# Earliest Sensor Detection Opportunity for Left Turn Across Path Opposite Direction Crashes

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*Abstract*—Left turn across path crashes with a vehicle traveling from the opposite direction (LTAP/OD) are a common and often fatal intersection crash scenario in the U.S. Intersection advanced driver assistance systems (I-ADAS) are active safety systems emerging in the vehicle fleet that are intended to help drivers safely traverse intersections. The objective of this study was to examine the earliest detection opportunity for I-ADAS in LTAP/OD intersection crashes. A total of 35 crashes were extracted for this study's analysis from the NASS/CDS crash database. EDR precrash records taken from each vehicle were then used to determine vehicle position with respect to time. Two scenarios are considered: one with and one without potential sight occlusions. The results suggest that, even if no sight obstructions are present, an I-ADAS that warns drivers of an impending collision will be greatly limited by perception–reaction time. Accordingly, systems that employ automated emergency braking are expected to be substantially more effective. Required detection distances and azimuth values are presented. The results highlight the need for careful tuning of sensor capabilities and the need to consider side-facing sensors for ensuring vehicle tracking prior to any potential collision conflict.

*Index Terms*—Active safety system, automated vehicles, driver assistance system, intersection, I-ADAS, sensors.

## I. INTRODUCTION

INTERSECTION crashes are among the most frequent and lethal crash scenarios in the U.S. each year [1], [2]. Intersection advanced driver assistant systems (I-ADAS) are active safety systems that aim to help drivers safely navigate intersections. These systems can detect oncoming vehicles using onboard sensors and in the event of an imminent crash can provide a warning for the driver and/or automatically avoid/mitigate the crash by using automatic emergency braking [AEB] [3], [4] or acombination of AEB and autonomous emergency steering [5], [6].

The left turn across path with a vehicle travelling from the opposite direction (LTAP/OD) crash mode accounts for approximately one-third (32%) of all fatal intersection crashes and

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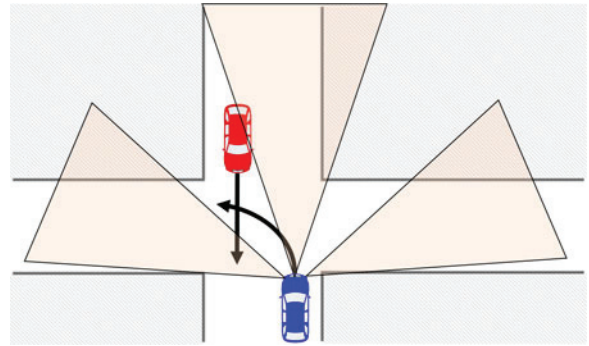
Fig. 1.    A depiction of an LTAP/OD crash scenario. The blue (left turning) vehicle is equipped with hypothetical forward and side facing.

one-fourth (26%) of all intersection crashes. LTAP/OD crashes are second only to straight crossing path (SCP) collisions in terms of frequency and fatal outcomes in intersection crashes [1], [2]. A schematic of a LTAP/OD crash is shown in Fig. 1. These crashes almost always (99% [7]) occur when either (a) both vehicles had a signal or (b) neither vehicle had a signal or stop sign on their approach. These crashes tend to occur when the turning driver either (a) failed to detect the oncoming vehicle or (b) misjudged the gap required to successfully perform the left turn. In fact, distraction (48%) and judgment errors (34%) are overwhelmingly the most commonly cited critical reasons for the crash having occurred [7].

Turning left at intersections with oncoming vehicles is an inherently complex maneuver. Drivers must scan for vehicles, yield the right of way when appropriate, and make a decision on when the intersection can be safely traversed. Older drivers have been found to be particularly vulnerable when performing left turns at intersections [8]–[10]. Frequently cited mechanisms for this susceptibility are that senior drivers tend to misjudge whether they have adequate time to make a left turn across another vehicles path in an intersection [11]–[13] or they failed to see the oncoming vehicle altogether [11]. A number of age-related deficiencies can explain this, including diminished cognitive-motor abilities [14], inadequate visual scanning [13], [15], and slower decision making [16]–[18]. The objective of I-ADAS is to continuously scan and detect oncoming vehicles and enhance the capacity for the crash to be avoided by either providing a warning or automatically evading the crash. Accordingly, this technology may prove useful for these senior drivers, which fail to detect or misjudge the location of a potential collision partner.
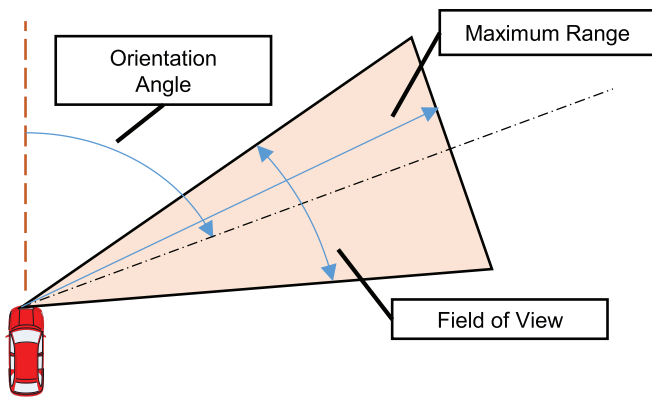
Fig. 2. A depiction of sensor orientation, maximum range, and field of view for detecting oncoming vehicles.

One challenge when designing I-ADAS is selecting sensor specifications that ensure that oncoming vehicles can be consistently detected in a timely manner. Most crash avoidance technologies rely on cameras or radar for vehicle detection [3], [4], [19]–[23], and some future vehicles will use a 360-degree lidar [24], [25]. The sensor specifications, such as detection range, field of view, and orientation, will directly influence performance of I-ADAS. These three parameters are depicted in Fig. 2. Previous studies [26]–[28] have examined the sensor design requirements for I-ADAS in SCP and left turn across path lateral direction (LTAP/LD) crashes. This study looks to expand upon these prior studies by examining the sensor design requirements for I-ADAS in an LTAP/OD crash scenario. The sensor design requirements for I-ADAS are unique in an LTAP/OD type crash when compared to other common intersection crash modes. In an LTAP/OD crash, vehicles are approaching one another from the forward facing direction, as depicted in Fig. 3. Most other intersection crash modes involve vehicles approaching one another from the lateral direction. Additionally, in an LTAP/OD crash, selecting appropriate sensor specifications are complicated by (a) detection requirements depending on which vehicle is equipped (i.e., the left turning or straight crossing) and (b) potential sight obstructions [29]. Both of these elements are explored in the current study.

I-ADAS technologies that utilize vehicle-based sensors to detect oncoming vehicles can be viewed as a near-term crash avoidance solution that is emerging in the vehicle fleet [3], [30], [31]. Two other technologies that have been under development and could prove useful to reduce the frequency of intersection crashes are (a) vehicle-to-infrastructure (V2I) and (b) vehicle-to-vehicle (V2V) communications. V2I relays information from roadway infrastructure to vehicles [32]–[40], while V2V exchanges information between vehicles [32]. These technologies have the capacity to transmit data being collected by infrastructure-based sensors [33], [41] or vehicle-based sensors [42], [43]. The types of messages being passed may include the location of other vehicles or a traffic signal phase. By communicating relative positions and speeds of vehicles, V2I and V2V communication can overcome many limitations caused by sightline obstructions. Although these technologies have shown
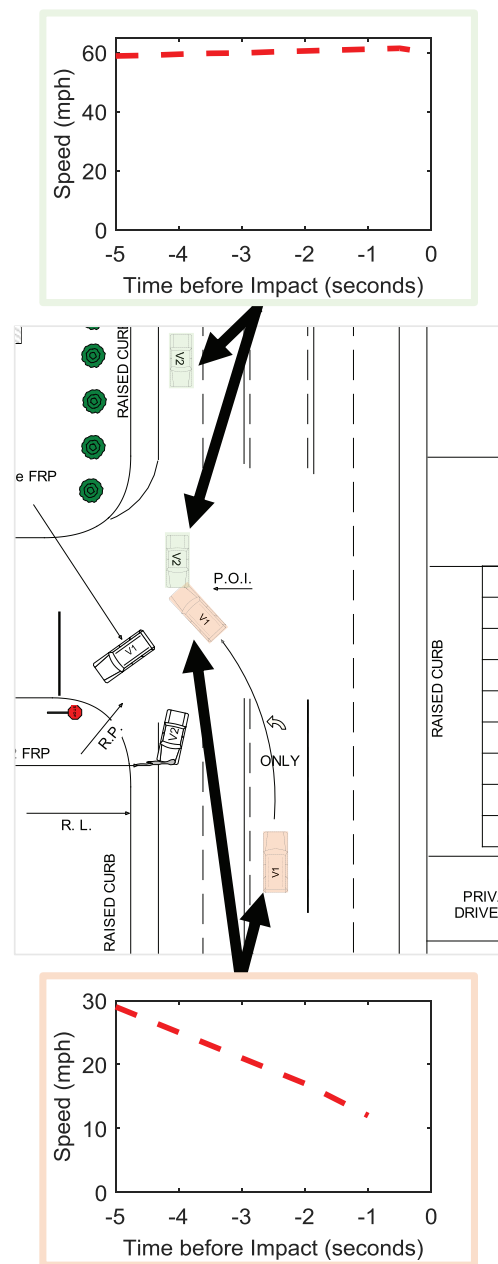


Fig. 3. The scene diagram for NASS/CDS case 2014-4-55. The EDR speed profile records are additionally included for both vehicles. The left turning vehicle (red) slowed down throughout the intersection approach and left turn. The straight crossing vehicle (green) maintained a relatively constant speed approximately 15 mph higher than the posted speed limit (speed limit = 45 mph).

great promise [44], phase-in will be gradual. Deploying V2I at all intersections will take time, and may be prohibitively expensive at some locations [41]. V2V technology requires both vehicles in a potential collision scenario to be equipped. Accordingly, effectiveness throughout the fleet will be a function of V2V penetration.

One method for determining appropriate design specifications is through the reconstruction of real-world crashes [26]–[28]. By tracing back the position of the vehicle throughout time, crashes can then be simulated forward as if either vehicle had

been equipped with I-ADAS. In doing so, design specifications can be determined in the context of the real-world scenarios that these technologies aim to prevent. Given the uncertainty associated with impact speed, crash avoidance action [45], and approach/traversal vehicle kinematics [46]–[48], the most reliable method for tracing back the pre-crash positions of vehicles is with the use of Event Data Recorders (EDRs) which are present in 96% of new U.S. passenger vehicles [49]. As an example, consider the case depicted in Fig. 3, which was included in this study's case set. In the event of a crash, the EDR has the potential to record a number of pre-crash parameters, such as vehicle speed, brake application, yaw rate, and steering wheel angle [50].

The objective of this study was to determine the required sensing specifications to ensure that an I-ADAS could detect an oncoming vehicle at the earliest possible opportunity. This study was specifically interested in an I-ADAS that activates *only* in a crash-imminent scenario. Our underlying assumption was that LTAP/OD non-crashes would continue to be avoided if the vehicles were equipped with an I-ADAS. Our target population, therefore, was crashes. Three research questions were posed. First, how much time is available for crash avoidance from detection of an oncoming vehicle until impact? Second, what detection range and azimuth is required for sensors to detect an oncoming vehicle at the earliest opportunity? Third, how will sensor specifications influence vehicle detection capacity?

## II. Methods

### A. Data Source

This study was based on LTAP/OD crashes collected as a part of the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS). This database is compiled annually by NHTSA with 4,000–5,000 tow away crashes collected within the U.S. vehicle fleet. NASS/CDS additionally assigns case weights, which allow for nationally representative estimates to be made [51].

### B. Case and EDR Module Selection Criteria

Several requirements were established for a case to be included in this study. First, only LTAP/OD collisions between two passenger vehicles were considered. Second, both vehicles must have had extracted EDR records that contained pre-crash vehicle speed. Third, each vehicle must have experienced either (a) an airbag deployment or (b) a non-deployment event with a change in velocity during the impact (delta-v) of over 5-mph. In the event of an airbag deployment, the pre-crash record is locked into the EDR module. However, with non-deployment events, these records can be overwritten by later events. A 5-mph threshold was used, because this delta-v magnitude would be unlikely to be associated with any event other than that described in NASS/CDS. Fourth, as has been done in previous studies [52], cases with a national weighting factor greater than 5,000 crashes were excluded to limit any potential skewing of the results. Previous work by Kononen *et al.* [52] indicated that cases with weights greater than 5,000 are typically extreme

outliers from the rest of the NASS/CDS survey data. Accordingly, any estimates generated are dramatically influenced by these excessively high case weights.

### C. Precrash Reconstructions

The pre-crash positions of each vehicle from the beginning of the EDR pre-crash records up until the point of impact were reconstructed for each vehicle in each crash. Positions were reconstructed using the scene diagram prepared by the crash investigator. Methods employed in a prior study were used to take measurements of the vehicle's path leading up to the crash [26]–[28], [53], [54]. These measurements, among others, included any evasive steering the driver may have performed, any turning on curved roads, any lane changes, and the turning path while traversing the intersection.

The pre-crash time series of each vehicle was then reconstructed using the EDR pre-crash vehicle speed records. As has been detailed extensively in prior studies [26], [27], four main steps were used to trace back the position of the vehicles with respect to time. First, vehicle speeds were shifted with respect to the impact time. EDR data is limited by uncertainty in when the last recorded speed was collected with respect to the moment of impact. With the exception of Toyota EDR modules which record vehicle speed at impact, the last recorded vehicle speed was assumed to have been recorded at one-half the sample time prior to impact. Second, linear extrapolation was used to determine vehicle impact speed. Third, because most EDRs record vehicle speed at 1-Hz, intermediate speeds were determined using linear interpolation. Fourth, the distance travelled by the vehicle with respect to the time was determined using trapezoidal numerical integration.

### D. Sensor Reconstructions

A primary objective of this study was to determine the required range, field-of-view, and orientation for on-board sensors to detect oncoming vehicles. This study modeled I-ADAS as monitoring for a potential collision partner only after the left turning vehicle first left its initial travel lane. At this time point, it was assumed the collision avoidance system would have recognized that a left turn was being attempted.

Other vehicles on the roadway in adjacent lanes could obstruct the sightline to any oncoming vehicles for some proportion of these crashes [29]. Two scenarios were considered for I-ADAS. First, we considered a best-case scenario, where a clear line-of-sight would have been available throughout the entire pre-crash. In this scenario, the earliest detection opportunity would have been the location where the left turning vehicle first departed its initial travel lane (i.e., where I-ADAS would begin monitoring for a collision partner). Second, we considered a worst-case scenario, as shown in Fig. 4, vehicles in adjacent lanes could obstruct the view from the left turning vehicle to the straight crossing vehicle. A queue of stopped vehicles were modeled as being present in the adjacent lane of the straight crossing vehicle. For this scenario, the earliest detection opportunity was modeled as occurring only after the left turning vehicle left its initial travel lane *and* a clear line-of-sight was available. It
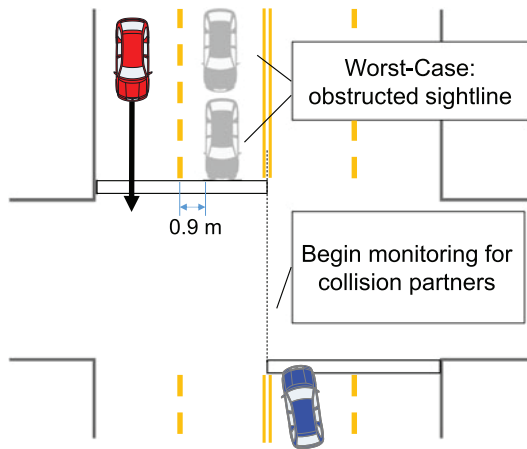
Fig. 4. The opportunities for earliest vehicle detection given sight obstructions. The worst-case earliest detection opportunity represents a scenario where (a) the left turning vehicle has begun initiating a left turn and (b) line-of-sight was obstructed by a queue of vehicles.

TABLE I
SENSOR SPECIFICATIONS THAT WERE EXAMINED IN THE CURRENT STUDY

|  | Wide Beam | Intermediate Beam | Narrow Beam |
|---|---|---|---|
| Range | 30 m | 90 m | 150 m |
| Azimuth | +/−45° | +/−30° | +/−15° |

should be noted that not all LTAP/OD involve a straight crossing driver with adjacent lanes that could obstruction line-of-sight. Accordingly, for crashes such as those occurring on a two-lane roadway, the best-case and worst-case earliest detection opportunities were assumed to occur at the same location (initial travel lane departure by left turning vehicle). Additionally, in the event that the left turning vehicle stopped beyond the earliest detection opportunity (as determined using the EDR records), the instance when the turning vehicle began accelerating was taken as the earliest detection opportunity.

At both of these locations, the required detection range and azimuth with respect to vehicle heading were of interest. For example, a vehicle that was directly straight ahead and 20-m away would have a required detection range of 20-m and a required detection azimuth of 0°. All range and azimuth measurements were taken from the front-center of the "equipped" vehicle. Additionally, several hypothetical sensors were considered, including a wide-short beam, a long-narrow beam, and an intermediate beam. Sensor characteristics that were used in this study are shown in Table I. The specifications used are within the capacity of 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. All simulations were performed with the assumption that the sensor would be oriented in the direction of the vehicle heading.

## III. RESULTS

A total of 44 crashes were considered for this study's analysis. One of the cases was excluded for missing a scene diagram
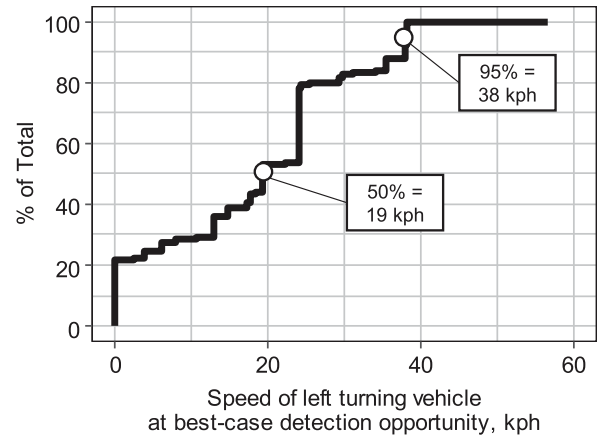


Fig. 5. The vehicle speed of the left turning vehicle at the best-case earliest detection opportunity. Vehicles with speed of 0 kph stopped within the intersection prior to accelerating into the path of the oncoming vehicle.
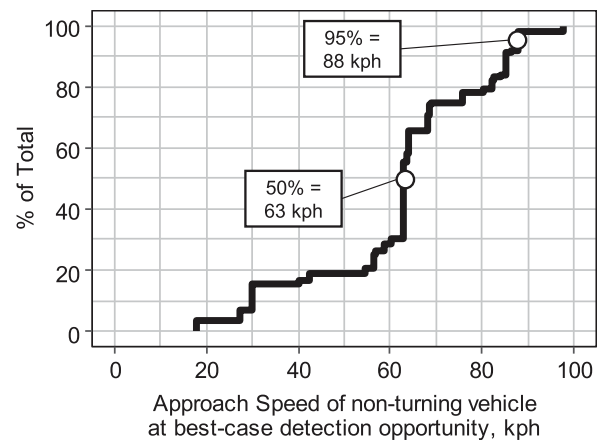


Fig. 6. The vehicle speed of the left turning vehicle at the best-case earliest detection opportunity. Vehicles with speed of 0 kph stopped within the intersection prior to accelerating into the path of the oncoming vehicle.

in the case documentation. An additional 6 cases were excluded because at least one of the vehicles likely experienced wheel slip (maximum deceleration greater than 1-g). Two cases were removed because the EDR pre-crash records were not sufficient for tracing the vehicle path back to the best-case detection opportunity. The final dataset consisted of 35 LTAP/OD crashes.

### A. Dataset Composition: Speeds of Vehicles Leading up to the Crash

As a first analysis, we examined the speeds of vehicles at the time point when the left turning vehicle first crossed out of their turn lane. This point was referred to as the best-case earliest detection opportunity. Fig. 5 shows the distribution of speeds for the left turning vehicle at this time point. A total of 22% of left turning drivers stopped within the intersection (after crossing out of their travelling lane) prior to accelerating through the intersection. The median left turn vehicle speed was 19 kph (12 mph) and 95% of speeds fell below 38 kph (24 mph).
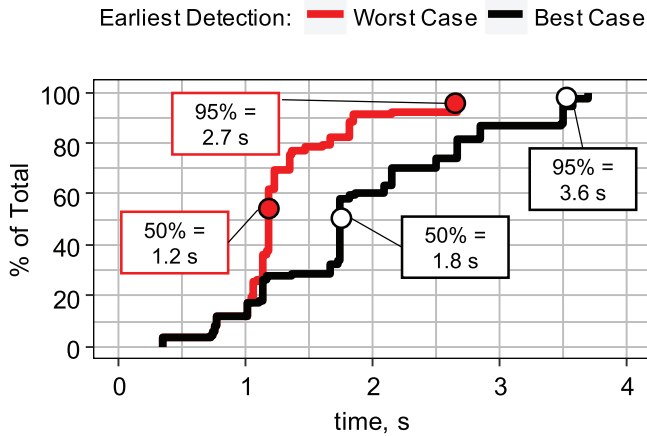
Fig. 7.   Interval between detection and impact under best-case and worst-case scenarios.

Fig. 8.   Detection distance between the front-center of the vehicles at the best-case and worst-case earliest detection opportunities.

Fig. 6 shows the speeds of the non-turning vehicles at the best-case earliest detection opportunity. The median speed for these non-turning drivers was 63 kph (39 mph). The 95th percentile of oncoming vehicles was 88 kph (55 mph).

### B.  How Much Time Is Available for Crash Avoidance From Detection of an Oncoming Vehicle Until Impact?

This study's second analysis examined the time available to avoid a crash after an oncoming vehicle could have been potentially detected. Two time points were considered. First, the best-case scenario was taken, i.e., a clear sightline was available at the instant the left turning vehicle initially departed in its initial travel lane. Second, the worst-case scenario was considered, where a queue of cars would have obscured the view to any oncoming vehicles. The time from crossing these time points until impact can be seen in Fig. 7. For the best-case scenario, 50% of the intervals from detection to impact fell below 1.8 s and 95% of the intervals fell below 3.6 s. For the worst-case scenario, the median time to impact was 1.2 s and 95% of times fell below 2.7 s.

One concern of these active safety systems is whether there would be sufficient time for a driver to respond to a warning. One major limitation of using a warning is perception-reaction time. In a previous simulator study at Monash University Research Center (MUARC) in Australia [55], researchers had participants drive down a stretch of road that consisted of several signalized intersections. While driving, right turning drivers (Australia has left-hand traffic) occasionally turned across the path of the subject vehicle at which point the driver would receive an audible or visual warning and respond by either braking or steering. The median reaction time (interval between warning and evasive action start) for these straight crossing drivers was 1.5 s. In a second simulator study performed by BMW Group Research and technology [56], forty males participated in a driving simulator study that replicated the participant being an occupant in a vehicle being driven by another person. Similar to that of a driving instructor, the participant was instructed to press
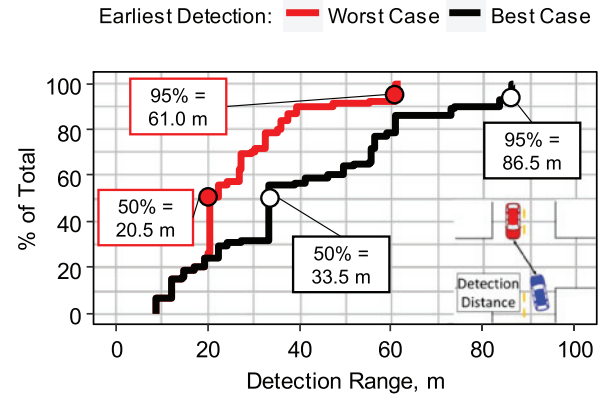
a brake pedal if they judged a situation to be potentially dangerous. These drivers then experienced several scenarios where the subject vehicle instead took a left turn across the path of a straight crossing driver and a visual warning was delivered. The median perception-reaction time (interval between warning and brake pedal press) for these drivers was also 1.5 s. In the current study, because 72% of best-case scenario times exceed 1.5 s, if every driver was to respond after 1.5 s we would expect these drivers to have the potential to *begin* reacting following a warning. This does not imply, however, that these drivers would have been able to successfully avoid the crash. Additionally, a mere 22% of drivers would have had 1.5 s to react if they received a warning at the worst-case earliest detection opportunity.

A second method for I-ADAS crash avoidance would be for the system to automatically evade the crash. The previous few years have seen the emergence of AEB and autonomous steering systems are also being developed and considered by designers [5]. The major advantage of automated crash evasion is a faster reaction than that of a driver. Although this technology is most commonly installed in frontal crash avoidance systems [23], Volvo released an updated version of "City Safety" in 2014 [4], [30], which is a combination of crash avoidance functions that aim to prevent a number of crash modes commonly occurring in cities, including LTAP/OD intersection crashes. The system specifically employs AEB if the equipped vehicle begins to turn left across the path of an opponent.

### C.  What Detection Range and Azimuth Is Required for Sensors to Detect an Oncoming Vehicle at the Earliest Opportunity?

This study's second analysis examined the required detection range and azimuth for detecting the opposing vehicle. As in the prior analysis, both the best-case and worst-case scenarios were considered. Fig. 8 shows the distance between the vehicles given the best and worst cases. The median detection range for the worst-case detection scenario was 20.5 m and 95% of distances fell below 61.0 m. In the best-case scenario, the median range was 33.5 m and 95% of distances fell below 86.5 m. This result suggests that in the absence of potential sight occlusions
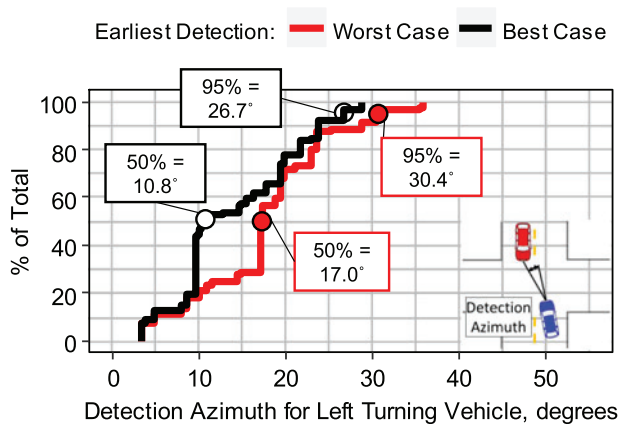
Fig. 9. Detection azimuth between the front-center of the vehicles for the left turning vehicle at the best-case and worst-case earliest detection opportunities.
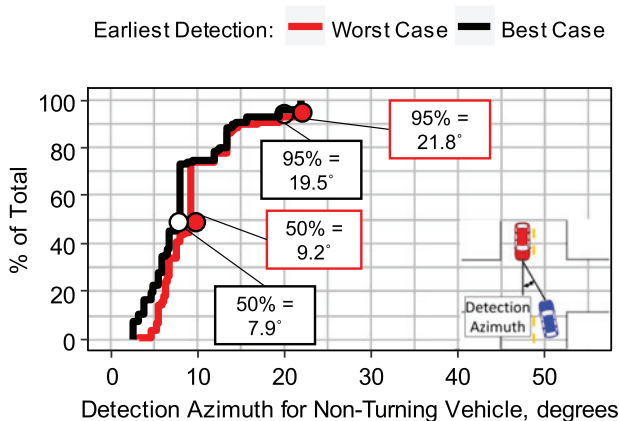


Fig. 10. Detection azimuth between the front-center of the vehicles for the straight crossing vehicle at best-case and worst-case earliest detection opportunities.

I-ADAS sensors with a maximum range capacity of 90 m would have the capacity to detect all oncoming vehicles in the dataset. Although sight occlusions are expected to be a limiting factor for I-ADAS, it is important that these systems have adequate sensing capacity for the ideal scenario (i.e., no sight occlusions). Failing to design for these more extreme scenarios could lead to failed crash avoidance in an otherwise avoidable scenario.

Fig. 9 shows detection angle values for the left turning vehicles at the best- and worst-case possible detection opportunities. At the best-case earliest time point, the left turning vehicle had a median required detection azimuth of 10.8° and 95% of azimuth values fell below 26.7°. As the vehicle continues its left turn, we would expect the azimuth values to grow. Accordingly, at the worst-case time point, the median required detection azimuth was 17.0° and 95% of azimuth values fell below 30.4°.

Fig. 10 shows required detection angle values for the straight crossing driver. At the best-case earliest detection time point, the median azimuth was 7.9° and 95% of values fell below 19.5°. Similarly at the worst-case earliest detection time point, the median azimuth was 9.2° and 95% of values fell below 21.8°. Two competing factors that dictate azimuth for the straight cross-
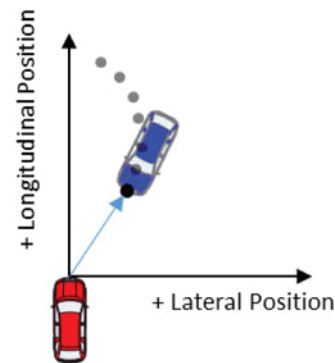


Fig. 11. Convention used to describe relative location of oncoming vehicle (blue vehicle) with respect to the equipped vehicle (red vehicle).

ing driver are (1) the proximity of the left turning vehicle and (2) the lateral position of the left turning vehicle. If the left turning vehicle never turned across the path of the straight crossing driver, the azimuth value would inherently become larger due to a narrowing of the longitudinal distance between the vehicles. Because these are all LTAP/OD crashes, the left turning driver is moving laterally into the path of the straight crossing driver, which is working to decrease the detection azimuth of the non-turning vehicle. These two competing mechanisms led to only slightly higher azimuth values at the worst-case earliest detection time point.

*1) How will sensor specifications influence vehicle detection capacity?:* The next objective was to determine the capacity for an onboard sensor to detect an oncoming vehicle. It is important, of course, to consider the perspective of both vehicles, because either vehicle could in theory take avoidance action. The convention shown in Fig. 11 was used to trace the position of the oncoming vehicle from the perspective of the equipped vehicle. The straight ahead position was taken to be the longitudinal direction. The origin was taken as the front-center of the equipped vehicle. The position of the oncoming vehicle with respect to the wide, intermediate, and narrow sensors orientated in the longitudinal direction was considered.

The perspective of the left turning driver was first considered. The position of the oncoming straight crossing vehicle from the best-case detection opportunity until impact is shown in Fig. 12. The specifications of three sensor beams oriented in the direction of the vehicle heading are also shown. A total of 83% of trajectories stayed within the intermediate beam from the best-case detection opportunity until the vehicles were 5-m from impact. Conversely, only 32% and 13% of the trajectories stayed within the wide and narrow beams, respectively. A sensor with at least a sensor azimuth 62 degrees was estimated to be required to detect all oncoming vehicles until 5-m from impact.

An "arc" was observed from the perspective of some of the left turning drivers. This arc is caused by (a) the changing heading of the left turning and (b) the increasing proximity of the straight crossing vehicle. Because of this arcing, the maximum required detection azimuth occurs at some point in the middle of the left turn. Accounting for the time-dependent relation of
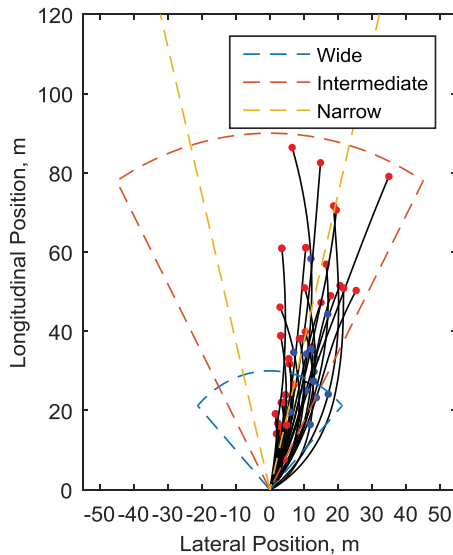
Fig. 12. The position of the straight crossing vehicle (oncoming) from the perspective of the left turning vehicle (equipped). The red dot indicates the best-case detection opportunity, while the blue dot represents the worst-case detection opportunity. The trace terminates at the point of impact. Three sensor beams are considered with the assumption that the sensor was oriented in the direction of the vehicle heading.
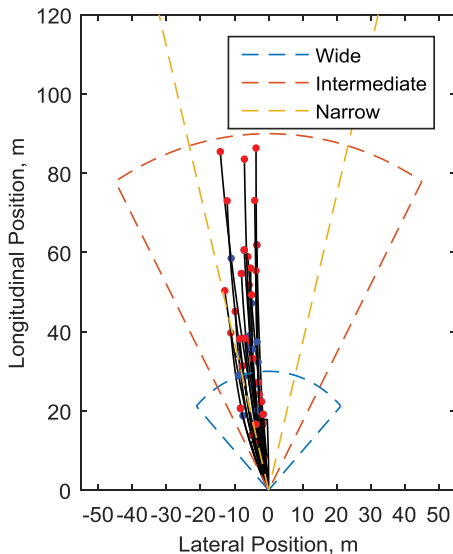


Fig. 13. The position of the left turning vehicle (oncoming) from the perspective of the straight crossing vehicle (equipped). The red dot indicates the best-case detection opportunity, while the blue dot represents the worst-case detection opportunity. The trace terminates at the point of impact. Three sensor beams are considered with the assumption that the sensor was oriented in the direction of the vehicle heading.

detection distance and azimuth is important for ensuring continuous tracking of the oncoming vehicle. In practice, an I-ADAS would constantly be reassessing the need for crash avoidance action. Accordingly, any gap in vehicle tracking could diminish system performance.

The perspective of the straight crossing vehicle was then considered in Fig. 13. The oncoming vehicle was within the

intermediate beam from the best-case time point to 5-m from impact for all crashes. For the narrow beam 83% of oncoming vehicles remained within the beam. The wide beam was less effective as only 31% of vehicles were within the sensor beam throughout this time period.

There are several important findings from this analysis. First, if a forward facing sensor was used, the intermediate beam specifications seem most appropriate for detecting oncoming vehicle. These sensors should, of course, be tuned to accommodate vehicle sensing throughout the encroachment. Second, only a forward facing sensor is considered in this analysis. Currently some of the I-ADAS technology used by vehicles on the market [3], [4] utilize a forward facing radar. I-ADAS designers should consider incorporating side-facing sensors to ensure continuous vehicle detection.

It is important to note that these results were generated exclusively from scenarios that resulted in a crash. The range and azimuth specifications described should be interpreted accordingly. The I-ADAS technology described throughout this paper only takes action (warning or automated crash avoidance) in crash-imminent scenarios. As this vehicle-based technology begins to take over other driving functions, such as performing the left turn through the intersection without driver intervention, the system may need to be able to detect vehicles additionally within the context of "normal" driving, i.e., non-crashes.

## IV. LIMITATIONS

There are a number of limitations to note in the current study. First, path reconstructions were made based on the depiction of pre-crash vehicle locations in the scene diagram prepared by the crash investigator. Some geometrical assumptions were made in order to interpolate vehicle position between these depicted positions. Second, EDR data is limited in recording duration, resolution, and sampling rate. Third, other roadway traffic which could limit sensor capacity was considered for only two discrete locations (best-case and worst-case). In a real-world scenario, we would expect earliest sensor detection to occur at some point between these two locations. Third, for an EDR record to be included in this study, the vehicle must have experienced an airbag deployment or a delta-v greater than 5-mph. Additionally, one of the vehicles had to have been towed from the scene to have been included in NASS/CDS. This dataset has some bias toward more severe intersection crashes, which should be considered when interpreting results or trying to translate these results to lower-speed collisions. Lastly, the results from this study were generated from a relatively small dataset. As more data becomes available, estimates will become more representative of the entire crash population and factors influencing the results can be explored.

## V. CONCLUSION

This study reconstructed 35 real-world LTAP/OD crashes that occurred in the U.S. vehicle fleet. The results suggest that sight occlusions due to other vehicles on the roadway will substantially limit the available time from detection to avoidance action. The time interval from detection to impact is, in general, well

below typical perception-reaction times observed for drivers in previous simulator studies. Accordingly, this finding indicates that I-ADAS has the potential to be limited if utilizing a warning for the driver rather than taking automated evasive action, such as with AEB. Required detection specifications, specifically the required detection distance and azimuth, are highlighted in the results. For left turning vehicles, maximum required detection azimuth tends to occur near the midpoint of the left turn. An intermediate sensor beam (90 m, $+/-30°$) was found to perform superior to both a wide or narrow beam sensor. The results highlight the need for careful tuning of sensor capabilities and the need to consider side-facing sensors for ensuring vehicle tracking prior to any conflict.

## ACKNOWLEDGMENT

## REFERENCES

[1] *Fatality Analysis Reporting System (FARS): Analytical User's Manual 1975-2015*, NHTSA, U.S. Dept. Transp., Washington, DC, USA, 2016.

[2] *National Automotive Sampling System (NASS) General Estimates System (GES): Analytical User's Manual 1988-2015*, NHTSA, U.S. Dept. Transp., Washington, DC, USA, 2016.

[3] *2016 S-Class Operator's Manual*, Mercedes-Benz USA, Atlanta, GA, USA, 2015.

[4] *2016 Volvo XC90 Owner's Manual*, Volvo Car Corp., Gothenburg, Sweden, 2015.

[5] *Nissan Announces "Autonomous Emergency Steering System*, Nissan Motor Corp., Yokohama, Japan, 2012.

[6] *Toyota Develops New Pedestrian Safety Technology*, Toyota Motor Corporation, Toyota, Japan, 2013.

[7] E. Bellis and J. Page, *National Motor Vehicle Crash Causation Survey SAS Analytical User's Manual*. Washington, DC, USA: Nat. Highway Traffic Safety Admin., 2008.

[8] R. Aizenberg and D. M. McKenzie, *Teen and Senior Drivers*. Sacramento, CA, USA: California Dept. Motor Veh., Res. Develop. Sec., 1997.

[9] K. J. Sifrit, J. Stutts, L. Staplin, and C. Martell, "Intersection crashes among drivers in their 60s, 70s and 80s," in *Proc. Human Factors Ergonom. Soc. Annu. Meeting*, 2010, pp. 2057–2061.

[10] D. W. Reinfurt, J. Stewart, J. C. Stutts, and E. A. Rodgman, "Investigations of crashes and casualties associated with older drivers," Project G. 8., Univ. North Carolina Highway Safety Res. Center, Chapel Hill, NC, USA, 2000.

[11] K. A. Braitman, B. B. Kirley, S. Ferguson, and N. K. Chaudhary, "Factors leading to older drivers' intersection crashes," *Traffic Injury Prevention*, vol. 8, pp. 267–274, 2007.

[12] S. Chandraratna and N. Stamatiadis, "Problem driving maneuvers of elderly drivers," *Transp. Res. Rec.: J. Transp. Res. Board*, vol. 1843, pp. 89–95, 2003.

[13] J. Oxley, B. Fildes, B. Corben, and J. Langford, "Intersection design for older drivers," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 9, pp. 335–346, 2006.

[14] G. E. Stelmach and A. Nahom, "Cognitive-motor abilities of the elderly driver," *Human Factors: J. Human Factors Ergonom. Soc.*, vol. 34, pp. 53–65, 1992.

[15] S. Bao and L. N. Boyle, "Age-related differences in visual scanning at median-divided highway intersections in rural areas," *Accident Anal. Prevention*, vol. 41, pp. 146–152, 2009.

[16] M. K. Janke, "Age related disabilities that may impair driving and their assessment," California Dept. Motor Vehicles Res. Develop. Section, Rep. no. RSS-94-156, 1994. [Online]. Available: https://www.dmv.ca.gov/portal/wcm/connect/3fbabce2-511b-4ec5-9185-d98f566d56f1/S6-156.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=3fbabce2-511b-4ec5-9185-d98f566d56f1

[17] S. M. Chown, "Age and the rigidities," *J. Gerontol.*, vol. 16, pp. 353–362, 1961.

[18] J. E. Birren, "Age changes in speed of behavior: Its central nature and physiological correlates," *Behav., Aging Nervous Syst.*, vol. 7, pp. 191–216, 1965.

[19] *Lexus 2016 NX300H Owner's Manual*, Toyota Motor Corp., Aichi Prefecture, Japan, 2016.

[20] R. Schubert, K. Schulze, and G. Wanielik, "Situation assessment for automatic lane-change maneuvers," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 607–616, Sep. 2010.

[21] A. G. Pakett, "Smart blind spot sensor," U.S. Patent 5 325 096A, Jun. 28, 1994.

[22] C. Hatipoglu, Ü. Özgüner, and K. Redmill, "Automated lane change controller design," *IEEE Trans. Intell. Transp. Syst.*, vol. 4, no. 1, pp. 13–22, Mar. 2003.

[23] K. D. Kusano and H. C. Gabler, "Comparison of expected crash and injury reduction from production forward collision and lane departure warning systems," *Traffic Injury Prevention*, vol. 16, pp. S109–S114, 2015.

[24] E. Guizzo, "How Google's self-driving car works," *IEEE Spectrum Online*, Oct. 18, 2011.

[25] *Toyota Brings Advanced Automated Vehicle Technology to U.S. Roads*, Toyota Motor Corp., Ann Arbor, MI, USA, 2014.

[26] J. M. Scanlon, K. Page, R. Sherony, and H. C. Gabler, "Using event data recorders from real-world crashes to investigate the earliest detection opportunity for an intersection advanced driver assistance system," SAE Tech. Paper 2016-01-1457, 2016.

[27] J. M. Scanlon, R. Sherony, and H. C. Gabler, "Predicting crash-relevant violations at stop sign-controlled intersections for the development of an intersection driver assistance system," *Traffic Injury Prevention*, vol. 17, pp. 59–65, 2016.

[28] J. M. Scanlon, R. Sherony, and H. C. Gabler, "Preliminary potential crash prevention estimates for an intersection advanced driver assistance system in straight crossing path crashes," in *Proc. IEEE Intell. Vehicles Symp.*, Gothenburg, Sweden, 2016, pp. 1135–1140.

[29] J. D. Chovan, L. Tijerina, J. Everson, J. Pierowicz, and D. Hendricks, "Examination of intersection, left turn across path crashes and potential IVHS countermeasures," Nat. Highway Traffic Safety Admin., Cambridge, MA, USA, Rep. DOT HS 808 154, 1994.

[30] *City Safety by Volvo Cars—Outstanding Crash Prevention that is Standard in the All-New XC90*, Volvo Car Corp., Gothenburg, Sweden, 2014.

[31] *2016 Audi Q7 Owner's Manual*, Audi AG, Ingolstadt, Germany, 2015.

[32] T. Samad and A. Annaswamy, "The impact of control technology: Overview, success stories, and research challenges," 2011. [Online]. Available: www.ieeecss.org

[33] P. Papadimitratos, A. La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 84–95, Nov. 2009.

[34] *First Toyota Cars to Include V2V and V2I Communication by the End of 2015*, IEEE Connected Vehicles Initiative, 2015.

[35] M. Shulman and R. Deering, "Vehicle safety communications in the United States," in *Proc. Conf. Exp. Safety Veh.*, 2007, Paper no. 07–0010.

[36] L. Wang, "On development of intellidrive-based red light running collision avoidance system," California PATH Program, Univ. California, Berkley, Richmond, CA, USA, 2009.

[37] S. Itagaki, Y. Noda, and T. Tanaka, "Outline of safety support systems for intersections and NEC's activity," *NEC Tech. J.*, vol. 3, pp. 11–15, 2008.

[38] I. Zohdy and H. Rakha, "Framework for intersection decision support in adverse weather conditions: Use of case-based reasoning algorithm," *Transp. Res. Rec.: J. Transp. Res. Board*, vol. 2324, pp. 20–28, 2012.

[39] L. Le, A. Festag, R. Baldessari, and W. Zhang, "Vehicular wireless short-range communication for improving intersection safety," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 104–110, Nov. 2009.

[40] C. Robinson and L. Delgrossi, "Integrating in-vehicle safety with dedicated short range communications for intersection collision avoidance," SAE Tech. Paper 0148-7191, 2010.

[41] Y. Cho and J. Rice, "Estimating velocity fields on a freeway from low-resolution videos," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 463–469, Dec. 2006.

[42] X. Li, W. Shu, M. Li, H.-Y. Huang, P.-E. Luo, and M.-Y. Wu, "Performance evaluation of vehicle-based mobile sensor networks for traffic monitoring," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1647–1653, May 2009.

[43] K. C. Fuerstenberg, K. C. Dietmayer, and V. Willhoeft, "Pedestrian recognition in urban traffic using a vehicle based multilayer laser scanner," in *Proc. IEEE Intell. Veh. Symp.*, Versailles, France, 2002, pp. 31–35.

[44] J. A. Misener *et al.*, *Cooperative Intersection Collision Avoidance System (CICAS): Signalized Left Turn Assist and Traffic Signal Adaptation.* Berkeley, CA, USA: Univ. California, Berkeley, 2010.

[45] J. M. Scanlon, K. D. Kusano, and H. C. Gabler, "Analysis of driver evasive maneuvering prior to intersection crashes using event data recorders," *Traffic Injury Prevention*, vol. 16, pp. S182–S189, 2015.

[46] A. M. Noble, K. D. Kusano, J. M. Scanlon, Z. Doerzaph, and H. C. Gabler, "Driver approach and traversal trajectories for signalized intersections using naturalistic data," in *Proc. 95th Annu. Meet. Transp. Res. Board*, Washington, DC, USA, 2016, Paper no. 16–1490.

[47] J. M. Scanlon, K. D. Kusano, and H. C. Gabler, "A preliminary model of driver acceleration behavior prior to real-world straight crossing path intersection crashes using EDRs," in *Proc. IEEE 18th Int. Conf. Intell. Transp. Syst.*, Canary Islands, Spain, 2015, pp. 938–943.

[48] J. M. Scanlon, R. Sherony, and H. C. Gabler, "Models of driver acceleration behavior prior to real-world intersection crashes," *IEEE Trans. Intell. Transp. Syst.*, to be published, doi: 10.1109/TITS.2017.2699079.

[49] *U.S. DOT Proposes Broader Use of Event Data Recorders to Help Improve Vehicle Safety*, Nat. Highway Traffic Safety Admin., Washington, DC, USA, 2012.

[50] H. C. Gabler, J. A. Hinch, and J. Steiner, *Event Data Recorders. A Decade of Innovation*. Warrendale, PA, USA: Soc. Autom. Eng., 2008.

[51] *National Automotive Sampling System—Crashworthiness Data System: 2015 Analytical User's Manual*, NHTSA, U.S. Dept. Transp., Washington, DC, USA, 2016.

[52] D. W. Kononen, C. A. Flannagan, and S. C. Wang, "Identification and validation of a logistic regression model for predicting serious injuries associated with motor vehicle crashes," *Accident Anal. Prevention*, vol. 43, pp. 112–122, 2011.

[53] J. M. Scanlon, K. D. Kusano, R. Sherony, and H. C. Gabler, "Potential of intersection driver assistance systems to mitigate straight crossing path crashes using U.S. nationally representative crash data," in *Proc. IEEE Intell. Veh. (IV) Symp.*, Seoul, South Korea, 2015, pp. 1207–1212.

[54] J. M. Scanlon, R. Sherony, and H. C. Gabler, "Injury mitigation estimates for an intersection driver assistance system in straight crossing path crashes in the US," *Traffic Injury Prevention*, vol. 18, pp. S9–S17, 2017.

[55] H. Chen, L. Cao, and D. B. Logan, "Investigation into the effect of an intersection crash warning system on driving performance in a simulator," *Traffic Injury Prevention*, vol. 12, pp. 529–537, 2011.

[56] S. Thoma, T. Lindberg, and G. Klinker, "Evaluation of a generic warning for multiple intersection assistance systems," *Human Factors, Security Safety*, Maastricht, The Netherlands: Shaker, pp. 173–188, 2009.

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