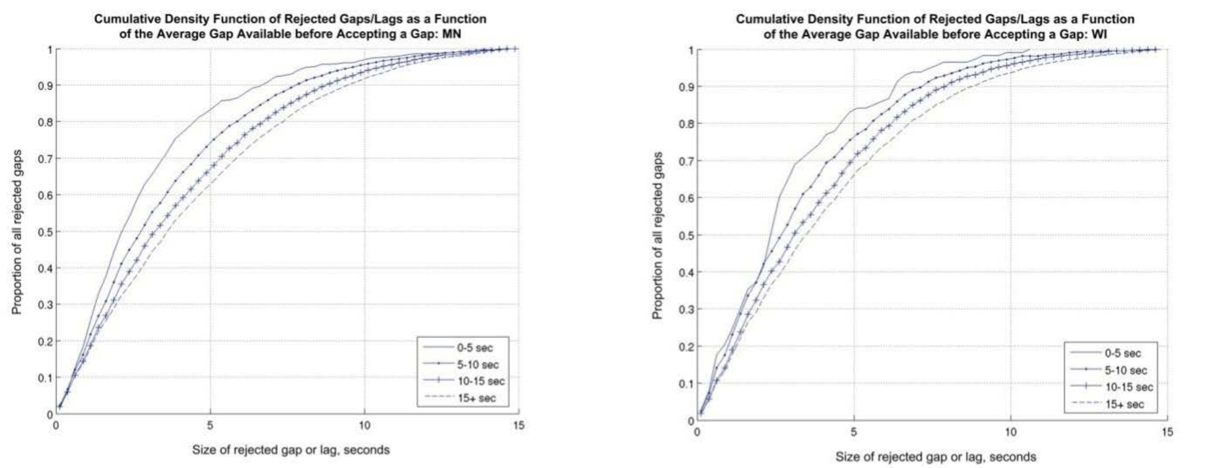
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
AM Rush	7.17	3909	6.42	2065	6.73	3137
Daytime	6.39	11898	6.59	15662	6.41	14133
PM Rush	6.35	6810	6.63	4997	6.39	6642
Evening	7.33	2828	6.78	3437	7.14	3878

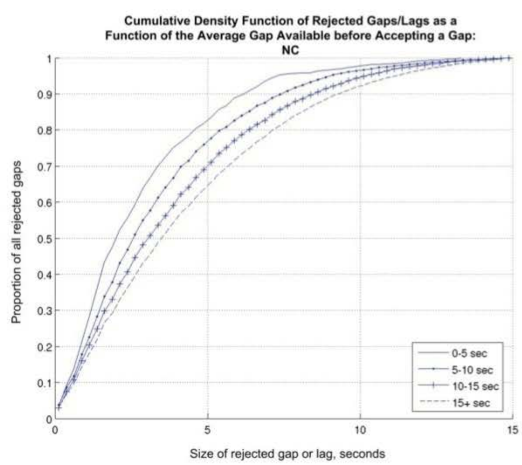
Figure 11. Gap rejection cumulative distribution functions as a function of the time of day for the rural, median-separated, thru-Stop expressway intersections.

Although the percentage of exposure to small gaps is low, it is under precisely these conditions that proceeding through the intersection results in very small safety margins or crashes. In a field operational test, a surrogate measure of system performance would be the 80% gap rejection threshold under these conditions. If the 80% gap rejection threshold were to increase (ideally beyond the 5 second point), the system would produce the desired effect on the motoring public.

6.4 Gap Rejection as a Function of Time Waiting for a Gap

It has been speculated that the time waiting for an acceptable gap influences the gap acceptance/rejection decision; the longer the wait, the lower the gap rejection threshold [17]. Because of this speculation, this effect was investigated; Figure 13 shows the effects of timing waiting for an acceptable gap on the distribution of rejected gaps.





80% Gap Rejection Threshold: Average Available Gap						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 5 Seconds	4.48	805	4.58	113	4.57	630
5 - 10 Seconds	5.86	8253	5.54	1790	5.43	6213
10 - 15 Seconds	6.72	6970	6.19	3142	6.35	6369
> 15 Seconds	7.36	9177	6.76	19430	7.14	14168

Figure 12. Gap rejection for the rural, median-separated, thru-Stop expressway intersections as a function of gaps presented to the driver. This measures the propensity of a driver to accept a smaller than expected gap when only presented small gaps.

The only sensitivity to the gap rejection threshold from time waiting for a gap is found during the 0-10 second wait period, where the gap rejection threshold is approximately four seconds lower than those for the other waiting periods. This behavior is found throughout the three states for which data for rural, median-separated, thru-Stop expressway intersections have been collected.

This phenomenon can be explained by examining the timing which is associated with this scenario. To be included in this sample population, the driver has to reject at least one lag or gap, *and* has to depart either the minor road or median in less than 10 seconds after arriving. The sample population of rejected gaps or lags presented to that driver will be of 10 second duration or less. As a subset of the population of all rejected gaps of duration 15 seconds or less, the expected value of the rejected gaps in this 10-second subset would be less than the expected value for all rejected gaps. The small 80% gap rejection threshold is a function more of the conditions and the sample population than it is an indication of a drivers propensity to rush the gap decision.

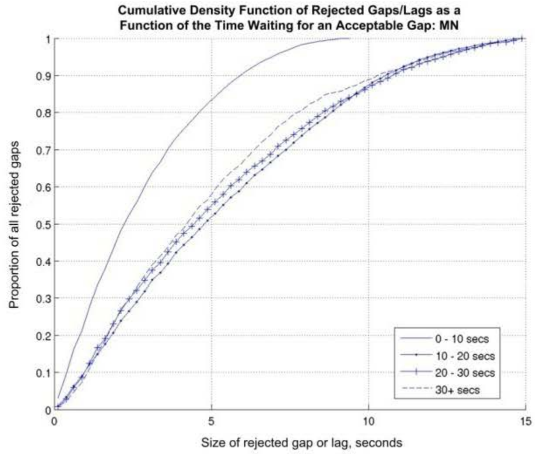
Reviewing the other categories of gap rejection threshold as a function of time waiting shows no trends which indicate a necessary modification to alert and warning timing as a function of time waiting for a gap. Those waiting for more than 30 seconds appear to have a lowered gap rejection threshold, but only Minnesota shows that the threshold is reduced significantly from the 10-20 second wait time period. However, the value to which it is reduced is consistent with gap thresholds in other analyses.

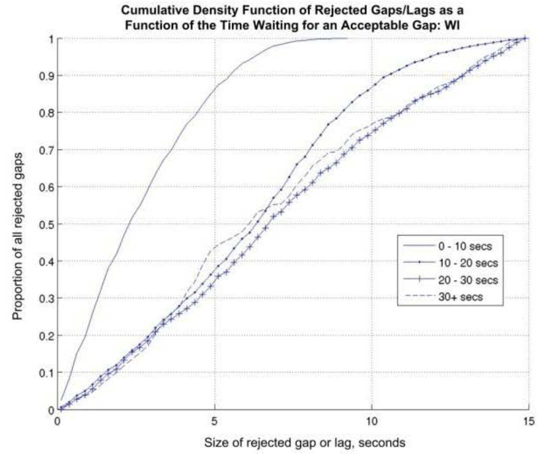
Adjustment of the waiting time categories for gap rejection produces a similar result. Figure 14 shows the CDFs for the time waiting categories of 5-15 seconds, 15-25 seconds, 25-35 seconds, and more than 35 seconds, respectively. The small 80% gap rejection threshold for the waiting time of 0 – 5 seconds shifted approximately 2 seconds longer for waiting times between 5 and 15 seconds.

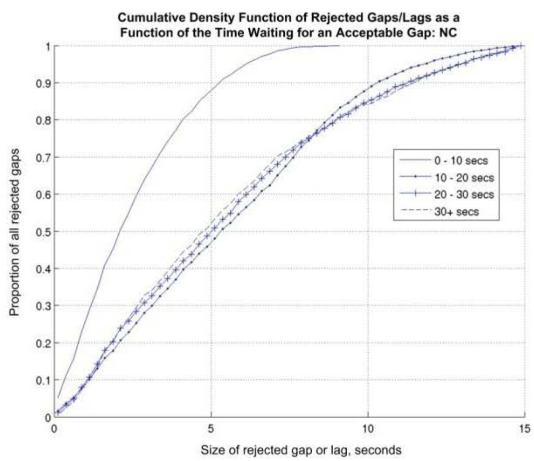
6.5 Gap Rejection as a Function of Departure Zone

A thru-Stop, median-separated expressway intersection has four points of departure: two from the minor road, and two from the median. These points of departure are shown for the Minnesota Test intersection in Figure 15; other state intersections use the same zone definitions.

From a zone of departure point of view, what stands out is that the gap rejection threshold is lower for the median points of departure (zones 7&8) than for the stop bar locations (zones 1&2). It is important to note that medians are generally served by “Yield” signs, rather than “Stop” signs. (The Wisconsin did have Stop signs in the median.) As such, drivers are not required to stop, but are allowed to continue moving through the median if conditions are favorable. Because the moving vehicle carries momentum and is not required to accelerate from a dead stop, a shorter gap can be chosen while maintaining a threat level similar to a stopped vehicle selecting a longer gap. Once again, drivers act upon a reasonably consistent perception of threat.

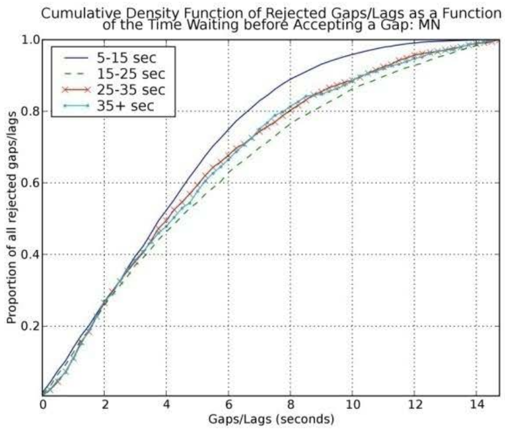


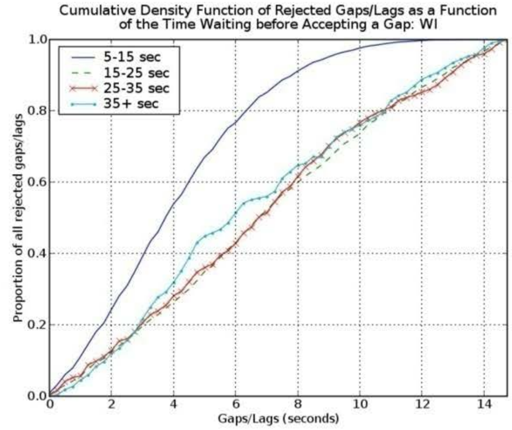


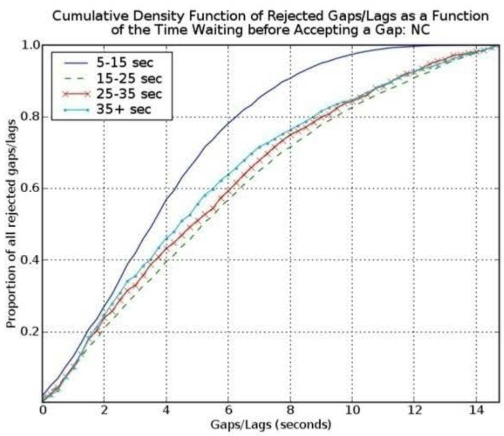


80% Gap Rejection Threshold: Time Waiting for a Gap						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 10 Seconds	4.61	12724	4.45	16202	4.1	14624
10 - 20 Seconds	8.81	7655	9.06	8277	8.72	8709
20 - 30 Seconds	8.56	2973	10.91	1318	9.01	2623
> 30 Seconds	7.74	2093	10.92	363	8.97	1867

Figure 13. Gap rejection for the rural, median-separated, thru-Stop expressway intersections as a function of time at the intersection waiting for a gap.







80% Gap Rejection Threshold: Time Waiting for a Gap from the Median

	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
5 - 15 Seconds	6.62	12100	6.33	16920	6.26	14429
15 - 25 Seconds	8.71	4739	10.90	3265	9.46	4742
25 - 35 Seconds	7.95	1821	10.71	529	9.02	1486
> 35 Seconds	7.78	1372	10.78	216	8.75	1346

Figure 14. Gap rejection for the rural, median-separated, thru-Stop expressway intersections as a function of time at the intersection waiting for a gap. The time waiting categories have been changed from Figure 13.

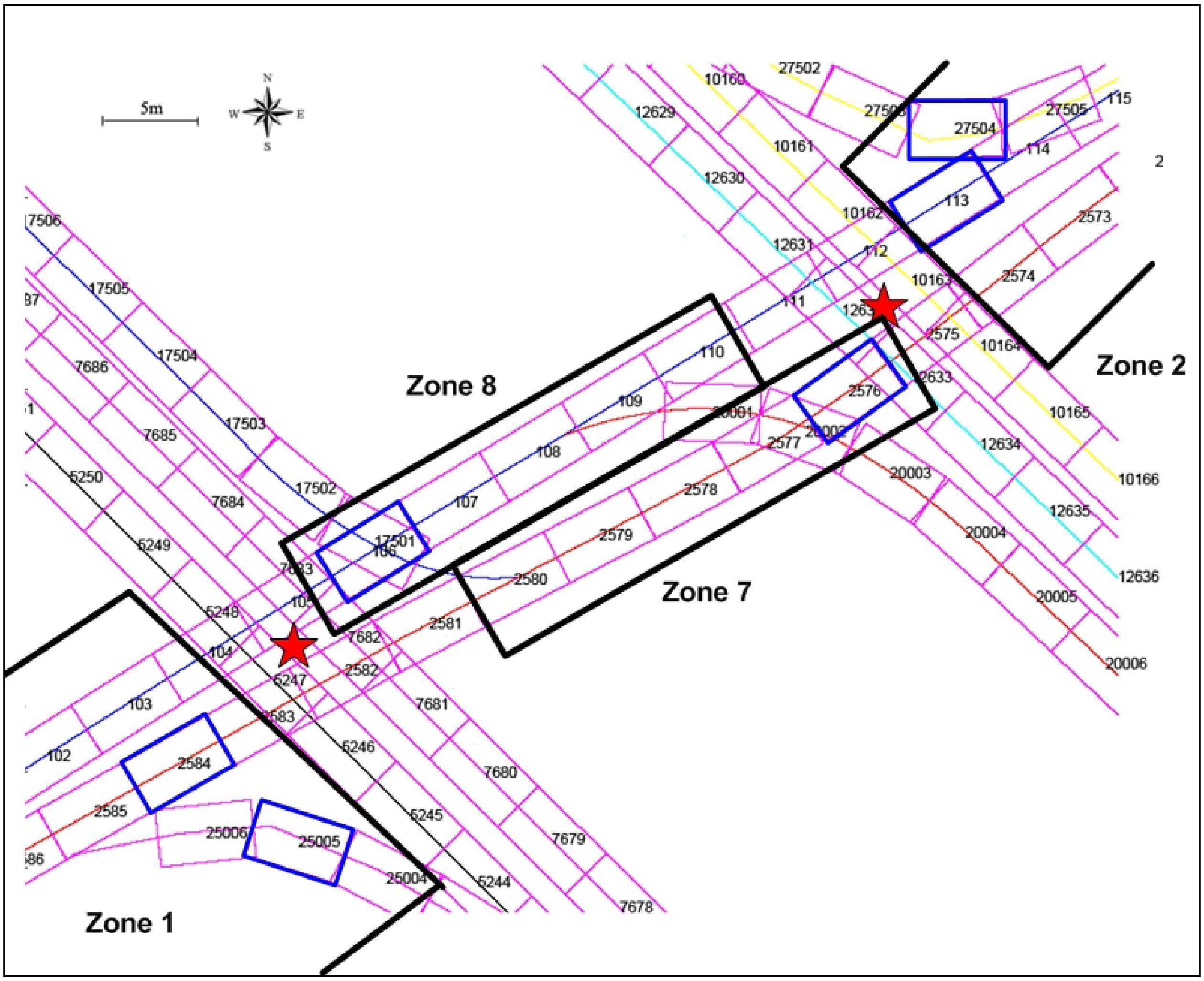
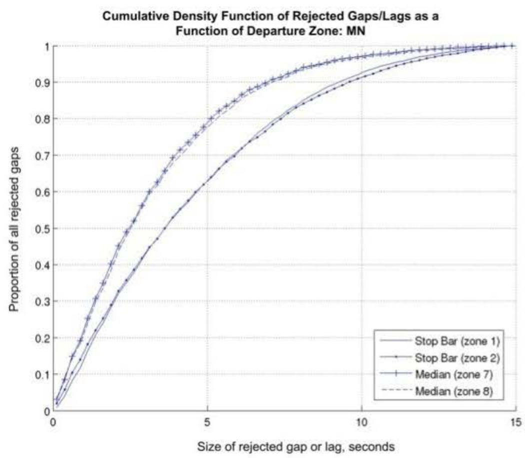
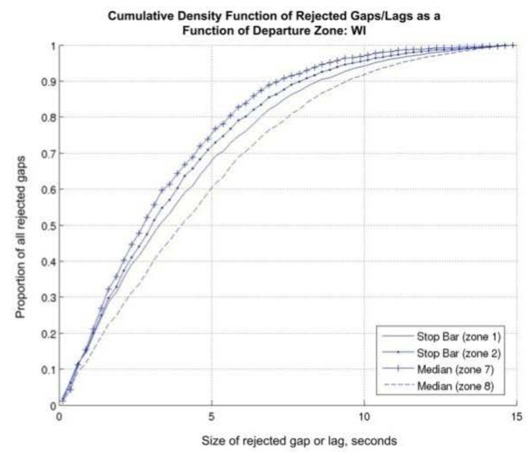
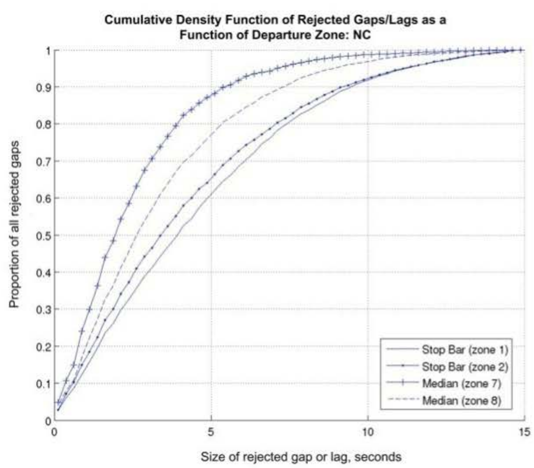


Figure 15. Layout of a typical median-separated rural expressway intersection. Zone 1 and Zone 2 represent the departure point for the minor road, and Zone 7 and Zone 8 represent the departure point for the median. These zone designations are generic, but the intersection shown above is the Minnesota Test Intersection.







80% Gap Rejection Threshold: Departure Zone						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Zone 1 (Stop bar)	7.24	9219	6.6	9267	7.4	11605
Zone 2 (Stop bar)	7.4	7059	6.08	5103	7.07	7061
Zone 7 (median)	5.13	4165	5.58	1538	3.92	4775
Zone 8 (median)	5.31	4878	7.49	7041	5.33	3966

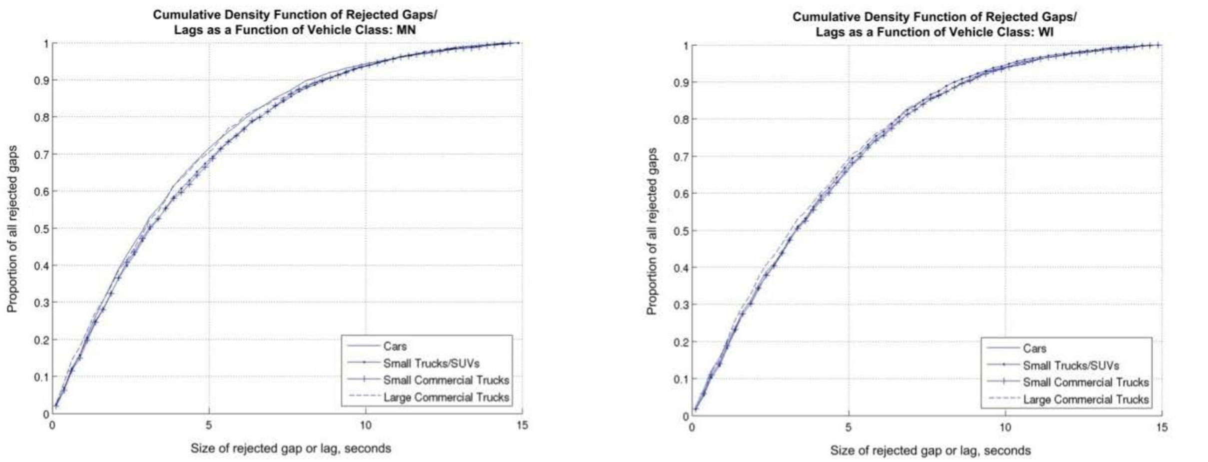
Figure 16. Gap rejection for the rural, median-separated, thru-Stop expressway intersections as a function of departure zone.

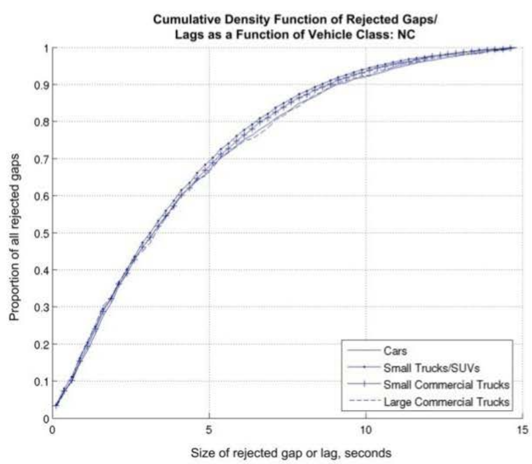
6.6 Gap Rejection as a Function of Vehicle Classification

Of all the analyses undertaken through this study, the results relating vehicle size classification to gap rejection thresholds produced the most surprising results. As described previously, the expectation was that longer, heavier vehicles would produce larger gap rejection thresholds because of the fact that acceleration capabilities of large vehicles are less than those for smaller vehicles, and that a longer vehicle requires additional time to clear the mainline road.

Figure 17 shows an incredibly tight distribution of gap rejection behavior for the three intersections. What is more remarkable is that the 80% threshold is so similar not only between vehicle classification, but between the states as well. Of the conditions explored in this study, this is the tightest coupling of intra-state results.

Because this result was unexpected, additional analysis was undertaken to ensure its accuracy. The first question raised was whether oncoming mainline traffic slowed more for large commercial vehicles than for smaller vehicles; if this were the case, the value of the rejected gap would be artificially decreased.





80% Gap Rejection Threshold: Vehicle Class

	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Cars	6.22	4747	6.7	2409	6.99	3044
Small Truck/SUV	6.64	10994	6.55	12668	6.49	16900
Small Commercial Trucks	6.65	2236	6.71	7626	6.64	6405
Large Commercial Trucks	6.1	1292	6.51	1919	7.08	542

Figure 17. Gap rejection behavior as a function of vehicle classification for the rural, median-separated, thru-Stop expressway intersections.

The second question is how the time-to-cross the major road lanes varies between heavy vehicles and light vehicles. If these vehicles cross in a comparable timeframe, then the level of risk taken by truck drivers will be similar to that taken by drivers of passenger cars. If the risk level is similar, then the results above are likely correct. This reflects the fact that people perceive threats in a reasonably consistent manner.

With respect to oncoming traffic, the reduction of speed for mainline traffic as a function of vehicle size/classification was undertaken to see if mainline traffic slows more for large vehicles than for smaller vehicles. Figure 18 shows the sequence of events for the analysis. As a vehicle has been determined to leave the stop bar zone, the time at which the vehicle departed is recorded as t0. To determine the reaction of mainline traffic to the vehicle crossing the highway, the speed of oncoming vehicles five seconds *before* the departure time of the minor road vehicle (i.e., t0-5 seconds), is subtracted from the speed two seconds *after* the departure time (i.e., t0+2 seconds). As is shown in Figure 19, mainline drivers respond with a greater variation in speed to the heavy vehicle, especially in the event that the minor road vehicle accepts a small gap. This behavior is consistent with what is expected.

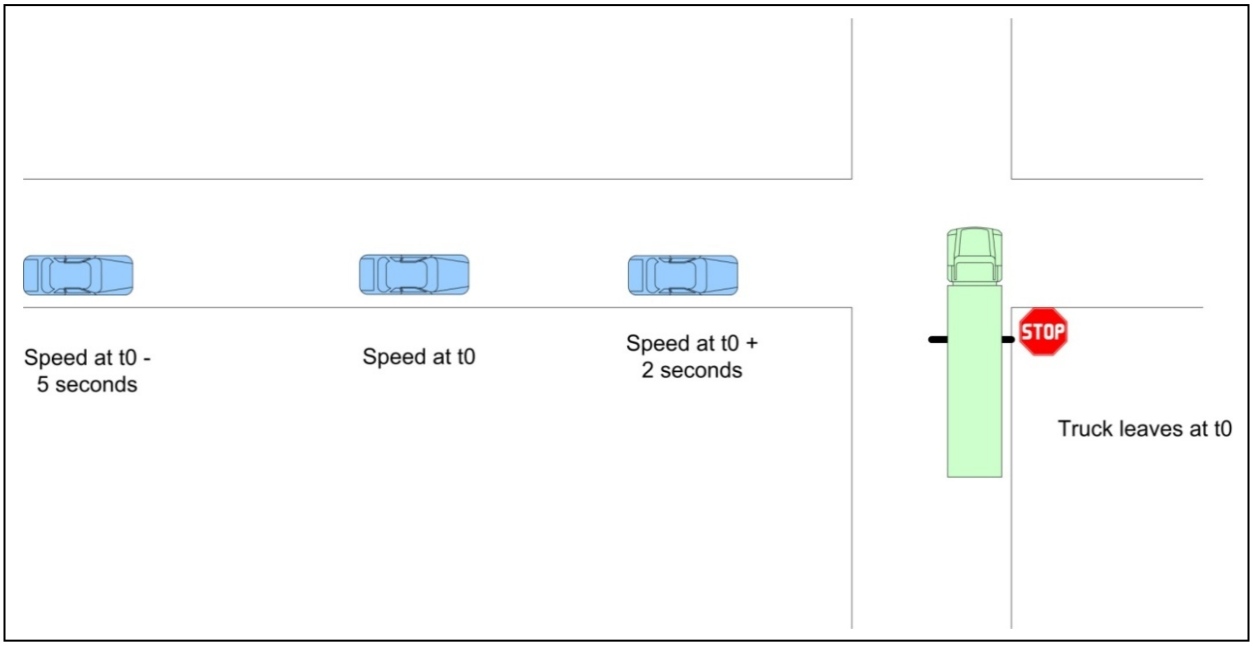


Figure 18. Procedure to determine whether mainline vehicle speed reductions are greater for larger entering vehicles than for smaller entering vehicles.

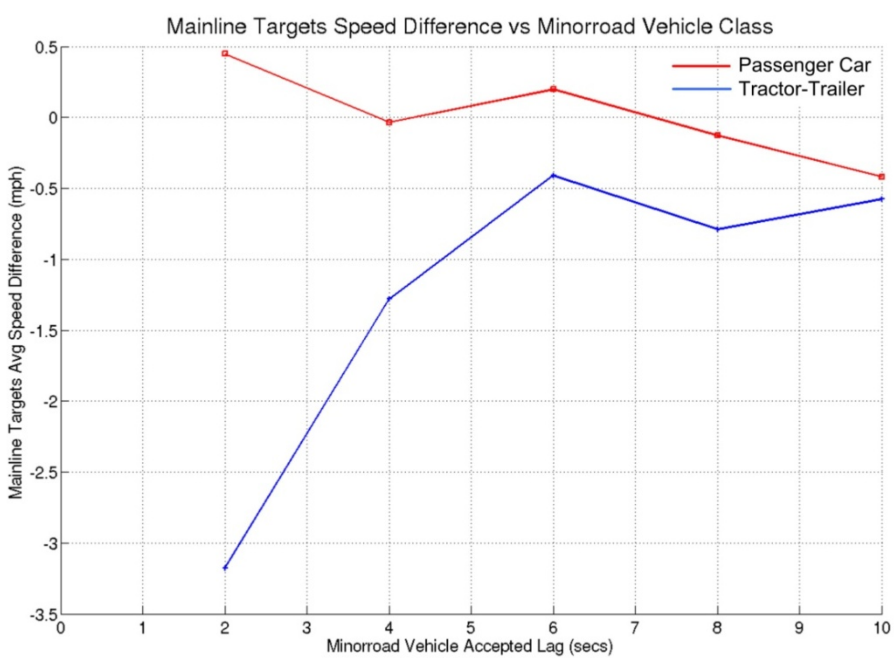


Figure 19. Speed changes on the mainline in response to a vehicle crossing the highway for the North Carolina test intersection. Speed differential is defined as the speed of the mainline vehicle 5 seconds *before* the minor road vehicle pulled out subtracted from the speed of the mainline vehicle 2 seconds *after* the minor road

vehicle pulled out. On US 74, the 20th percentile speed is 61 mph, 50% is 64.6 mph, and 80% is 69 mph.

The second test consisted of comparing the time for vehicles to cross the mainline of traffic from the stop bar. For this test, using Figure 15 as a reference, the timing of the event began when the *front* of a vehicle vacated either region 2584 (for eastbound traffic) or region 113 (for westbound traffic), and the timing ended when the *front* of a vehicle first entered region 2580 (for eastbound traffic) or region 110 (for westbound traffic), respectively.

The time to clear the mainline traffic is longer for a truck than a car because the length of the truck is greater than that for a car. Using time-to-cross data in Figure 20, and an assumption of constant acceleration corresponding to the mean time to cross the intersection as the vehicle moves from stop bar to median, the rear of the truck requires, on average, 2.5 more seconds to *clear* the mainline highway than does a passenger car.

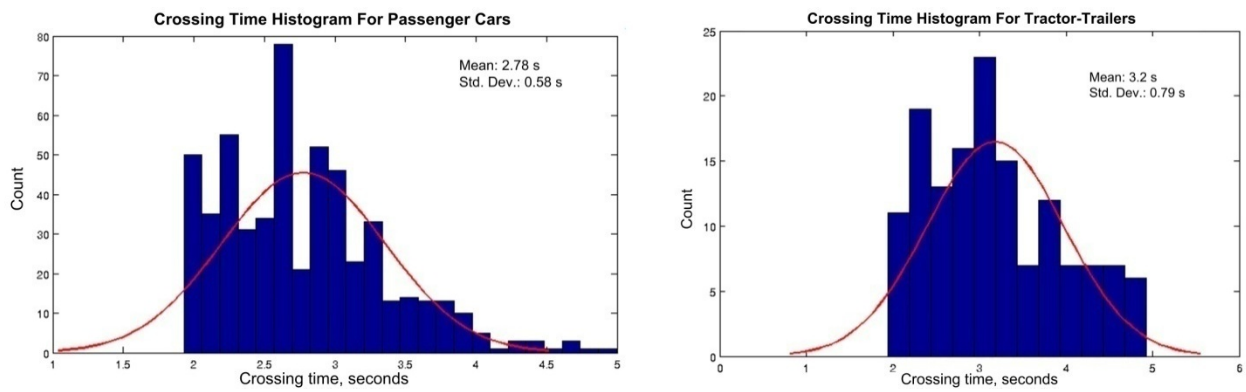


Figure 20. Time to cross mainline traffic from the minor road stop bar for the rural, median-separated, thru-Stop expressway intersections.

Vehicles on the mainline typically slow more for large targets than for small targets. As major road vehicles slow, the equivalent effect is to increase the gap. Although drivers of heavy vehicles may accept smaller than expected gaps, the effective gap that is accepted is larger than the gap which was originally accepted.

Figure 20 shows that highway crossing times between passenger cars and tractor-trailers, as measured by the front bumper of the crossing vehicle, differ in the mean by only 0.42 seconds. This result is somewhat unexpected; the overriding hypothesis was that trucks require considerably longer to complete that maneuver. The length of the truck results in a longer "time to clear" the major road, but from the drivers' viewpoint, small time-to-cross differences between trucks and cars exist. For small gaps, the reduction of mainline traffic speeds compensate for the longer time to clear timing for the tractor-trailers.

6.7 Weighted Average 80% Gap Rejection Threshold

Given the six conditions above, the weighted average gap rejection threshold for the conditions are provided below. The coupling of the results is exceptionally tight, both between conditions and between states. Table 6 - Table 11 below provide weighted averages for each of the six conditions.

Table 6. Weighted average 80% gap rejection threshold by maneuver for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Maneuver						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
ALL	6.67	23842	6.61	25902	6.56	26759
Straight	5.51	10860	6.78	21850	6.57	22708
Right turn	7.61	11967	4.67	2684	7.46	2097
Left turn	5.82	1015	6.44	1368	5.18	1954
Weighted Average	6.58		6.54		6.55	

Table 7. Weighted average 80% gap rejection threshold by time of day for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Time of Day						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
AM Rush	7.17	3909	6.42	2065	6.73	3137
Daytime	6.39	11898	6.59	15662	6.41	14133
PM Rush	6.35	6810	6.63	4997	6.39	6642
Evening	7.33	2828	6.78	3437	7.14	3878
Weighted Average	6.60		6.61		6.54	

Table 8. Weighted average 80% gap rejection threshold by average available gap for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Average Available Gap						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 5 Seconds	4.48	805	4.58	113	4.57	630
5 - 10 Seconds	5.86	8253	5.54	1790	5.43	6213
10 - 15 Seconds	6.72	6970	6.19	3142	6.35	6369
> 15 Seconds	7.36	9177	6.76	19430	7.14	14168
Weighted Average	6.60		6.59		6.51	

Table 9. Weighted average 80% gap rejection threshold by time waiting for an acceptable gap for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Time Waiting for Acceptable Gap						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 10 Seconds	4.61	12724	4.45	16202	4.1	14624
10 - 20 Seconds	8.81	7655	9.06	8277	8.72	8709
20 - 30 Seconds	8.56	2973	10.91	1318	9.01	2623
> 30 Seconds	7.74	2093	10.92	363	8.97	1867
Weighted Average	6.59		6.32		6.34	

Table 10. Weighted average 80% gap rejection threshold by time waiting for an acceptable gap for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Departure Zone						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Zone 1 (Stop bar)	7.24	9219	6.6	9267	7.4	11605
Zone 2 (Stop bar)	7.4	7059	6.08	5103	7.07	7061
Zone 7 (median)	5.13	4165	5.58	1538	3.92	4775
Zone 8 (median)	5.31	4878	7.49	7041	5.33	3966
Weighted Average	6.57		6.69		6.41	

Table 11. Weighted average 80% gap rejection threshold by vehicle class for the rural, median-separated, thru-Stop expressway intersections.

80% Gap Rejection Threshold: Vehicle Class						
	MN		WI		NC	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Cars	6.22	4747	6.7	2409	6.99	3044
Small Truck/SUV	6.64	10994	6.55	12668	6.49	16900
Small Commercial Trucks	6.65	2236	6.71	7626	6.64	6405
Large Commercial Trucks	6.1	1292	6.51	1919	7.08	542
Weighted Average	6.50		6.61		6.59	

These results show that despite how the distributions of gap rejection are classified, drivers generally perceive threats in similar fashions. Also important is the similarity of gap rejection behavior across the three states: in each category, the maximum variation between states in terms of a weighted average 80% gap rejection threshold is 0.26 seconds. Gap rejection behavior has been shown to be remarkably consistent.

6.8 Rural, Expressway Thru-Stop, Median-Separated Intersection Conclusions

The macroscopic analysis provided results which are generally consistent with what is known about rural thru-Stop intersection crashes, and one significant, unexpected finding.

With respect to what is known from crash records and captured crashes, in the case of “Yield” controlled medians, 80% of intersection crashes occur after a median departure. Likewise, the smallest gap rejection thresholds were associated with the median departure point, and in particular, with median departure points for gap acceptance waits of 10 seconds or less. If the CICAS-SSA system can increase the gap rejection thresholds for these situations, it is likely that the crash frequencies at those intersections will decrease.

Aside from this particular case of short wait times from a median departure point, all other gap rejection thresholds showed low sensitivity to other parameters. The primary unexpected result was that there appears to be only a slight sensitivity to gap rejection thresholds as a function of vehicle classification. Because this result was unexpected, two more analyses were performed to validate that conclusion. The other two analyses were consistent with the primary finding.

The fact that gap rejection thresholds are independent of vehicle classification has substantial implications for system deployment. Approximately ½ of the cost of the prototype CICAS-SSA system is devoted to the minor road vehicle classification system. Should vehicle classification not be needed, a substantial savings in the cost to deploy can be realized.

7 Chapter 6 Rural Expressway, Median-Separated, Thru-Stop, “T” Intersections

7.1 Introduction

As part of the pooled fund study, two “T” rural expressway intersections were instrumented: US-30 and T Ave., Boone County, IA, and US-395 and Gill Station Coso Road, Inyo County, in CA. What was interesting in this portion of the study was that although the intersections are both “T” intersections, they have significant geometric differences. As a result, driver performance values were disparate; trends, however, were similar.

Intersection Geometries and Gap Rejection Behavior.

The California intersection has long acceleration lanes for vehicles both turning right from the minor road leg of the “T” intersection, and turning left from the median. These long acceleration lanes represent more of a “merge” condition than a right or left turn into traffic. As a result, left turns from the median and right turns from the stop bar really fail to represent a conscious gap rejection decision by the driver. As a result, even though trajectories were measured, no left or right turns are considered in the California intersection analysis. In contrast, the IA intersection has neither right nor left acceleration lanes.

Thus, the only maneuvers considered in the CA analysis are “straight” maneuvers, either from the median or from the stop bar associated with the minor road.

In comparison to other intersections, the CA analysis seems unorthodox. However, this analysis is completely consistent with the study of the crash records associated with this intersection. According to the crash analysis performed by CH2MHill, the primary crash issue was not with vehicles leaving the minor road and crossing onto the median; the problem at the CA intersection was with vehicles making a left turn from the mainline, and being involved in a left turn across path (LTAP) crash [7]. Of the five crashes recorded at this intersection, all five involved drivers taking too small of a gap from the median crossing to the minor road.

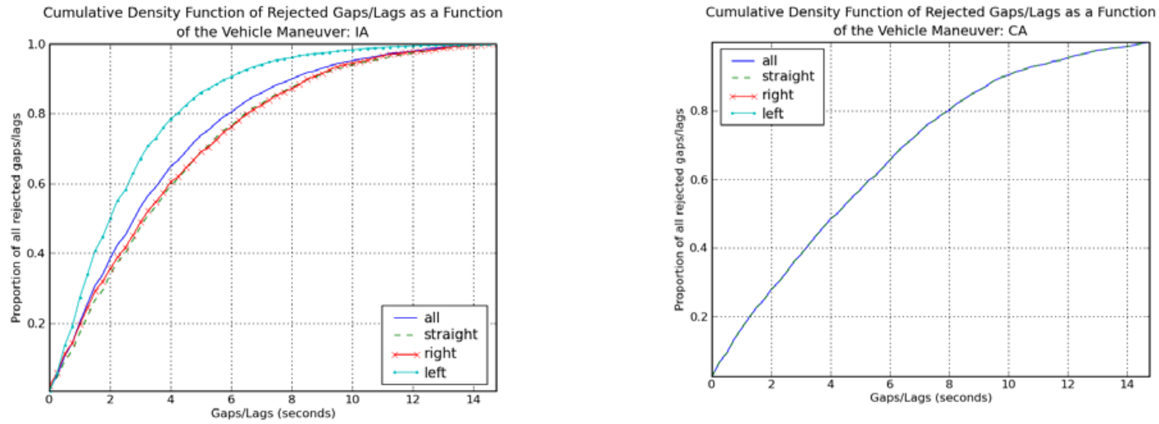
For the California intersection, 129 maneuvers were recorded from the minor road stop bar; 2492 were captured from the median to the minor road. It appears that the trajectory tracking LIDAR on that branch of the intersection had difficulty tracking vehicles. This is the only instance where such a problem arose.

Fortunately, the intersection surveillance system *did* successfully track vehicles from the median to the minor road.

It should be noted that CA has added a STOP sign with flashing LEDS on the eight vertices of the stop sign as a means to increase conspicuity of the stop sign and to provide an extra (implicit) indication of danger at this intersection.

7.2 Gap Rejection Threshold Sensitivity to Maneuver Type for “T” Intersections

The first comparison between the “T” intersections is by maneuver type; gap rejection thresholds as a function of maneuver types are shown below in Figure 21.



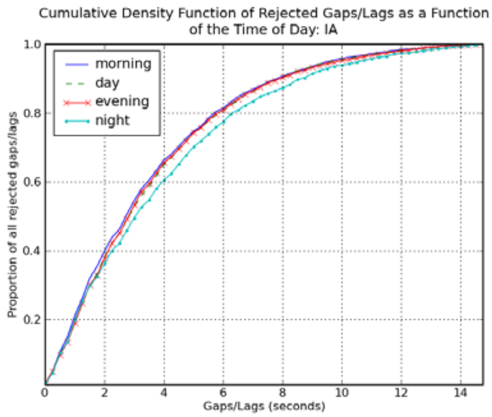
80% Gap Rejection Threshold: Maneuver				
	IA		CA	
	Threshold, s	Count	Threshold, s	Count
ALL	5.9	23479	7.95	2551
Straight	6.45	14398	7.95	2551
Right turn	6.51	2584	0	0
Left turn	4.2	6497	0	0
Weighted Avg.	5.83		7.95	

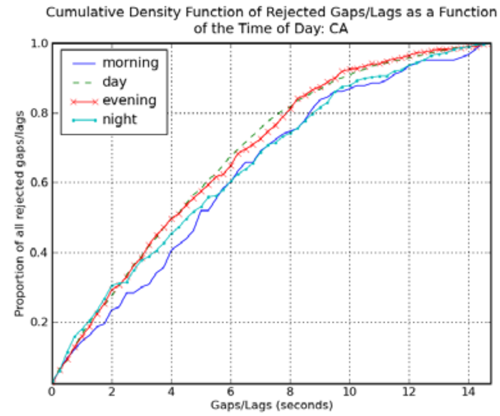
Figure 21. Cumulative density functions for the "T" intersections as a function of maneuver.

The IA plot mirrors that of the NC plot in Chapter 5. It is interesting to note that a driver making a left from the median looks at a horizontal curve while scanning for available gaps. The horizontal curve limits visibility, and is likely responsible for the small 80th percentile gap rejection threshold. The left turn 80th percentile gap rejection threshold measured here is the smallest determined in the study.

7.3 Gap Rejection Threshold Sensitivity to Time of Day for "T" Intersections

As has been the case throughout this paper, the gap rejection behavior of drivers at the "T" intersections shows little sensitivity to time of day effects. As shown in Figure 22, IA shows slight sensitivity at night, but that curve bias is likely due to a lack of traffic on the major road. Traffic volumes are relatively low at the California intersection, particularly at night and in the morning, which again leads to a slight sensitivity to time of day. However, in both cases, this bias is due to traffic conditions, and not driver behavior.





80% Gap Rejection Threshold: Time of Day

	IA		CA	
	Threshold, s	Count	Threshold, s	Count
AM Rush	5.7	5503	8.65	123
Daytime	5.86	10337	7.63	1699
PM Rush	5.8	6840	7.87	511
Evening	6.31	2633	8.77	288
Weighted Avg.	5.86		7.85	

Figure 22. Gap rejection cumulative distribution plots for "T" intersections as a function of time of day.

7.4 Gap Rejection Threshold Sensitivity to the Average Available Gap Prior to Gap Acceptance at "T" Intersections

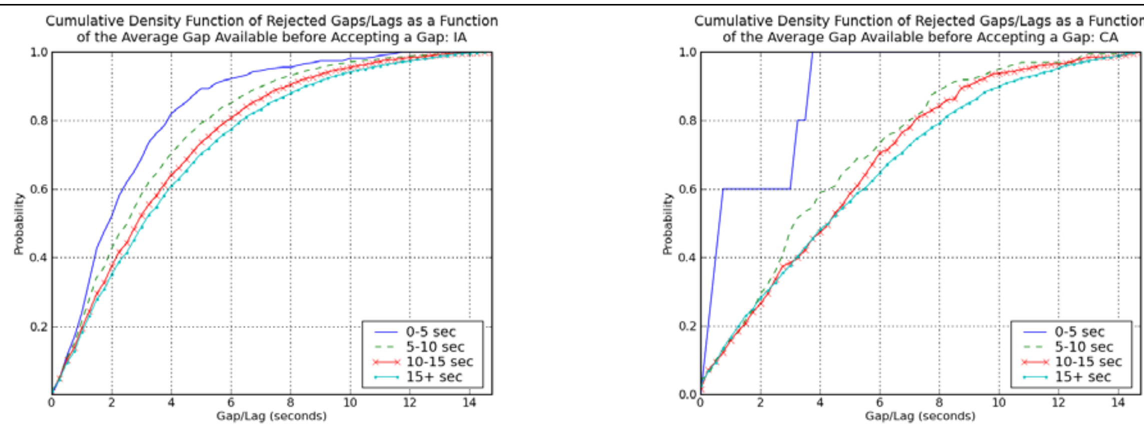
Figure 23 below shows the gap rejection behavior of drivers a function of the average available gap prior to a driver accepting a gap. Once again, the behavior of the "T" intersections is aligned with the behavior of the median-separated, thru-Stop expressway intersection. Because of light traffic levels on the major road at the California intersection, the 0-5 second average available gap plot saturates quickly. That trace aside, the remainder of the plots are consistent with behaviors viewed previously.

7.5 Gap Rejection Threshold Sensitivity to the Time Waiting for a Gap at "T" Intersections

Figure 24 below shows that gap rejection behavior with respect to the time waiting for an acceptable is consistent once again with the median-separated, thru-Stop expressway intersection. The California data shows "rough" curves; this is due to the low traffic volumes found on the mainline. Because of small traffic volumes, instances of drivers waiting more than 15 seconds are rare at the California intersection.

7.6 Gap Rejection Threshold Sensitivity with Respect to Departure Zone for “T” Intersections

Figure 25 shows the gap rejection behavior as a function of departure points for “T” intersections. The gap rejection behavior is again consistent with median-separated, thru-Stop expressway intersections. In particular, the Iowa intersection mimics the behavior captured at the North Carolina intersection.

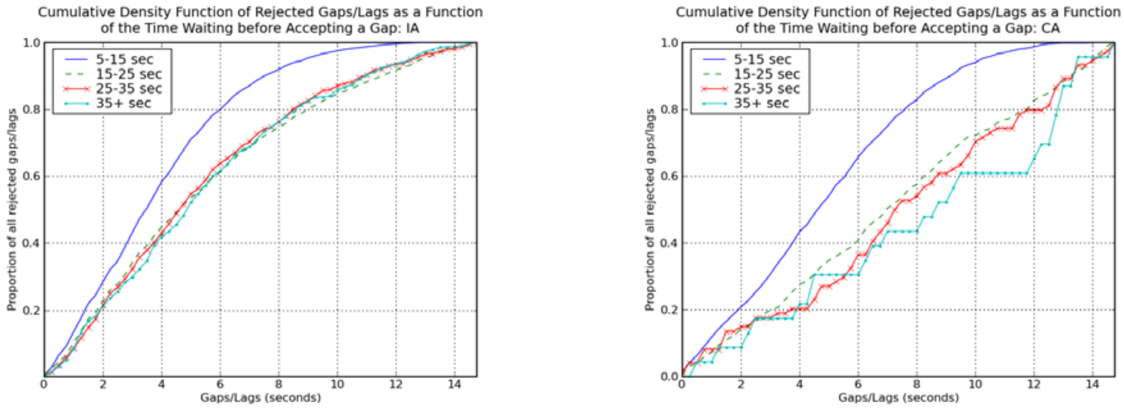


80% Gap Rejection Threshold: Average Available Gap				
	IA		CA	
	Threshold, s	Count	Threshold, s	Count
0 - 5 Seconds	3.86	384	3.5	5
5 - 10 Seconds	5.14	6352	6.98	161
10 - 15 Seconds	5.87	6163	7.19	336
> 15 Seconds	6.35	11860	8.1	2117
Weighted Avg.	5.88		7.91	

Figure 23. Gap rejection cumulative distribution plots for “T” intersections as a function of average available gap prior to gap acceptance.

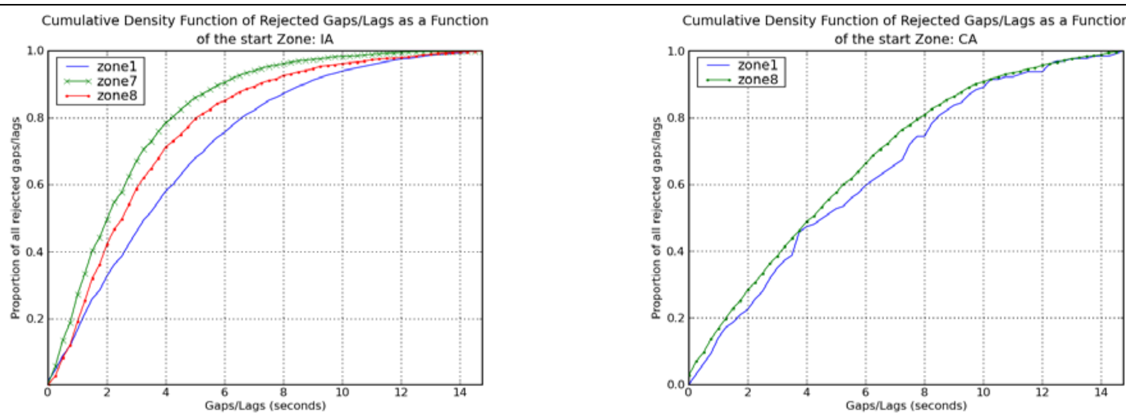
7.7 Gap Rejection Threshold Sensitivity with Respect to Vehicle Class for “T” Intersections

Once again, the gap rejection behavior for the Iowa “T” intersection replicates that for median-separated, thru-Stop expressway intersections. Figure 26 shows that the sensitivity to vehicle class is very low at the Iowa intersection. The California plots show some noise in the plots, particularly for both small and large commercial vehicles. The noise associated with these plots can be attributed to the relatively small numbers of valid maneuvers captured by the surveillance system. Noise aside, the CA intersection also shows small sensitivity to vehicle class.



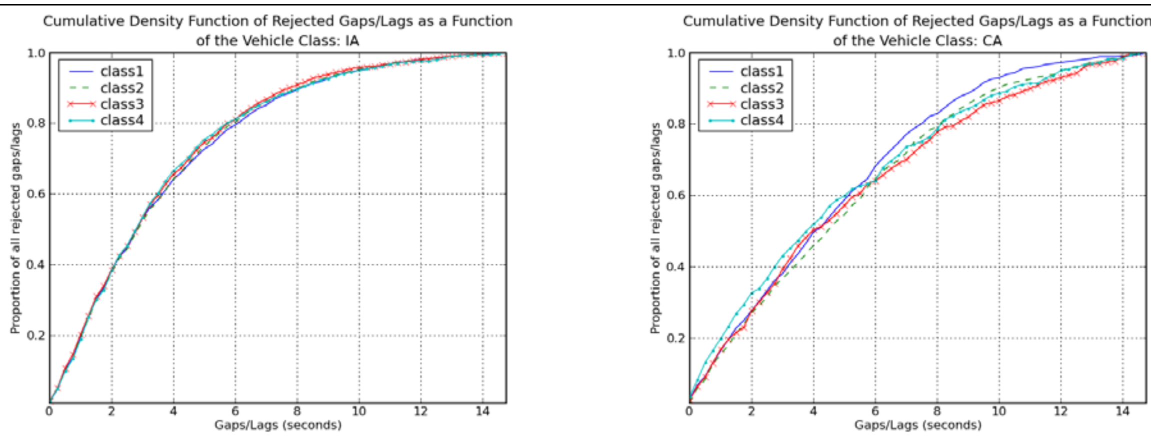
80% Gap Rejection Threshold: Time Waiting for Acceptable Gap				
	IA		CA	
	Threshold, s	Count	Threshold, s	Count
0 - 10 Seconds	6	13823	7.59	1713
10 - 20 Seconds	8.97	3938	11.76	403
20 - 30 Seconds	8.48	1020	12.3	74
> 30 Seconds	8.58	620	12.8	23
Weighted Avg.	6.82		8.56	

Figure 24. Gap rejection cumulative distribution plots for "T" intersections as a function of time waiting for an acceptable gap.



80% Gap Rejection Threshold: Departure Zone				
	IA		CA	
	Threshold, s	Count	Threshold, s	Count
Zone 1 (Stop bar)	6.58	15940	8.433	129
Zone 2 (Stop bar)	0	0	0	0
Zone 7 (median)	4.2	6152	0	0
Zone 8 (median)	5.04	2674	8.85	2492
Weighted Avg.	5.82		8.83	

Figure 25. Gap rejection cumulative distribution plots for “T” intersections as a function of departure zone.



80% Gap Rejection Threshold: Vehicle Class				
	IA		CA	
	Threshold, s	Count	Threshold, s	Count
Cars	6.06	4571	7.47	1033
Small Truck/SUV	5.91	12791	8.08	910
Small Commercial Trucks	5.75	5198	8.59	351
Large Commercial Trucks	5.71	1960	8.13	327
Weighted Avg.	5.89		7.91	

Figure 26. Gap rejection cumulative distribution plots for “T” intersections as a function of vehicle class.

8 Chapter 7 Rural Highway, Non-Median Separated, Thru-Stop Intersections

8.1 Introduction

Three intersections were associated with this category: Michigan, Georgia, and Nevada. The MI, GA, and NV intersections all had variations in geometry. As is expected, the absolute numbers regarding gap rejection statistics are different, but the trends across all three intersections are similar.

Geometries.

The geometries between intersections varied considerably between MI, GA, and NV. A summary of the geometric features are shown below in Table 12 and Table 13 below.

Table 12. Major road characteristic for highway, thru-Stop rural intersections.

State	Traffic lanes per direction	Rt. Turn Pocket?	Left Turn Pocket?
MI	1	Yes, both directions	No
GA	1	Yes, both directions	Yes, both directions
NV	2	Yes, both directions	Yes, both directions

Table 13. Minor road characteristic for highway, thru-Stop rural intersections.

State	Right turn island?	Right Turn Yield or Stop?	Right Turn Accel Lane?
MI	No	Stop	No
GA	Both directions	Yield (both directions)	No
NV	Both directions (South side is a painted island, north side is unmarked)	Stop (both directions)	No

These geometric and operational characteristics will be shown to have an effect on the gap rejection thresholds, but have no effect on the trends associated with gap rejection behavior. The fact that trends are consistent supports the hypothesis that one CICAS-SSA system will operate on a variety of rural highway, thru-Stop intersections. The difference in numbers attributed to intersection geometry will require variations in alert and warning timing so that these values match the behavior of drivers at that intersection.

Gap rejection process differences between median-separated and non-median separated, thru-Stop intersections.

The process of rejecting unsafe gaps at rural, non-median separated thru-Stop intersection is significantly different than that for median-separated intersections. The driver at a median-separated expressway thru-Stop intersection minor road has two potential maneuvers: straight-thru or right turn. Likewise, a driver in the median has only two choices: straight-thru or left turn. The driver at the minor road of a thru-Stop rural highway intersection has *three* choices: straight, left, and right. If the median-separated intersection is negotiated in two steps, a driver is concerned with approaching traffic coming from *one* side of the intersection in each of the steps. Unless a driver is making a right turn at a non-median separated thru-Stop intersection, the driver has to evaluate traffic coming from both directions.

As was shown in Chapter 5 and Chapter 6 for the median-separated case, the alert and warning timing for right turns, left turns, and straight-thrus was the same for all maneuvers. Thus, an unsafe gap for a right turn implies that that gap is also unsafe for a straight-thru, and *vice versa.* Likewise, if a gap is inadequate for a left turn, it is also inadequate for a straight-thru, and *vice versa.*

This insensitivity in alert and warning timing to maneuver simplifies the design of the driver interface; a driver at either the minor road or median sees *only one icon* which represents what maneuvers are not recommended. Figure 27 demonstrates the icons visible by the driver. For the median-separated case, a driver only has to process one icon from each location (i.e, either minor road or from the minor road).

For the non-median separated situation, a driver can make a right turn when sufficiently large lag is available from traffic approaching from the left. Traffic approaching from the right has no influence on this gap rejection decision. If gaps presented from the left are unsafe but gaps from the right are not unsafe, a driver cannot leave the stop bar. If a sufficiently large lag exists to the left, but not the right, the driver can turn right, but not proceed left or travel straight-thru. The two icons bracketed as "Non-median Separated" capture the entirety of the decision states.

Thus, for the thru-Stop non-median separated intersection, the driver on the minor road will have to make a decision based on *two* inputs – one involving traffic from the right, and one involving traffic from the left. Likewise, the driver will have to interpret one of two icons from a single location. This two-step process affects the interpretation of the gap rejection behavior of drivers at the non-median separated thru-Stop intersections.

8.2 Gap Rejection Threshold Sensitivity to Maneuver Type

Gap rejection cumulative distribution functions for rural highway, thru-Stop non-median separated intersections are shown below in Figure 28 below. No surprises are provided in this figure; the wider the intersection, the greater the 80th percentile gap rejection threshold. Drivers have further to travel to cross lanes, and therefore require a larger gap to safely enter or cross the traffic stream. Yield controlled right turn lanes and right turn islands provide smaller 80^{th} percentile gap rejection thresholds than intersections without minor road turn islands or turn lanes. This follow convention in that yield-control does not require a stop, and that a right turn island points the vehicle in the direction of the intended trajectory. In both instances, both the traffic control and geometry expedite the entrance of the vehicle into the traffic stream.

Right turns in GA and NV have smaller gap rejection thresholds for right turns, and the variance in the gap rejection behavior for left turns and straight-thrus remains small. Thus, right-turn alert and warning timing can be different than left/straight-thru timing while maintaining consistency with the two-icon approach illustrated in Figure 27 below.

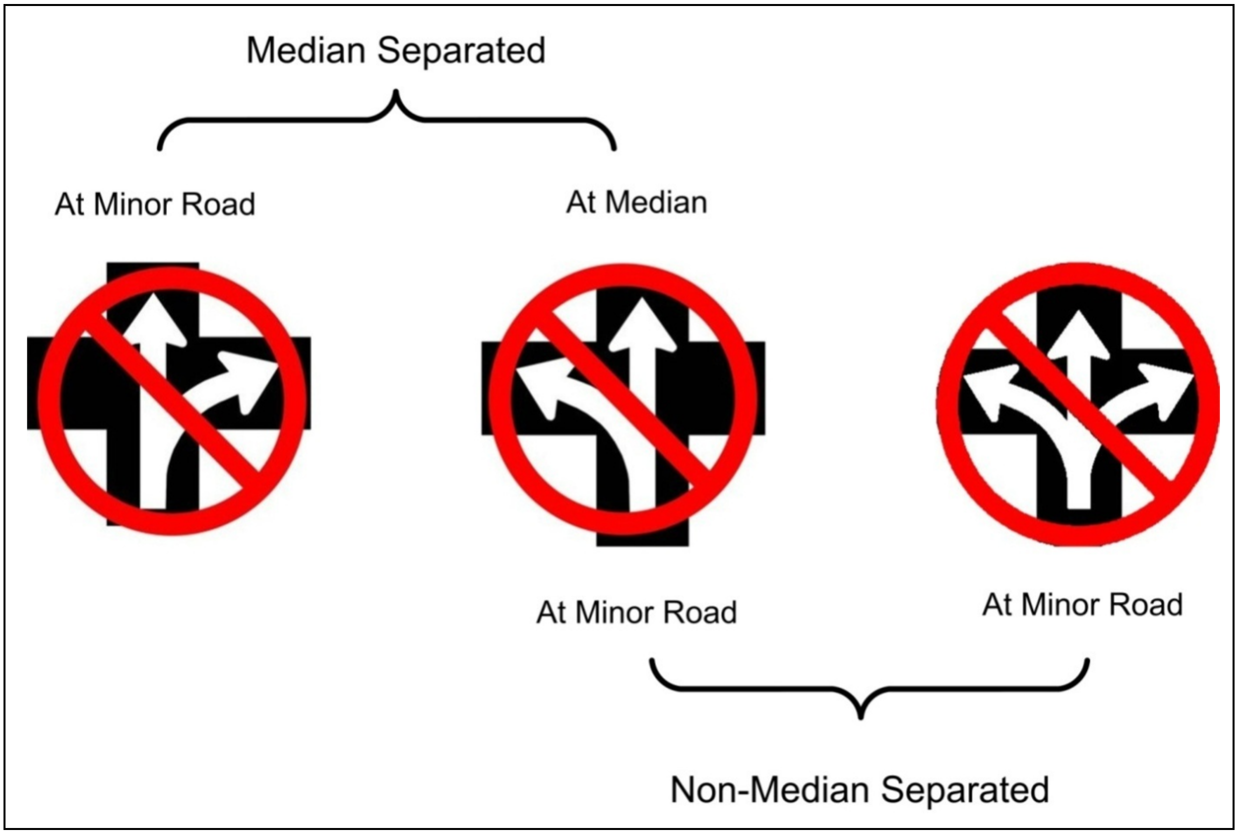
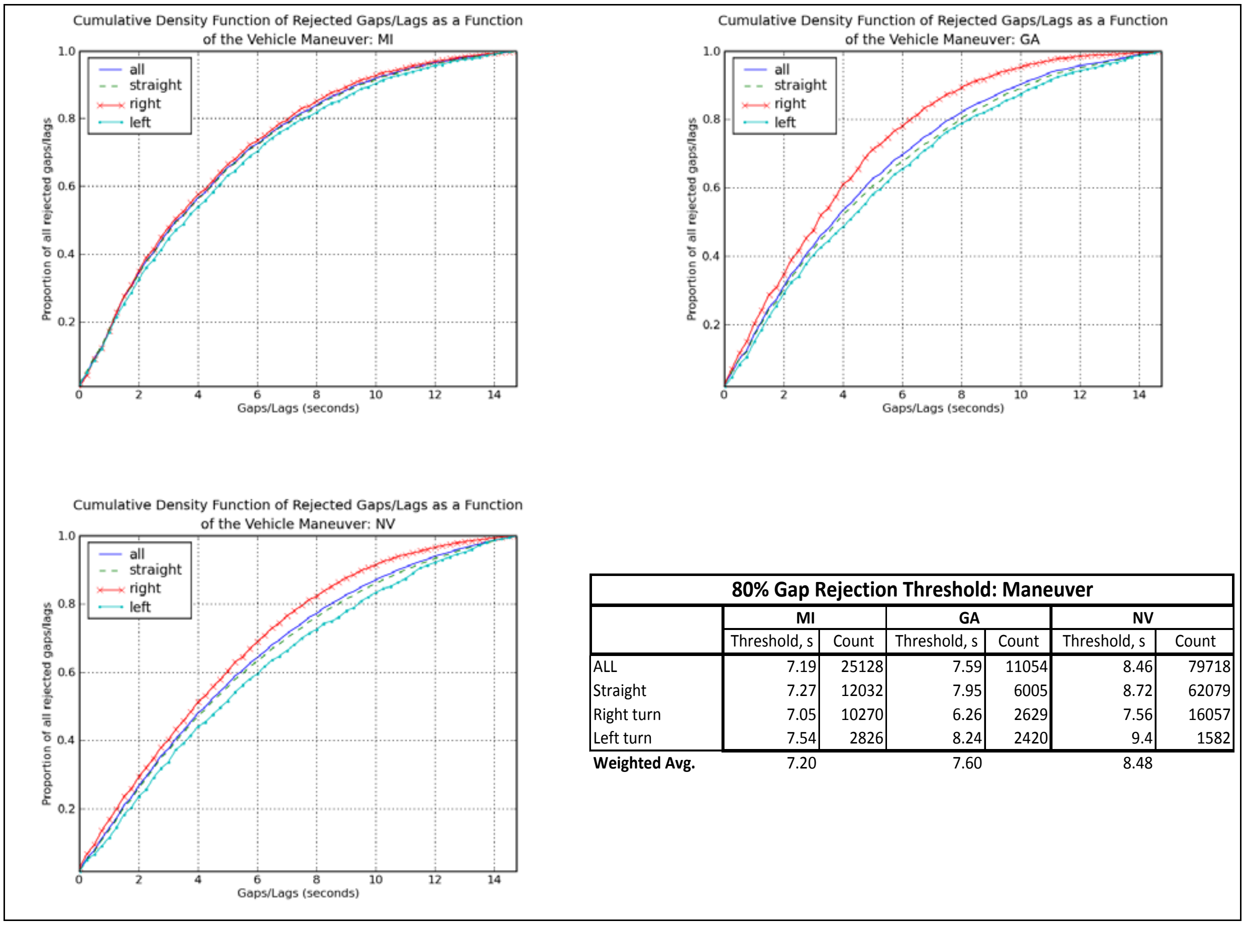


Figure 27. "Prohibitive" icons for the DII. Adaptation of the DII design for a median-separated intersection is for illustrative purposes; the DII for a non-median separated intersection has not been designed.

Also important to note is that the trend (or order) of the 80th gap rejection threshold is consistent among the three intersections; right turns exhibit the smallest, followed by straight-thru maneuvers, followed by left turns. This is indicative that a standard CICAS-SSA system will work with non-median separated highways of different geometries.



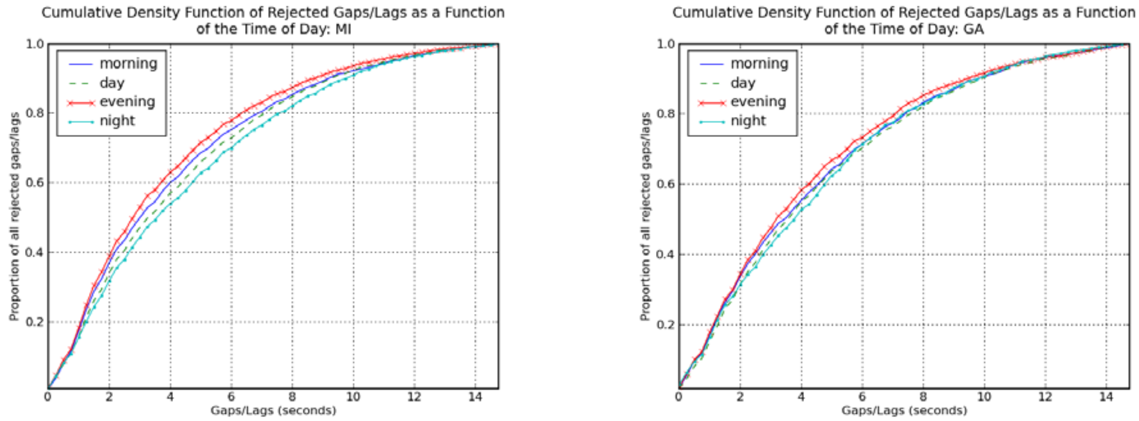
80% Gap Rejection Threshold: Maneuver

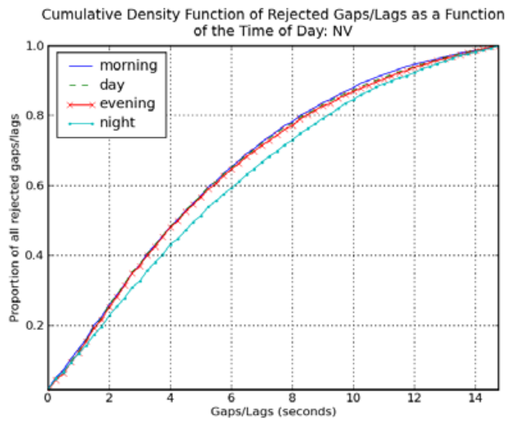
	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
ALL	7.19	25128	7.59	11054	8.46	79718
Straight	7.27	12032	7.95	6005	8.72	62079
Right turn	7.05	10270	6.26	2629	7.56	16057
Left turn	7.54	2826	8.24	2420	9.4	1582
Weighted Avg.	7.20		7.60		8.48	

Figure 28. Gap rejection cumulative distribution plots for rural highway, thru-Stop non-median separated intersections.

8.3 Gap Rejection Threshold Sensitivity to Time of Day

Figure 29 shows the effect of time of day on gap rejection cumulative distributions as a function of the time of day. Once again, the plots are consistent across intersection geometries, and little sensitivity is shown with respect to the time of day. This implies that no specific timing changes need to be made to alert and warning timing as a function of the time of day. As is expected, the fewer lanes to cross, the smaller the 80th percentile gap rejection threshold.





80% Gap Rejection Threshold: Time of Day						
	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
AM Rush	6.87	6297	7.39	1937	8.26	16538
Daytime	7.08	11091	7.57	6586	8.37	54754
PM Rush	6.33	9067	7.06	3227	8.45	22722
Evening	7.55	4018	7.35	1227	9.17	7424
Weighted Avg.	6.88		7.40		8.43	

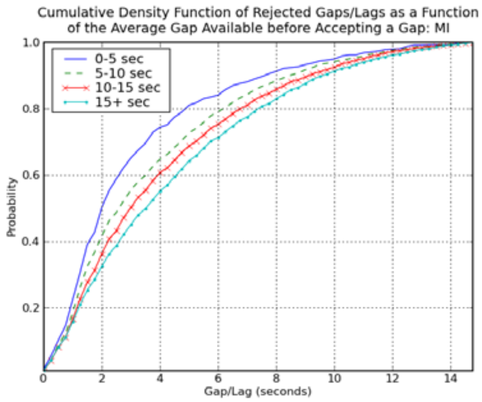
Figure 29. Gap rejection cumulative distribution plots as a function of time of day for rural highway, thru-Stop non-median separated intersections.

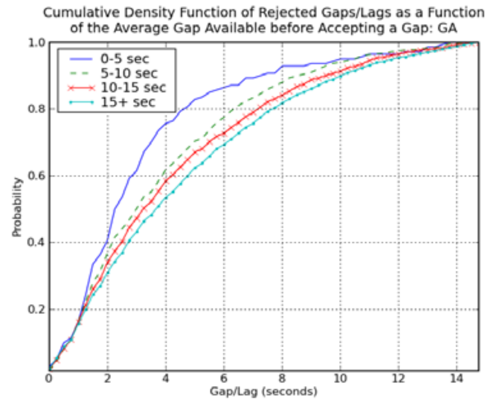
As was the case with median-separated, expressway thru-Stop intersection, the largest 80th percentile gap rejection threshold is associated with evening; this is explained by the fact that traffic densities are lowest in the evening, and that larger gaps are more prevalent. With a smaller percentage of smaller gaps available, the CDF is pushed to the right.

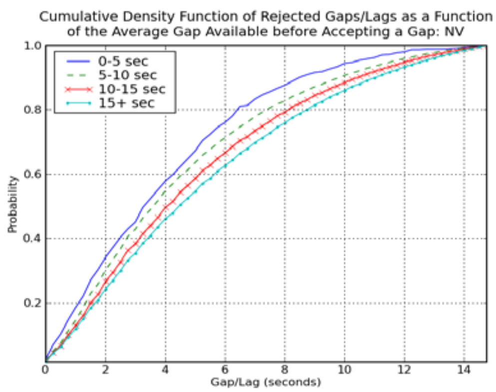
8.4 Gap Rejection Threshold Sensitivity to the Average Available Gap

In this section, the propensity of a driver to "rush" through an intersection when small gaps are present is examined. If only smaller gaps are available, will a driver compromise safety to more quickly cross or enter the traffic stream?

Figure 30 below shows the cumulative distribution plots for rural highway thru-Stop non-median separated intersections. Once again, trends are consistent between the intersection geometries. With small average available gaps (0-5 seconds), the 80th percentile rejected gap threshold is smaller than the others. It is important to note, however, that the trends between the three intersection geometries and controls are once again shown to be consistent among themselves as well as consistent with rural expressway, median-separated, thru-Stop intersections.







80% Gap Rejection Threshold: Average Available Gap

	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 5 Seconds	4.87	813	4.625	140	6.41	734
5 - 10 Seconds	6.17	5951	6.34	1087	7.4	11056
10 - 15 Seconds	6.75	6693	7.16	1647	8.11	20070
> 15 Seconds	7.39	15064	7.67	83334	8.74	66543
Weighted Avg.	6.91		7.64		8.44	

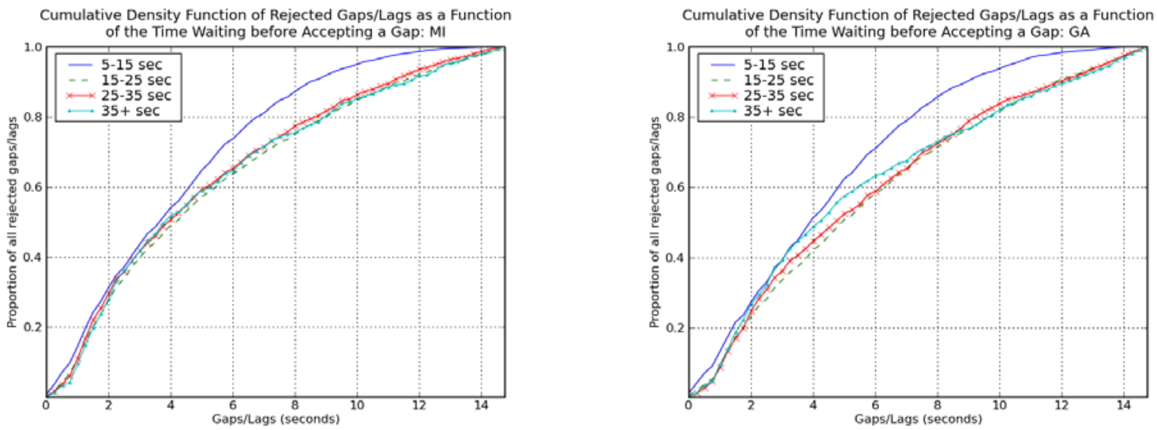
Figure 30. Gap rejection cumulative distribution plots as a function of average available gap for rural highway, thru-Stop non-median separated intersections.

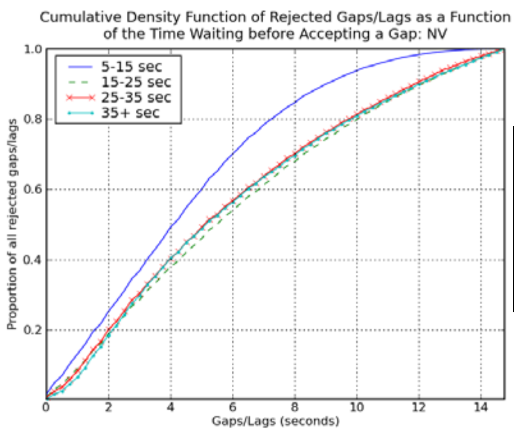
8.5 Gap Rejection Threshold Sensitivity to the Time Waiting for a Gap

One hypothesis examined as part of this study is that as drivers become more impatient waiting for what the driver perceives as a safe gap, the driver is willing to shift his or her gap rejection threshold to a lower (less safe) value to expedite passage across or into the traffic stream. The test of this hypothesis is shown below in Figure 31.

The hypothesis that the longer a driver waits the more likely he or she is willing to compromise their safe gap rejection threshold is false; the difference in gap rejection thresholds between three of the four waiting periods is quite small. As was the case with the rural, median-separated, thru-Stop expressway intersection, only the shortest wait time curve is different from the others.

This phenomenon can again be explained by examining the timing which is associated with this scenario. To be included in this sample population, the driver has to reject at least one lag or gap, *and* has to depart either the minor road or median in less than 10 seconds after arriving. The sample population of rejected gaps or lags presented to that driver will be of 10 second duration or less. As a subset of the population of all rejected gaps of duration 15 seconds or less, the expected value of the rejected gaps in this 10-second subset would be less than the expected value for all rejected gaps. The small 80% gap rejection threshold is a function more of the conditions and the sample population than it is an indication of a drivers propensity to rush the gap decision.





80% Gap Rejection Threshold: Time Waiting for Acceptable Gap

	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
0 - 10 Seconds	6.76	15705	7.14	6587	7.24	38060
10 - 20 Seconds	8.96	6753	9.64	2701	10	22306
20 - 30 Seconds	8.63	2087	9.2	1048	9.73	11484
> 30 Seconds	8.94	1089	9.61	688	9.8	19930
Weighted Avg.	7.58		8.10		8.78	

Figure 31. Gap rejection cumulative distribution plots as a function of time waiting for an acceptable gap.

8.6 Gap Rejection Threshold Sensitivity with Respect to Starting Location

Unless a highway thru-Stop intersection exhibits by a strange geometry, the hypothesis governing driver gap rejection behavior would be that the 80th percentile gap rejection threshold is unaffected by the minor road by which a driver departs.

Departure zones for the non-median separated, thru-Stop intersections are shown in Figure 32 below.

Figure 33 below shows that the departure zone does have an effect on the 80th percentile gap rejection threshold. From these plots, the curves suggest that the alert and warning timing would be different for each of the two zones. The validity of this suggestion can be examined through the use of Figure 34, which shows the cumulative distribution of rejected gaps as a function of maneuver for each departure zone.

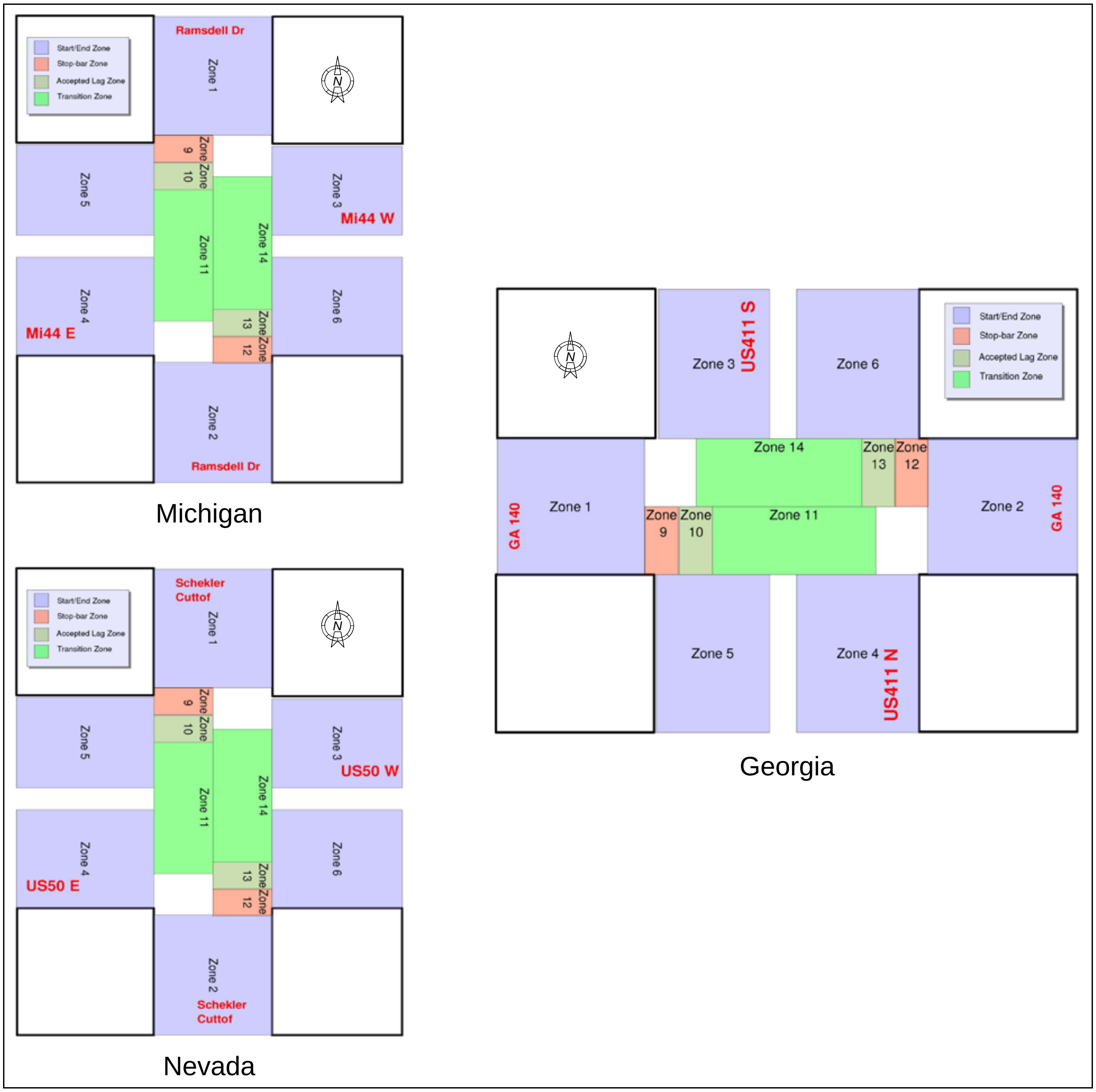
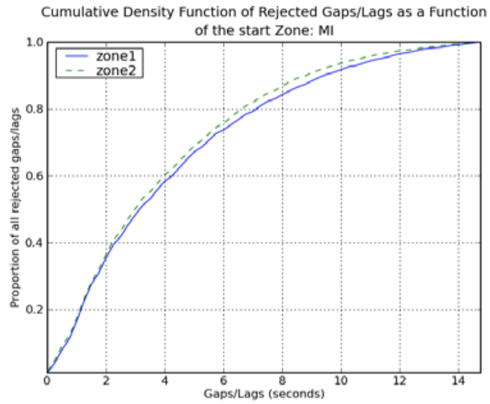
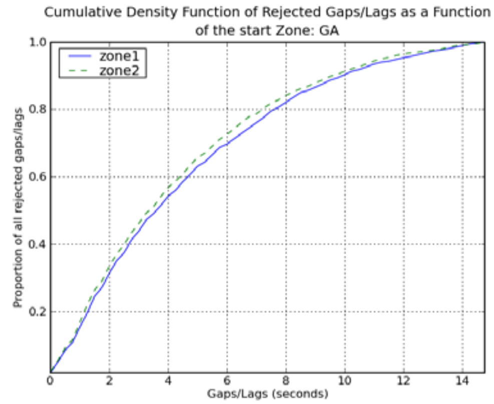
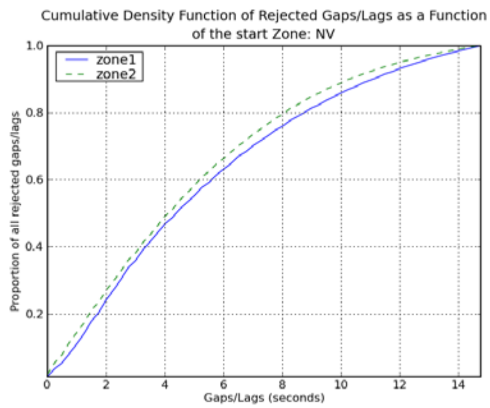


Figure 32. Position zones for rural, non-median separated highway intersections in Michigan, Georgia, and Nevada.







80% Gap Rejection Threshold: Departure Zone

	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Zone 1 (Stop bar)	7.11	17330	7.59	6019	8.75	58433
Zone 2 (Stop bar)	6.62	13143	7.19	6958	8.08	43001
Weighted Avg.	6.90		7.38		8.47	

Figure 33. Gap rejection cumulative distribution plots as a function of departure point for rural, non-median separated highway intersections.

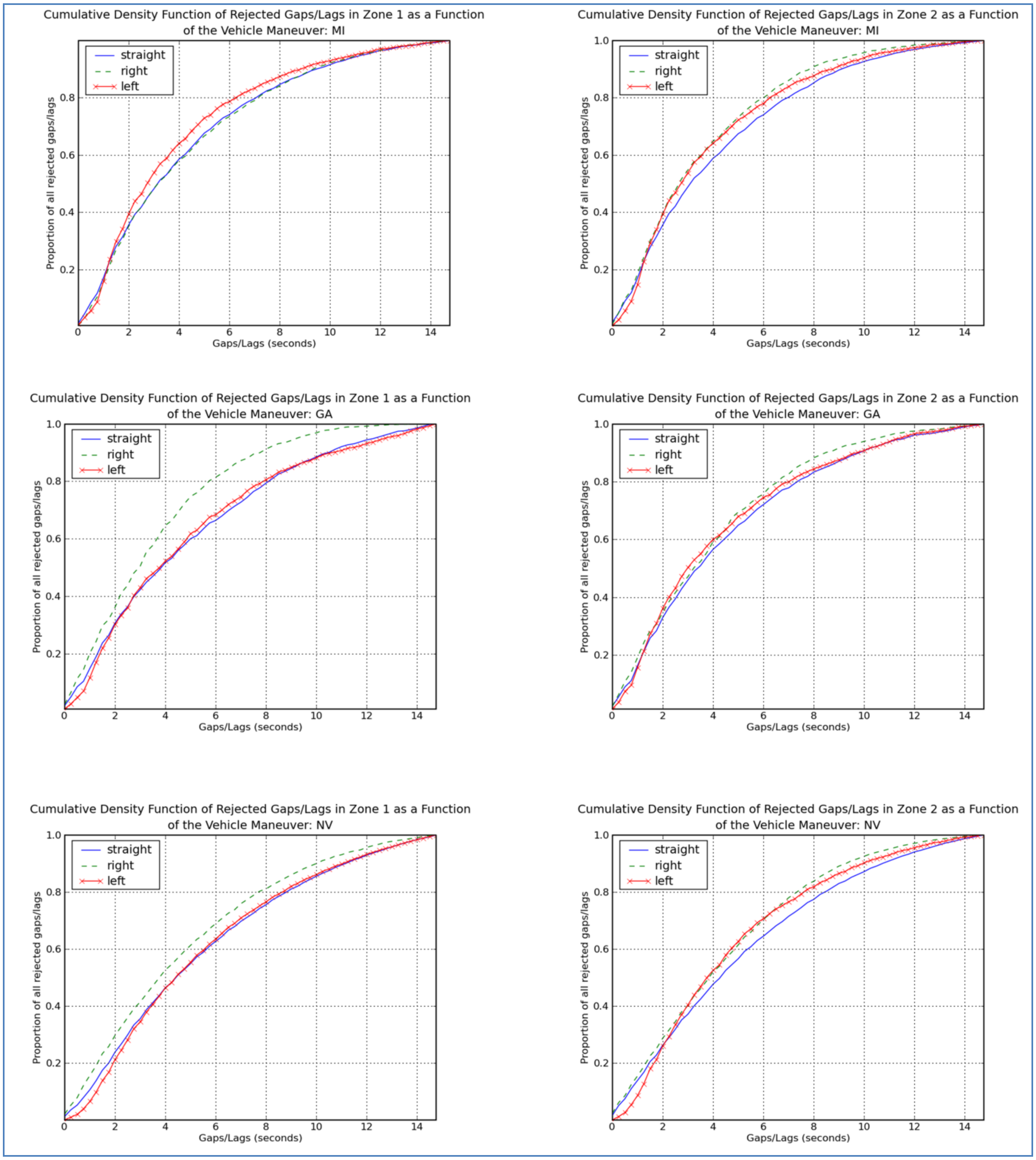


Figure 34. Gap rejection cumulative distribution plots for rural, thru-Stop non-median separated highway intersections as a function of maneuver and departure zone.

The variability of the gap rejections CDFs is less than that for the median-separated, rural thru-Stop expressway intersections (see Figure 16 above). The primary difference in timing for these intersections would be specific alert and warning timing for right turns from zone 1 for both GA and NV intersections.

8.7 Gap Rejection Threshold Sensitivity to Vehicle Classification

The last element of the rural, non-median separated thru-Stop intersection to examine is the effect of vehicle classification on gap rejection. Plots of the cumulative distribution functions for vehicle class is shown in Figure 35 below.

As was the case for the median-separated, expressway thru-Stop intersections, the Michigan intersection showed very little sensitivity to vehicle class. However, the same cannot be said for Georgia and Nevada; the larger the vehicle, the larger the 80th percentile gap rejection threshold.

This phenomenon can be explained by the geometry of the intersection. For each of the rural, median-separated, thru-Stop intersections, a vehicle either made a left turn, right turn, or crossed two lanes of traffic. This is precisely the geometry (and case) for the Michigan intersection; a vehicle never had to cross more than two lanes of traffic.

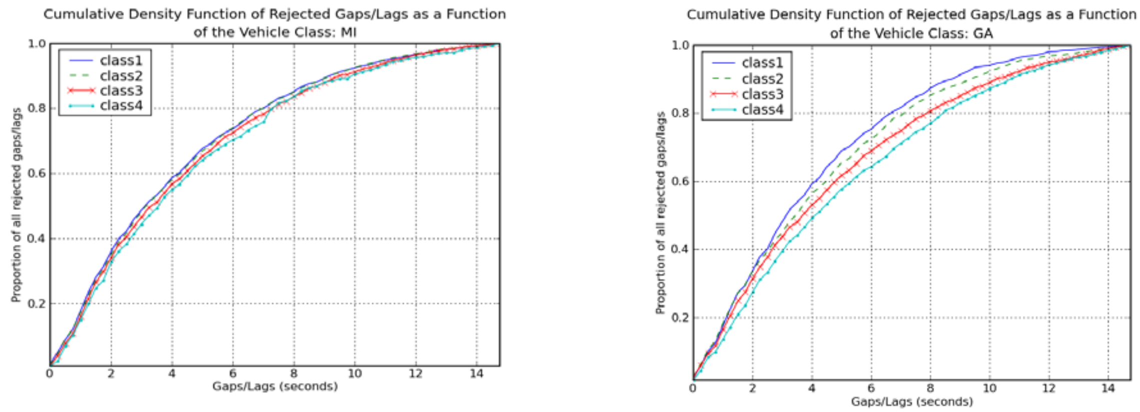
However, in Georgia, a driver must cross three lanes of traffic to execute a straight-thru maneuver, and must cross two lanes of traffic to execute a left turn because of the center left-turn pocket. Similarly, in Nevada, a driver must cross five lanes of traffic to execute a straight-thru, and must cross three lanes of traffic (two lanes and one left turn pocket) to execute a left turn. As vehicles increase in size and weight, more time is required to cover a greater physical distance.

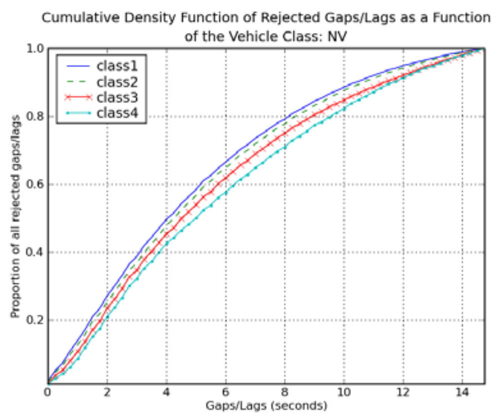
Figure 36 and Figure 37 below illustrates gap rejection cumulative distribution plots as a function of vehicle class and maneuver. From these plots, it is important to note that

- Sensitivity to vehicle class with respect to right turns is small. This is consistent with the median-separated thru-Stop intersections and with the findings from the MI intersection. One right turn timing will adequately address all vehicle classes. (In both GA and NV, the only real sensitivity to right turn gap rejection threshold is for Class 4 vehicles.)
- The difference in the gap rejection cumulative distribution plots for straight-thru and left turn maneuvers for each vehicle class are relatively small. Because straight-thrus and left turns are linked in the DII, alert and warning timing will be consistent for both maneuvers.
- The gap rejection thresholds for NV are consistently longer than those for GA for straight-thrus and left turns. This is consistent with the greater distance a vehicle must travel from a minor road stop bar in NV to complete a maneuver.
- Class 2 and Class 3 vehicle gap rejection behavior is quite similar; the main variation in gap rejection behavior comes primarily from Class 4 vehicles. In GA, heavy vehicles account for 17% of the traffic using the intersection from the minor road; in NV, that percentage is 5.5%.

Given this behavior, a strategy for alert and warning timing for straight-thru and left turns in GA and NV would be to use the behavior associate with Class 3 vehicles. This provides slightly conservative timing for Class 1 vehicles, proper timing for Class 2 and Class 3 vehicles (the vast majority of vehicles using the intersection from the minor road), and a bit aggressive for Class 4 vehicles. However, as was shown in Chapter 5, mainline vehicles will decelerate in response to heavy vehicle making an aggressive maneuver. Moreover, Class 4 vehicles are under-represented in the crash records, indicating that drivers of these vehicles are not having problems with the recognition of unsafe gaps in approaching traffic.

Clearly, should a CICAS-SSA system be deployed on a non-median separated highway intersection, alert and warning timing would have to be optimized for each location. However, trends are very consistent among intersections with varied geometry, indicating that a common solution to thru-Stop intersection crashes is certainly feasible.





80% Gap Rejection Threshold: Vehicle Class						
	MI		GA		NV	
	Threshold, s	Count	Threshold, s	Count	Threshold, s	Count
Cars	6.96	4353	6.65	1341	8.14	39909
Small Truck/SUV	6.95	15939	7.1	4394	8.37	39573
Small Commercial Trucks	7.266	6542	7.87	3954	8.91	16413
Large Commercial Trucks	7.27	639	8.4	1955	9.56	5537
Weighted Avg.	7.03		7.53		8.43	

Figure 35. Gap rejection cumulative distribution plots for vehicle class for rural, non-median separated thru-Stop intersections.

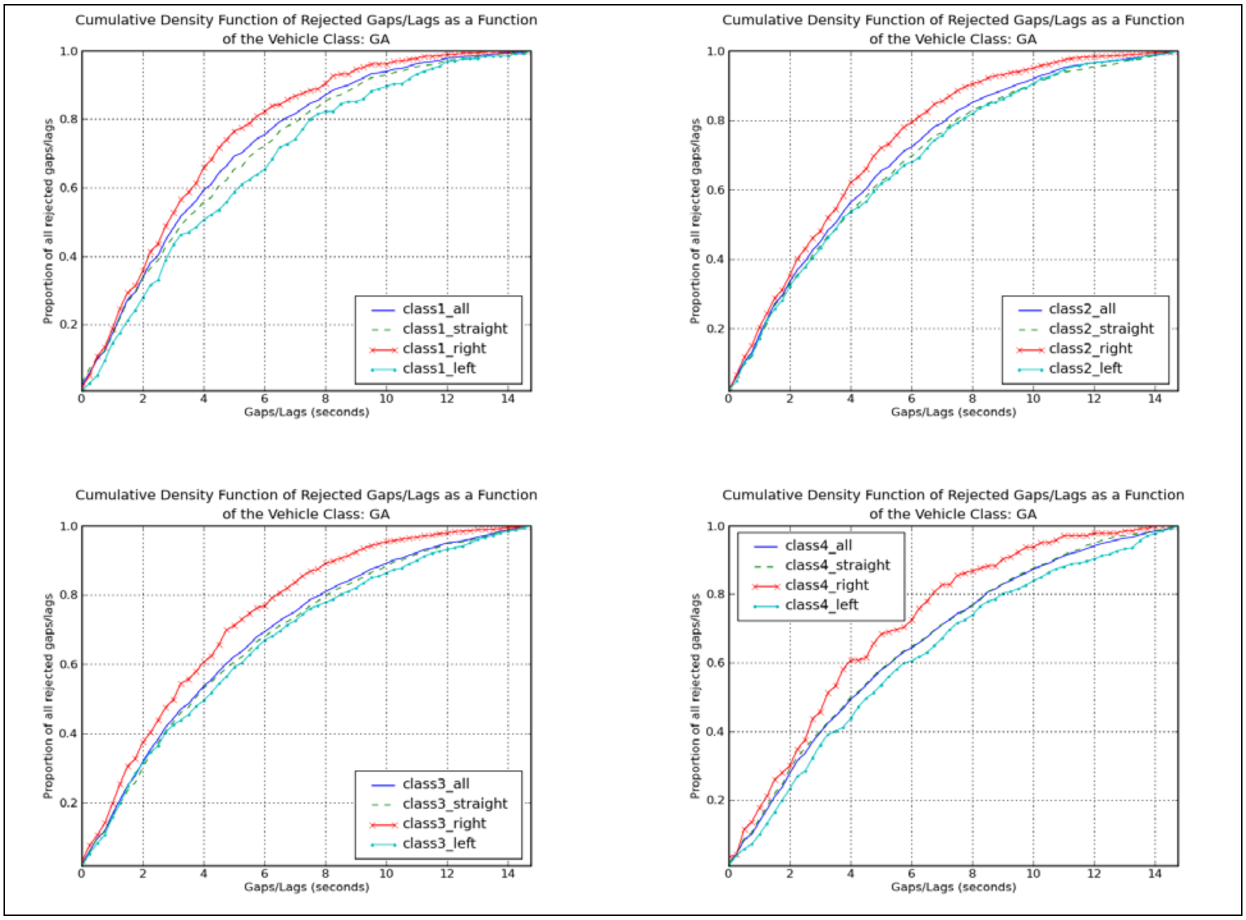


Figure 36. Gap rejection cumulative distribution plots for the GA intersection as a function of vehicle class and maneuver.

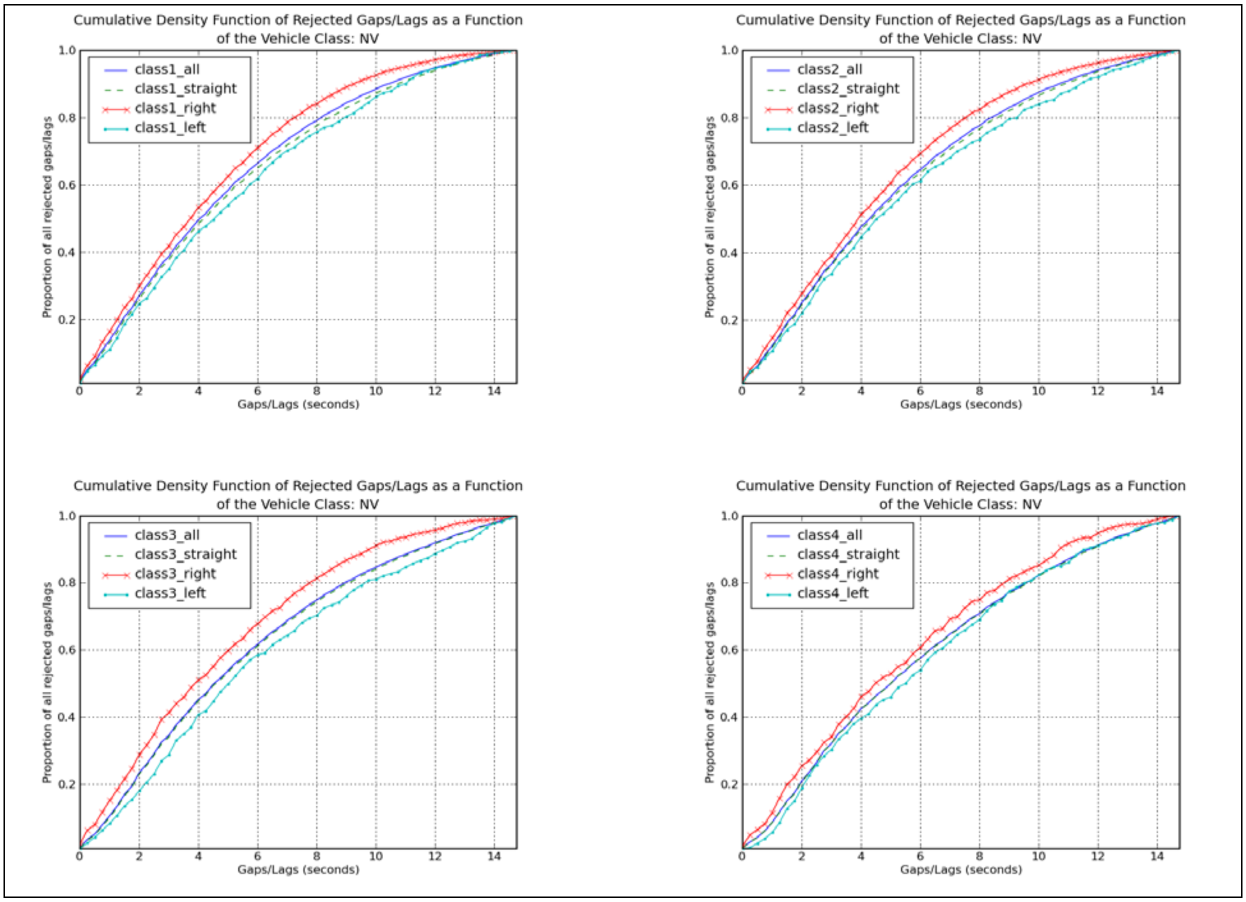


Figure 37. Gap rejection cumulative distribution plots for the NV intersection as a function of vehicle class and maneuver.

9 Chapter 8 Conclusions and Future Work

9.1 Conclusions

A number of important conclusions arise from this report:

- Driver gap rejection behavior is extremely consistent between rural, median-separated, thru-Stop expressway intersections and rural, median-separated “T” thru-Stop intersections. This is not unexpected as “T” intersections are really a subset of the expressway thru-Stop intersection.
- Gap rejection behavior at these intersections are insensitive to
    - Time of Day
    - Maneuver
    - Time waiting for an acceptable gap
    - Average size of available gap
    - Vehicle classification
    - Point of departure

Rural, non-median separated thru-Stop intersections follow the trends established by the rural, thru-Stop expressway and "T" intersections. However, some sensitivity was detected for highway intersections wider than two lanes. These sensitivities, however, can be overcome by altering the timing algorithm to accommodate the extra time needed to traverse the extra lane(s).

Although differences in intersection geometry confound results somewhat, regional differences do not appear to affect gap rejection behavior. Although 80th percentile gap rejection numbers vary, trends in gap rejection behavior are similar enough that CICAS-SSA could be deployed in any area of the US. Deployment in different areas may require tuning of the alert and warning timing, but the fundamental concept should work regardless of geographic location.

The CICAS-SSA concept will need modifications to work for non-median separated rural highway intersections. One key area of concern is the conveyance of prohibitive information in the DII; with median-separated highways, only one prohibitive message is associated with the minor road, and only one prohibitive message is associated with the median. With a non-median separated rural highway, a driver must recognize and respond to two prohibitive messages: one addressing right turns, and one addressing left turns and straight-thrus. This represents a significant departure from the CICAS-SSA system designed for median-separated roads.

9.2 Future Work

The CICAS-SSA system addresses the primary causal factor for rural thru-Stop intersections; unsafe gap rejection behavior. However, its effectiveness has yet to be proven on a broad scale. To test its effectiveness, the system should be deployed at a number of intersections throughout the country in a series of field operational tests.

This field operational test program is underway; Minnesota will carry out a field operational test under its CICAS-SSA program at the intersection of US 52 and CSAH 9 south of Cannon Falls, MN. Under the FHWA Rural Safety Initiative Program (RSIP), a CICAS-SSA system will be deployed at the intersection of US 53 and County 77 in Minong, WI. The Minnesota system is expected to go live in October of 2009; the Wisconsin system is expected to go live in November, 2009.

After the field operational tests are underway, the next step should be to develop the CICAS-SSA system for rural, non-median separated highway thru-Stop intersections. Gap rejection behavior data collected under this study and presented herein indicate that a system based on CICAS-SSA will work for these non-median separated highways. The basic CICAS-SSA sensing and computation systems are directly applicable; alert and warning timing will likely have to be tuned to accommodate intersections more than two lanes across the major road.

What is needed for these non-median separated highway intersections, however, is a closer look at the driver interface. The key question is whether the CICAS-SSA DII can be adapted to the non-median separated intersection. As discussed in the body of the report, a driver on a minor road must process information regarding two classes of maneuvers: right turns and left-turns/straight-thrus. Research must be undertaken to ensure that a driver can effectively and reliably process these two different messages. If a driver cannot process these messages, a new design of the DII must be initiated.

References

[1] *AASHTO Strategic Highway Safety Plan*. American Association of State Highway and Transportation Officials, Washington, D.C., 1998.

[2] T. Neuman, R. Pfefer, K. Slack, D. Harwood, I. Potts, D. Torbic, and E. Rabbani *NCHRP Report 500 (Volume 5): A Guide for Addressing Unsignalized Intersection Collisions*, TRB National Research Council, Washington, D.C., 2003. http://gulliver.trb.org/publications/nchrp/nchrp_rpt_500v5.pdf

[3] H. Preston, R. Storm, M. Donath, and C. Shankwitz, *Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support (IDS)*, Mn/DOT Final Report MN/RC-2004-31, St Paul, MN, 2004.

[4] J.D. Chovan, L. Tijerina, J.A. Pierowicz, and D.L. Hendricks, *Examination of Unsignalized Intersection Straight Crossing Path Crashes and Potential IVHS Countermeasures*, Report DOT HS 808 152, DOT-VNTSC-NHTSA-94-2. Volpe National Transportation Systems Center, Washington, D.C., August 1994.

[5] H. Preston, R. Storm, M. Donath, and C. Shankwitz, *Review of Michigan's Rural Intersection Crashes: Application of Methodology for Identifying Intersections for Intersection Decision Support (IDS)*, CH2MHill, Mn/DOT Final Report MN/RC-2006-33, St. Paul, MN, August 2006.

[6] H. Preston, R. Storm, M. Donath, and C. Shankwitz, *Review of North Carolina's Rural Intersection Crashes: Application of Methodology for Identifying Intersections for Intersection Decision Support (IDS)*, CH2MHill, Mn/DOT Final Report MN/RC-2006-32, St. Paul, MN, August 2006.

[7] H. Preston, R. Storm, C. Shankwitz, and M. Donath, *Review of Wisconsin's Rural Intersection Crashes: Application of Methodology for Identifying Intersections for Intersection Decision Support (IDS)*, CH2MHill, MnDOT Final Report MN/RC-2006-10, April 2006.

[8] H. Preston, R. Storm, M. Donath, C. Shankwitz, G. Crowson, *Overview of Rural Intersection Crashes at Candidate Intersections for the Intersection Decision Support (IDS)System*, CH2MHill, MnDOT Final Report MN/RC-2008-53, November, 2008.

[9] L. Alexander, P. Cheng, M. Donath, A. Gorjestani, A. Menon, B. Newstrom, C. Shankwitz, "The Minnesota Mobile Intersection Surveillance System," Proceedings of the 9th International IEEE Conference on Intelligent Transportation Systems, Toronto, Ontario, Canada, September, 2006.

[10] D.W. Harwood, J.M. Mason, and R.E. Brydia, "Design policies for sight distance at stop-controlled intersections based on gap acceptance," *Transportation Research Part A* 33, pp. 199-216, Pergamon, 1999.

[11] A. Gorjestani, A. Menon, P. Cheng, C. Shankwitz, M. Donath, *The Design of a Minimal Sensor Configuration for a Cooperative Intersection Collision Avoidance System – Stop Sign Assist: CICAS-SSA Report #2*, Mn/DOT, August 2010.

[12] M.S. Raff, J.W. Hart, *A volume warrant to urban stop signs*, Eno Foundation for Highway Traffic Control, Saugatuck, CT, 1950.

[13] W. Brilon, R. Koenig, and R.J. Troutbeck, "Useful estimation procedures for critical gaps," Transportation Research Part A 33, pp. 161-186, Pergamon, 1999.

[14] N. Lerner, R. Huey, H. McGee, A. Sullivan, *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection*, Report No. FHWA-RD-93-168. Federal Highway Administration, Washington, D.C., 1995.

[15] M. Kyte, Z. Tian, Z. Mir, Z. Hameedmansoor, W. Kittelson, M. Vandehey, B. Robinson, W. Brilon, L. Bondzio, N. Wu, R. Troutbeck, *Capacity and Level of Service at Unsignalized Intersections, Final Report: Volume 1 - Two-Way Stop-Controlled Intersections*, National Cooperative Highway Research Program 3-46, TRB National Research Council, Washington, D.C., 1996.

[16] L. Alexander, P. Cheng, M. Donath, A. Gorjestani, A. Menon, B. Newstrom, C. Shankwitz, N. Ward, "Gap Acceptance Analysis for a Rural Unsignalized Intersection," Proceedings of the 86'th Annual Meeting of the TRB, Washington, DC, 2007.

[17] M. Pollatschek, A. Polus, M. and Livneh, "A decision model for gap acceptance and capacity at intersections," Transportation Research Part B 36, pp. 649-663, Pergamon, 2002.

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free “Help Line” 866-367-7487
www.its.dot.gov

U.S. Department of Transportation

Research and Innovative Technology Administration