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## Using Event Data Recorders from Real-World Crashes to Investigate the Earliest Detection Opportunity for an Intersection Advanced Driver Assistance System

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### Abstract

There are over 4,500 fatal intersection crashes each year in the United States. Intersection Advanced Driver Assistance Systems (I-ADAS) are emerging active safety systems designed to detect an imminent intersection crash and either provide a warning or perform an automated evasive maneuver. The performance of an I-ADAS will depend on the ability of the onboard sensors to detect an imminent collision early enough for an I-ADAS to respond in a timely manner. One promising method for determining the earliest detection opportunity is through the reconstruction of real-world intersection crashes. After determining the earliest detection opportunity, the required sensor range, orientation, and field of view can then be determined through the simulation of these crashes as if the vehicles had been equipped with an I-ADAS. This study reconstructed 40 Straight Crossing Path (SCP) and Left Turn Across Path Lateral Direction (LTAP/LD) crashes using pre-crash speed data extracted from the event data recorder (EDR) in both vehicles. The EDR contains the actual pre-crash speed of the vehicle prior to the crash, and can be used to determine the kinematics of the vehicle prior to impact. The crashes were then simulated as if either vehicle had been equipped with an I-ADAS sensor (i.e. a side-facing radar located on the front of the vehicle). The ability of the I-ADAS sensor to detect an oncoming vehicle was evaluated at the instant the first vehicle entered the intersection, which was defined as the earliest detection opportunity. For one-half the crashes analyzed, the Time-to-Collision (TTC) at the earliest detection opportunity was less than one-second. The distance between vehicles was less than 50 m at the earliest detection opportunity for nearly every crash. The angle from the vehicle heading to the oncoming vehicle varied by approximately

$\pm 30^\circ$  at the earliest detection opportunity. An intermediate beam radar (90 m,  $\pm 30^\circ$ ) directed at  $43^\circ$  from the vehicle heading was found to be capable of detecting the highest proportion of approaching vehicles. These results have important implications for designers of an I-ADAS who are considering the necessary range, azimuth, and orientation for detecting an approaching vehicle.

### Introduction

Intersection crashes in the United States account for over 4,500 fatal crashes each year [1]. Intersection Advanced Driver Assist Systems (I-ADAS) are emerging, vehicle-based active safety systems that aim to help drivers safely navigate through intersections. An example depiction of I-ADAS can be found in [Figure 1](#). These systems can detect a potential intersection-related crash and provide either a warning to the driver or activate automatic braking and/or steering.

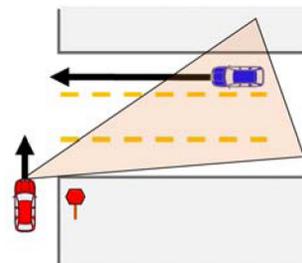


Figure 1. A depiction of an I-ADAS sensor beam located on a red vehicle and directed laterally.

Two of the most frequent intersection crash modes observed in the U.S. are Straight Crossing Path (SCP) and Left Turn Across Path Lateral Direction (LTAP/LD) crashes, which are depicted in Figure 2. Together these scenarios account for one-half (50.4%) of all U.S. intersection crashes [2]. In both crash modes, the vehicles approach the intersection from lateral directions with respect to one another.

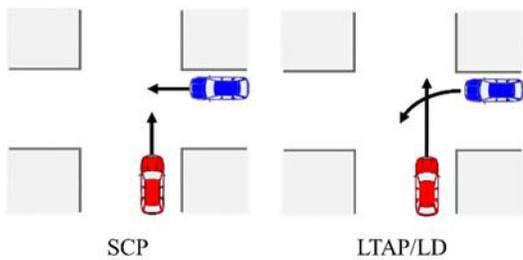


Figure 2. A depiction of SCP and LTAP/LD intersection crash modes.

Onboard vehicle detection sensors are becoming increasingly more common within the U.S. vehicle fleet. Forward collision warning (FCW) systems are emerging systems that use a forward facing radar to detect an imminent forward collision [3]. In addition, some early intersection assistance systems utilize this forward radar for cross traffic object detection (pedestrian, vehicle, animal) [4, 5]. Side-facing sensors are currently being implemented for blind spot detection [6, 7] and rear cross traffic alert systems [7], and may be useful for a future automated lane change system [8, 9]. However, no commercially available vehicles currently utilize a side-facing sensor on the front of the vehicle for vehicle detection. Cross traffic intersection crashes, such as SCP and LTAP/LD, may benefit from this side-facing sensor, because vehicles are approaching one another from lateral directions.

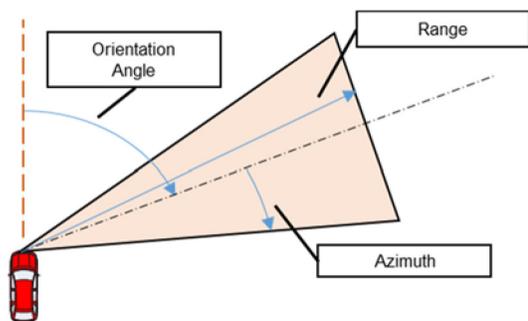


Figure 3. A depiction of sensor orientation, range, and azimuth for detecting an oncoming vehicle.

The performance of an I-ADAS will depend on the ability of the onboard sensors to detect an imminent collision early enough for an I-ADAS to respond in a timely manner. There are several vehicle sensing technologies potentially useful for I-ADAS implementation, including radar, lidar, and cameras. Many commercially available vehicles currently rely on cameras or radar for vehicle detection [4, 5, 7]. More futuristic cars, such as the Google's self-driving car [10] and OEM research vehicles [11], utilize a 360 degrees lidar located on top of the vehicle or lidar sensors located in the bumpers for vehicle detection. However, there are limitations to consider when designing these systems. First, these sensors are limited in the distance, or range, that they can detect an oncoming vehicle. Second, with the exception of the 360 degrees lidar, these sensors have a limited field of view, or azimuth. Additionally, there is an inherent trade-off

between the range and azimuth for which these sensors can detect oncoming vehicles (i.e. longer range sensors have a narrower azimuth). Figure 3 depicts three important sensor specifications, which are expected to play an important role in the detection capabilities of these systems.

Typical driver action and vehicle kinematics will also likely play a part in the performance of I-ADAS, because these factors directly influence the available time for the system to respond. Specifically, these systems must accommodate how drivers currently navigate through intersections prior to real-world crashes. For example, crashes involving at least one vehicle stopped prior to entering the intersection (approximately one-half of all SCP crashes [12]) would yield greater time for an I-ADAS to respond. Our previous work has shown that drivers in intersection crashes typically accelerate faster into intersections than in normal driving [13]. Lastly, four-fifths of non-turning drivers already take some form of evasive action (i.e. steering and braking) during real-world intersection crashes [14]. Proposed I-ADAS systems should seek to improve upon the timing of current driver evasive actions.

Sightline restrictions from an I-ADAS equipped vehicle to the oncoming vehicle will limit the ability of an I-ADAS sensor to detect the approaching vehicle. This study assumes that no sightline obstructions were present after the first vehicle enters the intersection. The time point when the first vehicle enters the intersection is referred to as the earliest detection opportunity. This is of course a best case scenario as sightline obstructions can impede the performance of I-ADAS. This study investigates the requirements of a side-facing sensor given the need to detect the oncoming vehicle at the earliest detection opportunity.

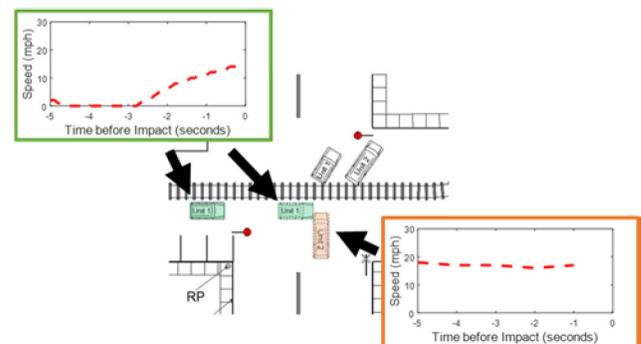


Figure 4. The downloaded EDRs for a SCP intersection crash (NASS/CDS 2013-76-166). The vehicle indicated in green stopped at a stop sign then accelerated into the intersection as indicated by the EDR download extracted from the vehicle. The vehicle indicated in orange did not have a traffic control device, and was travelling at approximately 20 mph for the 5-seconds prior to impact as indicated by the EDR download.

A useful technique for evaluating the potential sensor detection needs of I-ADAS is through reconstructing real-world intersection crashes and then simulating the crashes as if the vehicles had been equipped with an I-ADAS. There are only a few vehicles [4, 5] commercially available that are equipped with these systems, and at the time of this study, none of these vehicles used side-facing sensors. This study simulates real-world crashes as they actually occurred, but includes hypothetical I-ADAS sensors in order to investigate their potential vehicle detection capability in a real-world crash scenario.

One limitation of reconstructing real-world crashes is that there is often uncertainty in the pre-crash driver behavior (e.g. travel speed, evasive braking). One promising method for determining these precrash vehicle kinematics is through the use of Event Data Recorders, or EDRs. These “black boxes” are present in 96% of new U.S. passenger vehicles [15]. In the event of some triggering event (e.g. airbag deployment, high delta-v), EDRs can record pre-crash information, such as vehicle speed, for up to 5-seconds prior to the crash. Example EDR downloads extracted from two vehicles involved in a SCP intersection crash are shown in [Figure 4](#). In this study, reconstructions were accomplished by coupling the pre-crash vehicle speed EDR downloads with the pre-crash path recorded by a scene investigator in a scene diagram.

This study seeks to answer three research questions. First, what were the time-to-collision (TTC) values at the earliest detection opportunity? TTC is the elapsed time from the earliest detection opportunity until impact. TTC at this earliest detection opportunity is important to consider when designing I-ADAS, because sufficient time is required for an I-ADAS to alert the driver. Second, what were the detection distances and angles from the subject vehicle to the approaching vehicle at the earliest detection opportunity? Given range and azimuth limitations in I-ADAS sensor technology, this information provides basic requirements for the design of these systems. Third, how does varying sensor position, orientation, and range/azimuth specifications influence the sensor detection capability of I-ADAS?

## Methods

Our approach was to reconstruct real-world SCP and LTAP/LD crashes between vehicles without I-ADAS, and then simulate the crashes as if the vehicles were equipped with an I-ADAS sensor. Reconstructions were accomplished by coupling the pre-crash vehicle speed EDR downloads with the pre-crash path recorded by a scene investigator in a scene diagram.

## Data Source

This study extracted a series of crashes investigated by the National Highway Traffic Safety Administration (NHTSA) as part of the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) for case years 2004 to 2014. NASS/CDS is comprised of 4,000 to 5,000 detailed crash investigations each year, and contains information about the vehicles, occupants, and environment. In addition, each case includes a national weighting factor, which allows for nationally representative estimates to be generated [16].

Several criteria were required for a crash to be included in this study. First, only crashes that occurred at an intersection were included. Crashes involving driveways, alleys, or interchanges were excluded. Second, only SCP or LTAP/LD crashes, shown in [Figure 2](#), were included. Third, the extracted EDR module had to have either recorded an airbag deployment event or have been triggered by a non-deployment crash with a delta-v of at least 5 mph. In addition,

only crashes where the first event listed in the NASS/CDS database was most severe event were analyzed. These criteria helped ensure that the first impact being described in the database corresponded to the associated EDR pre-crash record. Fourth, the extracted EDR must have recorded pre-crash speed. Fifth, the recorded pre-crash speed must have been sufficient to trace the vehicle path back to the location of intersection entry. Most EDRs record up to 5-seconds of pre-crash data. Occasionally, this 5-seconds was not long enough to trace the vehicle position back to the intersection entry location. Sixth, both vehicles involved in the crash must have had an EDR. Seventh, as has been previously done in the literature [17], cases with a national weighting factor greater than 5,000 crashes were excluded to eliminate skewing of the results.

## Pre-crash Vehicle Kinematics Reconstructions

Crash reconstructions were performed in three parts. First, the crash scene diagram was utilized to perform path reconstructions. Second, intersection boundary lines were drawn to determine when the approaching vehicles entered the intersection. Third, the pre-crash EDR download was used to reconstruct vehicle location and speed throughout the intersection approach and traversal.

## Path Reconstructions

The paths of all vehicles involved in the dataset were reconstructed using measurements taken from the scene diagram. Seven categories were used to describe the movements that a vehicle could have experienced prior to or within the intersection, and the required measurements were unique to the movements observed in the scene diagrams. These categories are depicted in [Figure 5](#). The potential lateral movements included (a) a road curvature prior to the intersection, (b) a road curvature prior to and within the intersection, (c) a lane offset within the intersection that requires the entering vehicle to move laterally, (d) a lane change prior to or within the intersection, (e) an evasive steering maneuver, and (f) a left turn was performed at the intersection.

If no lateral movement was performed prior to the crash, the only metric required to reconstruct the vehicle path was the vehicle heading prior to entering the intersection. The driver was then assumed to have maintained this heading throughout the entire precrash approach.

The measurements required for curved roads depended on whether the road curvature was prior to the intersection or extended through the intersection. If the road was only curved prior to the intersection, two measurements were required, i.e. the vehicle path radius of curvature and the distance from the end of the curved road to the intersection boundary line. For roads with curvature that extended through the intersection, only the vehicle path radius of curvature was measured. In addition to these measurements, the direction of the curvature (i.e. to the left or right) was also indicated.

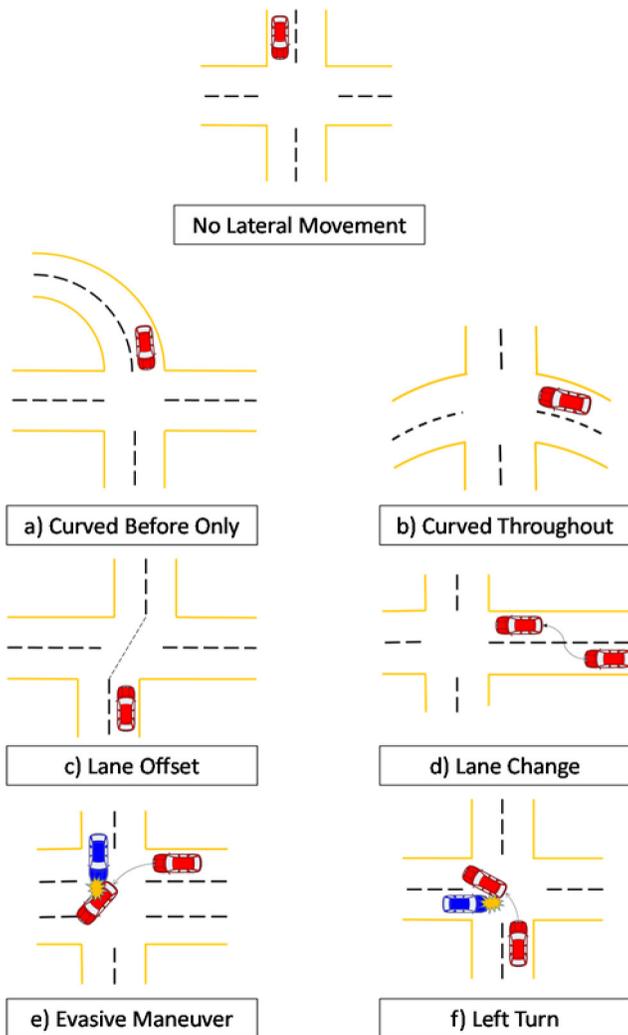


Figure 5. Seven pre-crash movement categories used to reconstruct vehicle paths.

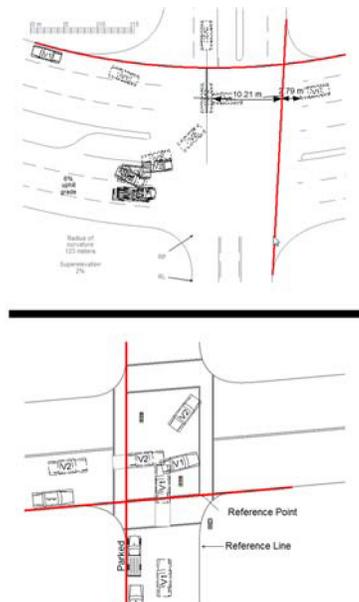


Figure 6. Examples for how intersection boundary lines (red) were drawn. The scene diagram on the top was taken from NMVCCS case 2007-74-62. The scene diagram on the bottom comes from NMVCCS case 2006-03-043.

Vehicle paths with a lane offset or lane misdirection were modeled as taking a straight path from the intersection boundary to the impact location. For an evasive steering maneuver, the vehicle was assumed to have taken a straight path from the start of the evasive maneuver (as indicated on the scene diagram) to the impact location. The distance that each vehicle travelled laterally (with respect to vehicle heading prior to entering the intersection or beginning the evasive maneuver) was measured. For drivers that performed an evasive maneuver, the longitudinal travelling distance (with respect to vehicle heading prior to evasive maneuver) from the evasive starting point to the impact location was measured. In addition, the direction of the lateral movement (i.e. to the left or right) was indicated.

Lane changes were modeled as being an instantaneous change in lateral position. The location of where the lane change was indicated as having started was measured relative to the intersection boundary. The lateral direction of the lane change was also indicated.

Left turns were modeled using an arc of constant radius. This method allowed for the retention of the depicted heading at impact and the heading prior to the initiation of the left turn.

### Determining Intersection Boundary Crossing

Intersection boundary lines were drawn for every scene diagram. The intersection boundary lines signify the location at which the approaching vehicles enter the intersection, and were drawn by extrapolating the road edge through the intersection. Examples of drawing these intersection boundary lines (shown in red) can be found for two cases in [Figure 6](#).

### Time Series Reconstructions

The EDR pre-crash vehicle speed was used to reconstruct the location of the vehicle through time. This was accomplished in three steps.

First, in general, there is some uncertainty in the time stamp associated with a given EDR pre-crash record. EDRs are continuously collecting pre-crash data. In the event of some triggering event, such as an airbag deployment or high delta-v, the EDR stores the pre-crash data to memory. However, the EDR time axis is not the same as the actual time axis with respect to the time of impact due to the asynchronous nature of the EDR recordings. With the exception of Toyota EDRs, most vehicle manufacturers do not record vehicle speed at the point of impact, i.e. the last EDR-recorded vehicle speed was obtained at some point within the sample time prior to impact. For example, GM EDRs always indicate the last precrash speed data point as having been collected at one sample time prior to impact (1 Hz EDR would indicate last data point as occurring 1-second prior to impact). This source of uncertainty is accentuated by the relatively coarse frequency (1 Hz) most EDRs collect data, and is further complicated by the fact that the sampling strategy varies by make, model, and year of the vehicle. This source of error in EDR pre-crash data has been described at length in a previous study [14].

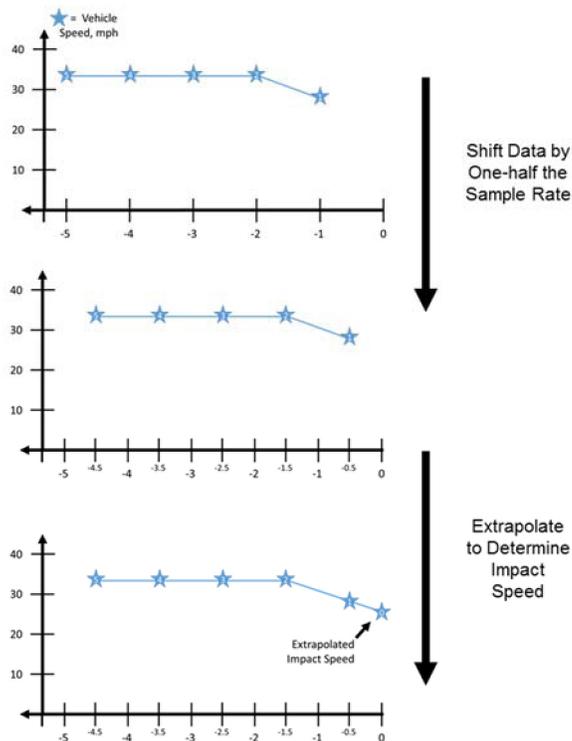


Figure 7. An example case for accounting for uncertainty in sample time step using a 1-Hz EDR. The top-figure shows a typical GM EDR recording of vehicle speed. Time zero represents impact. The last EDR-recorded vehicle speed (labeled as 1) was recorded at some point within 1-second prior to impact. In the middle figure, due to uncertainty in when the last EDR-recorded vehicle speed was recorded, the time series was shifted by one-half the sample time (0.5 s). In the bottom figure, impact speed was determined through linear extrapolation.

To account for this uncertainty, the last EDR-recorded speed was assumed to have been obtained at one-half the sample time prior to the crash. In reality, the final time point could have been collected as early as one-full sample time prior to impact. However, the exact time when the final time point was collected cannot be determined from the EDR. Impact speed was then determined using linear extrapolation. A depiction of this method can be found in Figure 7 for a typical GM EDR.

Second, the modified velocity profile was numerically integrated using trapezoidal integration in order to determine position of the vehicle throughout the pre-crash time series. Third, travel distances were compared to the distance measured from intersection entry to impact. In cases where the recorded travel distance was less than the measured distance, the case was excluded due to insufficient EDR data.

### Detection Distance and Angle Calculations

Detection distance and angle values were generated for each vehicle at the earliest detection opportunity for each simulation. The first vehicle to enter was assumed to be equipped with the I-ADAS sensor. The detection distance was computed as the distance between the vehicles. The detection angle was computed as the angle between the headings of the I-ADAS equipped vehicle to the location of the approaching vehicle.

### Sensor Modeling

Nine variations (3 sensor type  $\times$  3 sensor orientations) of radar sensors were simulated in this study for every crash in order to investigate the sensors ability to detect an oncoming vehicle at the earliest detection opportunity. The vehicles involved in the crash were not equipped with these systems during the crash. Rather, this study considers the kinematics taken by the vehicle during the crash, and determines whether the specified radar would have detected the oncoming vehicle. The three sensors modeled were intended to represent wide, intermediate, and narrow beam radars, where there is an inherent trade-off between sensor distance (distance) and angle (azimuth) that the oncoming vehicle could have been detected. The simulated radar sensor specifications were based on several commercially available, vehicle-based radars, including Delphi Corporation's Electronically Scanning Radar, Smartmicro's UMRR Automotive Radar Sensors, and Eaton's VORAD® VS-400. The sensors were modeled as being pointed in each direction at 0, 45, and 80 degrees relative to the travelling direction. The nine combinations of sensor specifications and configurations are shown in Table 1.

Table 1. Sensor combinations modeled in this study.

Orientation (degrees) Range (m) Azimuth (+/- degrees)		Sensor Orientation (degrees relative to forward direction)		
		0°	45°	80°
Sensor Type	Wide Beam	0° 30 m +/- 45°	45° 30 m +/- 45°	80° 30 m +/- 45°
	Intermediate Beam	0° 90 m +/- 30°	45° 90 m +/- 30°	80° 90 m +/- 30°
	Narrow Beam	0° 150 m +/- 15°	45° 150 m +/- 15°	80° 150 m +/- 15°

### Results and Discussion

A total of 46 crashes were extracted from NASS/CDS, where both vehicles were equipped with an I-ADAS. One crash was excluded due to a NASS case weighting greater than 5,000 crashes. Five additional crashes were excluded due to an insufficient duration of recorded pre-crash speed for reconstructing the path back to intersection entry. The final dataset consisted of 80 EDRs extracted from 40 real-world crashes, i.e. each crash involved two vehicles equipped with an EDR that recorded pre-crash speed.

#### What Were the Time-to-Collision (TTC) Values at the Earliest Detection Opportunity

The first analysis examined TTC values at the earliest detection opportunity. In our study, the earliest detection opportunity is defined as the instant the first vehicle crosses the intersection boundary. Figure 8 shows a cumulative distribution plot of time to collision from intersection entry for (1) all vehicles in the crash and (2) only the first vehicle to enter the intersection. For the first vehicle to enter the intersection, the median elapsed time was 0.99 s, and a total of 25% of drivers had greater than 1.79 seconds to see an impending impact from intersection entry to impact.

I-ADAS needs adequate time to detect an approaching vehicle and deliver a response (e.g. warning to driver, automated evasive action). However, these time intervals are very brief if considering an I-ADAS that alerts the driver of an approaching vehicle at the instant the vehicle enters the intersection. For example, an experimental study performed by Mazzae et al. [18] investigated typical braking reaction time in response to an intersection incursion. This NHTSA sponsored study placed 245 subjects in vehicles and had them drive on a test track with wet or dry pavement. A two-way stop-controlled intersection was setup on the track with the experimental vehicle having no stop sign on their intersection approach. During this study, the driver was distracted by being told to maintain a 200 feet following distance from the leading vehicle. A display on the center dashboard was installed to relay the current following distance to the driver. When the driver was 2.5 s to 3.0 seconds from the intersection, a foam car was towed into the intersection in order to simulate an incursion. The results suggested that driver response to an intersection incursion began within 1.37 s to 1.51 s depending on the road surface conditions and driver gender. Our findings indicate that the majority of drivers would not be able to respond fast enough if a warning was delivered at the time the first driver entered the intersection. However, it should be noted that the driver's reaction time to a warning was not investigated in this study. Additionally, the reaction time values presented in the Mazzae et al. study are for distracted drivers. Although distraction is one of the leading causes of intersection crashes [2], these reaction time values may not be applicable for all real-world intersection crashes.

This is an interesting finding in light of previous work characterizing "typical" evasive actions taken by drivers in real-world crashes. In a previous study [14], the authors found that approximately four-fifths of drivers took some form of evasive action (i.e. steering/braking) prior to an impending intersection crash. This implies that some drivers may have recognized an imminent collision prior to entering the intersection, but did not have adequate time to react and avoid the crash. For an I-ADAS to be effective, the system must help to improve upon the current evasive action response of drivers in intersection crashes.

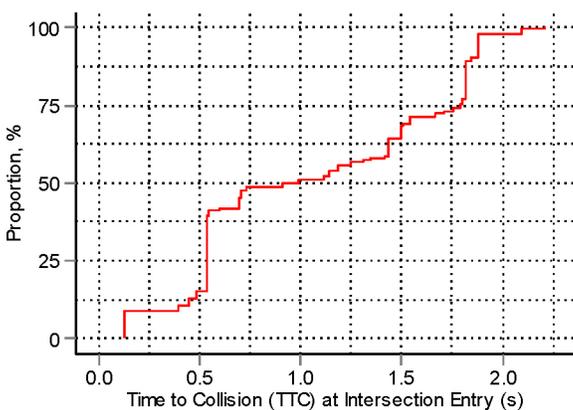


Figure 8. Cumulative Distribution plot of TTC values at the earliest detection opportunity.

### What Were the Distributions of Detection Distances and Angles at the Earliest Detection Opportunity

The second analysis investigated the distribution of detection distance and angle values at the earliest detection opportunity. This information provides I-ADAS designers and evaluators with the basic sensor needs for the design of these systems. All detection distance and angle estimates were taken from the perspective of the first vehicle.

Figure 9 shows the distribution of detection distance values for the first vehicle to enter the intersection. The median detection distance was 14.3 m. A total of 95% of the detection distances values fell below 41.6 m.

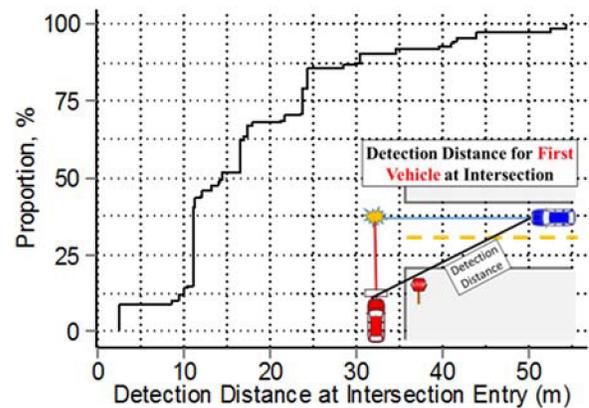


Figure 9. Cumulative Distribution plot of detection distance values for the first vehicle to enter the intersection.

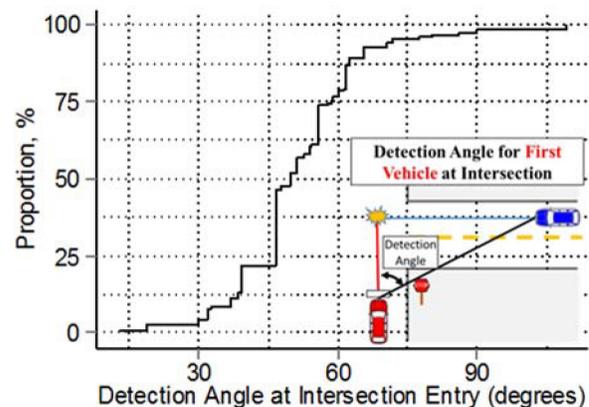


Figure 10. Cumulative Distribution plot of azimuth values for the first vehicle to enter the intersection.

Figure 10 shows the distribution of detection angles at the earliest detection opportunity. The median detection angle was 49.9 degrees. The middle 50% of detection angle values fell between 46.5 degrees and 58.5 degrees. The middle 95% of detection angles fell between 29.6 degrees and 89.9 degrees.

In general, either vehicle could have been equipped with an I-ADAS. This analysis examined only detection angle and distance from the perspective of the first vehicle to enter the intersection. These results suggest that nearly all detection distances fell below 50-m, and nearly all detection angles fell within a 60 degrees window (the middle 95% of azimuth values were between 29.6 and 89.9 degrees).

### ***Which Sensor Specifications and Orientations Could Best Detect an Oncoming Vehicle at Intersection Entry***

The ability of an I-ADAS sensor to detect an oncoming vehicle at the point of intersection entry was investigated for three sets of sensor specifications (wide, intermediate, and narrow beam) and three orientations (0°, 45°, and 80° from the forward direction).

Table 2 shows how vehicle detection varies with sensor orientation and specifications. The results indicate that an intermediate beam oriented at 45° from the heading direction would be most capable of detecting an oncoming vehicle when the first vehicle entered the intersection. The least successful sensor orientation was found to be the forward facing radar. This is an interesting finding when considering the fact that only forward facing intersection assist systems are currently available on the automotive market for LTAP/OD crashes and cross traffic object detection (pedestrian, vehicle, animal) [19, 20]. These results suggest that a side-facing sensor would be most effective for detecting an oncoming vehicle in SCP and LTAP/LD intersection crashes if equipped to the first vehicle to enter the intersection.

The optimal sensor orientation for detecting an approaching vehicle was additionally explored at intersection entry. The results for this analysis is shown in Table 3. This was done for all three sensor types. Our results indicate that an intermediate sensor oriented at 43° will be most effective at detecting an oncoming vehicle. Given these sensor specifications and orientation, the model predicts a large majority of vehicles could be detected at intersection entry (95.3%).

Table 2. Sensor detection at intersection entry for three sets of sensor specifications and orientations. The greyed cell represents the sensor with the greatest number of oncoming vehicles detected.

Unweighted Proportion Detected (%)		Sensor Orientation (degrees relative to forward direction)		
		0°	45°	80°
Weighted Proportion Detected (%)				
Sensor Type	Wide Beam	23%	70%	55%
	(30 m, +/- 45°)	22%	87%	79%
	Intermediate Beam	10%	83%	65%
		(90 m, +/- 30°)	4%	94%
Narrow Beam	3%	53%	23%	
	(150 m, +/- 15°)	1%	73%	9%

Table 3. Optimal sensor orientation for detecting an approaching vehicle at intersection entry.

Optimal Sensor Orientation (degrees)		Sensor Orientation (degrees relative to forward direction)
Weighted Proportion Detected (%)		Optimal Orientation
Sensor Type	Wide Beam	46°
	(30 m, +/- 45°)	87.2%
	Intermediate Beam	43°
(90 m, +/- 30°)		95.3%
Narrow Beam	52°	
	(150 m, +/- 15°)	83.9%

### ***Limitations***

There are several limitations to the findings of this study that should be considered. First, only EDRs with ample pre-crash data were included in this study, i.e. cases were excluded if the EDR did not record vehicle entry into the intersection. This biases this study's results toward crashes with shorter elapsed time from intersection entry to impact and lower detection distance values. Approximately one out of every nine cases was excluded due to this criteria.

Second, potential sight obstructions were not considered in this study. We considered a "best case scenario" that cars, trees, off-road signs, etc. were not impeding the sightline between the vehicles after the first enters the intersection. This assumption is not unreasonable given current roadway design policies set forth by the American Association of State Highway and Transportation Officials (AASHTO) in the Policy on Geometric Designs of Highways and Streets [21]. AASHTO policy defines a decision point (14.5 feet from the intersection boundary) which represents a location when the "vehicle is stopped relatively close to the major road" prior to entering the intersection. At the decision point, the driver must be able to see an oncoming passenger vehicle that is 7.5 seconds from the intersection given that the oncoming vehicle travelling at the roadway design speed. For example, if the design speed of the road is 25 mph (11.2 m/s), the driver of the subject vehicle must be able to see 84 m ( $11.2 \text{ m/s} \times 7.5 \text{ s} = 84 \text{ m}$ ) along the approaching vehicle's path when at the decision point.

Third, this study only considered crashes where the vehicle experienced an airbag deployment or a delta-v greater than 5-mph. As such, these findings are likely biased toward more severe crashes, where the vehicles may have been travelling faster prior to impact.

### ***Conclusions***

This study reconstructed 40 real-world SCP and LTAP/LD intersection crashes and simulated the crashes as if the involved vehicles had been equipped with an I-ADAS. The results suggest that one-half of the crashes occurred less than one second after the first vehicle entered the intersection. Nearly all detection distances at the

earliest detection opportunity were less than 50 meters, and the maximum and minimum detection angle values differed by approximately +/- 30 degrees. Lastly, an intermediate beam radar (90 m, +/- 30°) directed at 43° from the vehicle heading showed the most promise for detecting an approaching vehicle. These results have important implications for designers of an I-ADAS considering the necessary range, azimuth, and orientation for detecting an approaching vehicle.

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