

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)

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Executive Summary

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. 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 undertook the Cooperative Intersection Collision Avoidance Systems-Stop Sign Assist (CICAS-SSA) program. CICAS-SSA uses sensing technology, a computer processor and algorithms to determine unsafe conditions, and a driver interface to provide timely alerts and warnings designed to reduce the frequency of crashes at rural expressway intersections.

Work undertaken separately 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 in Minnesota and other states in the U.S. The focus of this report is the alert and warning timing used to provide a driver with assistance in recognizing and taking appropriate action when presented a gap that could be considered unsafe. The work presented herein uses both macroscopic data collected by roadside sensors and data acquisition equipment in Minnesota, Wisconsin, and North Carolina, and microscopic data collected using an instrumented vehicle and test subjects at the Minnesota Research Intersection.

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

1. **The CICAS-SSA system is designed to assist drivers 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 unsafe gap rejection.
2. **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.
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.

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.

Three important findings arose from the macroscopic study. 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 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.

Third, and most surprising, is the finding that gap rejection is *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 half 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 mainline 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 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.

The microscopic study also produced a surprising result: driver gender and driver age have no substantial effect on the time it takes a driver to cross the mainline traffic. A second result, consistent with macroscopic data and crash analyses, is that drivers require less time to cross the mainline traffic when starting from the median than from the minor road. This can be explained because most medians for rural expressways are “Yield” controlled, and don’t require a driver to stop before entering. If a driver maintains some momentum, crossing times will be less than if all momentum had been lost.

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.

Finally, situations where conflicts between minor road vehicles and vehicles located in the median might occur are addressed, and recommendations for those situations are also provided.

2 7BMotivation

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. 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 [3]. 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. [4] found that the primary causal factors for drivers who stopped before entering the intersection were:

1. The driver looked but did not see the other vehicle (62.1 %)
2. The driver misjudged the gap size or velocity of the approaching vehicles (19.6 %),
3. The driver had an obstructed view (14.0 %), or
4. 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 [5] North Carolina [6] and Wisconsin [7] 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.

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 [3], 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.

3 8BDesign 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:

1. 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.
2. 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.
3. 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. The CICAS-SSA system should provide some of the safety benefits of a signal-controlled intersection without the adverse effects on mainline capacity, throughput, and congestion.

4 9BSystem Description

Figure 1 below provides a plan view of the research version of the CICAS-SSA as it is installed on a rural expressway intersection. (The “production” version of the system will use a considerably smaller sensor suite.) For the research surveillance system, mainline sensing is provided by an array of radar sensor 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

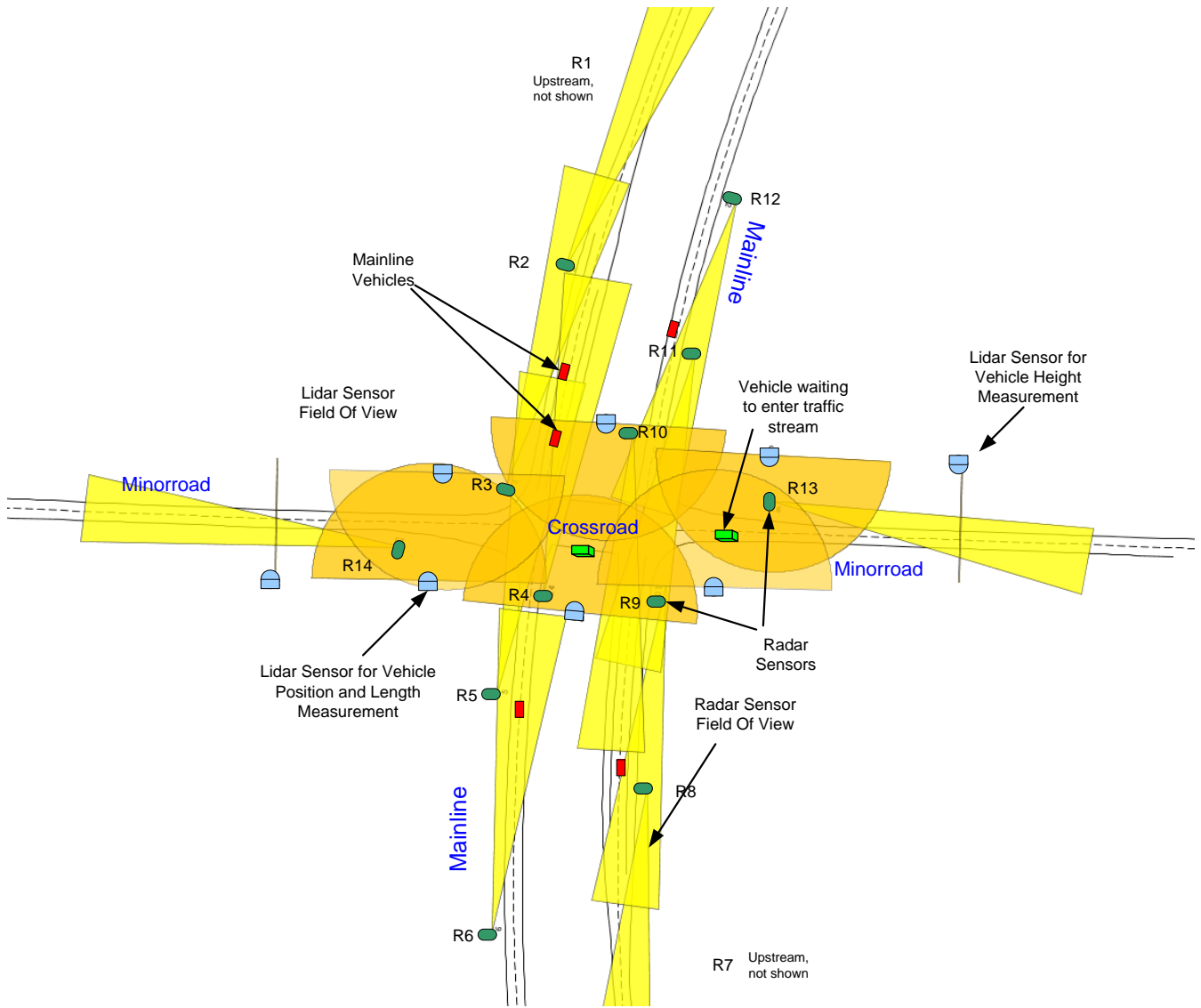


Figure 1. Plan view of a typical instrumented rural expressway intersection. Sensors are radar and scanning lidar; all data is broadcast wirelessly from sensor processors to the main data acquisition computer via 802.11b wireless devices. Of particular interest for driver behavior research is the crossroad 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 IDS 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 [8].

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 driver-vehicle interface (DVI). The timing for the alerts and warnings presented on the DII is the subject of this report.

The research 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 [9]. 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 intersections in Minnesota, Wisconsin, and North Carolina.

Second, because of wireless capabilities, it is possible to support the collection of microscopic data acquired from an in-vehicle instrumentation suite, and synchronize that data with macroscopic data collected by the infrastructure-based macroscopic system. A pool of test subjects entering and crossing the mainline traffic driving an instrumented vehicle provides insight into gap acceptance and rejection at a resolution previously unavailable. The ability to precisely define and measure the point at which a vehicle is committed to cross or enter a traffic stream at a rural intersection provides significant insight into gap acceptance behavior, and provides a complement to the objective of supporting accurate unsafe gap rejection.

Third, 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.

Finally, it should be noted that the 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

5 10B 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 on-board system to assess the threat, and determine whether an alert or warning is warranted at that time. 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. At the time this report was written, simulator studies were underway to determine which of the two driver interface designs will be tested at the Minnesota Research Intersection. To give the reader context, prototype DIIs are shown below in Figure 2 below. 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.

Work continues on the evaluation of the two candidate DIIs to determine which is more appropriate for *in-situ* testing at the intersection and for deployment. The alert and warning timing derived herein is presently in use during the simulator testing phase, and will also serve as the baseline for testing at the Minnesota Research Intersection during the summer of 2008.

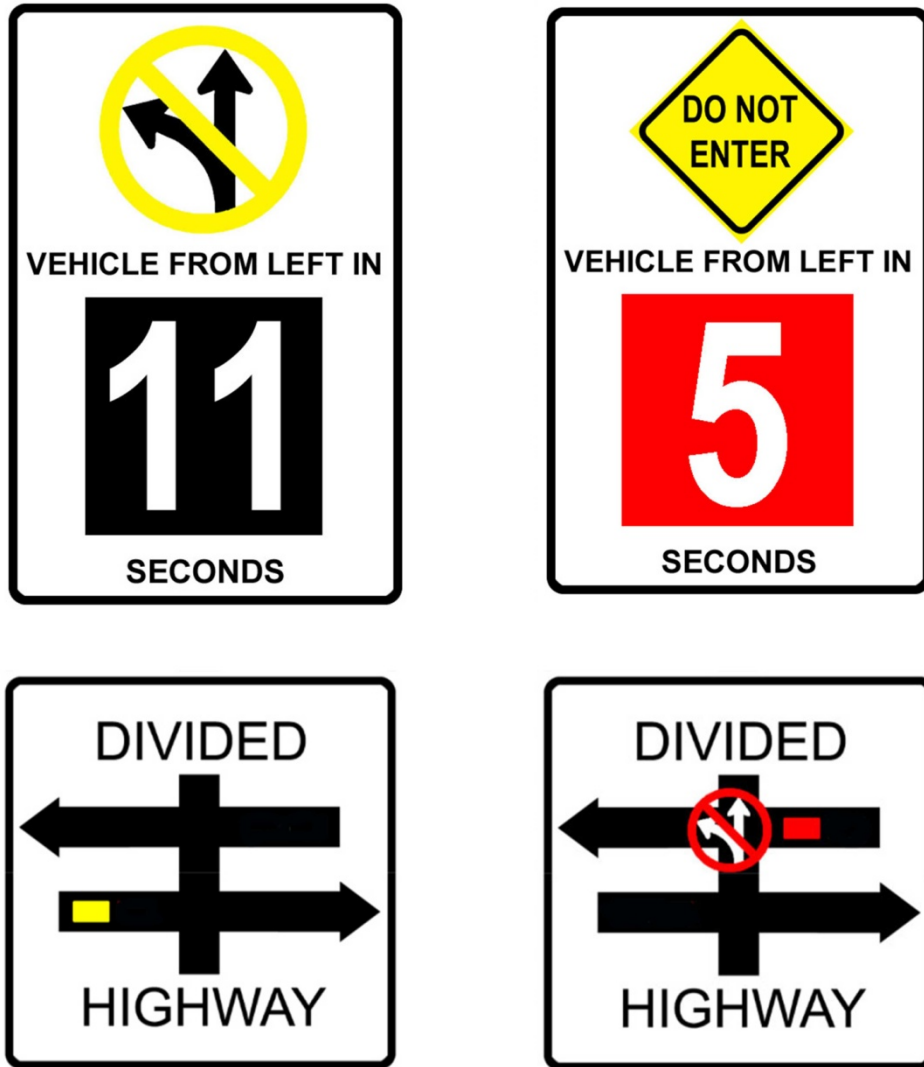


Figure 2. Prototype DIIs presently tested in the HumanFIRST driving simulator. Upper left represents the Countdown DII in an alert mode (11 seconds to the vehicle approaching from the left); the upper right indicates a warning mode (red background, white letters indicating 5 seconds to the vehicle on the left). Lower left shows an alert mode (traffic approaching from the left), and the lower right shows a warning mode (vehicle too close from the right). If realized at an intersection, the countdown sign would measure 2.2m wide x 2.5m high; the icon sign would measure 3.3m wide x 2.6m high.

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 [10]. 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 aspect 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 [11]. 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 [11], 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.

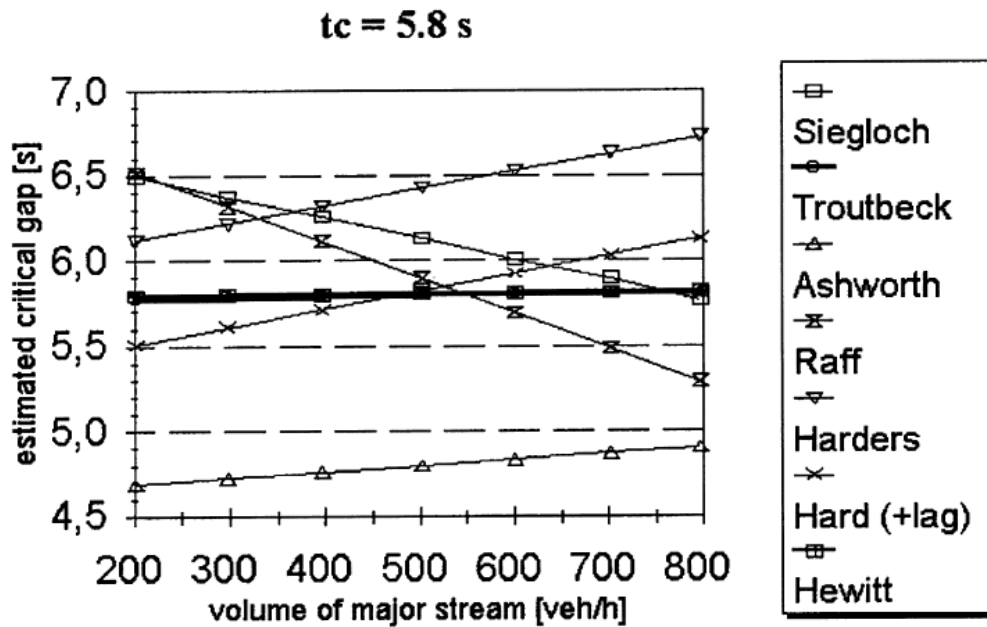


Figure 3. Comparison of critical gap values for a variety of critical gap estimation techniques; graph taken from [11]. Note that a considerable spread exists with differences approaching 40% in some cases.

Note that a considerable variability exists in the estimation of the critical gap amongst the various methods. In general, the Ashworth method provides the smallest estimate of the critical gap, and the Raff 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 1.

Comparison of gap acceptance field study results with results from other studies [9],[12],[13] 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 1. Critical gap estimates for a variety of intersections.

| Maneuver | Harwood et al., [9] | | Lerner et al., [12] | Kyte et al., (1996) [13] |
|------------|---------------------|---------------------|---|---------------------------|
| | 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 [9], 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.

7 Chapter Framework, Goals, and Context

3

The framework for the analysis leading to alert and warning timing is presented herein. Both macroscopic and microscopic approaches are taken in the analysis. Gap rejection is the focus of the macroscopic work, and the behavior of a driver crossing the mainline after accepting a gap is the focus of the microscopic study.

Once the macroscopic and microscopic studies are described, the context of the warning system will be described, as will the goals of the analysis. The analyses provided herein are not designed to provide a broad model of driver gap rejection and acceptance behavior; instead, the goal is to provide a structured approach to determine baseline alert and warning timing to support both simulator studies and an initial *in-situ*, instrumented test of the DII as it operates with the surveillance system at the Minnesota Research Intersection. It is important to note that in the context of the DII, the alert and warning timing has been tested (albeit with a small sample group) at the Minnesota Research Intersection. Of the many goals of the *in-situ* testing is to determine the acceptability of the alert and warning timing, as well as the human sensitivity to any perceived errors with the alert and warning timing. Determination of these sensitivities is a long term research goal, and one of the subjects of the proposed FOT.

8 11B Macroscopic Studies

The Minnesota Mobile Intersection Surveillance System (MMISS) was used to collect the macroscopic data used for the analyses presented herein. Data was collected in three states: Minnesota, Wisconsin, and North Carolina. 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 [3], [6], [7]. Data was collected for at least eight weeks in each location. Minnesota data was collected in the December 2006 – January 2007 time period. Wisconsin data was collected in the May – June 2006 timeframe, and North Carolina data was collected from March-May 2007.

Data collected by the MMISS is summarized in Table 2 for the mainline, minor road, median, and atmosphere.

Table 2. 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 |
| | | | 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 based on length and height. Laser scanners located in the highway median 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 facilitates 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 [9] 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 become 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.

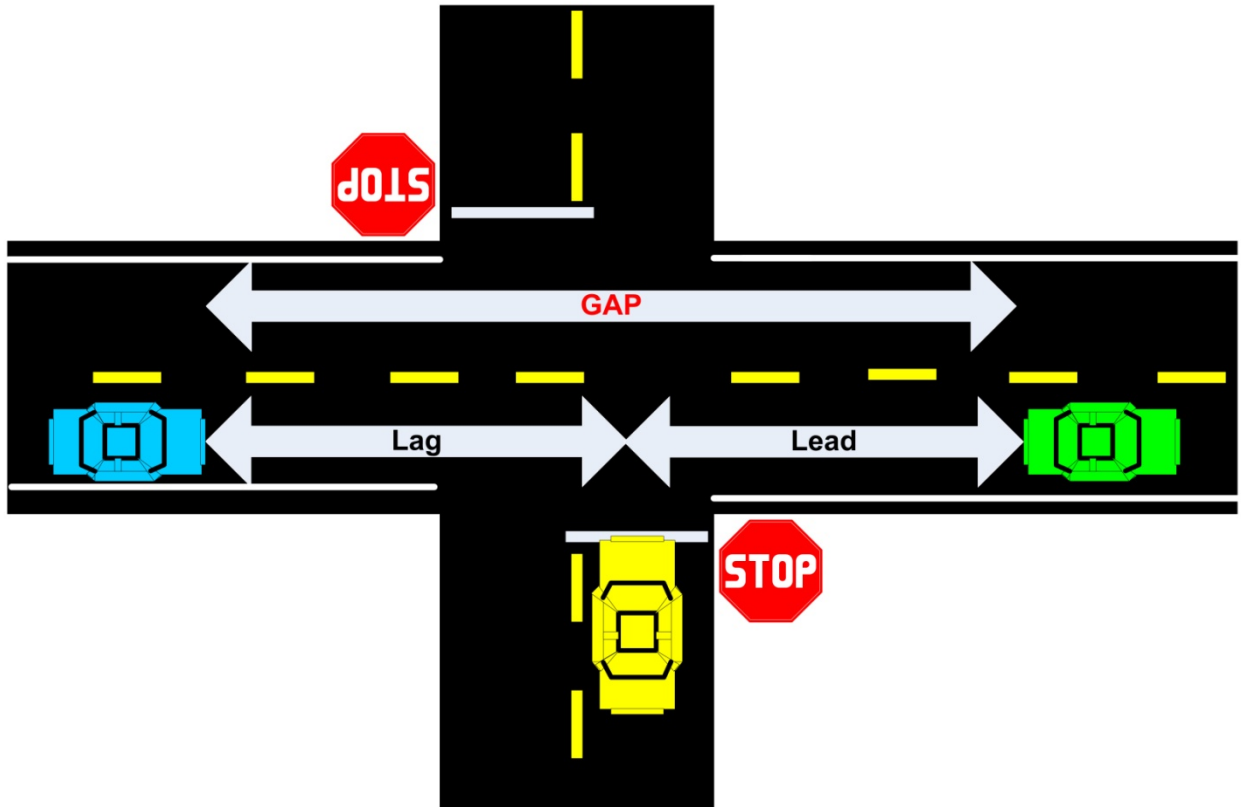


Figure 4. Geometrical definitions associated with gap acceptance and rejection.

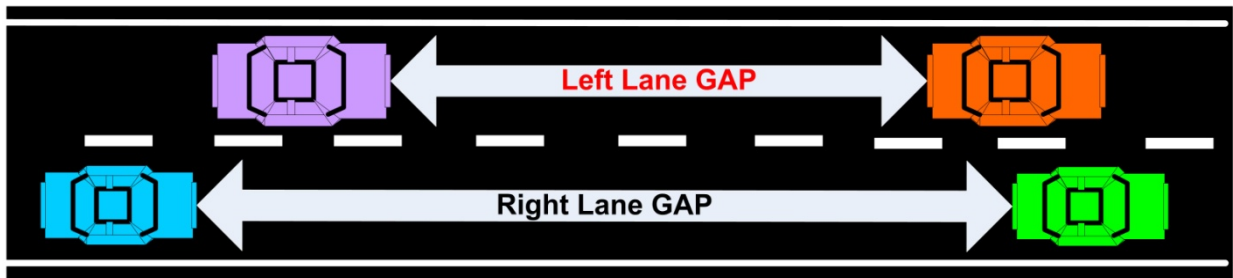


Figure 5. Gap definition for multi-lane roads. Gaps, leads, and lags are defined on a per-lane basis.

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.

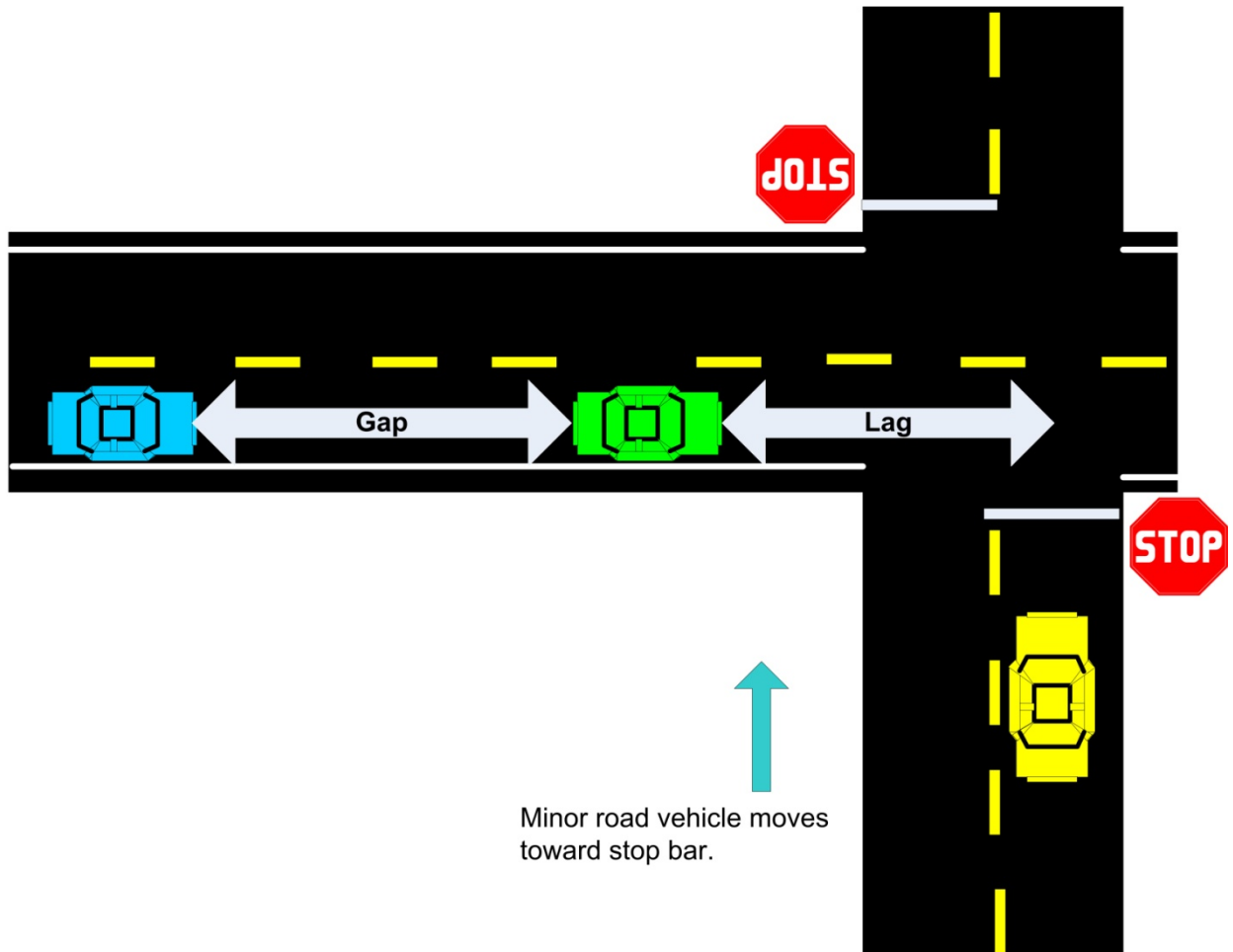


Figure 6. Single lag acceptance/rejection opportunity as a minor road vehicle approaches an intersection with a major road. The vehicle approaching the stop bar has only one opportunity to either accept or reject a lag; acceptance or rejection is noted at the time the minor road vehicle occupies the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

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. Because a driver only has one lag decision which can be made, the relative frequency of rejected lags will be less than those for rejected 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 3 below. Drivers are generally not waiting for more than two gaps to arrive before departing the intersection.

Table 3. Relative frequency of gap acceptance after both single and multiple gap rejections. Clearly, most drivers reject the initial lag, 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 | |
|--|-------|
| Rejected gap is the only gap rejected for maneuver: | 1603 |
| Rejected gap is not the only gap rejected for maneuver | 1915 |
| Number of rejected lags only | 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.

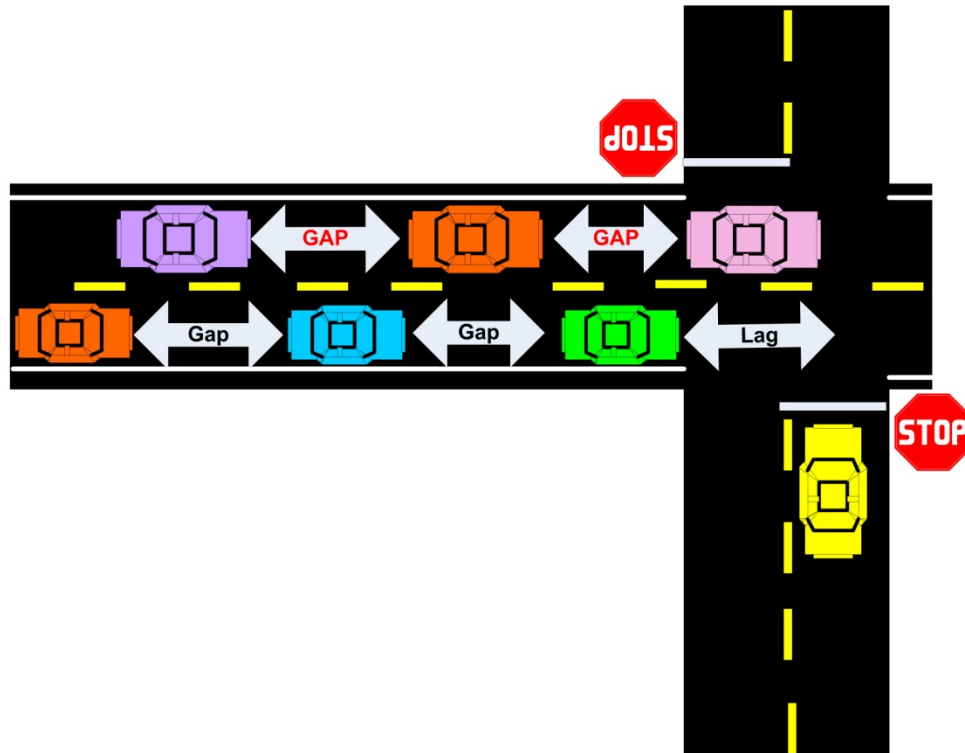


Figure 7. Example situation where lane-by-lane gap definition could produce rejected gap measurement bias. In this example, assume that each lane-by-lane gap for both the left and right lanes is ten seconds, and that the lag depicted above is five seconds. This puts the spacing between a vehicle on the 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, in essence, the minor road driver is really rejecting a sequence of five second lags. This discrepancy can lead to measurement bias.

Macroscopic study goals.

As such, macroscopic data will be used to determine

- Regional differences in gap acceptance and rejection. (At this point in CICAS-SSA, data collection in all states for the Intersection Pooled Fund project is not yet complete. When that data becomes available, inter-state differences will be examined.)
- 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.

9 12B Microscopic Analysis

Microscopic analysis adds an instrumented vehicle to the macroscopic data set described above. The data acquisition computer installed in the instrumented vehicle is synchronized with the MMISS data acquisition computer, so that the state of the intersection can be accurately represented throughout the time that the test subject is travelling through the intersection.

Because of reasons described above, the lead and lag values associate with the accepted gap are difficult to determine from the macroscopic point of view. Although gap rejection is the primary

focus of the modeling effort, time-to-cross the mainline traffic data can provide insight into safety margins preferred by drivers of different ages and genders. If time to cross data is available, then safety margins can be computed. The alert and warning timing which has been selected can be measured against normative time to cross values determined in the microscopic analysis to compare the safety margin preferred by drivers by that allowed by the alert and warning timing.

For the microscopic studies, a Nissan M45 served as the instrumented vehicle. The instrumentation suite includes dual frequency, carrier phase differential GPS (accurate to 2-5 cm) which provides position measurements at 10 Hz, a six axis (three axes of rotational rates, three axes of acceleration) Inertial Measurement Unit (IMU), brake sensors (indicating brake actuation), a throttle position sensor, and eight channels of video (driver's forward view, driver's hands, driver's feet, driver's face, vehicle left side, and vehicle right side).

Microscopic study goals.

The specific goals of the microscopic study are to determine

- normative safety margins associated with lag acceptance
- age effects on safety margins associated with alert and warning timing
- gender effects on safety margins associated with alert and warning timing
- effective safety margins with recommended alert and warning timing.

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.** Crashes occur when drivers fail to recognize an unsafe gap. 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, 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 [14], 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.

Macroscopic Data Analysis: Basis for the Alert and Warning Timing

Three important findings arise from the macroscopic study. 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 *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 vehicle 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 $\frac{1}{2}$ of the cost of the CICAS-SSA system, significant cost savings can be realized.

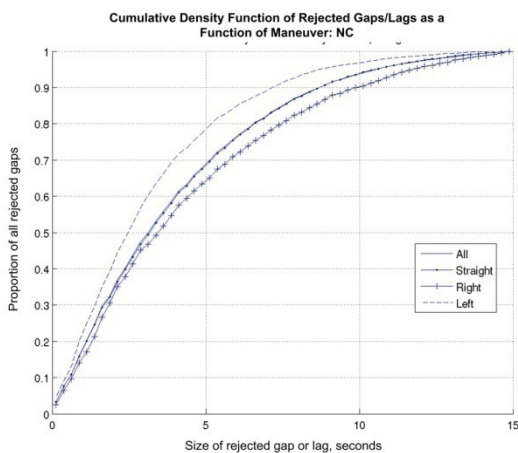
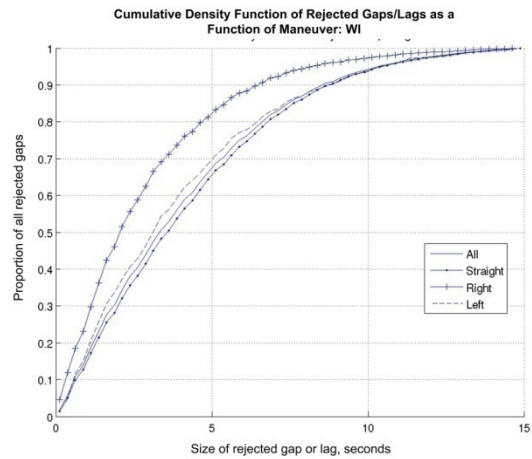
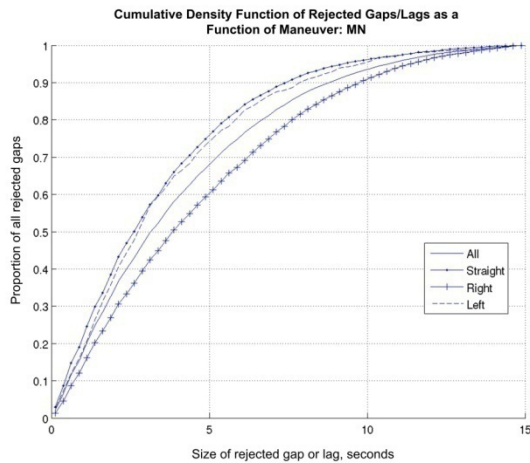
The sensitivities to gap rejection threshold as a function of

- 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)
- Vehicle classification

are described below.

12 13B Gap Rejection Threshold Sensitivity to Maneuver Type

Cumulative Density Functions (CDF) for maneuvers by type are shown in Figure 8. In these examples, the abscissa is the proportion of all *rejected* gaps which are less than the ordinate value.



| 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 left shows the gap corresponding to the 80th percentile of all rejected gaps.

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. (When presented a lag fifteen-seconds or greater, every driver will enter or cross the traffic stream. Any gaps or lags greater than 15 seconds are removed from the data pool.)

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 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 (hopefully) 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 in the sequel, 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.

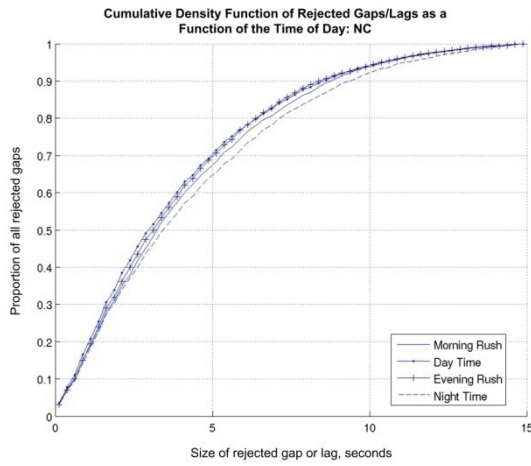
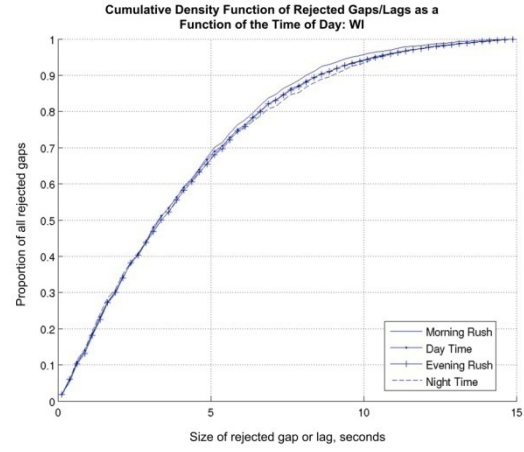
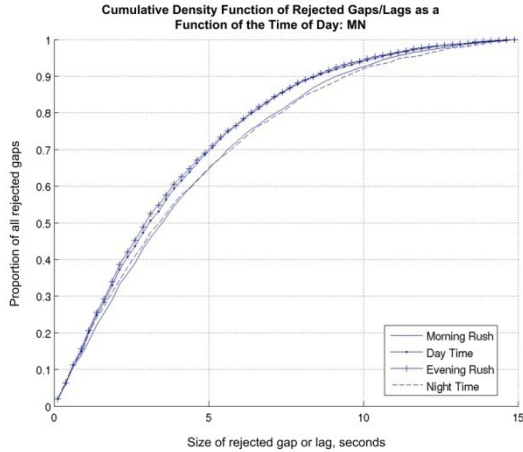
The primary anomaly in the data is the extremely low 80% gap rejection threshold for WI right turns. The primary hypothesis for this short duration is that the WI research intersection is located on a large horizontal curve, and visibility is somewhat restricted from the east side of the intersection.

13 14B Gap Rejection Threshold Sensitivity to Time of Day

Gap rejection by time of day for each of the three states is shown in Figure 9 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.



| 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 9. Gap rejection cumulative distribution functions as a function of the time of day.

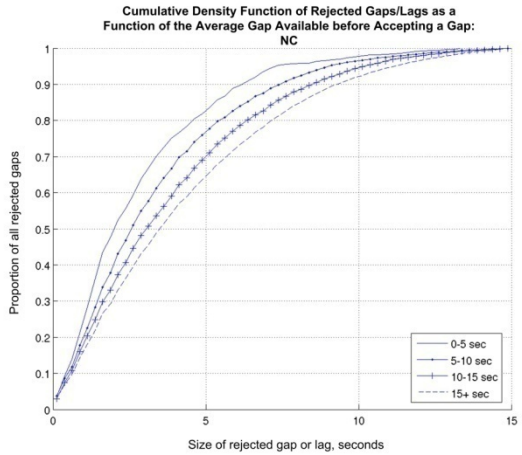
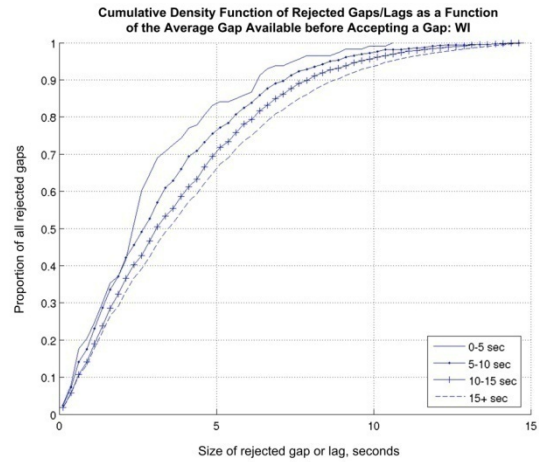
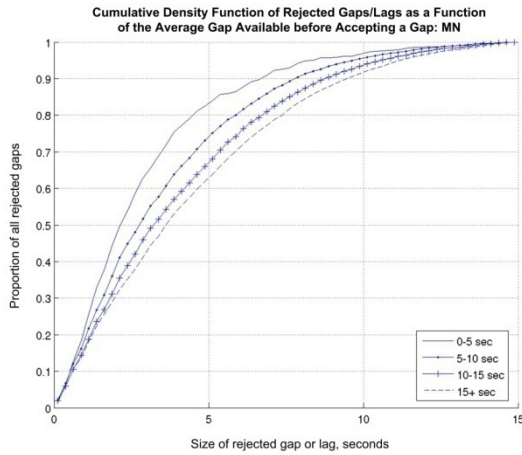
14 15B Gap Rejection Threshold Sensitivity to the Average Size of Previously Available Gaps

Figure 10 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 10, 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%.

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 be having the desired effect on the motoring public.



| 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 10. Gap rejection for all three states 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.

15 16B 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 [15]. Because of this speculation, this effect was investigated; Figure 11 shows the effects of timing waiting for an acceptable gap on the distribution of rejected 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 has been collected.

This phenomenon can be explained by examining the timing which is associated with this scenario. To be included in this sample population, 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.

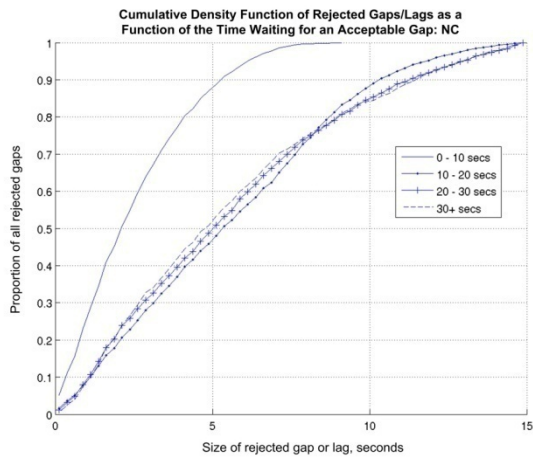
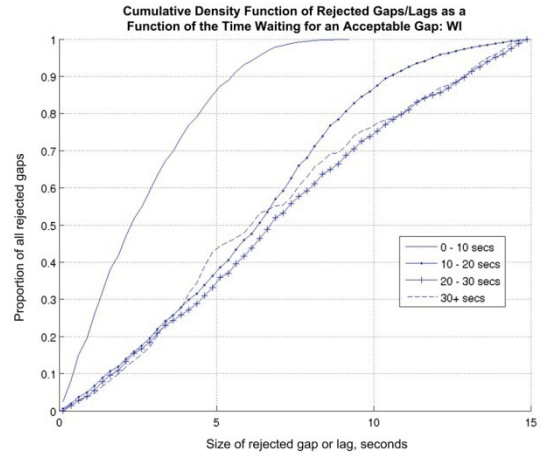
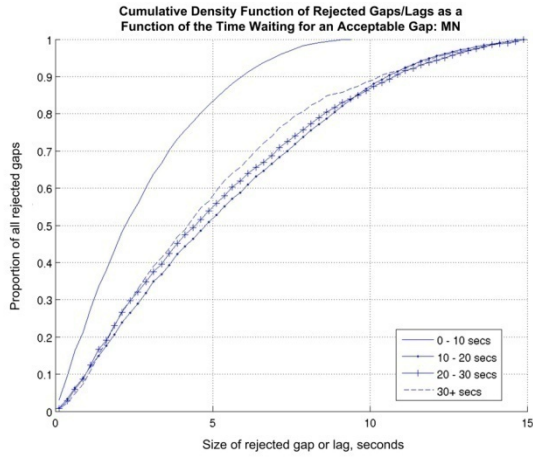
Reviewing the other categories of gap rejection threshold as a function of time waiting shows no trends which indicate a necessary modification to alert and warning timing as a function of time waiting for a gap. Those waiting for more than 30 seconds appear to have a lowered gap rejection threshold, 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 categories for gap rejection produces a similar result. Figure 12 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.

16 17B Gap Rejection as a Function of Departure Zone

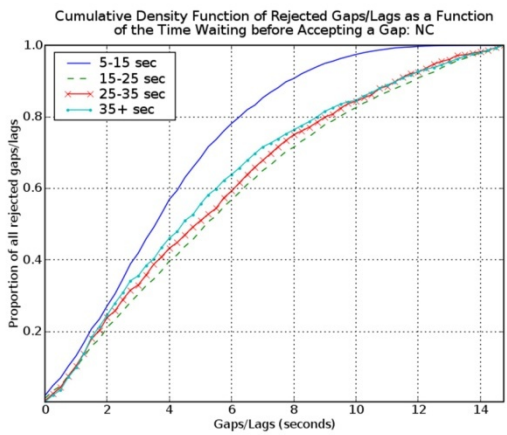
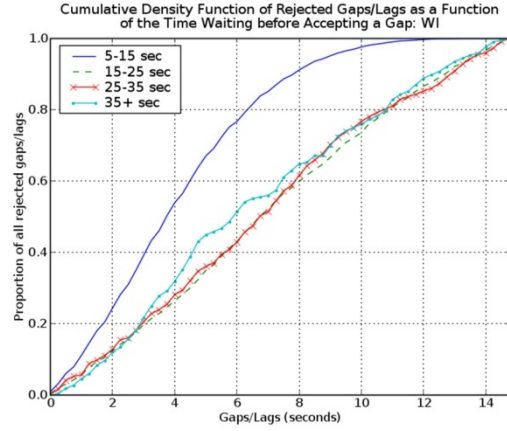
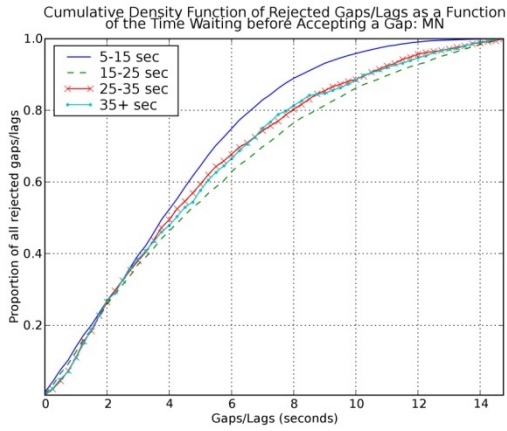
A thru-Stop, median separated expressway intersection has four points of departure: two from the minor road, and two from the median. These points of departure are shown for the Minnesota Test intersection in Figure 13; other state intersections use the same zone definitions.

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. 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 small gap can be chosen while maintaining a threat level similar to a stopped vehicle selecting a larger 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 11. Gap rejection for all three states 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 12. Gap rejection for all three states as a function of time at the intersection waiting for a gap. The time waiting categories have been changed from Figure 11.

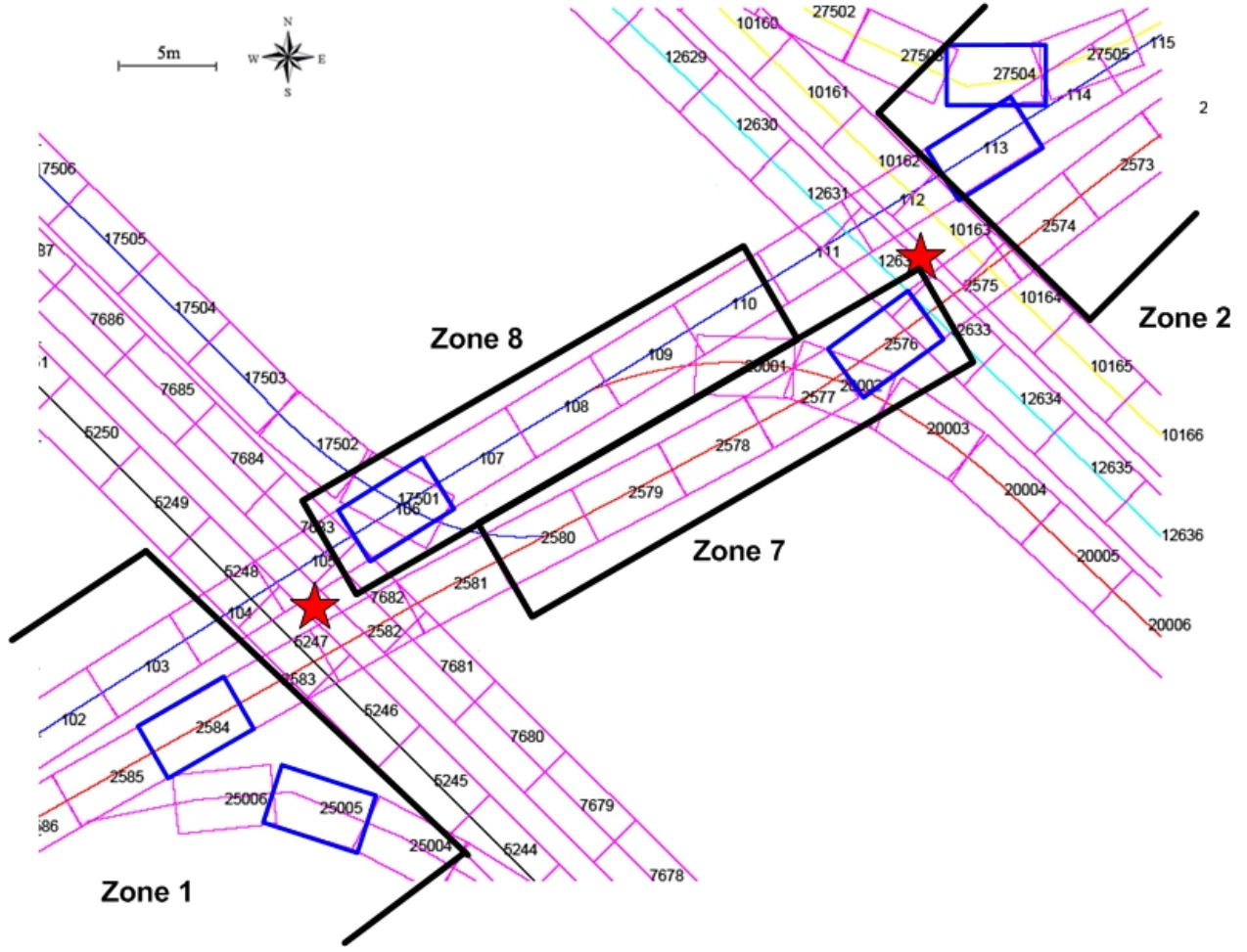


Figure 13. Layout of a typical median-separated rural expressway intersection. Zone 1 and Zone 2 represent the departure point for the minor road, and Zone 7 and Zone 8 represent the departure point for the median. These zone designations are generic, but the intersection shown above is the Minnesota Test Intersection.

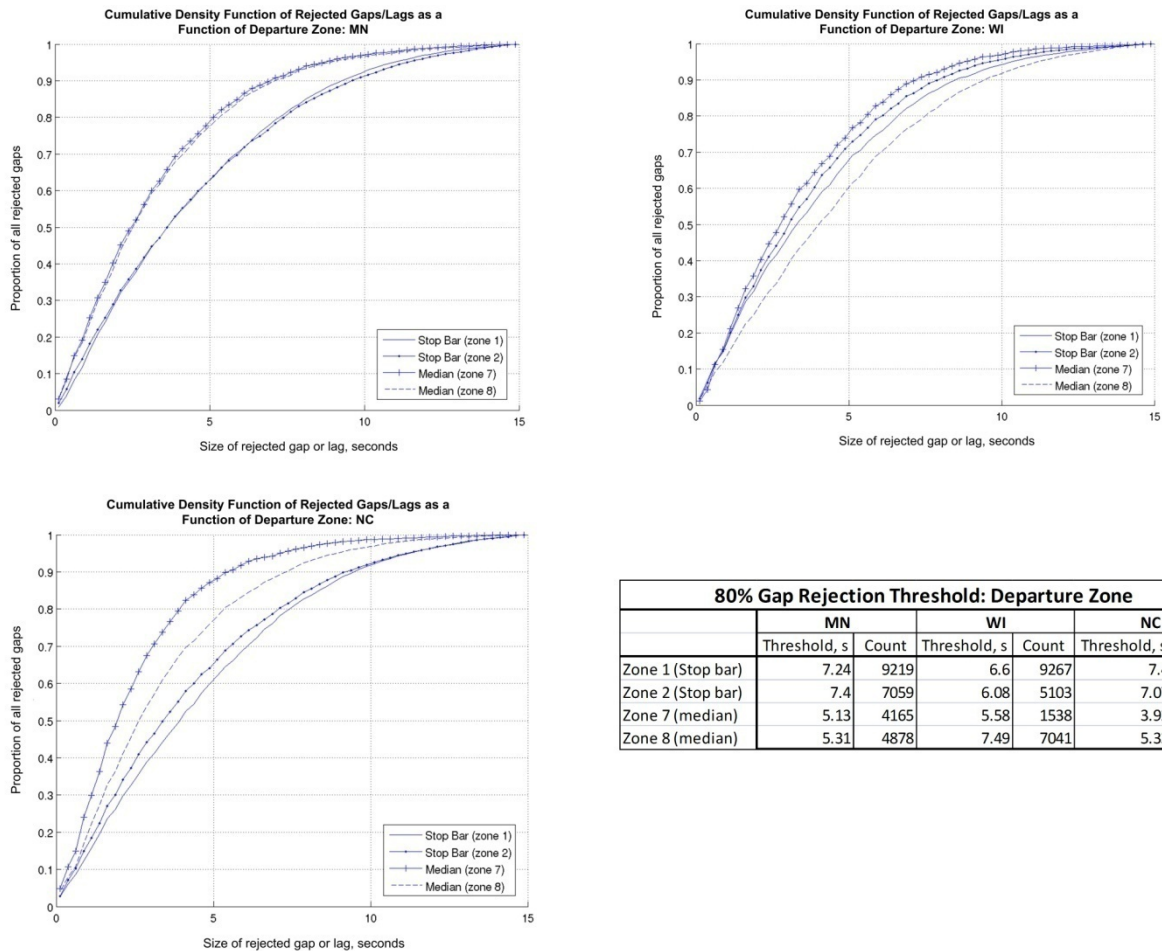


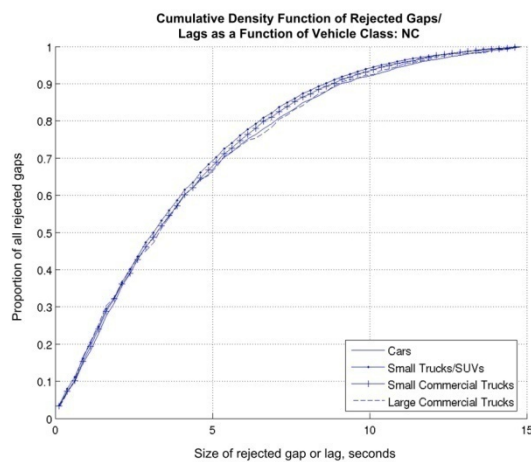
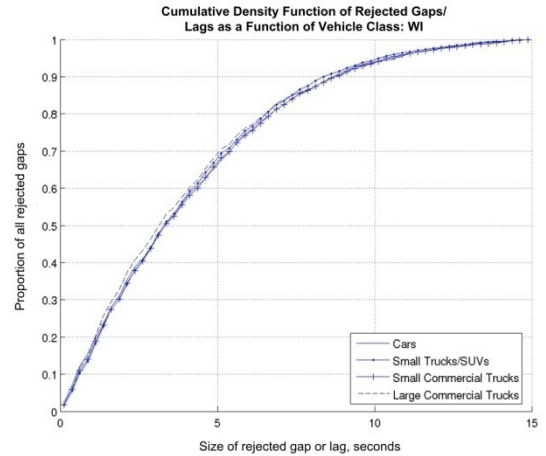
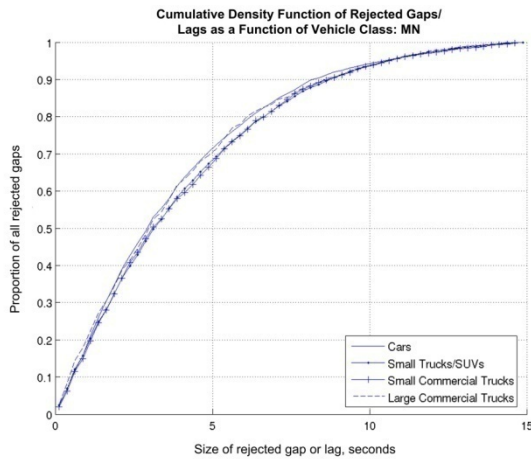
Figure 14. Gap rejection for all three states as a function of departure zone.

17 18B 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 15 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 15. Gap rejection behavior as a function of vehicle classification.

The second question is how the time-to-cross the major road lanes compares 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 16 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 t_0 . 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., t_0-5 seconds), is subtracted from the speed two seconds *after* the departure time (i.e., t_0+2 seconds). As is shown in Figure 17, 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.

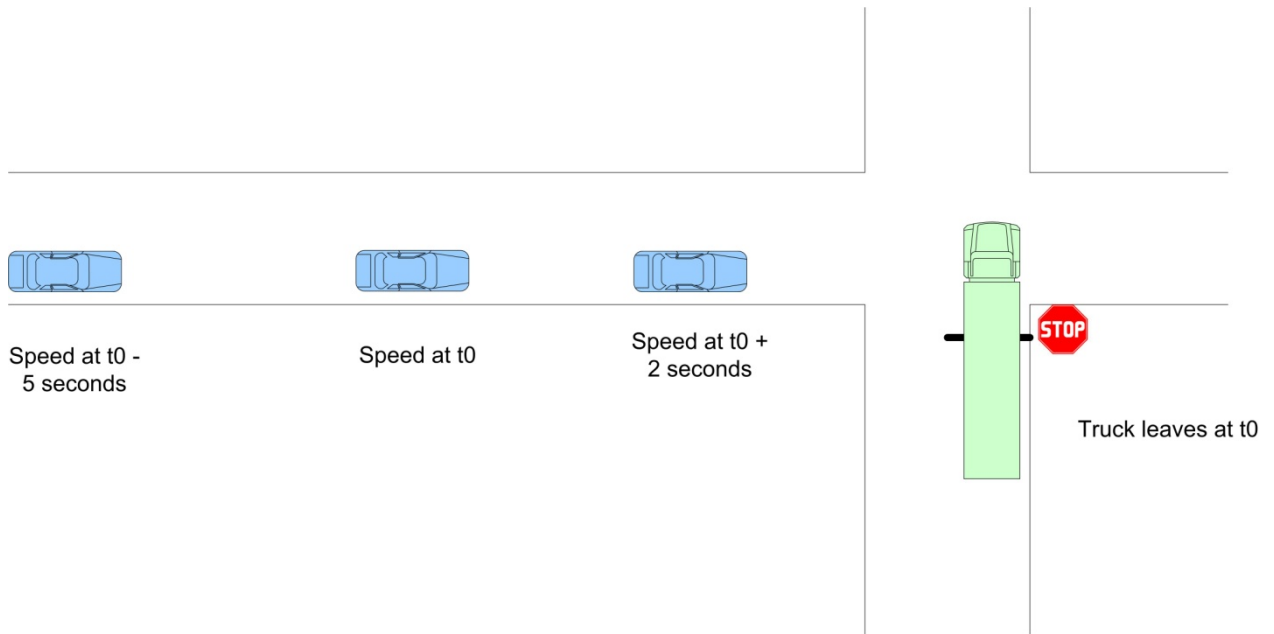


Figure 16. Procedure to determine whether mainline vehicle speed reductions are greater for larger entering vehicles than for smaller entering vehicles.

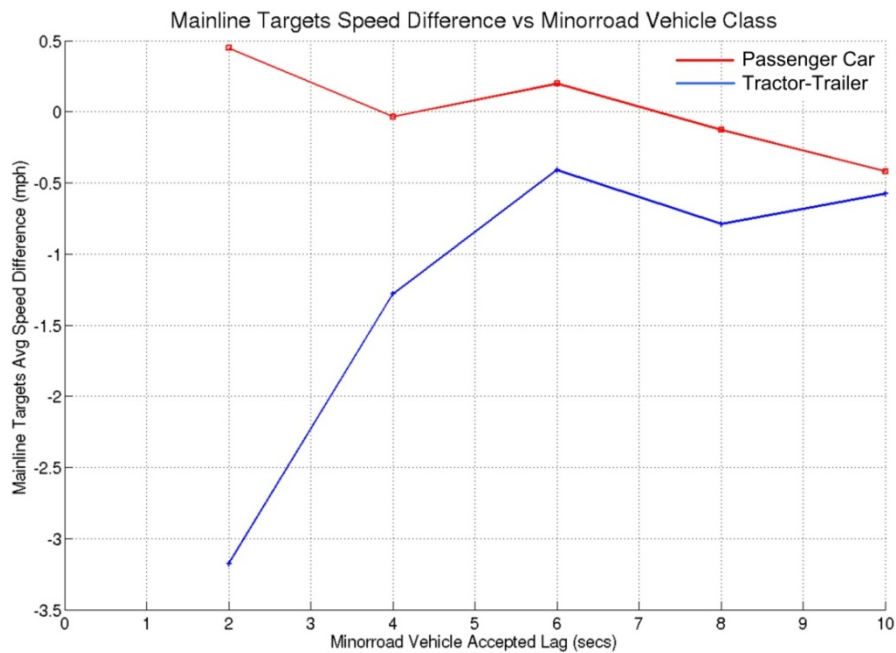


Figure 17. Speed changes on the mainline in response to a vehicle crossing the highway for the North Carolina test intersection. Speed differential is defined as the speed of the mainline vehicle 5 seconds *before* the minor road vehicle pulled out subtracted from the speed of the mainline vehicle 2 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 13 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 a car. Using time-to-cross data in Figure 18, 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.

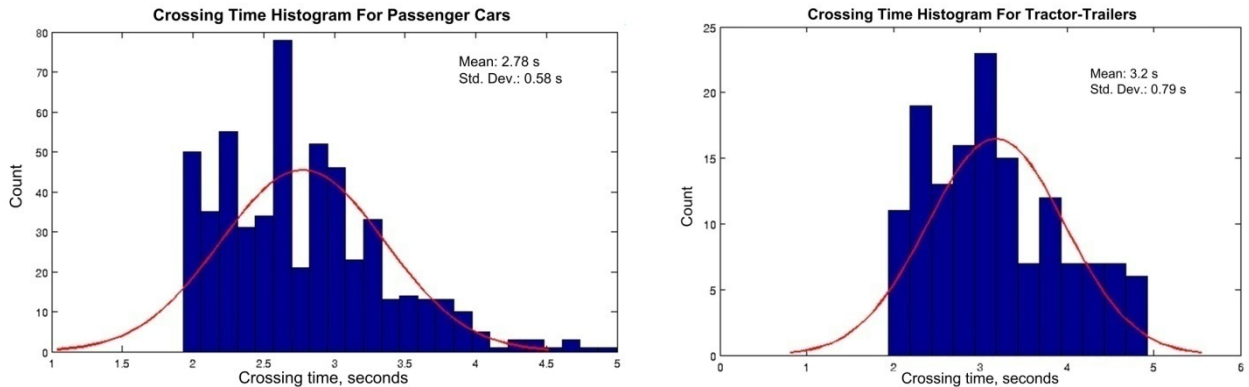


Figure 18. Time to cross mainline traffic from the minor road stop bar.

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 18 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.

18 19B Weighted Average 80% Gap Rejection Threshold

Given the six conditions above, the weighted average for the conditions are provide below. The coupling of the results is exceptionally tight, both between conditions and between states. Tables 3-8 and weighted averages for each of the six conditions are provided below.

Table 4. Weighted average 80% gap rejection threshold by maneuver.

| 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 5. Weighted average 80% gap rejection threshold by time of day.

| 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 6. Weighted average 80% gap rejection threshold by average available gap.

| 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 7. Weighted average 80% gap rejection threshold by time waiting for an acceptable gap.

| 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 8. Weighted average 80% gap rejection threshold by time waiting for an acceptable gap.

| 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 9. Weighted average 80% gap rejection threshold by vehicle class.

| 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.

19 20B Macroscopic Analysis 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, median departure points and 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.

20 5B Chapter

6

Microscopic Analysis to Determine Safety Margins

In contrast to the macroscopic study which focused on gap rejection, the focus of the microscopic study was on the behavior of a driver who accepted a gap. Because of the instrumentation in the test vehicle, a consistent definition of the “go” behavior of a driver was formulated, and used to compare the effect of age and gender as they cross mainline traffic. This microscopic view of driver behavior allows the safety margins with respect to gap rejection thresholds to be determined as a check of the effects of alert and warning timing.

The specific goals of the microscopic study are to determine

- normative safety margins associated with lag acceptance
- age effects on safety margins associated with alert and warning timing
- gender effects on safety margins associated with alert and warning timing
- effective safety margins with recommended alert and warning timing.

21 21B Microscopic Testing Overview

Test subjects.

Thirty five test subjects were recruited for this study. A table summarizing the ages and genders of the subjects is shown in Table 10.

Table 10. Age and gender distribution for microscopic gap acceptance study.

| Gender | Young (18-19) | Middle (35-50) | Older (>60) |
|---------------|----------------------|-----------------------|-----------------------|
| Male | 6 | 5 | 6 |
| Female | 6 | 6 | 6 |

Test vehicle and instrumentation.

A Nissan M45 served as the instrumented vehicle. The instrumentation suite includes dual frequency, carrier phase differential GPS (accurate to between 2-5 cm) which provides position measurements at 10 Hz, a six axis (three axes of rotational rates, three axes of acceleration) Inertial Measurement Unit (IMU), brake sensors (indicating brake actuation), a throttle position sensor, and eight channels of video (driver's forward view, driver's hands, driver's feet, driver's face, vehicle left side, and vehicle right side).

Critical to the utility of the instrumented vehicle is the capability to synchronize on-board data collection with data collection at the intersection. Inter-computer synchronization is handled via NTP – Network Time Protocol. The NTP is manifest through the use of a local 802.11b wireless network located at the test intersection. Low network traffic volume leads to robust synchronization.

Wiring Schematics M-45

Parts List

- VehDAQ computer
- VehDAQ computer chassis
- Cameras
- GPS: Trimble MS-750
- IMU: Crossbow
- Throttle sensor (on/off only)
- Brake sensor (on/off only)
- GPS Corrections (900 MHz radio)
- 802.11 wireless
- experimenter's interface
- big alternator
- inverter

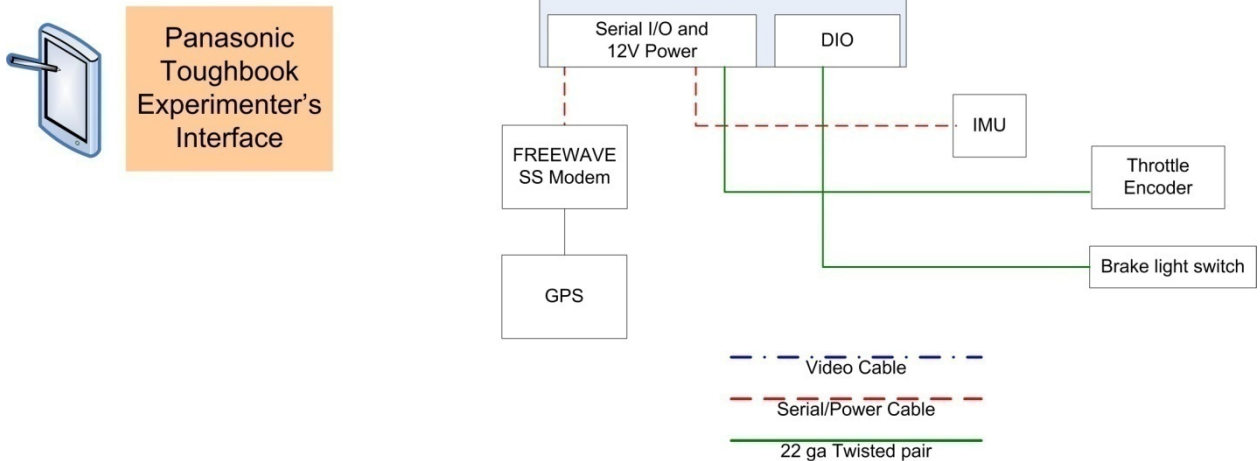


Figure 19. Instrumentation and data flow for M45 for microscopic analysis.

Test Protocol.

One of the requirements for test subjects recruited for this in-vehicle study was that they were familiar with this intersection, and use it on a “regular” basis.

Driving tests were performed in the afternoon; the first test was run at 1:00 PM. The second test initially began at 4:00 PM, but after a few subjects were tested at 1:00 PM, it became apparent that two hours was sufficient for driver training, system calibration, and test execution. Thus, 3:00 PM became the starting time for the second battery of tests.

Three maneuvers are possible at the test intersection: left turn, right turn, or straight-through. Each driver performed each maneuver twice during a test session; the order in which the test subject performed the maneuvers was scripted and determined prior to testing. An experimenter travelled with each driver and provided instructions specific to the maneuver which was to be executed. Straight-through maneuvers were initiated on both the east and west sides of US 52; left and right turns were initiated only on the east side of US 52.

22 22BResults

Time-to-Cross.

The first analysis undertaken from the microscopic point of view is “time-to-cross.” The mean and variance of the time-to-cross behavior is an important component in the analysis of safety margins associated with alert and warning timing. This analysis is undertaken to determine whether age or gender differences exist in the time-to-cross behavior of drivers; if differences do exist, alert and warning timing may have to be adjusted to compensate for behavioral differences.

The time-to-cross the mainline traffic was measured from two starting points: from the minor road stop bar and from the median. The start of the maneuver was defined as the point in time at which the throttle opening first crossed the 5% point; the end of the maneuver was defined at the time the rear bumper of the M45 test vehicle crossed the fog line which separates the mainline road from either the median (for maneuvers starting from the minor road) or the minor road (for maneuvers starting from the median).

Figure 20 illustrates the distribution of time-to-cross for departure point (minor road or median), gender, and age (young = 18-19, middle = 35-50, and old = 60+).

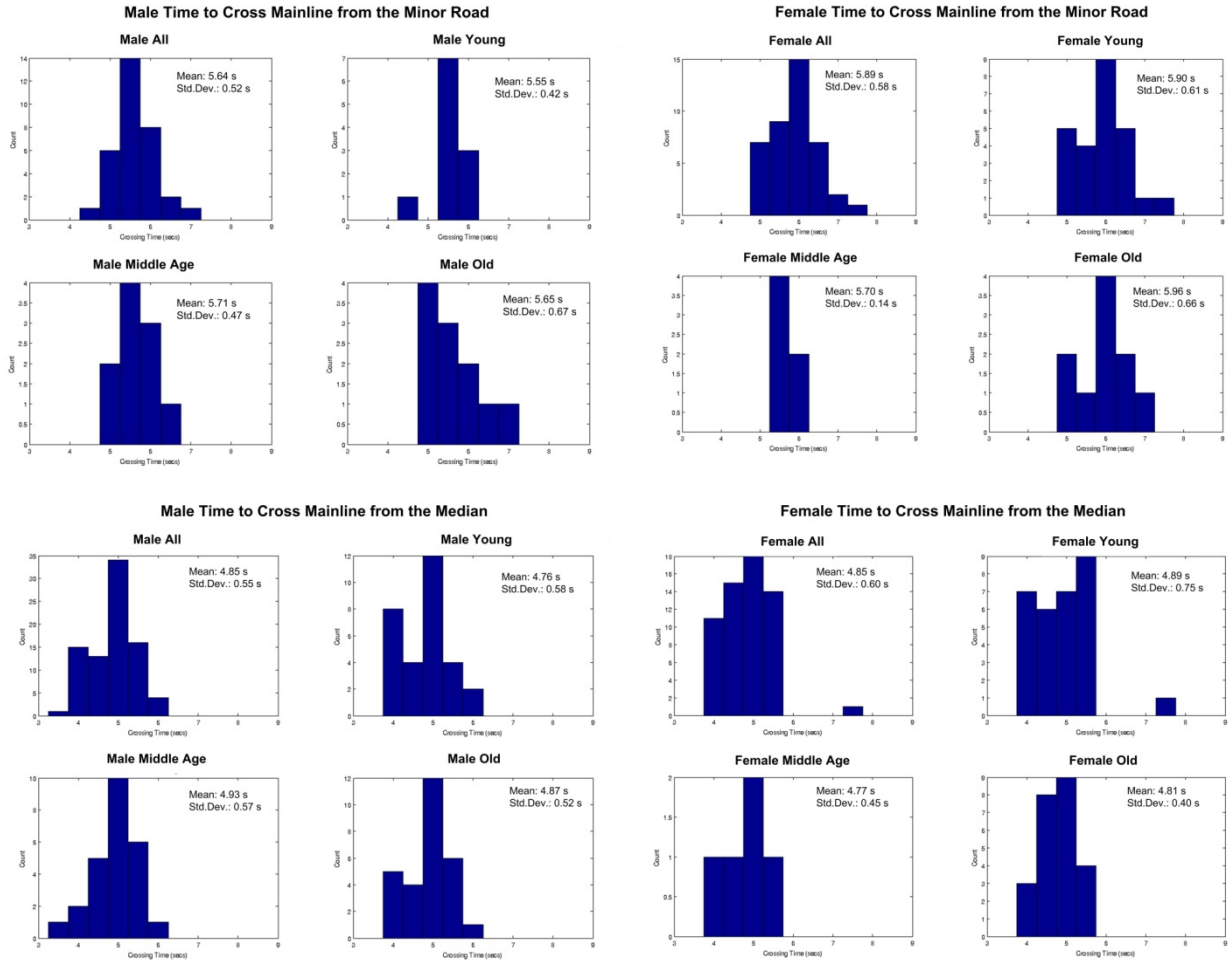


Figure 20. Distributions of “time-to-cross” mainline traffic for separated by departure point, age, and gender.

Results of the time-to-cross experiments are summarized in Table 11 below. Surprisingly, the means and variance across age groups and gender are quite tightly coupled, with no functional difference between the two categories.

Table 11. Tally of the means and standard deviations for time-to-cross data for instrumented vehicle tests at the Minnesota Test Intersection.

| Departure Point | Gender | Age | mean, s | Std. Dev., s |
|------------------------|---------------|------------|----------------|---------------------|
| Minor road | Male | All | 5.63 | 0.52 |
| | | Young | 5.55 | 0.42 |
| | | Middle | 5.71 | 0.47 |
| | | Old | 5.65 | 0.67 |
| | Female | All | 5.89 | 0.58 |
| | | Young | 5.9 | 0.61 |
| | | Middle | 5.7 | 0.13 |
| | | Old | 5.96 | 0.66 |
| Median | Male | All | 4.85 | 0.55 |
| | | Young | 4.76 | 0.58 |
| | | Middle | 4.93 | 0.57 |
| | | Old | 4.87 | 0.52 |
| | Female | All | 4.84 | 0.6 |
| | | Young | 4.89 | 0.75 |
| | | Middle | 4.77 | 0.45 |
| | | Old | 4.81 | 0.4 |

With respect to departure point, a trend emerges: drivers take less time-to-cross from the median than they do from the crossroads. Macroscopic data showed that the 80% gap rejection threshold for a median departure was generally shorter than that for minor road departures. This again can be explained that in general, medians are “Yield” controlled, where complete stops are not required. If a driver is starting the maneuver in motion, it will take less time to cross, all other things being equal.

For the macroscopic data, the one exception to the median departure point 80% gap rejection threshold being less than that for minor road departure points occurred in Wisconsin. It is interesting to note that in Wisconsin, the median is under the control of a “Stop” sign. This likely explains the apparent anomaly in the data.

It is noted that the crossing times as reported in the microscopic analysis are considerably longer than those reported in the macroscopic section of this report (Chapter 5). The difference in time-to-cross definitions accounts for this difference in reported timing. The macroscopic timing definition is based on the location of the front of the vehicle for both event initiation and conclusion, whereas the microscopic definition is based both on driver behavior (5% throttle opening) and vehicle location (rear of vehicle clears mainline road boundary). Clearly, the microscopic definition will lead to longer reported crossing times.

Safety margin. The integrated roadside-vehicle instrumentation system facilitates the examination of the safety margin in general, and the minimum safety margin a driver will accept when accepting a gap at a minor road in particular.

For the series of experiments conducted with the instrumented vehicle at the Minnesota Research Intersection, two safety margins were computed; one for the near lane with respect to the

departure point, and one for the far lane with respect to the departure point. Two departure points were used: the minor road stop bar and the median.

The safety margin is defined as the time headway from the front of the major road vehicle to the center of the minor road vehicle as the rear bumper of the minor road vehicle crosses the far-side lane boundary of the near or far side lane of the major road, respectively. These definitions follow the model used to measure time-to-cross, and are illustrated in Figure 21.

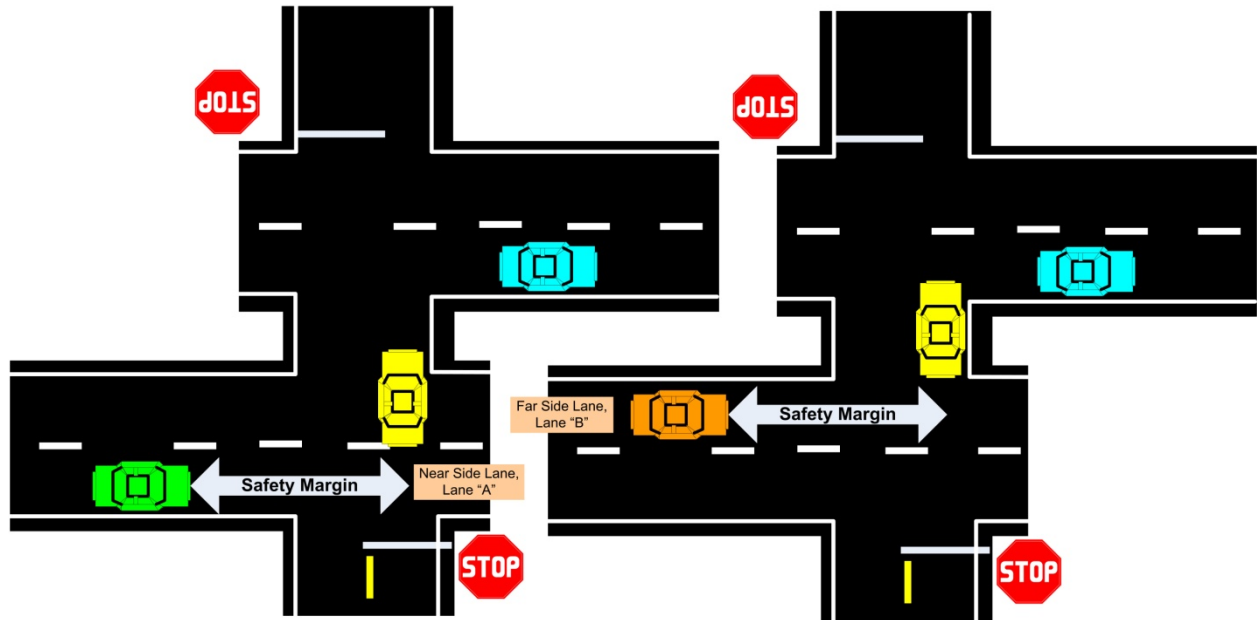


Figure 21. Safety margins for instrumented vehicle study. Safety margin for near side lane (Lane “A”) is shown on the left; the safety margin for the far side lane (Lane “B”) is shown on the right.

Results. Safety margins as a function of driver age and driver gender for both departure points were analyzed. Graphs of safety margins are presented in Figure 22 below for the minor road departure point, and in Figure 23 for the median departure point.

Three results are apparent from the data. First, a wide range of safety margins were identified. It is important to note, however, that because of relatively sparse traffic on the major road, it is very likely that a large safety margin in one lane accompanies a smaller safety margin in the other lane. Second, the mode for the distributions of safety margins lies between five and six seconds. Third, with the exception of one driver (male, less than 20 years old) departing from the minor road who accepted a one second safety margin, the minimum safety margin acceptable to drivers was 2 seconds. This is a bit lower than expected, but consistent with the proposed alert and warning timing discussed in Chapter 7 below.

As was seen with time-to-cross, there appears to be no substantial difference between safety margin as a function of age or gender. Young and older women accept gaps which produce safety margins approximately 0.25 seconds greater than men; middle age women and middle age men generally accept gaps which produce equal safety margins.

In general, drivers departing from the median accept gaps with larger safety margins than do drivers departing from the minor road. This is consistent with the “rolling stop” in the median; vehicles which fail to stop in the median carry momentum, which allows a shorter crossing time.

Drivers from either the minor road or the median likely accept gaps consistently, but the higher speed at the point of acceptance in the median produces higher safety margins.

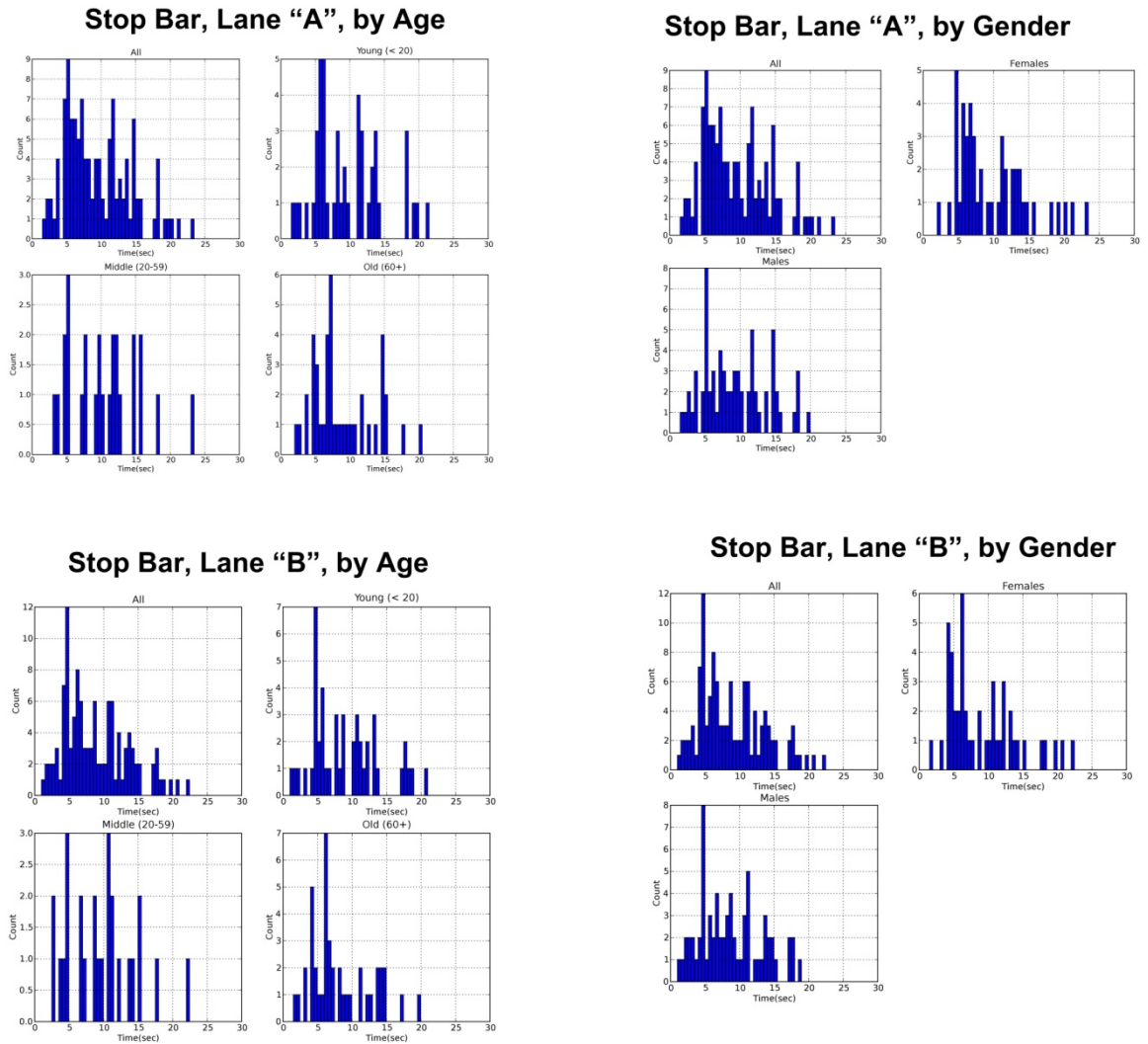


Figure 22. Safety margin results for age, gender from the stop bar departure point. Lane "A" is the first lane crossed, and Lane "B" is the second lane crossed.

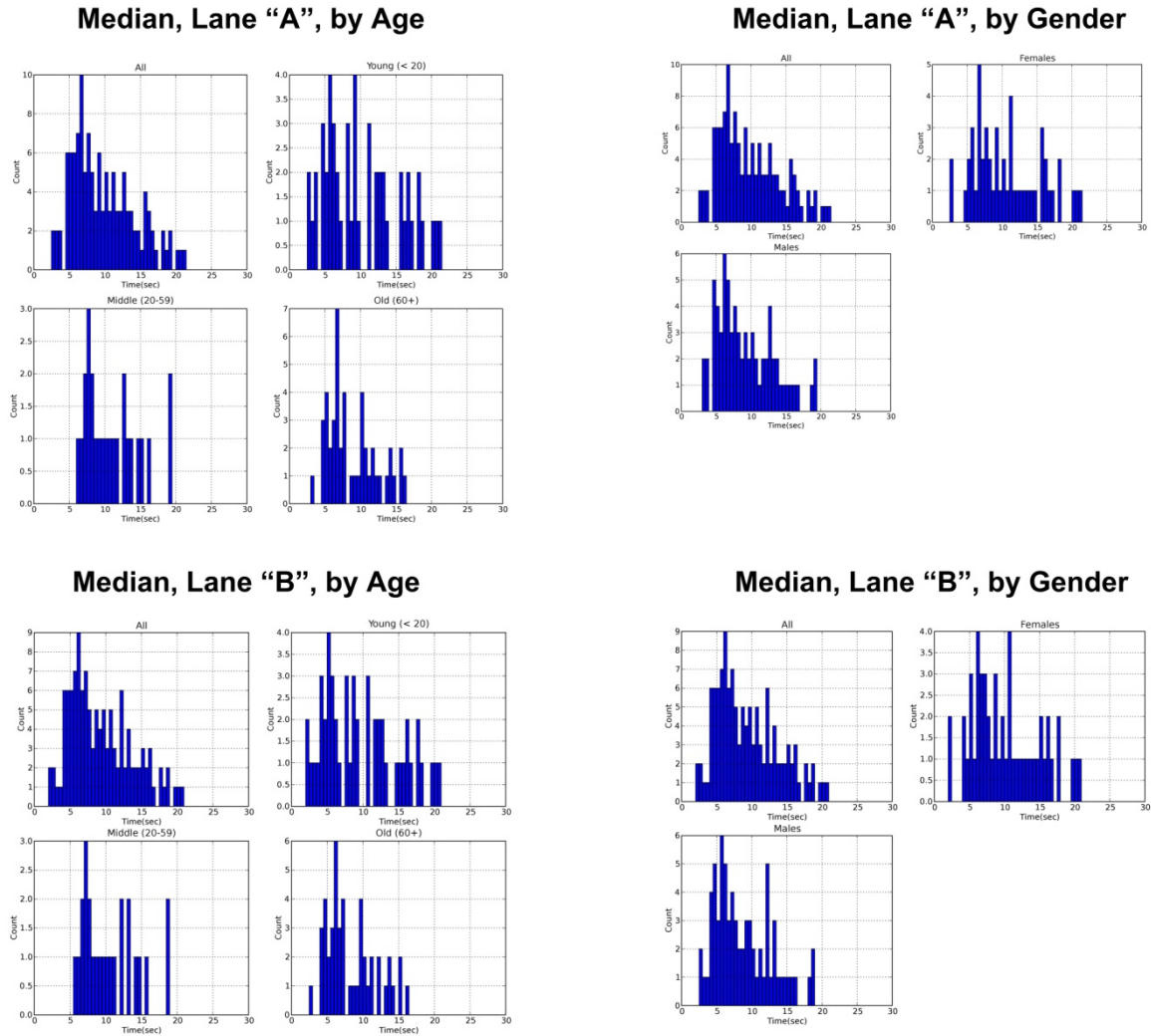


Figure 23. Safety margin results for age, gender from the median departure point. Lane “A” is the first lane crossed, and lane “B” is the second lane crossed.

23 23BConclusions

Contrary to expectations, there appears to be no difference in the time-to-cross the major road when age and gender effects are considered. A difference in time-to-cross as a function of departure point does exist; drivers cross in less time from the median than from the minor road. This is consistent with the gap rejection behavior indentified in the macroscopic analysis, where median departure gap rejection thresholds were consistently less than minor road gap rejection thresholds. This can be explained by the typical “Yield” control found in the median of rural expressways.

With respect to safety margins, young and older women accept gaps which produce safety margins approximately 0.25 seconds greater than men; middle age women and middle age men generally accept gaps which produce equal safety margins.

Maneuvers beginning from the median produce higher safety margins than do maneuvers from the minor road. This is consistent with the findings regarding time-to-cross, where the time-to-cross is shorter, in general, from the median. If a vehicle is “rolling” through the intersection, it begins its maneuver with higher speed, requiring less time to cross. Drivers accept gaps (and risk) consistently; shorter crossing times produce greater safety margins for any given gap.

Chapter 7 Recommended Alert and Warning Timing

24 24BSingle Vehicle Conditions

Alert timing. Although some ambiguity exists in the literature, the CICAS-SSA baseline alert timing is based on the literature and on-site testing of prototypes of the proposed DIIs.

Kittleson and Vandehey [16] showed that all gaps longer than 12 seconds are accepted, and therefore should not be considered when estimating the critical gap. Teply, et al. [17] recorded a similar result, and suggested that drivers facing gaps greater than 13 seconds face a “non-choice” situation because all gaps of this size and larger are accepted.

Using 12 seconds as a baseline value, a prototype DII was tested at the Minnesota Research Intersection. The twelve second gap is consistent with the findings in [16]; it is a non-choice. To bring the alert timing into the decision-making regime, an alert threshold of 11 seconds was chosen as a baseline value. If the lag to which a driver is exposed crosses the 11 second threshold, the alert on the DII will be activated.

This 11 second indication will be used for both median and minor-road departure points, and will remain constant with respect to age, gender, previously available gap average, and vehicle classification.

Warning timing. On average, drivers perceive threats in very similar manners, and as shown in Chapter 5, the weighted mean 80% gap rejection threshold varies no more than 0.26 seconds between conditions and between states. Thus, a single value can be used as the baseline warning timing for all conditions and vehicle classifications.

The value 6.5 seconds represents the average weighted 80% gap rejection threshold for MN and WI; 6.34 seconds represents the 80% gap rejection threshold for North Carolina. If the time to recognize and comprehend the message from the DII is assumed to be one second, this puts the DII warning timing at 7.5 seconds. This timing will work for the “Icon” DII; the warning time would move to 8 seconds for the countdown timer because the countdown timer displays only integers.

Time-to-cross data, combined with the warning timing of 7.5 seconds, provides bounds on the safety margin which would be experienced by a driver who chooses to proceed through an intersection at the instant the warning is activated. These bounds are shown in Table 12 below.

Table 12. Safety margins which would result from warning timing of 7.5 seconds for mean driver time-to-cross behavior, and “slow” (mean + 2 standard deviations) time-to-cross behavior.

| Departure | Gender | Age | Mean, s | Std. Dev., s | Safety margin for mean time-to-cross, s | Safety Margin for Mean + 2 Std. Dev. time-to-cross, s |
|------------|--------|--------|---------|--------------|---|---|
| Minor road | Male | All | 5.63 | 0.52 | 1.87 | 0.83 |
| | | Young | 5.55 | 0.42 | 1.95 | 1.11 |
| | | Middle | 5.71 | 0.47 | 1.79 | 0.85 |
| | | Old | 5.65 | 0.67 | 1.85 | 0.51 |
| | Female | All | 5.89 | 0.58 | 1.61 | 0.45 |
| | | Young | 5.9 | 0.61 | 1.6 | 0.38 |
| | | Middle | 5.7 | 0.13 | 1.8 | 1.54 |
| | | Old | 5.96 | 0.66 | 1.54 | 0.22 |
| Median | Male | All | 4.85 | 0.55 | 2.65 | 1.55 |
| | | Young | 4.76 | 0.58 | 2.74 | 1.58 |
| | | Middle | 4.93 | 0.57 | 2.57 | 1.43 |
| | | Old | 4.87 | 0.52 | 2.63 | 1.59 |
| | Female | All | 4.84 | 0.6 | 2.66 | 1.46 |
| | | Young | 4.89 | 0.75 | 2.61 | 1.11 |
| | | Middle | 4.77 | 0.45 | 2.73 | 1.83 |
| | | Old | 4.81 | 0.4 | 2.69 | 1.89 |

Warning timing for the 80% gap rejection threshold, assuming a *mean* time-to-cross value, produces safety margins consistent with the minimum safety margin chosen by drivers in the instrumented vehicle. (Recall that for the microscopic testing described herein, the drivers were not provided any decision support.) However, for drivers who proceed slowly through the intersection (where “slowly” is defined to be two standard deviations longer than the mean), safety margins become considerably smaller, particularly for older females departing from the minor road. However, a safety margin still remains, and the data in Table 12 does not account for mainline traffic deceleration which is likely to occur should a driver accept too small of a gap.

Clearly, a tradeoff exists between warning timing which is amendable to the general driving public and warning timing for less aggressive drivers. However, because safety margins exist with the prescribed warning timing even for drivers who proceed slowly, the 7.5 second warning timing threshold will be used as the baseline for both simulator and the initial intersection studies. Should this prove inaccurate, timing can be adjusted in the field.

25 25B Validity Testing

Although the gap rejection behavior is very consistent both among conditions and between states, a simple validation study was undertaken to make sure that the timing passed the “common sense” test.

The “Icon” DII was implemented on an older Hewlett-Packard tablet PC so it could be run inside a test vehicle at the Minnesota Research Intersection. Intersection state data (geometric map, vehicle speed, position, and lane of travel for the mainline) was broadcast to the tablet PC, similar to how data would be transmitted to a vehicle for an in-vehicle application.

Two simple tests were undertaken. The first test protocol was quite straightforward. A driver would pull the test vehicle equipped with the Tablet PC driver interface to the intersection (either the minor road or median), and the test driver would indicate the point at which the approaching gap would be rejected. The difference between the time the DII indicated a warning and the time the driver reached his gap rejection threshold recorded using a stop watch.

The mock driver interface as implemented in the test vehicles is shown in Figure 24.

Although only three middle age drivers were tested, the test driver rejection threshold was found to be within approximately 0.5 seconds of the indication in the driver interface. This timing was found to be appropriate for an initial implementation in the driving simulator.

A second test was undertaken to gain insight into the result that gap rejection behavior of heavy trucks was similar to that for smaller vehicles. The Tablet PC driver interface was allowed to run, and the response of heavy trucks observed. Overall, the gap rejection behavior of the truck drivers was consistent with the driver interface.



Figure 24. Alert and warning validation testing at Minnesota research intersection. Tablet PC is provided state map data, and is controlling the content of the driver interface, updating every 100 msec.

26 26B Multiple Vehicle Conditions

Other considerations to the alert and warning timing algorithms are also provided. An example of one such consideration is the situation where a driver in a vehicle in the median intends to make a

left turn when a minor road vehicle driver facing the vehicle in the median intends to either turn right or pass straight to the median. The vehicle in the median is under the control of a “Yield” sign, and the vehicle on the minor road has a stop sign, so the median vehicle has the right-of-way. The algorithm controlling the driver interface has to provide a message consistent with the traffic laws.

The initial approach to these considerations is also presented as a preliminary result; experience gained from additional in-vehicle studies and field testing will provide more information regarding how the algorithms should be structured and executed.

Six conditions are discussed below.

The first condition considered is that of a stop controlled minor road, a yield controlled median, and two vehicles facing one another. This is shown in Figure 25 below.

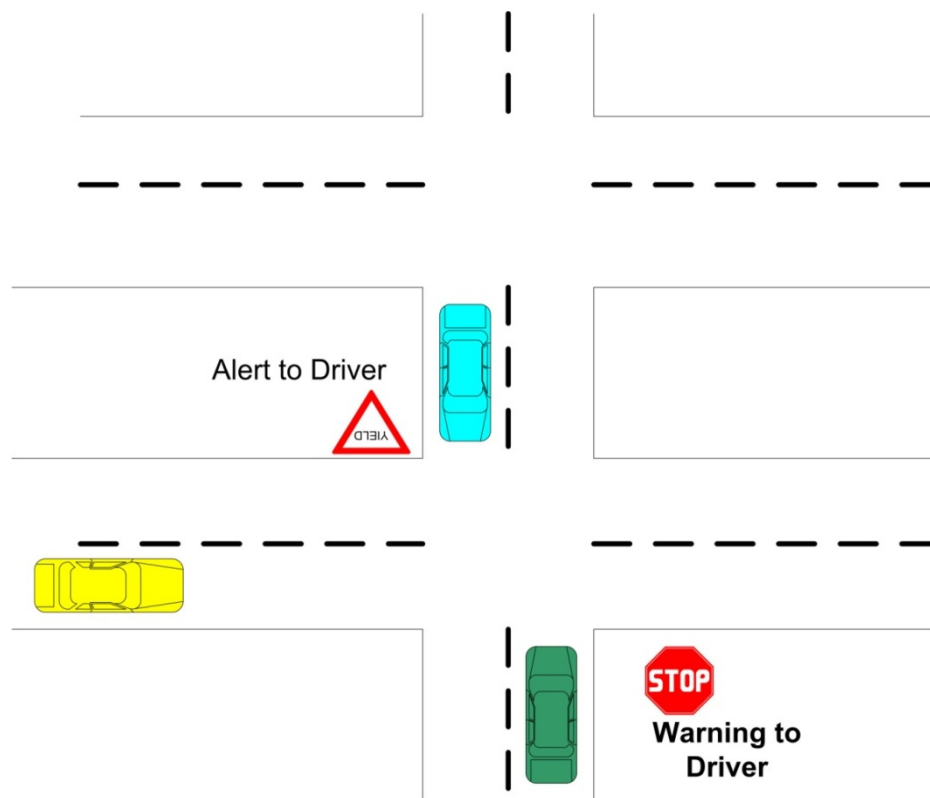


Figure 25. Face to face conflict at yield controlled median, stop controlled minor road.

In this situation, the yellow, major road vehicle presents a lag which would normally represent an alert condition should only one vehicle be present. However, because the blue vehicle in the median has the right-of-way, the green minor road vehicle is presented a warning to not proceed so as to avoid a collision conflict with the vehicle in the median, which is presented an alert on the DII.

In a cooperative scenario, driver intent for both the minor road vehicle and the median vehicle might be known because a turn-signal activation state would be available. However, because not all drivers use turn signals, this assumption cannot be relied upon to a high level of confidence.

The second condition arises when both the median and the minor road are controlled with stop signs. This is shown in Figure 26 below. Again, would only one vehicle be present at either the

minor road or the median, an alert would be provided. However, because the right-of-way belongs to the vehicle which arrives first (minor road vehicle in Figure 26), that vehicle is provided an alert, and the vehicle to arrive second is provided a warning.

The third condition is shown in Figure 27. In this case, the left turn pocket and the mainline are occupied, but the gap is sufficient to both locations to only warrant an alert if only a single vehicle is waiting to cross the mainline. However, because the median is “Yield” controlled, the vehicle in the median has the right-of-way. To avoid conflict, the vehicle at the “Stop” controlled minor road is provided a warning so as to avoid a conflict with the vehicle in the median.

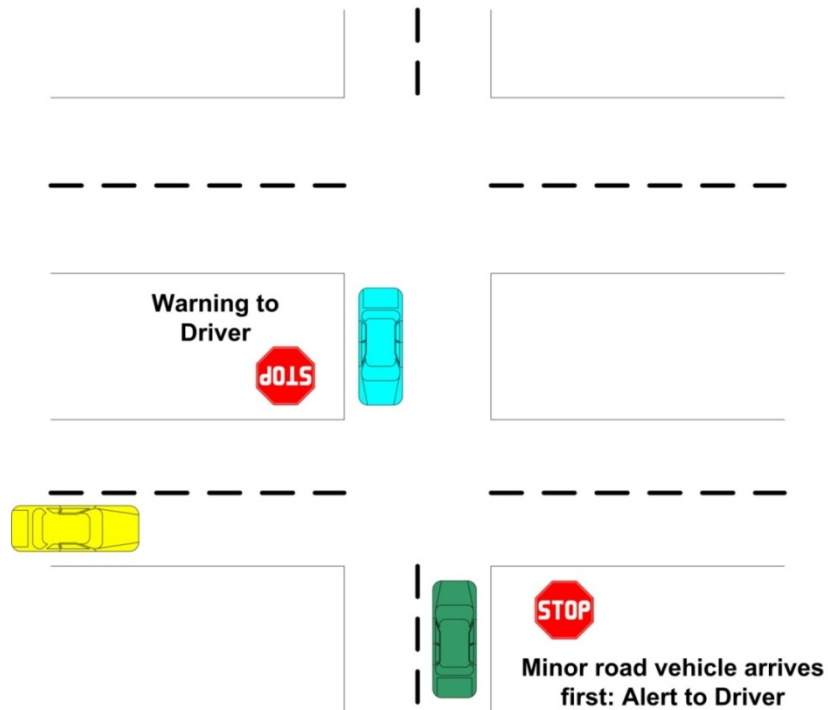


Figure 26. Face to face conflict at “Stop” controlled median, “Stop” controlled minor road.

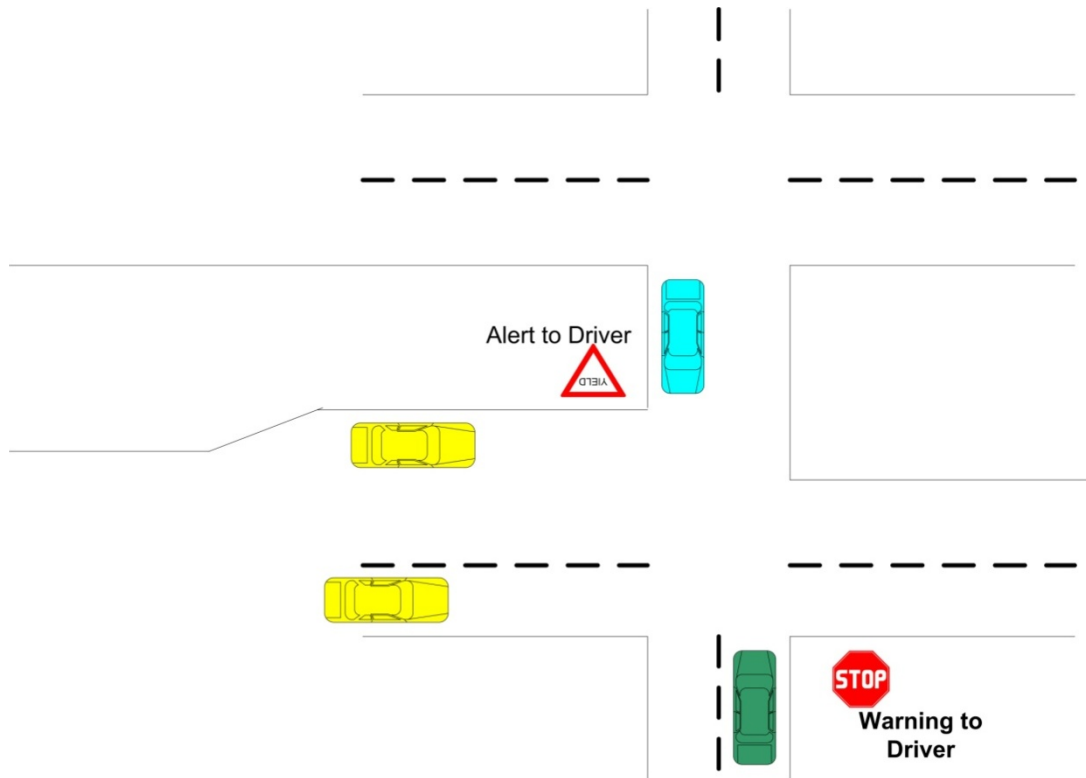


Figure 27. Face-to-face conflict with occupied left turn pocket. Blue median vehicle has right of way.

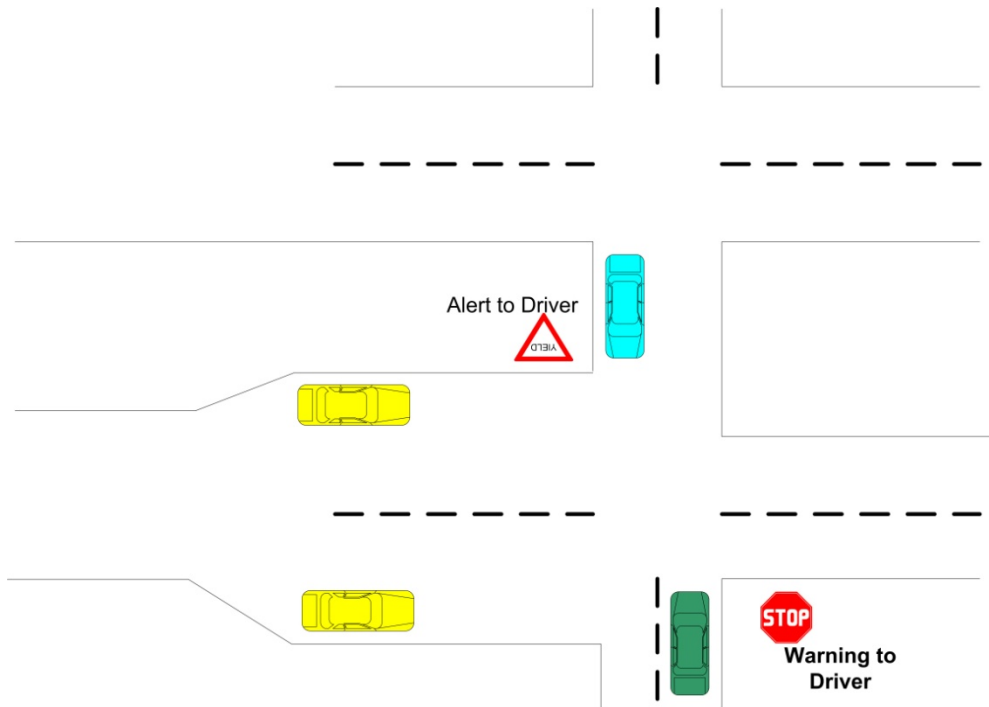


Figure 28. Face to face conflict with occupied left and right turn pockets. Median vehicle has right-of-way because of “Yield” control, so the alert condition is presented in the median.

Figure 28 represents a situation similar to that shown in Figure 27, but with the inclusion of a vehicle in the right lane turn pocket. Once again, the vehicle in the median has the right of way because of “Yield” control, so as to avoid a conflict, the minor road vehicle, under “Stop” control, is issued a warning.

Figure 29 represents another situation where the approaching traffic would normally warrant an alert condition, but because driver intent is unknown and because insufficient room to hold two vehicles exists in the median, the driver on the minor road is issued a warning. Should a right turn be indicated through a cooperative means, the warning could be reduced to an alert for right turns, but without driver intent known, a warning would be issued to avoid conflict in the median.

The final case examined is illustrated in Figure 30. The right turning, mainline vehicle does not pose a threat to the minor road vehicle, and without a vehicle in the median, would only warrant an alert to the vehicle on the minor road. However, with the vehicle in the median, two threats are present to the median vehicle: the minor road vehicle entering or crossing the mainline traffic stream, or the right turning vehicle in the turn pocket. If the intent of the vehicle in the median is not known, the median vehicle warrants a warning to avoid the two potential conflicts.

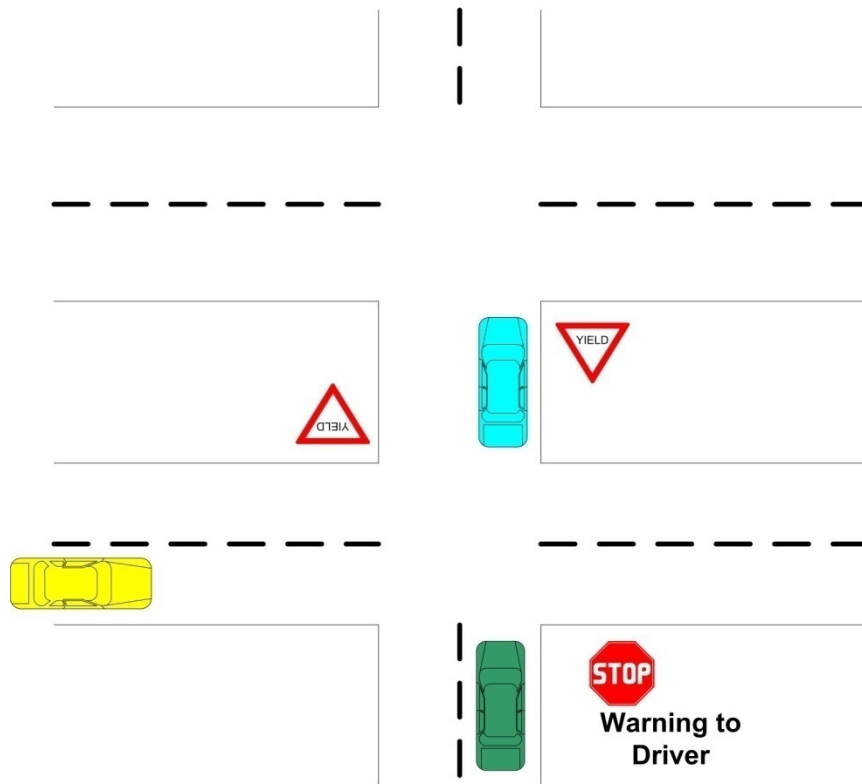


Figure 29. Because of median occupancy, the driver on minor road is issued a warning.

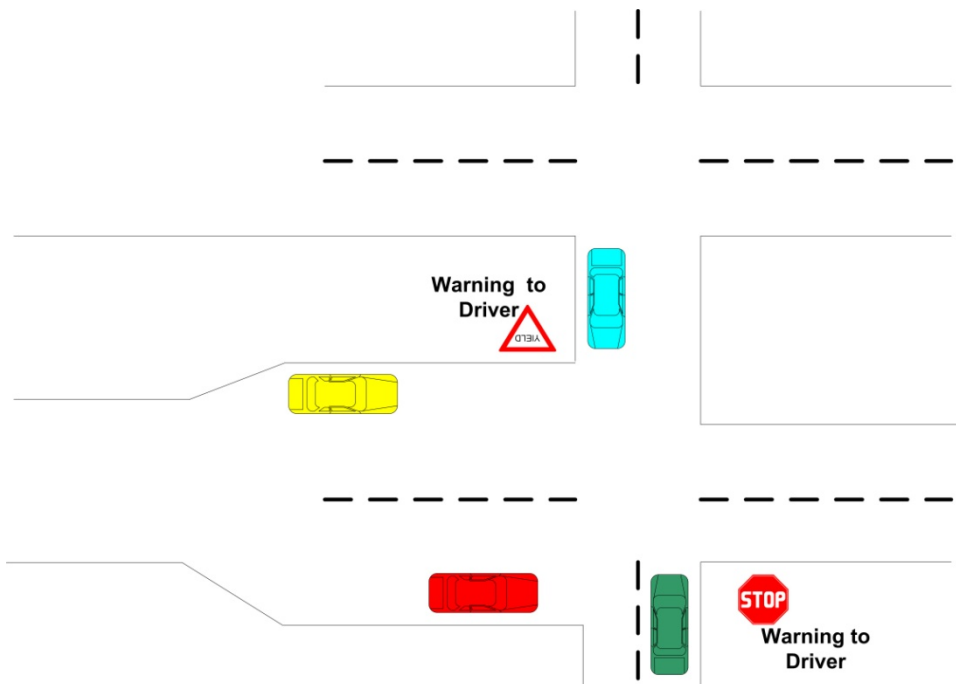


Figure 30. In this case, to avoid conflict on the minor road with median vehicle and right-turning vehicle, the vehicle in the median is warned not to proceed.

27 27BConclusion

Based on the literature, 80% gap rejection threshold, and a one-second assumed perception and interpretation period for the driver interface, alert timing is initiated at the 11 second point, and continues until a 7.5 second lag is achieved. At the 7.5 second epoch, the alert becomes a warning, and that warning state is held until the threatening vehicle passes by.

The “Countdown” DII only exhibits integer values of “time to intersection.” Because of integer limitations, the warning for the “Countdown” DII will indicate a warning at the 8 second epoch. Conditions with multiple vehicles present should follow the protocol established in Figure 25 - Figure 30.

As was shown by Table 12, warning timing based on the 80% gap rejection threshold, combined with the mean time-to-cross values produces safety margins consistent with the minimum safety margin of approximately two seconds chosen by drivers in the instrumented vehicle study. If the time it takes a driver to cross an intersection increases by two standard deviations, safety margins diminish substantially, but remain positive. It is likely that drivers on the mainline will detect the driver who is slow to cross, and reduce speed accordingly to avoid a collision.

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, St. Paul, MN, April 2006.
8. L. Alexander, P-M. Cheng, M. Donath, A. Gorjestani, A. Menon, B. Newstrom, and C. Shankwitz, "The Minnesota Mobile Intersection Surveillance System," Proceedings of the 9th International IEEE Conference on Intelligent Transportation Systems, Toronto, Ontario, September, 2006.
9. 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.
10. M.S. Raff, and J.W. Hart, "A volume warrant to urban stop signs," Eno Foundation for Highway Traffic Control, Saugatuck, CT, 1950.
11. W. Brilon, R. Koenig, and R.J. Troutbeck, "Useful estimation procedures for critical gaps," *Transportation Research Part A 33*, pp. 161-186, Pergamon, 1999.

12. N.D. Lerner, R. Huey, H. McGee, and 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.
13. M. Kyte, Z. Tian, Z. Mir, Z. Hameedmansoor, W. Kittelson, M. Vandehey, B. Robinson, W. Brilon, L. Bondzio, N. Wu, and 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.
14. L. Alexander, P. Cheng, M. Donath, A. Gorjestani, A. Menon, B. Newstrom, C. Shankwitz, and N. Ward, "Gap Acceptance Analysis for a Rural Unsignalized Intersection," Proceedings of the 86th Annual Meeting of the TRB, Washington, D.C., 2007.
15. M.A. Pollatschek, A. Polus, and M. Livneh, "A decision model for gap acceptance and capacity at intersections," *Transportation Research Part B* 36, pp. 649-663, Pergamon, 2002.
16. W.K. Kittelson, and M.A. Vandehey, "Delay effects on driver gap acceptance characteristics at two-way stop controlled intersections," *Transportation Research Record* 1320, pp. 154-159, Transportation Research Board, Washington, DC, 1991.
17. S. Tepley, M.I. Abou-Henaidy, and J.D. Hunt, "Gap acceptance behavior: aggregate and logit perspective," *Traffic Engineering and Control* 38, pp. 474-482, 1997.

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