U.S. Department of Transportation
National Highway Traffic Safety Administration

NHTSA

DOT HS 813 082B

March 2022

Event Data Recorder Duration Study

Appendix to a Report to Congress

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Suggested APA Format Citation:

Chen, R. J., Tatem, W. M., & Gabler, H. C. (2022, March). *Event data recorder duration study* (Appendix to a Report to Congress. Report No. DOT HS 813 082B). National Highway Traffic Safety Administration.

Note: This report is an appendix to a Report to Congress, which has the following citation:

National Highway Traffic Safety Administration. (2022, March). *Results of event data recorders pre-crash duration study: A report to Congress* (Report No. DOT HS 813 082A).

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 813 082B		

4. Title and Subtitle	5. Report Date
Event Data Recorder Duration Study	March 2022
	6. Performing Organization Code
7. Authors Rong Jackey Chen, Whitney M. Tatem, and H. Clay Gabler, Virginia Tech Department of Biomedical Engineering and Mechanics College of Engineering	8. Performing Organization Report No.
9. Performing Organization Name and Address Virginia Tech Department of Biomedical Engineering and Mechanics College of Engineering,	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE Washington, DC 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

This report is an appendix to a Report to Congress, *Results of Event Data Recorders Pre-Crash Duration Study: A Report to Congress*, Report No. DOT HS 813 082A.

16. Abstract

Widespread deployment of event data recorders offers opportunity to determine crash causation and better understand driver pre-crash behavior. New EDRs yield comprehensive snapshots of the vehicle kinematics and driver inputs prior to a crash including vehicle speed, yaw rate, acceleration, accelerator position, brake application, and steering inputs. However, one limitation is that most EDRs only record up to 5 seconds of pre-crash data, insufficient to determine crash or pre-crash actions in some cases. Extending recording duration would let EDRs more fully capture time history and driver car-following behavior prior to rear-end crashes. The goal of this project is to determine the EDR recording duration needed to investigate crash causation. In the first phase, the project examined three crash modes, rear crashes, intersection crashes, and road departures, and the time needed to capture driver errors. The second phase used data from the 100-Car Naturalistic Driving Study and the Second Strategic Highway Research Program NDS to understand the complete duration of driver actions in car following, intersection traversal, and lane departure. The EDR analysis cannot provide insight into what duration beyond 5 seconds of pre-crash data is needed to capture crash causation.

17. Key Words	18. Distribution Statement
event data recorder, EDR, naturalistic driving study, crash causation	Document is available to the public from the DOT, BTS, National Transportation Library, Repository & Open Science Access Portal, rosap.ntl.bts.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	83	

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

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1 Introduction

Widespread deployment of event data recorders (EDRs) offers a unique opportunity to use EDR data to determine crash causation and better understand driver pre-crash behavior. The latest generation of EDRs can provide a comprehensive snapshot of the vehicle kinematics and driver inputs in the seconds prior to a crash. Pre-crash EDR data elements may include vehicle speed, yaw rate, acceleration, accelerator position, brake application, and steering inputs.

However, one limitation of current EDRs is that most of these devices only record up to 5 seconds of pre-crash data. In many cases, this duration may not be sufficient to determine the factors that led to the crash or the pre-crash actions taken by the driver to avoid the collision. For example, driver time-to-collision in car-following events may exceed 5 seconds depending on vehicle speed and driver preference Chen et al., 2015a; Kusano et al.,2014b). Extending the recording duration would enable EDRs to more fully capture the time history and facilitate efforts to characterize and understand driver car-following behavior prior to rear-end crashes. In the longer term, we anticipate that a better understanding of driver pre-crash behavior may assist in the evaluation of emerging active safety systems (e.g., lane departure warning, lane keeping assist, forward collision avoidance, and intersection movement assistance systems) (Gabler et al., 2009; Kusano, et al., 2013a, 2013b; Kusano & Gabler, 2012; Scanlon, Kusano & Gabler, 2015a, 2015b; Scanlon, Page, Sherony, & Gabler, 2016a; Scanlon, Sherony, & Gabler, 2016b). .

The goal of this project is to determine the EDR recording duration needed to investigate crash causation.

2 Approach

The research project was conducted in two phases. In the first phase, the project has examined the frequency with which EDRs failed to capture driver pre-crash actions. Required EDR recording duration was expected to vary by crash mode. To meet this need, the analysis was conducted by three crash modes, i.e., rear crashes, intersection crashes, and road departures. For each of these crash modes, including intersection crashes, rear crashes, and road departures, we determined the duration of time needed to capture driver errors. When appropriate data were available, we examined the required recording duration of both drivers involved in a crash. The EDR records of both drivers are important to understand the crash as the actions of both drivers affect the risk of crash occurrence as well as the outcome. Specifically, the project examined whether the EDR was capable of capturing all of the driver inputs to the vehicle, i.e., braking, steering, or acceleration immediately preceding a crash.

In the second phase of the project, we analyzed the data from two naturalistic driving studies (NDSs), the 100-Car NDS and the Second Strategic Highway Research Program (SHRP-2) NDS, to understand the complete duration of drivers' actions in car following, intersection traversal, and lane departure. The EDR dataset analysis conducted in the first phase will provide an estimate of the frequency with which EDRs fail to record a sufficient duration of pre-crash data. However, the EDR analysis cannot provide insight into what duration beyond 5 seconds of pre-crash data is needed to capture crash causation. The emphasis in the second phase of the project will be on driver actions in normal driving.

3 Phase 1 – Evaluation of Crash Modes That Would Benefit From More Than 5 Seconds of Pre-Crash Recording Time

The first phase of the project sought to evaluate the capability of current EDR recording duration to capture the initiation of driver pre-crash maneuver during rear-end, road departure and intersection crashes. Driver inputs to the vehicle immediately preceding a crash may have either been driver errors, e.g., a rolling stop at a stop sign, or actions that the driver undertook in an attempt to avoid a crash, e.g., emergency braking or swerving. In both cases, a complete record of braking, steering, and accelerator inputs (or lack thereof) immediately preceding a crash are a critical component of reconstructing crash causation.

3.1 Methodology

3.1.1 Data Sources

3.1.1.1 NASS/CDS

In this phase of the project, each EDR record was first matched with the corresponding National Automotive Sampling System Crashworthiness Data System (NASS/CDS) case. Combining NASS/CDS data with the EDR data provided access to NASS/CDS case information that was not recorded by the EDR but was needed for the analysis, including scene diagrams, scene photos, data elements to identify crash mode, and contributing factors (e.g., driver impairment and investigator-coded crash avoidance actions). Each year NASS/CDS conducts in-depth investigation of approximately 5,000 cases, selected from police reported crashes at 24 sites across the United States. Due to the limited number of investigations performed each year, weighting factors are assigned to each NASS/CDS case to obtain a nationally representative sample. In the following study, NASS/CDS sampling weights were used in the calculation unless otherwise specified.

In many cases, NASS/CDS investigators could download EDR data from the involved vehicles. Since calendar year 2000 NASS/CDS investigators have downloaded more than 10,000 EDRs from General Motors, Ford, Chrysler, and Toyota vehicles. In the event of a crash involving air bag deployment, the recorded pre-crash information is “locked,” or stored permanently, in the EDR. Crashes in NASS/CDS with EDR data are currently available for calendar years 2000 to 2015.

3.1.1.2 NMVCCS

This study also analyzed EDR events extracted from the National Motor Vehicle Crash Causation Study (NMVCCS) database, compiled by NHTSA from 2005 to 2007 and containing 6,949 investigated crashes and 433 EDR downloads. For a crash to be included in the study, NMVCCS required that investigators must have arrived at the scene of a crash before emergency responders cleared the scene. Due to the on-scene data collection, investigators were able to interview witnesses and first responders to identify crash causation and record driver behavioral factors. This subtask applied the methodology described above for the analysis of NASS/CDS EDR data to determine the frequency with which EDRs did not capture all driver pre-crash actions.

In addition to driver pre-crash actions, NMVCCS in many cases, allowed the project to determine if any vehicle malfunctions reported by the driver were detected by the EDR. The NMVCCS database identifies any vehicle malfunction as a contributing crash cause, and all EDR downloads were examined to determine if the vehicle malfunction could have been detected by an EDR and if the recording duration was sufficient.

3.1.2 Crash Selection

The following selection criteria were implemented to extract relevant vehicles in each crash mode.

3.1.2.1 Rear-End

- Striking (following) vehicle in a rear-end crash
- Front of the vehicle incurred the most significant damage, i.e., the rear-end crash was the most significant event
- Single-event crashes
- NASS/CDS weight < 5000[1]

3.1.2.2 Intersection

- Vehicle to vehicle intersection crashes involving only two vehicles
- Single-event crashes
- NASS/CDS weight < 5000[1]

In addition, the vehicles included in the study were required to conform to one of the intersection crash scenarios shown in Figure 1. The intersection crash scenarios were selected based on the *accident type (ACCTYP)* variable recorded by NASS/CDS, which defines vehicle crash configuration. The vehicle crash configuration definitions were adopted from a previous study by Najm et. al. (2001), and is tabulated in Table 1.

[1] Cases with weighting factors >5000 were excluded because they exerted an undue influence on the results of the analysis. There were 33 such cases out of 1,616, but they comprised over 30 percent of the weighted total.

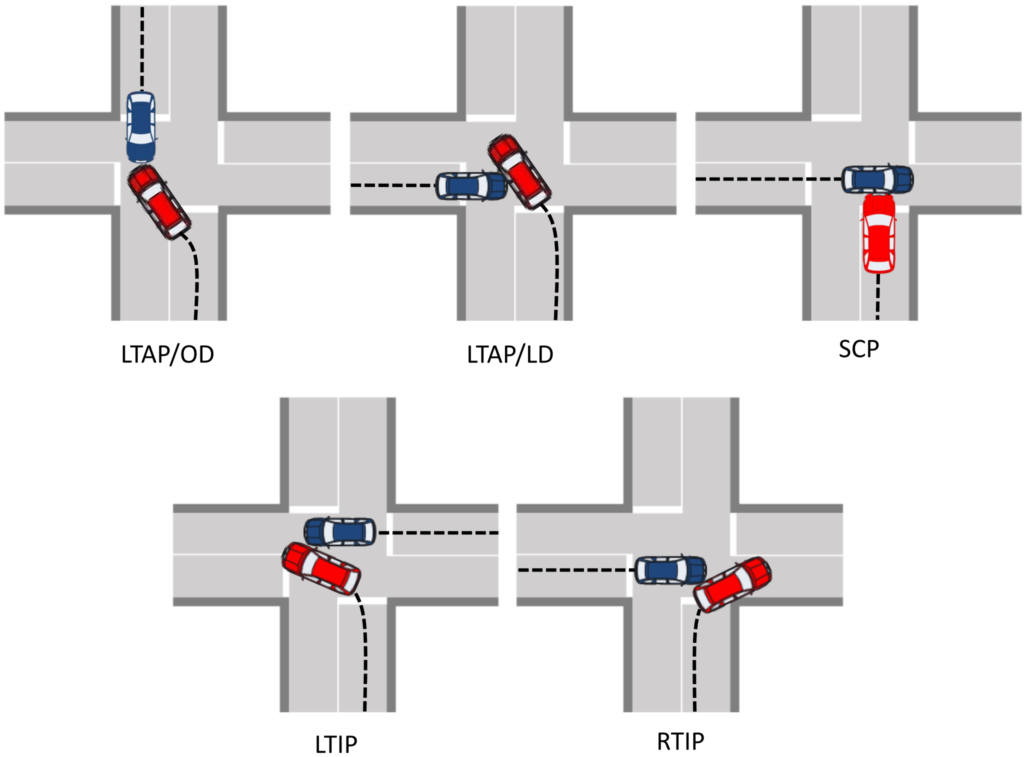


Figure 1. Schematics of Common Intersection Crash Scenarios

Table 1. Vehicle Crash Configuration in Intersection Crash Scenarios

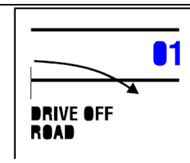
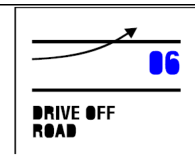
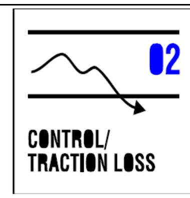
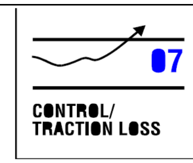
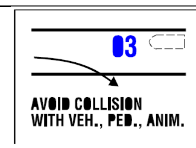
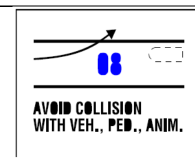
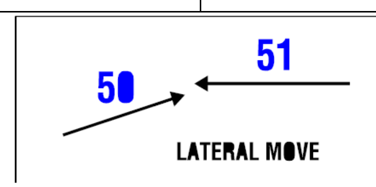
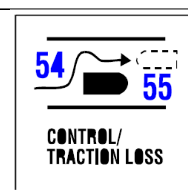
Crash Configuration	Vehicle 1 ACCTYP	Vehicle 2 ACCTYP
Left Turn Across Path – Opposite Direction (LTAP/OD)	68 – Initial Opposite Direction Turning Left	69 – Initial Opposite Direction Going Straight
Left Turn Across Path – Lateral Direction (LTAP/LD)	82 – Turn Into Opposite Direction Turning Left	83 – Turn Into Opposite Direction Going Straight
Straight Crossing Path (SCP)	86, 88 – Striking From the Left or Right	87, 89 – Struck on the Left or Right
Left Turn Into Path (LTIP)	76 – Turn Into Same Direction Turning Left	77 – Turn Into Same Direction Going Straight
Right Turn Into Path (RTIP)	78 – Turn Into Same Direction Turning Right	79 – Turn Into Same Direction Going Straight

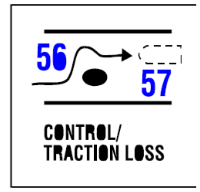
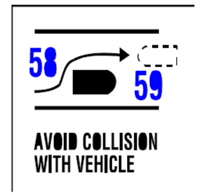
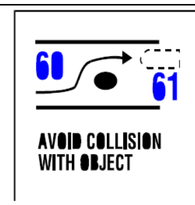
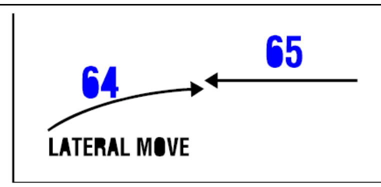
3.1.2.3 Road Departure

- Striking vehicle in lane and road departure crashes
- Single-event crashes with no rollovers OR single impact followed by a rollover
- NASS/CDS weight < 5000[1]

Road departure crashes were selected based on the *accident type (ACCTYP)* variable recorded by NASS/CDS, which defines vehicle crash configuration. Table 2 describes the crash configurations that were included as lane and road departure crashes in the analysis. Description and Figure were transcribed from the NASS/CDS Coding and Editing Manual (Bean, 2012).

Table 2. Vehicle Crash Configuration in Road Departure Crash Scenarios

ACCTYP - Crash Configuration	Description	Figure	
01 & 06 – Left/Right Roadside Departure: Drive Off Road	Vehicle departed the road under a controlled situation (e.g., was distracted, fell asleep, intentional departure, etc.)		
02 & 07 – Left/Right Roadside Departure: Control/Traction Loss	Vehicle departed the road with evidence that the vehicle lost traction or "got away" from the road in some other way (e.g., the vehicle spun off the road as a result of surface condition, oversteer phenomena, or mechanical malfunctions).		
03 & 08– Left/Right Roadside Departure: Avoid Collision With Vehicle, Pedestrian	Vehicle departed the road to avoid something on the road. “Phantom” vehicle situations, pedestrians, bicyclists, and other cyclists and non-motorists are included here.		
50 - Head-On: Lateral Move (Left/Right)	Vehicle that leaves its lane immediately before colliding head-on with another vehicle, when the vehicles are traveling on the same traffic way in opposite directions.		
54 - Forward Impact: Control/Traction Loss	Vehicle whose frontal area strikes another vehicle due to loss of control or traction (during a maneuver to avoid a collision with a third vehicle) while the vehicles are traveling on the same traffic way in opposite directions.		

ACCTYP - Crash Configuration	Description	Figure
56 - Forward Impact: Control/Traction Loss	Vehicle whose frontal area strikes another vehicle due to loss of control or traction (during a maneuver to avoid a collision with an object) while the vehicles are traveling on the same traffic way in opposite directions.	
58 - Forward Impact: Avoid Collision with Vehicle	Vehicle whose frontal area strikes another vehicle while maneuvering to avoid a collision with a non-involved vehicle, when loss of control or traction was not a factor, and the vehicles were traveling on the same traffic way, in opposite directions.	
60 - Forward Impact: Avoid Collision With Object	Vehicle that struck the front of another vehicle with the frontal plane while maneuvering to avoid collision with an object, when loss of control or traction was not a factor, and the vehicles were traveling on the same traffic way, in opposite directions.	
64 - Sideswipe/Angle: Lateral Move (Left/Right)	Vehicle that infringed upon the other in a Crash Category: Change Traffic Way Opposite Direction, Crash Configuration: Sideswipe/Angle Collision.	

3.1.3 EDR Event Selection

Each EDR with pre-crash data was examined to determine the time interval between any pre-crash avoidance actions taken by the driver and the impact. We also examined EDR pre-crash data elements to determine the fraction of EDRs that showed braking at $t = -5$ seconds (indicating that the driver was braking prior to $t = -5$ seconds). In a limited number of EDR module types, braking status for the preceding 8 seconds was recorded. These longer-duration EDRs were examined to determine if this extended duration was capable of capturing driver pre-crash actions. Similarly, we examined pre-crash steering inputs at $t = -5$ seconds in those EDRs configured to record steering. Finally, in the limited number of EDRs in which accelerator position was recorded, driver accelerator application was examined.

While EDR records for air bag deployment events are permanently stored, most EDRs have the capability to also store non-deployment events that meet the criteria for algorithm enable. To correctly select the event record that corresponds to the crash, we selected EDR data associated with air bag deployment events, as well as all non-deployment events with maximum change in velocity (delta V) greater than or equal to 5 mph to be included in the sample. If the EDR had a "Complete File Recorded" flag, we excluded any cases in which "Complete File Recorded = False," indicating that the EDR pre-crash recording was interrupted.

3.1.4 Pre-Crash Maneuver Time Calculation

Pre-crash maneuver times, including braking, steering, and accelerator input, were calculated for each event to determine whether or not the 5-second recording duration was sufficient to capture the initiation of driver pre-crash maneuver. Pre-crash maneuver time was defined as the time between driver input and time of impact, and we defined EDR algorithm enable time (t = 0) as the time of impact. Certain EDRs in the dataset are capable of recording up to 8 seconds of pre-crash information. To normalize the recording duration of EDRs in our sample, data from EDRs with 8-second recording capability were truncated to 5 seconds in the pre-crash maneuver characterization.

Driver brake application time was calculated as the time between impact and the earliest time point at which the brake switch was recorded as "ON." In those cases in which the brake switch was repeatedly cycled between "ON" and "OFF," i.e., driver depressed the brake pedal several times, the earliest time point at which the brake switch was recorded as "ON" was taken as the time of brake application.

For steering maneuvers, "Steering Input" time was calculated as the time between impact and the earliest non-zero steering angle record. Similarly, accelerator input time was calculated as the earliest time the driver completely released the accelerator, i.e., the accelerator position reads 0. No accelerator input time was calculated for events in which the driver never depressed the accelerator pedal or if the accelerator pedal was never completely released.

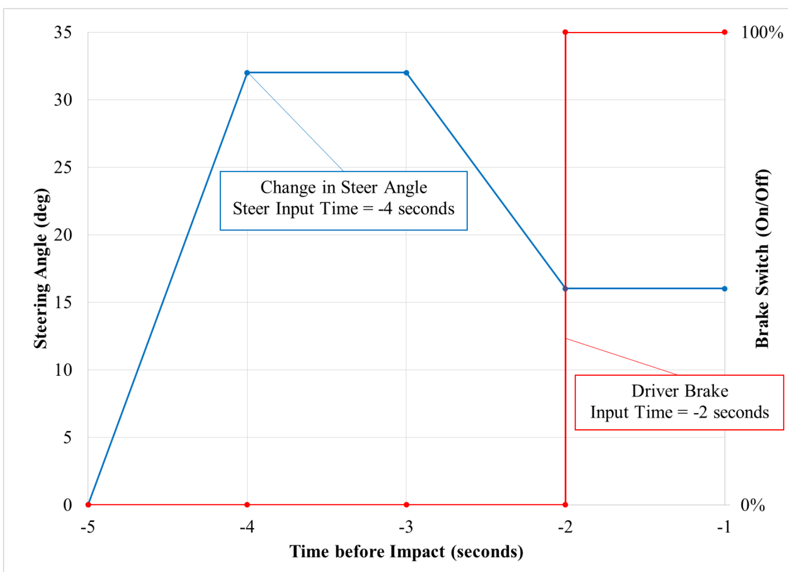


Figure 2. Hypothetical Pre-Crash EDR Trace Showing Brake and Steering Input Time

The majority of the EDR data was recorded at 1 Hz or 2 Hz sampling rate, therefore there are inherent uncertainties in the recorded pre-crash data due to this low sampling rate. For example, if the driver initiated braking at t = -4.99 seconds, an EDR sampling at 1 Hz will report brake "OFF" at t = -5 seconds, and brake initiation at t = -4 seconds. To accommodate this uncertainty, our analysis calculates an "Upper Bound" measurement, in which we assumed that the actual driver input time is one time step earlier than the reported time. Therefore, each pre-crash maneuver time was adjusted to one sample step (1 second, 0.5 second, or 0.1 second) earlier than the reported time, i.e., a reported braking time at t = -4 second would be treated as braking at t =

-5 seconds. In addition, for the events that showed pre-crash maneuver at the limit of the recording duration, e.g., t = -5 seconds, no adjustment in pre-crash maneuver time was done and braking time was calculated as t = -5 seconds. In other words, if the EDR record showed braking at t = -5 seconds, the initiation of the braking event is uncertain since the recording duration is limited. The actual braking initiation occurred at some time equal or greater than 5 seconds from impact. In addition, we also reported a "Lower Bound" measurement in the results, which corresponds to the driver input time reported by the EDR.

3.1.5 Intersection Approach and Traversal Reconstruction

The sequence of driver actions leading to and resulting in an intersection collision can be divided into four phases, as shown in Figure 3: the approach phase, the traversal phase, any evasive action and finally the impact. For almost all intersection crash types, the driver actions that lead to the crash, e.g., running a red light, occur during the approach phase. Once the vehicle enters the intersection, the error has already been committed. The one exception is LTAP/OD, in which the errors are made during gap selection. If EDR recording can capture the approach phase of an intersection crash, then the entire crash will be captured. Of particular interest is when the transition between the approach and traversal phase occurs. EDRs that record sufficient duration can capture stop sign running, rolling stops, and red-light-running. The research question is to determine how frequently EDRs can capture the transition between the approach and traversal phase.

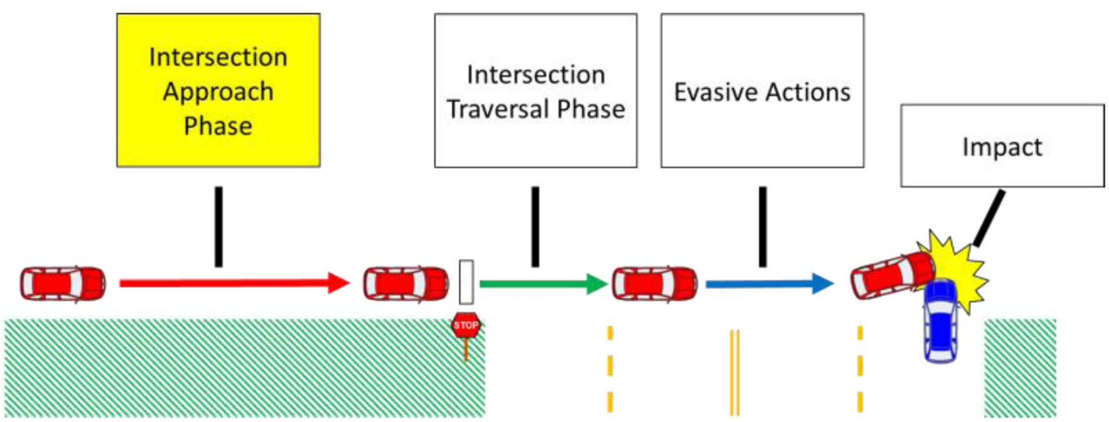


Figure 3. Intersection Crash Phases

To determine vehicle position with respect to the intersection boundary, our study makes use of a set of vehicle path reconstructions conducted in a previous study by Scanlon et. al. (2016a), for a subset of intersection crashes from NASS/CDS. The vehicle path reconstruction relies on both a distance estimation and position estimation. The distance estimation was based on numerically integrating the pre-crash vehicle speed from EDR data, starting from the time of impact to the last available pre-crash speed data, using trapezoidal integration to estimate the distance traveled by the vehicle during each time series segment. The position estimation was done by estimating the path of the vehicles by connecting each available vehicle position prior to the impact as drawn in the scene diagram. For a vehicle traveling straight and following a straight road, a linear line was used to connect the vehicle positions, otherwise, a curved spline equal in radius of curvature to the road was drawn to estimate the path of the vehicle. Intersection boundaries were used as a reference point to divide the approach and traversal phase of the event. In cases where the scene diagram shows a stop bar or a crosswalk, the edge of the stop bar or cross walk closest to the center of the intersection was used as the boundary. In other cases, boundary lines were drawn based upon the edge of the roadway.

Figure 4 shows an example case. The red line represents the intersection boundary and the blue line shows the vehicle path. Vehicle 1 is traveling a straight path, while vehicle 2 follows a curved road prior to the impact.

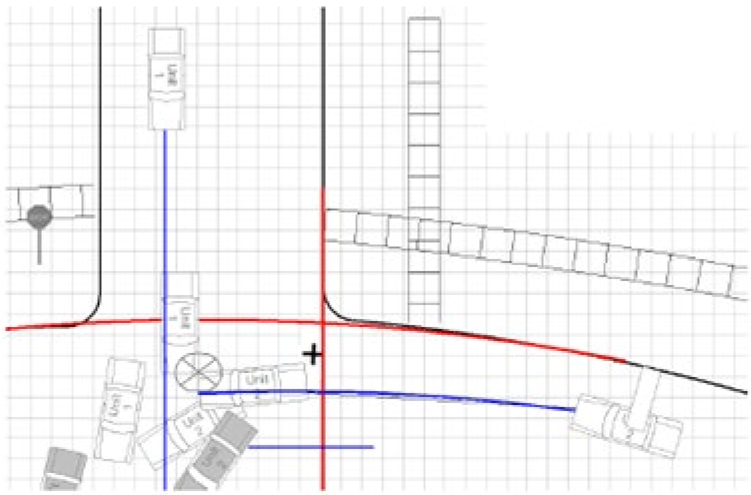


Figure 4. Vehicle Path Reconstruction for Straight and Curved Road

3.1.6 Road Departure Crash Reconstructions

Road departure traversal time is also an important characteristic to help determine the sufficiency of the 5-second recording duration. Traversal time during road departure events refers to the time between when the vehicle leaves the road or lane edge to the time of first impact and/or final rest. During the period between road departure and final rest, drivers may initiate a series of maneuvers to bring the vehicle to rest or guide the vehicle back to the roadway. Similar to traversal time in intersection crashes, EDRs that record sufficient duration to capture the traversal time in road departure events can capture driver corrective maneuvers after the initial departure.

Vehicle road departure traversal times were estimated based on reconstruction of scene diagrams from each crash, similar to the run off road crash reconstruction method used in the National Cooperative Highway Research Program project 17-22 (Mak et al., 2010). We selected a subset of single vehicle road departure crashes from NASS/CDS case year 2012, and estimated both the distance traveled and respective vehicle speed at each available vehicle position. The traversal time from initial departure to first impact, and from initial departure to final rest was then calculated as the distance traveled divided by the vehicle speed at each position in the scene diagram.

Figure 5 shows an example scene diagram of a road departure crash. The subject vehicle in Figure 5 departs the roadway at position 2, initially strikes a utility pole at position 3 and then a second impact with a guide wire at position 4, and finally strikes a tree and comes to rest at the "Final Rest" position. The reconstruction starts from the "Final Rest" position and first estimates the impact velocity based on the reported delta V of the crash. The velocity at position 4 was estimated by computing the reduction in vehicle velocity between the "Final Rest" position to position 4. In this study, the reduction in vehicle velocity was computed based on drag between the surface of travel (gravel, dirt, asphalt, etc.) and the tires. Last, the velocity reduction was added to the impact speed to obtain vehicle velocity at position 4. This process is repeated for all known positions up until the point of initial departure.

Last, special attention was given to events that resulted in breakaway pole objects, as these impacts absorb less energy than non-breakaway impacts. In the event of an impact that resulted in pole fracture, the change in kinetic energy due to breaking the pole object was determined based on the pole diameter and material, and has been previously calculated by Mak et al. (1980).

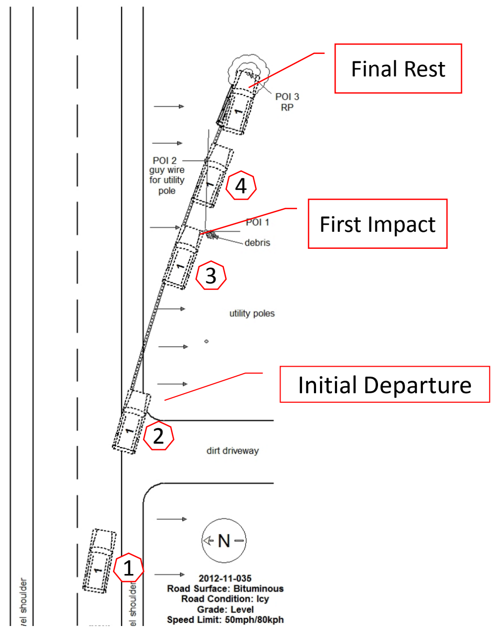


Figure 5. Vehicle Path Reconstruction for Road Departure Crashes

3.2 Analysis of NASS/CDS EDRs for Incomplete Pre-Crash Recording

3.2.1 Dataset Summary

Table 3 shows a summary of the EDRs downloaded from NASS/CDS crashes. Our initial dataset was comprised of a total of 10,895 EDR downloads from NASS/CDS case years 2000 to 2015. A total of 8,373 EDRs were downloaded from vehicles involved in single-event crashes. Within the subset of single-event EDRs, a total of 5,131 EDRs had a deployment event or delta V greater than 5 mph, and 3,786 EDRs recorded pre-crash information. Finally, we extracted 1,616 EDRs from crash modes of interest according to the selection criteria listed in section 3.1.2. After excluding cases with weight greater than 5,000, 1,583 cases remained for analysis: 329 EDRs from rear-end crashes, 839 EDRs from intersection crashes, and 415 EDRs from road departure crashes.

Table 3. Dataset Summary of EDRs – NASS/CDS

Group	Count
All EDRs	10,895
EDRs With Single Event	8,373
EDRs With Deployment Event or DV > 5 mph	5,131
EDRs With Pre-Crash Data	3,786
EDRs in Crash Modes of Interest	1,616
EDRs With Weight <5000	1,583
EDRs in Rear-End Crashes	329
EDRs in Intersection Crashes	839
EDRs in Road Departure Crashes	415

Figure 6 shows the distribution of OEMs in the combined sample of vehicles from rear-end, intersection, and road departure crashes. As shown by the figure, the dataset included EDR modules from Chrysler, Ford, GM, and Toyota. The majority of the vehicles were 1,358 GM vehicles.

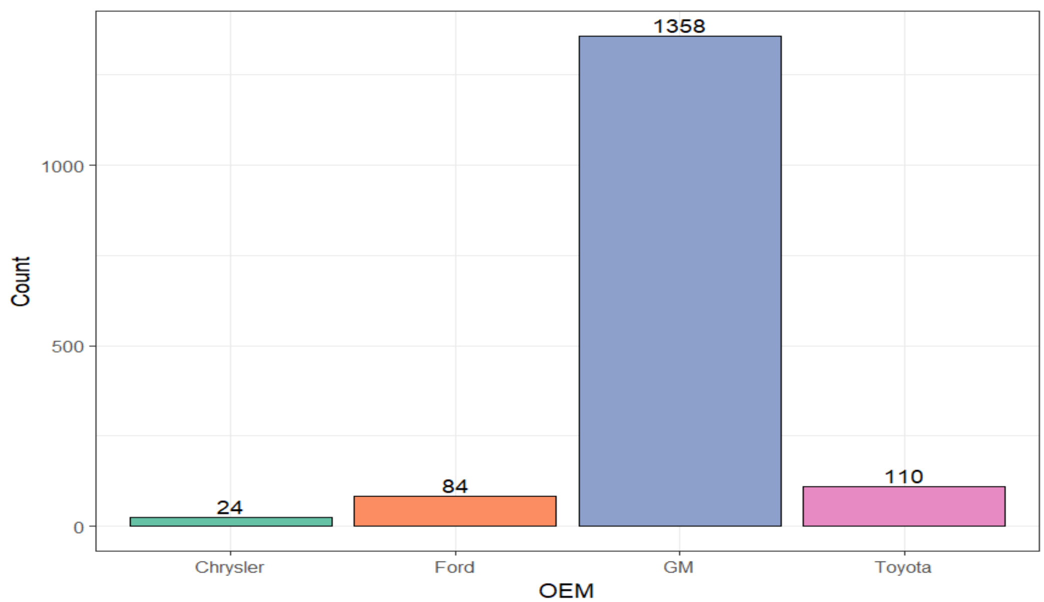


Figure 6. Distribution of OEM for Deployment Event EDRs – NASS/CDS

Figure 7 shows the distribution of vehicles in our dataset by model year. The blue histogram shows the unweighted case count and the red line shows the weighted cumulative distribution of vehicle model years. As shown in the figure, the weighted median vehicle model was 2006.

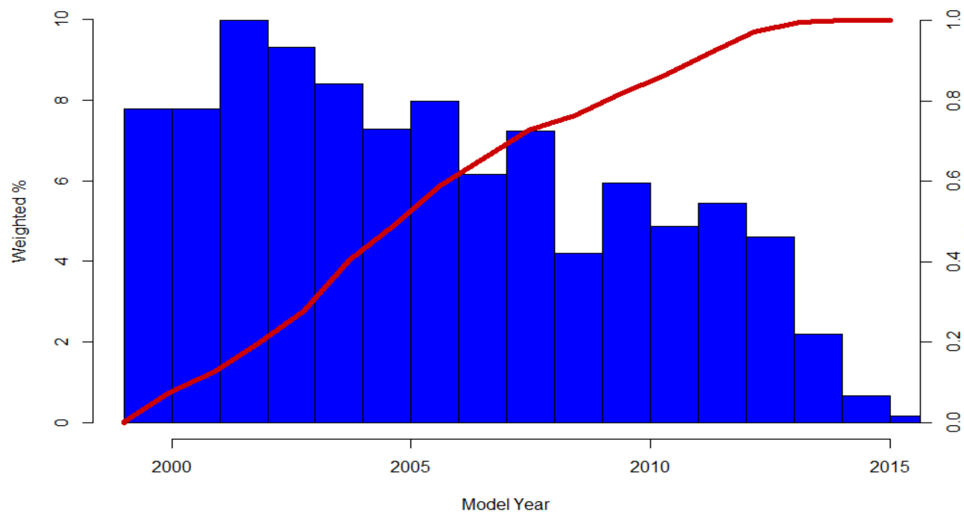


Figure 7. Histogram and Weighted Cumulative Distribution of Vehicle Model Year – NASS/CDS

Table 4 shows the distribution of EDRs with pre-crash information by model year. As the table shows, braking data was available for MY 1999 to 2015 vehicles in the current dataset, while the availability of accelerator and steering input information was available from 2005 and continues to be reported for MY 2015 vehicles in the current dataset.

Table 4. Summary of EDRs With Pre-Crash Information by Model Year – NASS/CDS

Model Year	Braking	Steering	Accelerator
1999	14	0	0
2000	137	0	0
2001	148	0	0
2002	155	0	0
2003	166	0	0
2004	148	0	0
2005	94	20	30
2006	102	30	76
2007	86	20	70
2008	104	14	84
2009	72	12	56
2010	84	24	62
2011	81	22	60
2012	61	25	55
2013	35	24	34
2014	19	10	19
2015	4	2	4
Total	1510	203	550

Table 5 shows a tabulation of model years of all vehicles that were equipped with an EDR capable of recording up to 8 seconds of pre-crash braking information. All 915 vehicles shown in Table 5 are GM vehicles. This extended recording period was most prevalent during the MY 2000 to 2003, and decreased in frequency until 2010.

Table 5. Summary of Vehicle Model Year With 8 Second Pre-Crash Braking Information – NASS/CDS

Model Year	Count
1999	14
2000	137
2001	148
2002	155
2003	166
2004	147
2005	84
2006	39
2007	15
2008	9
2010	1
Total	915

Table 6, Table 7, and Table 8 show the distribution of OEM pre-crash data sampling frequency for braking, steering, and accelerator data. As shown in the tables, each manufacturer adopted different strategies for sampling frequency. Chrysler opted for 10 Hz in braking, steering, and accelerator pre-crash data recording. GM and Ford use both 2 Hz and 1 Hz sampling rate for their braking and accelerator pre-crash data recording.

Table 6. Pre-Crash Braking Data Sampling Frequency Distribution by OEM – NASS/CDS

Sampling Frequency (Hz)	Chrysler	Ford	GM	Toyota
10	24	0	0	0
2	0	68	218	20
1	0	16	1,074	90

Table 7. Pre-Crash Steering Data Sampling Frequency Distribution by OEM – NASS/CDS

Sampling Frequency (Hz)	Chrysler	Ford	GM	Toyota
10	17	58	0	0
2	0	0	0	20
1	0	0	116	0

Table 8. Pre-Crash Accelerator Data Sampling Frequency Distribution by OEM – NASS/CDS

Sampling Frequency (Hz)	Chrysler	Ford	GM	Toyota
10	22	0	0	0
2	0	68	218	20
1	0	16	206	0

3.2.2 Rear-End

3.2.2.1 Dataset Composition

Table 9 shows the final dataset composition of rear-end crashes. A total of 549 EDR downloads were extracted from NASS/CDS 2000 to 2015 based on the selection criteria. Rear-end crashes in which the frontal air bags did not deploy were excluded unless the maximum delta V was 5 mph or higher. In addition, older generation EDRs that did not record pre-crash data were also excluded.

Table 9. Dataset Composition – Rear-End NASS/CDS

Group	Count	Weighted Count
Total EDR Downloads From Single-event Rear-End Crashes	549	566,055
Excluded – Non-Deployment Events	107	109,089
Excluded – No Pre-Crash EDR Data	113	127,303
Resultant Dataset	**329**	**217,019**

3.2.2.2 Pre-Crash Brake Application

Figure 8 shows the weighted distribution of time to brake application. The vertical green line denotes -5 seconds prior to impact, corresponding to the current EDR recording minimum time requirement. Drivers initiated pre-crash maneuver in 237 of the 305 events with available braking information. In other words, the brake pedal was not depressed (i.e., switch was never “ON”) in the other 68 events. As shown in Figure 8, the “Upper Bound” measure estimates that approximately 35 percent of the sample initiated braking time greater than 5 seconds prior to impact.

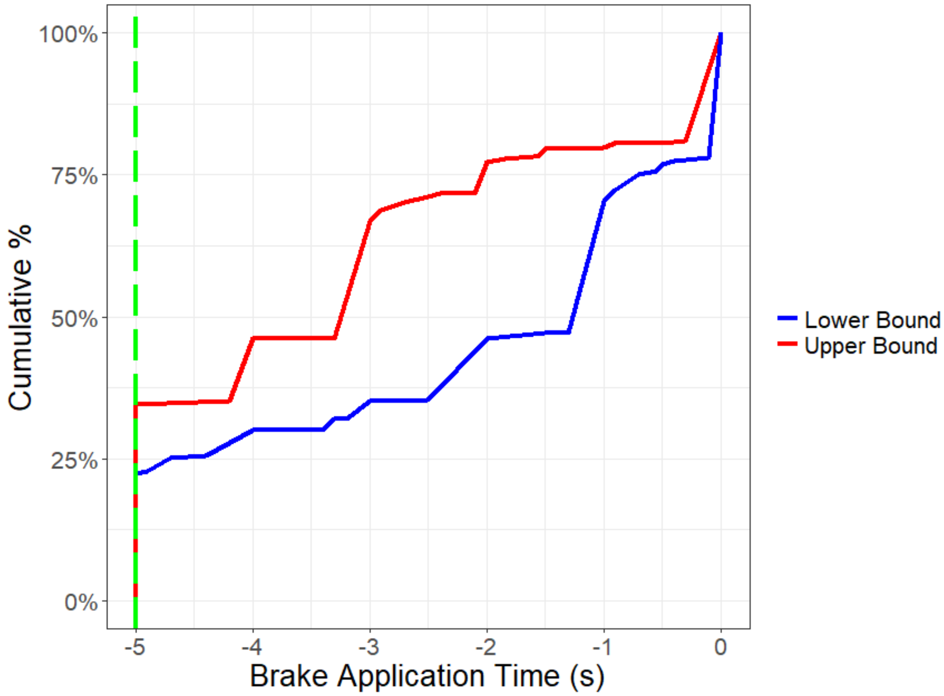


Figure 8. Weighted Distribution of Time to Brake Application (n = 305) – Rear-End NASS/CDS

Figure 9 shows the weighted distribution of total brake switch "ON" time during the pre-crash period. The time duration computed here directly reflects the times reported by the EDRs. As shown in the figure, in ~75 percent of the events, the brake switch was "ON" for a period of 2.5 seconds or less prior to impact.

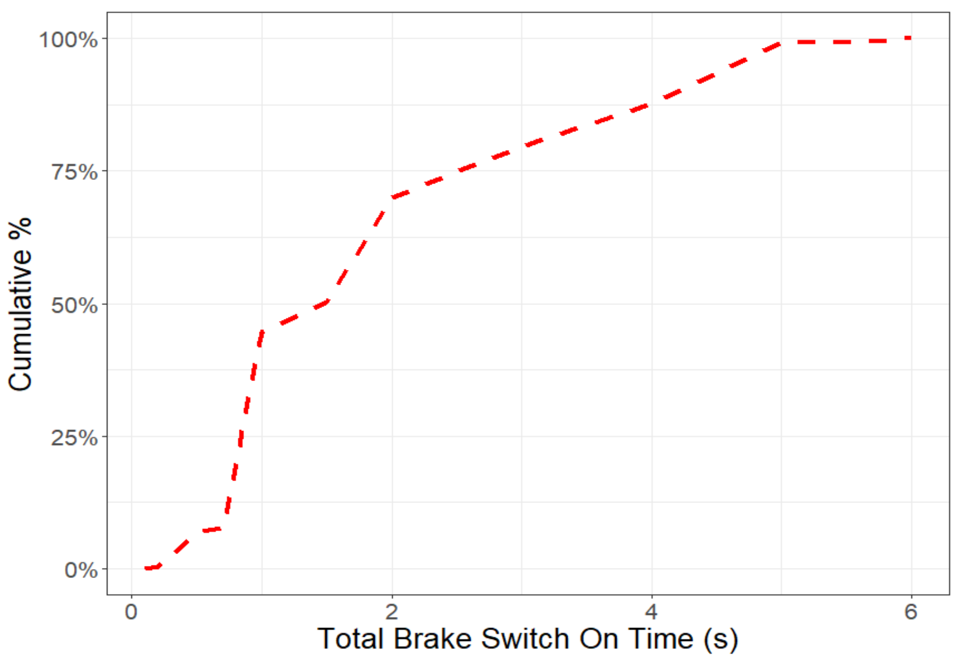


Figure 9. Weighted Distribution of Total Brake Switch ON Time (n = 305) – Rear-End NASS/CDS

3.2.2.3 Pre-Crash Steering Input

Figure 10 shows the weighted distribution of time to steering input. The vertical green dashed line denotes the -5 seconds time point, corresponding to the current EDR minimum recording requirement. As shown by Figure 10, about 80 percent of the events show non-zero steering angle at 5 seconds. However, the distribution is only comprised of 44 vehicles that had available EDR records.

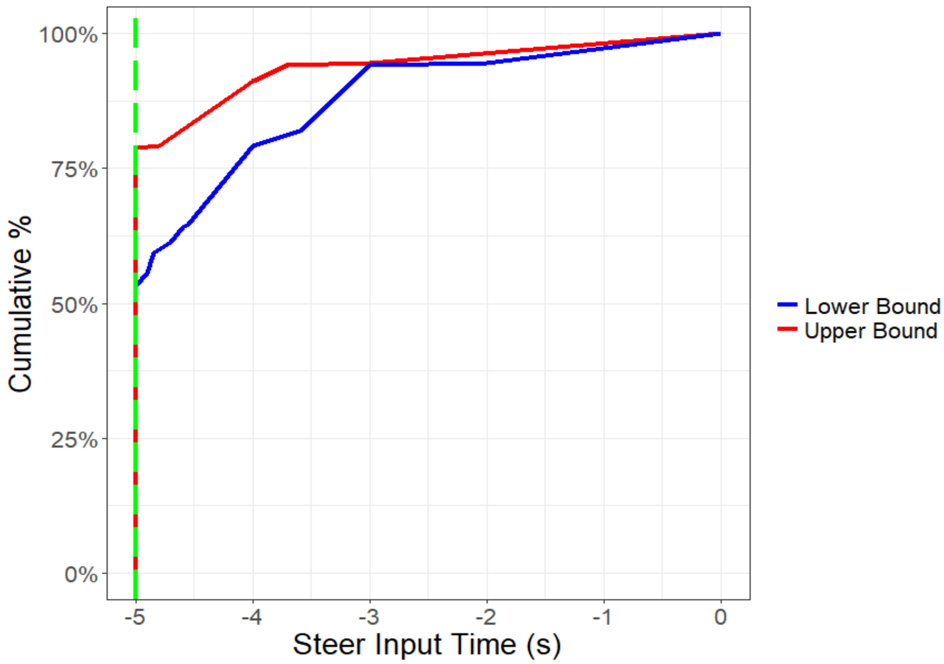


Figure 10. Weighted Distribution of Time to Steering Input (n = 44) – Rear-End NASS/CDS

3.2.2.4 Pre-Crash Accelerator Pedal Input

Last, Figure 11 shows the weighted distribution of accelerator pedal input time. As shown in the figure, 131 EDRs in the dataset recorded pre-crash accelerator pedal position information. Approximately 9 percent of the sample had accelerator input time at or greater than 5 seconds prior to impact.

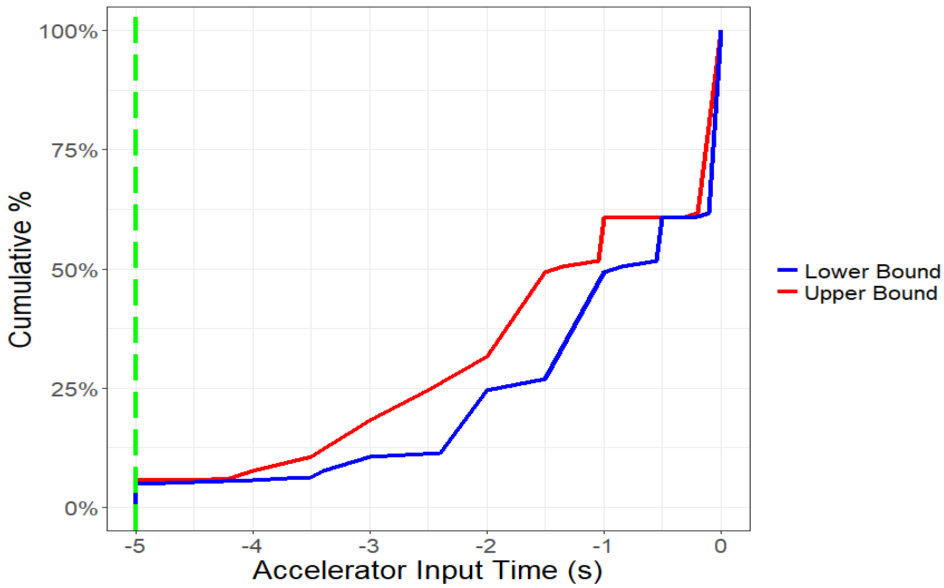


Figure 11. Weighted Distribution of Time to Accelerator Input (n = 131) – Rear-End NASS/CDS

3.2.2.5 Discussion and Conclusions

The overall objective of this analysis was to evaluate crash modes that would benefit from more than 5 seconds of pre-crash recording time. This subsection focused on striking vehicles in rear-end crashes. The approach was to characterize driver pre-crash maneuvers from EDR data extracted from rear-end striking vehicles. A total of 329 EDRs downloaded from NASS/CDS 2000-2015 were included in the analysis, representing approximately 329,664 vehicles when case weights were applied.

Braking information was the most frequently available pre-crash EDR data element examined in this study. Approximately 96 percent of the EDRs in the sample included braking information, while only 14 percent of the EDRs in the sample included steering information, and 39 percent of the EDRs in the sample included accelerator input. Most vehicles in our sample (90%), were manufactured before model year 2012 when Part 563 took effect. While brake status and accelerator pedal position was required for all EDRs optionally equipped with EDRs under Part 563 (Table I Elements), steering angle data was only an optional variable (Table II Element); therefore, the availability of steering information was substantially lower than braking and accelerator records in the current analysis.

The distributions of time to pre-crash driver maneuvers presented in Figure 8, Figure 10, and Figure 11, show that the current 5-second EDR minimum recording requirement failed to capture the initiation time for nearly 35 percent of driver pre-crash braking maneuvers. The pre-crash maneuver times are an upper bound on driver maneuver initiation time that reflects the low resolution of EDR recording. Driver initiation was missing in about 80 percent of pre-crash steering, and 9 percent of pre-crash accelerator release in our sample. However, this was based on a small sample and should be revisited with a larger dataset when available.

3.2.3 Intersection

3.2.3.1 Data Composition

Table 10 shows the final dataset composition. A total of 839 EDR downloads were extracted from NASS/CDS 2000-2015 based on the selection criteria, representing approximately 320,166 vehicles in the United States. Intersection crashes in which one or both vehicle crash configurations were listed as unknown or did not conform to one of the scenarios described in Figure 1 were excluded. In addition, older generation EDRs that did not record pre-crash data were also excluded.

Table 10. Dataset Composition – Intersection NASS/CDS

Group	Count	Weighted Count
Total EDR Downloads from Intersection Crashes	1,176	447,759
Excluded – Unknown or Other Intersection Crash Scenario	22	5,705
Excluded – No Pre-Crash EDR Data	320	122,861
Resultant Dataset	**839**	**320,166**

Figure 12 shows the distribution of intersection crash types in the resultant dataset. LTAP/OD intersections make up the largest portion of intersection crashes in our sample, followed by SCP scenarios.

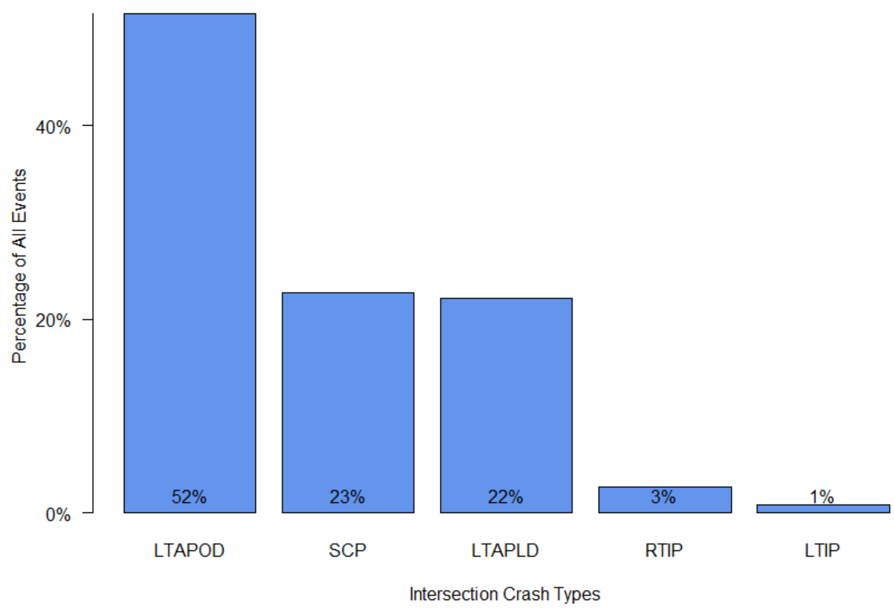


Figure 12. Distribution of Vehicles in Sample by Intersection Crash Types

3.2.3.2 Pre-Crash Driver Maneuvers

Table 11 shows the summary of EDR downloads with pre-crash information. Approximately 89 percent of the EDRs contained pre-crash braking information, while only 12 percent and 30 percent of the EDRs contained pre-crash steering and accelerator pedal information, respectively.

Table 11. Summary of EDR Downloads With Pre-Crash Information – Intersection NASS/CDS

Group	Count	Weighted Count	Weighted %
Events With Braking Information	801	311,528	97%
Events With Steering Information	109	37,403	12%
Events With Accelerator Pedal Information	283	96,129	30%
Total EDRs	**839**	**320,166**	**100%**

3.2.3.3 Pre-Crash Brake Application

Figure 13 shows the distribution of time to brake application. The vertical green line denotes the 5-seconds-prior-to-impact current EDR minimum recording requirement. As shown in Figure 13**,** the "Upper Bound" measurement estimates that approximately 35 percent of the drivers applied brakes greater than 5 seconds prior to impact.

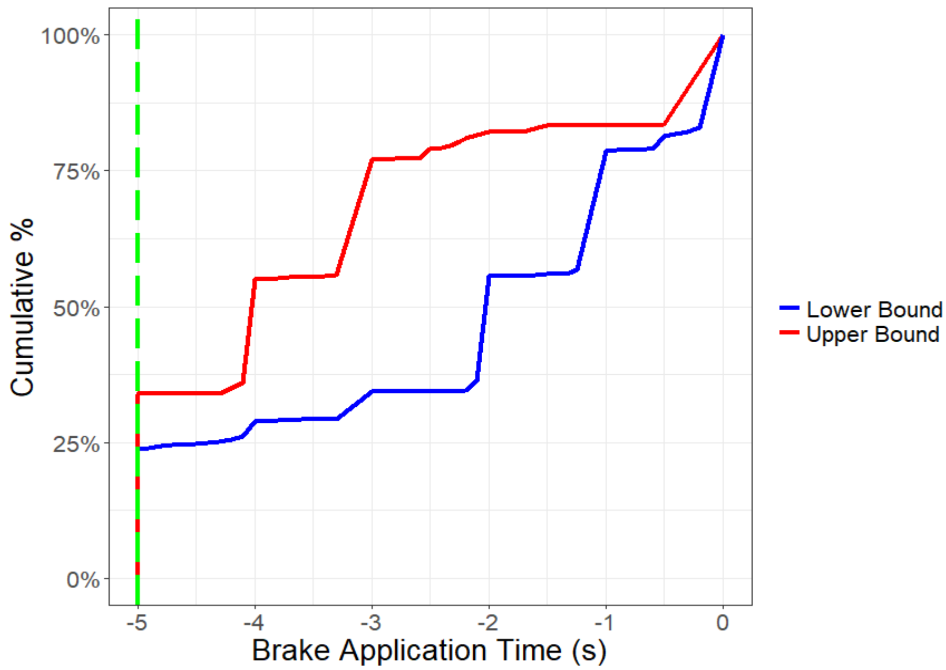


Figure 13. Distribution of Time to Brake Application (n = 801) – Intersection NASS/CDS

3.2.3.4 Pre-Crash Steering Input

Figure 14 shows the distribution of time to steering input. The vertical green dashed linehighlights the -5 seconds time point, corresponding to the current EDR minimum recording requirement. As shown by Figure 14, approximately 64 percent of the events showed a non-zero steering angle at t = -5 seconds.

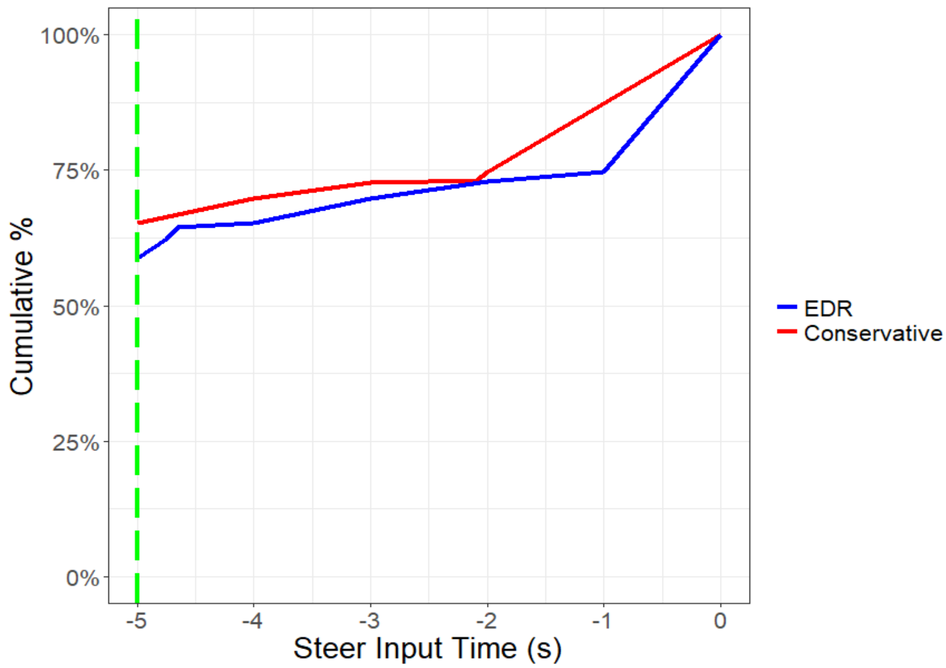


Figure 14. Distribution of Time to Steering Input (n = 109) – Intersection NASS/CDS

3.2.3.5 Pre-Crash Accelerator Pedal Input

Figure 15 shows the distribution of accelerator pedal input time. As shown in the figure, a total of 283 EDRs in the dataset recorded pre-crash accelerator pedal position information. Only about 4 percent of the drivers in our intersection dataset released the accelerator pedal at 5 seconds or earlier prior to impact.

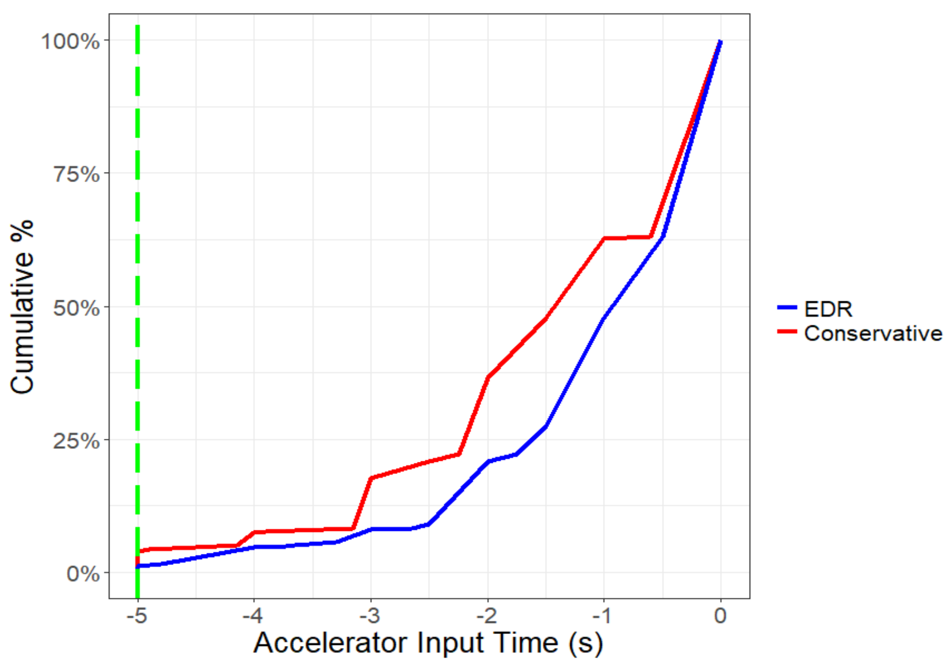


Figure 15. Distribution of Time to Accelerator Input (n = 283) – Intersection NASS/CDS

3.2.3.6 Intersection Approach and Traversal Time

The second portion of the results aimed at investigating existing EDR's capability of recording the traversal duration of intersection crashes. A total of 429 vehicles path reconstructions were included in the approach and traversal analysis.

Figure 16 shows the schematic of time of intersection entry to time of impact during intersection crashes. This time duration is particularly important to capture any driver errors, such as running a red light, failure to completely stop, or rolling stop, as well as any potential evasive maneuver the driver may have initiated prior to the impact. Figure 17 shows the distribution of time of intersection entry with respect to impact for all 429 reconstructed crashes. This time duration is computed based on crash reconstructions from scene diagrams. As shown by the figure, in approximately 13 percent of the weighted total (64 of 429 cases), the vehicles crossed the intersection boundary greater than 5 seconds prior to impact. In other words, 13 percent of the EDRs in the dataset did not have sufficient recording duration to capture the time of intersection boundary crossing.

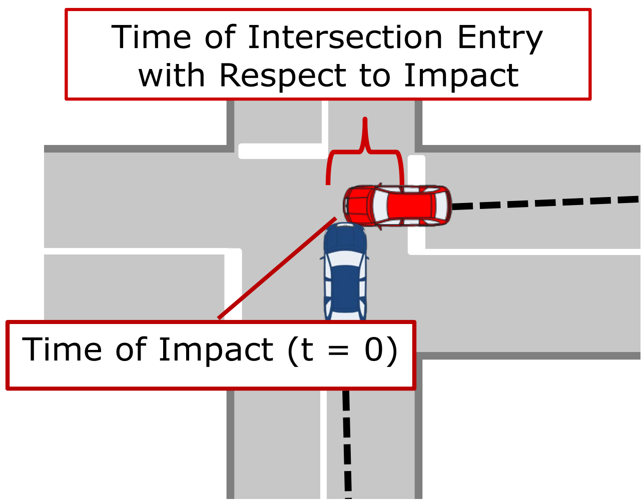


Figure 16. Schematic of Time of Intersection Entry and Time of Impact in Intersection Crashes

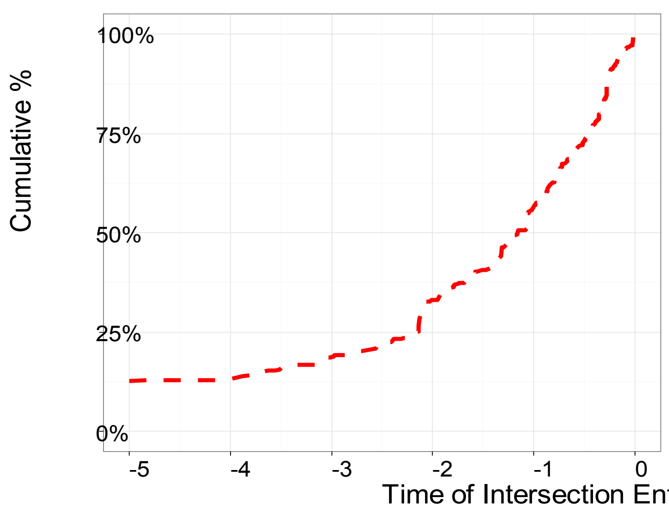


Figure 17. Distribution of Time of Intersection Entry With Respect to Impact – Intersection NASS/CDS

Table 12 shows the distribution of intersection control devices in each intersection crash for which we have a vehicle path reconstruction. The parentheses indicate the side at which the control device is placed. For example, "2-way Signalized (Other Vehicle)" refers to a 2-way signalized intersection in which the signal controlled the traversal of the other vehicle. Events categorized as "non-controlled intersection" were typically un-signalized left turns into residential areas or places of business. As shown in Table 12, 4-way signalized intersections were the most common control device in our dataset.

Table 12. Distribution of Intersection Control Devices – Intersection NASS/CDS

Control Device	**Count**
Non-Controlled Intersection	48
2-Way Signalized (Other Vehicle)	2
2-Way Stop Sign (Other Vehicle)	54
2-Way Signalized (This Vehicle)	2
2-Way Stop Sign (This Vehicle)	33
4-Way Signalized	270
4-Way Stop Sign	17
Unknown	3
Total	429

3.2.3.7 Discussion and Conclusions

The analysis of this subtask focused on vehicles in intersection crashes. The approach was to examine driver pre-crash maneuvers from EDR data extracted from vehicles involved in intersection crashes. In addition, the analysis conducted reconstructions of the vehicle path prior to impact to analyze EDR's capability to capture driver action prior to entering the intersection. A total of 839 EDRs downloaded from 2000-2015 were included in the analysis, representing approximately 320,166 vehicles nationwide.

The distribution of pre-crash driver maneuver shows that the current 5-second EDR recording duration was not sufficient to capture all driver pre-crash maneuvers during intersection crashes. The "Upper Bound" measurement estimated that approximately 35 percent of drivers in intersection crashes who applied brakes did so 5 seconds prior to impact or earlier. Similarly, approximately 64 percent of EDR's in striking vehicles showed steering input at 5 seconds or earlier. Approximately 4 percent of EDR's in striking vehicles showed earliest accelerator input at 5 seconds or earlier.

In addition, the results showed that the current EDR recording duration requirement also did not always capture driver approach in intersection crashes. A total of 13 percent of the EDRs in the dataset (64 of 429 cases with path reconstruction) did not have sufficient recording duration to capture the time of intersection boundary crossing.

3.2.4 Road Departures

3.2.4.1 Dataset Composition

Table 13 shows the final dataset composition. A total of 415 EDRs downloaded from road departure crashes were extracted from NASS/CDS 2000-2015 based on the selection criteria. The selection criteria excluded 197 EDRs associated with non-deployment events and 177 EDRs that did not record pre-crash data.

Table 13. Dataset Composition – Road Departure NASS/CDS

Group	Count	Weighted Count
Total EDR Downloads From Road Departure Crashes	789	316,869
Excluded – Non-Deployment Events	197	103,562
Excluded – No Pre-Crash EDR Data	177	65,186
Resultant Dataset	**415**	**148,121**

3.2.4.2 Pre-Crash Driver Maneuvers

Table 14 shows the summary of EDR downloads with pre-crash information. Approximately 96 percent of the EDRs contained pre-crash braking information, while only 14 percent and 38 percent of the EDRs contained pre-crash steering and accelerator pedal information, respectively.

Table 14. Summary of EDR Downloads With Pre-Crash Information – Road Departure NASS/CDS

Group	Count	Weighted Count	Weighted %
Events With Braking Information	404	141,535	96%
Events With Steering Information	50	20,198	14%
Events With Accelerator Pedal Information	136	56,315	38%
Total EDRs	**415**	**148,121**	**100%**

3.2.4.3 Pre-Crash Brake Application

Figure 18 shows the distribution of time to brake application. The vertical green line denotes the 5 seconds prior to impact - the current EDR minimum recording requirement. As shown in Figure 18**,** the “Upper Bound” measurement estimates that approximately 35 percent of the drivers applied brakes greater than 5 seconds prior to impact.

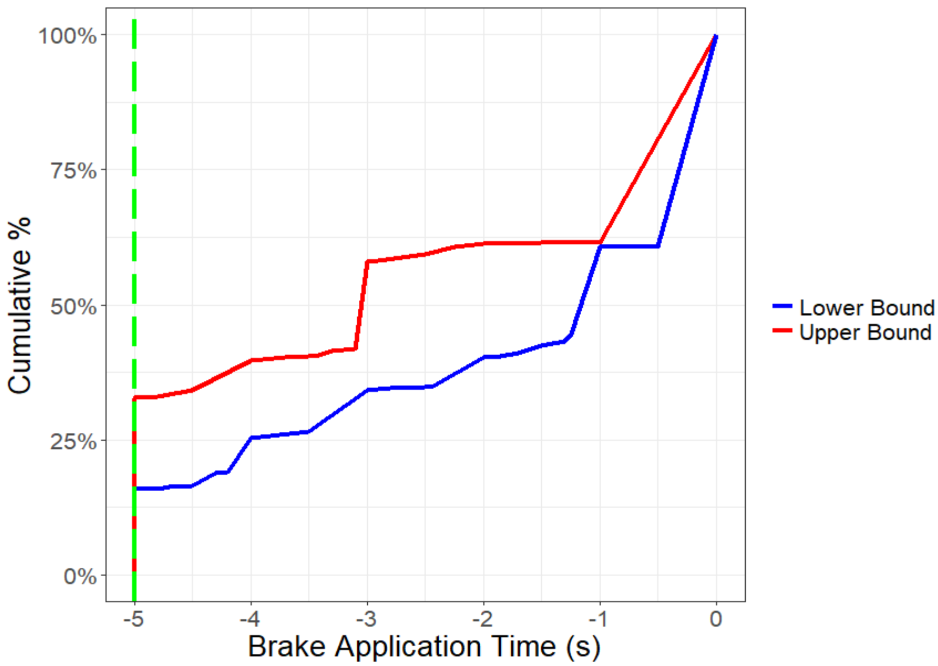


Figure 18. Distribution of Time to Brake Application (n = 404) – Road Departure NASS/CDS

3.2.4.4 Pre-Crash Steering Input

Figure 19 shows the distribution of time to steering input. The vertical green dashed linehighlights the -5 seconds time point, corresponding to the current EDR minimum recording requirement. As shown by Figure 19, nearly 88 percent of the events showed a non-zero steering angle at t = -5 seconds. However, we emphasize that this distribution is based on a small number of cases (n = 50), and this calculation should be revisited with a larger sample when available.

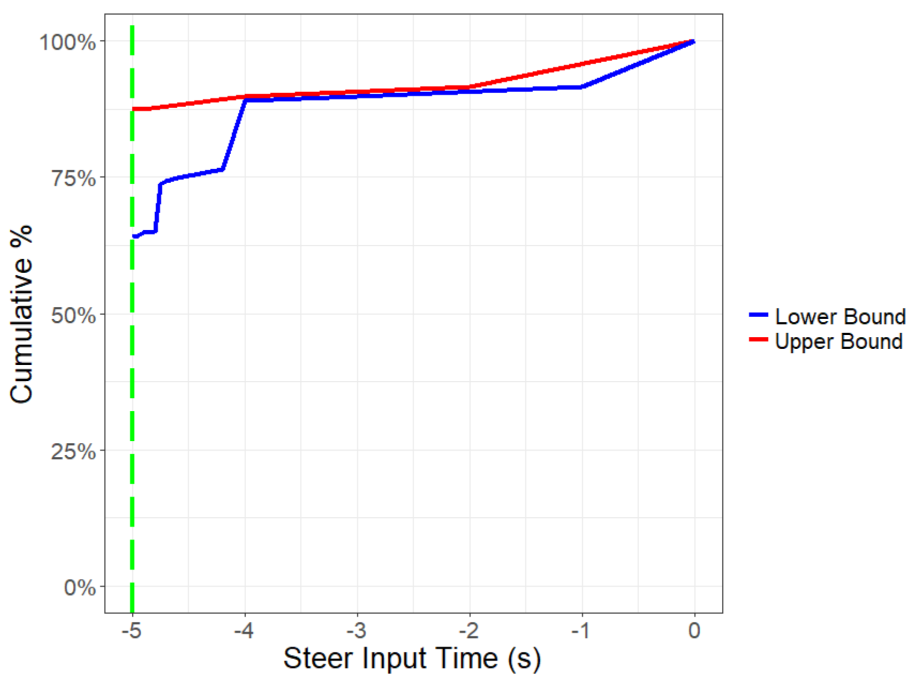


Figure 19. Distribution of Time to Steering Input (n = 50) – Road Departure NASS/CDS

3.2.4.5 Pre-Crash Accelerator Pedal Input

Figure 20 shows the distribution of accelerator pedal input time. As shown in the figure, a total of 136 EDRs in the dataset recorded pre-crash accelerator pedal position information. Only about 8 percent of the drivers in the intersection dataset released the accelerator at 5 seconds or earlier prior to impact.

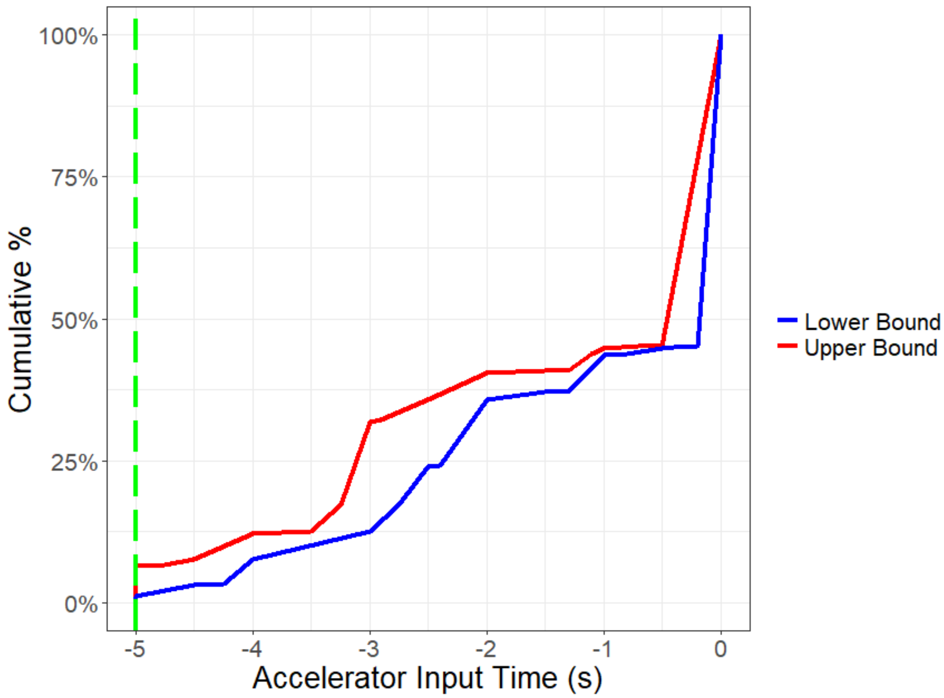


Figure 20. Distribution of Time to Accelerator Input (n = 136) – Road Departure NASS/CDS

3.2.4.6 Road Departure Traversal Time

In addition to driver pre-crash behavior, we also investigated the capability of existing EDRs to record off-road traversal time during road departure crashes. Presumably the error that led to the road departure occurred prior to leaving the road. If a vehicle was off-road longer than 5 seconds the EDR would not capture any driver action prior to the departure. A total of 212 single vehicle run-off road crashes from NASS/CDS 2012 were included in the road departure traversal time analysis.

Table 15 shows the distribution of cases by road departure side in the subset of reconstructed crashes. As shown Table 15, the majority of the road departure events are right-side departures.

Table 15. Distribution of Road Departure Side – Road Departure NASS/CDS

Road Departure Type	Count
Drive Off Road – Right Side	142
Driver Off Road – Left Side	70
Total	212

Figure 21 shows the distribution of time intervals from the point of departure to initial impact. As shown by the figure, the median time of departure to initial impact was approximately 1.2 seconds. Nearly all vehicles in the subset of road departure crashes reached the initial impact point in less than 5 seconds.

Figure 22 shows the distribution of time duration between the point of departure and final rest. Similar to the distribution of time duration between departure to initial impact, nearly all vehicles in the subset of road departure crashes reached the final rest position in less than 5 seconds. The median time of departure to final rest was approximately 1.5 seconds, and the maximum time between departure to final rest was 6 seconds.

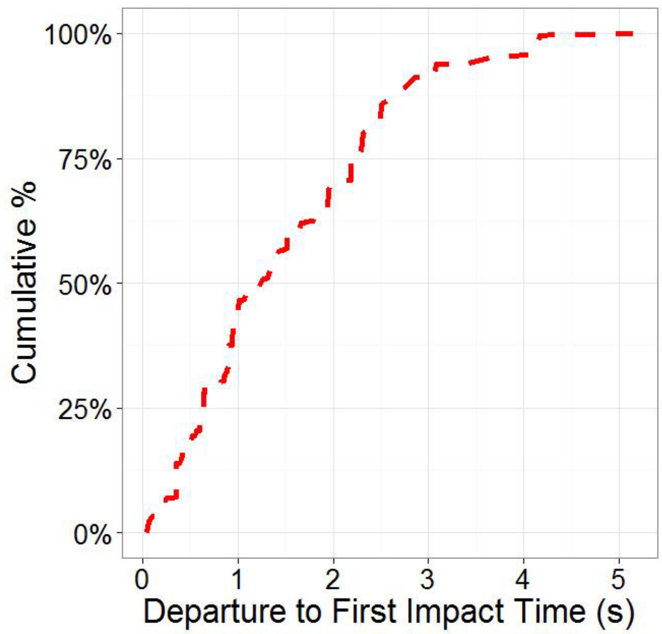


Figure 21. Distribution of Vehicle Road Departure to First Impact – Road Departure NASS/CDS

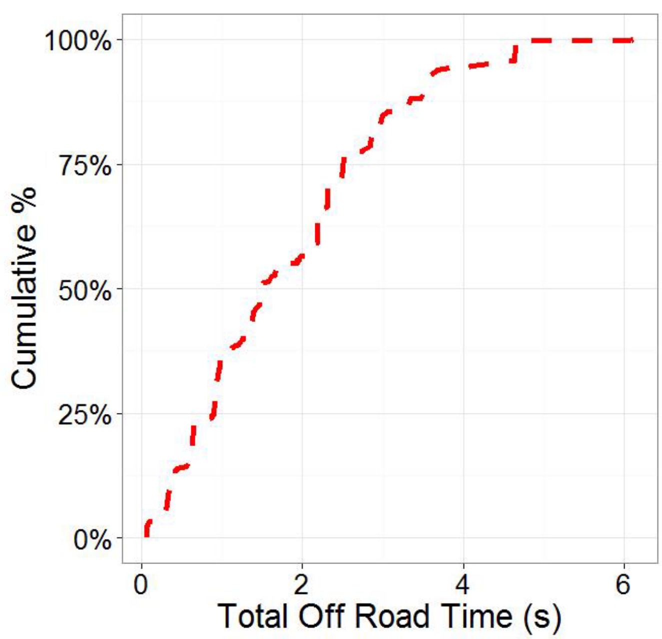


Figure 22. Distribution of Vehicle Road Departure to Final Rest (Total Off Road Time) – Road Departure NASS/CDS

3.2.4.7 Discussion and Conclusions

The last subtask analyzed vehicles in road departure crashes. The approach was similar to the previous analysis of rear-end and intersection crashes, and examined driver pre-crash maneuvers from EDR data extracted from vehicles involved in road departure crashes. An additional analysis of road departure traversal was completed using reconstruction of selected single-vehicle road departure crashes from NASS/CDS 2012. A total of 415 EDRs downloaded from NASS/CDS 2000-2015 were included in the analysis of driver pre-crash maneuver, and 212 vehicle reconstructions were included in the analysis of road departure traversal time.

The analysis showed that the 5-second EDR recording duration was not sufficient to capture all driver pre-crash maneuvers during road departure crashes. The "Upper Bound" measurement estimated that approximately 35 percent of drivers in road departure crashes who applied brakes did so 5 seconds prior to impact or earlier. There were few cases with steering data, though the fraction of cases studied show that 88 percent of cases exhibit some steering angle 5 seconds prior to impact or earlier. Approximately 8 percent of EDR's in striking vehicles showed earliest accelerator release at 5 seconds.

In addition, the results showed that the current EDR recording duration requirement was able to capture the time duration off-road in nearly all road departures. Nearly all 212 vehicles in the subset of road departure crashes reached the initial impact point in less than 5 seconds. Similarly, the time duration between initial departure to final rest was less than 5 seconds for almost all vehicles. In a typical road departure event the initial impact point is often the final rest. For example, a vehicle may veer off the roadway and strike a nearby utility post and come to rest; therefore we expect that for the majority of the events the time duration between initial impact and final rest differs only slightly, if at all.

3.3 Analysis of NMVCCS EDR Dataset

3.3.1 Dataset Summary

Table 16 shows the dataset summary of EDRs downloaded from NMVCCS crashes. From 2005 to 2007, NMVCCS investigated 6,949 cases and collected 433 EDR downloads. To be included in our analysis, we required that the vehicle from NMVCCS must have been involved with in single-event crash, resulting in an air bag deployment or a delta V greater than 5 mph. Several crashes in NMVCCS contained zero case weights. These zero-weight events were either cases investigated during the initial phase in period, or there were invalid/missing police crash reports (PCR) for the particular case. For the following analysis, events with zero weight and case weight greater than 5,000 have been excluded. The resultant dataset contained EDRs from 50 vehicles involved in the crash modes of interest (rear-end, intersection, and road departure). All 50 vehicles in the final dataset were GM vehicles. Due to the small sample size in the NMVCCS database, distributions of driver pre-crash behavior, similar to NASS/CDS, did not result in meaningful conclusions. Therefore, distribution of pre-crash maneuvers were omitted for the NMVCCS analysis.

Table 16. Dataset Summary of EDRs - NMVCCS

Group	Count
All EDRs	433
EDRs With Deployment Event or DV > 5 mph	231
EDRs With Pre-Crash Data	134
EDRs With Single Event	82
EDRs With Non-Zero Weight and Weight < 5,000	62
EDRs in Crash Modes of Interest*	50
EDRs in Rear-End Crashes	11
EDRs in Intersection Crashes	32
EDRs in Road Departure Crashes	7
* All 50 Vehicles Were GM Vehicles	

Figure 23 shows a histogram and weighted cumulative distribution of model years of all 50 vehicles in the final dataset. The blue histogram shows the unweighted frequency and the red line shows the weighted cumulative distribution of vehicle model years. As shown in the figure, the most common vehicle model year was 2002.

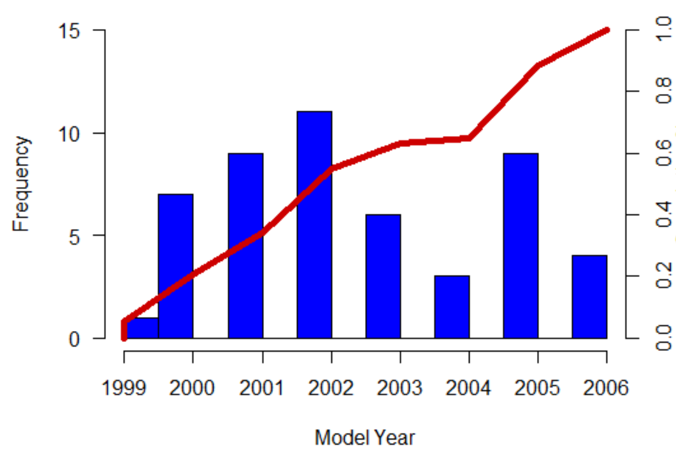


Figure 23. Histogram and Weighted Cumulative Distribution of Vehicle Model Year - NMVCCS

3.3.2 Frequency of Vehicle Failure

One of the unique aspects of the NMVCCS is the detailed vehicle malfunctions reported by the on-site investigator. For each NMVCCS event in the dataset, the following vehicle failures were examined to determine if EDRs were involved in crashes with vehicle malfunctions.

- Tire/wheel deficiency (e.g., blowout, air out, etc.)
- Braking system deficiency or malfunction
- Engine related problem (e.g., stalling, missing, and throttle problems)
- Transmission deficiency or malfunction

- Suspension component (shock absorber, strut, etc.) malfunction contributed to loss of stability or control
- Lighting component (headlights, taillights, etc.) malfunction
- Steering component malfunction

After examining the dataset, none of the 50 vehicles in the final dataset were reported as having any of the above malfunctions.

4 Phase 2 – Detailed Study of Selected Crash Modes

In the second phase of the project, we analyzed the data from two NDSs, the 100-Car NDS and the Second Strategic Highway Research Program (SHRP-2) NDS, to determine the duration of driver in-car actions in following, intersection traversal, and lane departure events. The EDR dataset analysis conducted in the first phase provided an estimate of the frequency with which EDRs fail to record sufficient duration of pre-crash data. However, the EDR analysis cannot provide insight into what duration beyond 5 seconds of pre-crash data is needed to capture crash causation. The emphasis in the second phase of the project was on driver actions in normal driving. Crashes are rare in NDS studies, but when available were reported in this second phase of the project.

4.1 Methodology

4.1.1 Data Sources

4.1.1.1 100-Car NDS

This phase of the study analyzed data extracted from the 100-Car NDS, a large-scale NDS conducted by the Virginia Tech Transportation Institute. Approximately 100 vehicles were instrumented with cameras and inertial measurement devices along with personal computers to collect and store the data. Participants drove the vehicles normally without a researcher present for approximately one year per vehicle. The result was over 1.2 million miles traveled by participants in over 139,000 trips. Vehicle instrumentation included a yaw rate sensor, dual axis accelerometers, and a GPS navigation unit. In addition, radar sensors were mounted on the front and rear of the vehicles to track other vehicles. The vehicles were equipped with the Road Scout lane-tracking system to detect proximity to lane markings. All data was sampled at a rate of 10 samples per second. Five cameras offered continuous views in and around the vehicle.

4.1.1.2 SHRP-2 NDS

This phase of the study also analyzed data extracted from the SHRP-2 NDS, a recent NDS led by the Transportation Research Board of the National Academies of Science. As in the 100-Car NDS Study, SHRP-2 used unobtrusive retrofitted instrumentation to collect data on everyday driving situations. In all, 3,362 private vehicles equipped with cameras, radars, and other sensors collected a total of 6,650,519 trips, accounting for 49,657,037 miles and over 3 years of data. The SHRP-2 effort was the largest NDS to date in terms of both the number of vehicles and driving area. Six study centers spread across six U.S. cities were involved in the data collection effort. Due to the wide geographic spread of the data collection locations and large number of participants, SHRP-2 may better capture the diversity of driver behavior nationwide.

4.1.2 100-Car NDS Case Selection

A total of 108 primary drivers and 299 secondary drivers were included in the 100-Car NDS study period in which all driving in an instrumented vehicle was recorded (Scanlon, Sherony, & Gabler, 2016b). Primary drivers were the primary owners or leasees of the instrumented vehicles. Secondary drivers occasionally drove the vehicles. Primary drivers accounted for 89 percent of all miles driven during the study period. The entire 100-Car NDS database contains approximately 1.2 million miles of driving, of which 1,119,202 miles were driven by primary drivers in 139,367 trips (McClafferty & Hankey, 2010).

Some primary drivers drove in several different vehicles. For the current study, only trips where a primary driver was driving in the vehicle that was most frequently used during the study, i.e., the primary vehicle, were selected. Two drivers were excluded because they were enrolled in the study for very short periods of time resulting in few trips. These two drivers were excluded, leaving 106 primary drivers.

Prior to the analysis, the status of all time-series data was inspected. Instrumentation data such as the front-facing radar, vehicle speed, brake switch status, yaw rate signals, and lane tracking signal were checked for missing or invalid data. The following study only included vehicles that had valid radar, brake switch, speed, yaw rate, and longitudinal acceleration data in at least 60 percent of all trips and 60 percent of all distance traveled. The 60 percent threshold was determined by a distribution of distance traveled and trips with valid sensor data. For most other drivers, the proportion of distance and trips traveled with valid data were proportional.

4.1.3 Rear Crashes

4.1.3.1 SHRP-2 Case Selection

In the SHRP-2 database 111 cases of subject vehicles being involved in rear-end crashes as the striking vehicles were identified. For each of these 111 crashes, approximately 30 seconds of pre-crash data is available. Prior to any analysis, the status of all relevant time-series data was inspected. Instrumentation data such as the accelerator pedal status, brake switch status, and steering wheel position were checked for missing or invalid data. Each analysis of the following study only included vehicles that had valid, relevant data. For example, if a case has valid accelerator and brake data but invalid steering data, that case would be included in the accelerator and brake analysis but excluded from the steering analysis.

4.1.3.2 100-Car NDS Automated Lead Vehicle Identification

The research team used a previously developed automated lead vehicle identification algorithm to extract relevant braking events and identify the correct lead vehicle in the 100-Car NDS study data (Kusano, Montgomery, & Gabler, 2014a). The accuracy of the automated search algorithm was validated against video inspection, in which our researchers manually examined video footages from 323 trips containing 3,765 miles of travel and 115 hours of data. For each braking event, the results of the automated search algorithm were compared to the results of the manual video review. The comparison between the algorithm output and the manual inspection shows that our automated search algorithm correctly identified the lead vehicle in 90 percent of the validation sample.

4.1.3.3 Brake Duration

One metric we used to characterize driver braking behavior is braking duration. In this study braking event is detected based on the recorded brake light switch status. Braking duration was calculated as the total time duration between when the driver applies the brake (brake switch "ON"), and when a driver takes the foot off the brake (brake switch "OFF").

4.1.3.4 Time to Collision

One of the common metrics of quantifying driver braking behavior is time-to-collision (TTC). TTC measures the time it takes a subject vehicle to collide with the target vehicle, assuming the two vehicles maintain constant acceleration and their paths do not vary. NHTSA's current forward collision warning confirmation test requires the system to deliver a warning within a specified TTC threshold when approaching a stopped, decelerating, and constant speed vehicles (NHTSA, 2013).

The equation for TTC is derived based on the equations of motion in which the distance between two point masses is calculated as shown in Equation 1.

$$D = D_o + \frac{1}{2} * A_r * t^2 + V_r * t \qquad \textit{Equation 1}$$

Where D is the distance between two objects at time t, D_0 is the distance between the two objects, A_r is the relative acceleration of the objects with respect to time t, and V_r is the relative speed of the two objects with respect to time.

For each braking event, we can compute the TTC by solving for the time (t) when the distance between the two vehicles (D) equals to zero. The quadratic formula was used to transform the equations of motion in Equation 1 to solve for the time, as shown in Equation 2.

$$TTC = \frac{-V_r - \sqrt{{V_r}^2 - 2 * A_r * D}}{A_r} \qquad \textit{Equation 2}$$

Where V_r is the relative speed between the two vehicles, A_r is the relative acceleration between the vehicles, and D is the distance between the two vehicles.

Characterizing TTC at the start of the braking event provides a threshold at which the driver feels it is necessary to begin braking. Driver braking in pre-crash scenarios is typically initiated later than normal and therefore have lower TTC as compared to normal braking events (Lee et al., 2007). The time threshold of TTC during normal braking events provide an upper limit of time duration to characterize driver input in pre-crash scenarios. In this study we are also interested in the minimum TTC and the time to minimum TTC. Minimum TTC is calculated as the shortest TTC the driver experiences during each braking event. The time to minimum corresponds to the elapsed time between when the driver reached the minimum TTC and the start of the braking event.

4.1.3.5 Time to Closest Approach

Another key brake event time duration in NDSs is the time to closest approach. The time to closest approach is calculated as the time between driver brake applications to time when the instrumented vehicle is at the closest longitudinal distance with respect to the lead vehicle. Figure 24 shows the progression of longitudinal range during each stage of a theoretical braking event. In the following study, longitudinal range was directly measured by the on-board radar.

In the example shown in Figure 24 instrumented vehicle driver (blue vehicle) response to a slow-moving lead vehicle (red vehicle) in front and initiates braking in stage 1. As the driver continues to apply braking the blue vehicle continues to approach the red vehicle and eventually reach the closest approach distance in stage 2. Finally, the lead vehicle begins to accelerate and the braking event ends in stage 3 as the two vehicles separate.

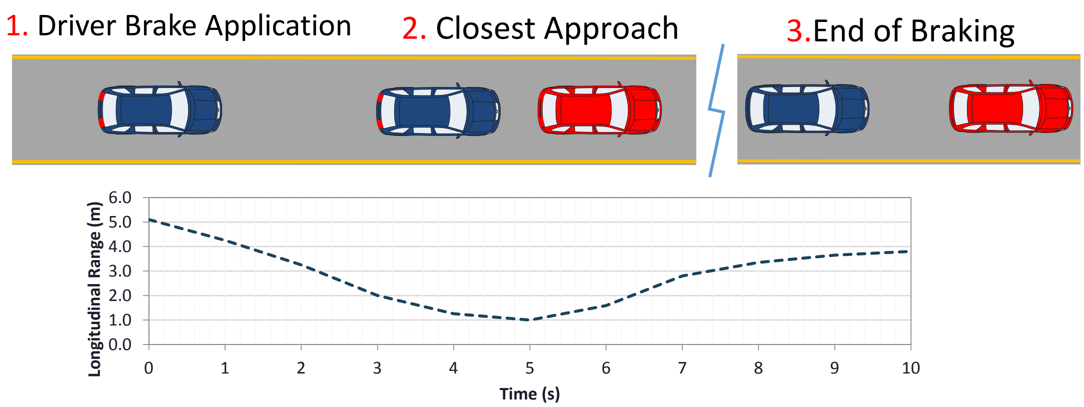


Figure 24. Longitudinal Range During a Theoretical Normal Braking Event

4.1.3.6 Accelerator Release

One metric we used to characterize driver pre-crash behavior is final accelerator release prior to impact with the lead vehicle. Final accelerator release was detected based on the accelerator status recorded during the SHRP-2 study. In this study accelerator status is recorded as percent depression where 0 indicates the driver is not on the accelerator at all and 100 would be a fully depressed accelerator. Many cases of accelerator status had to be corrected for a calibration offset prior to analysis. Time of final accelerator release was then calculated as the time point prior to impact, where impact is time 0, when the driver releases the accelerator (accelerator status "0") for the final time.

4.1.3.7 Brake Initiation

Another metric we used to characterize driver pre-crash behavior is final brake initiation prior to impact with the lead vehicle. A braking event is detected based on the brake light switch status recorded during the SHRP-2 study. A depressed brake pedal correlates to a brake status of "1," and a released brake pedal correlates to a status of "0." Therefore, final brake initiation was calculated as the time point prior to impact when the driver depresses the brake pedal (brake switch "1") for the final time.

4.1.3.8 Evasive Steering

The final key metric used to characterize driver pre-crash behavior is evasive steering maneuvers. This metric is not as straightforward as a pedal being depressed such as the accelerator and brake. Steering wheel position is recorded during the SHRP-2 study. Steering rate was calculated for each recorded point in time (every 10 ms) as the total change in steering wheel position in degrees from the prior time point. To classify evasive steering from normal steering, some steering rate threshold is needed. By manual inspection of the few crashes with steering data, a threshold of 500°/s was set as an indicator of evasive steering. Time of evasive steering initiation was then calculated as the time point prior to impact when the driver's steering rate equaled or exceeded 500°/s for the first time.

4.1.4 Lane Departures

4.1.4.1 SHRP-2 Case Selection

The SHRP-2 NDS includes road departure crashes that are either of minor severity, such as curb strikes, or major severity and police reportable events, such as run-off the road events. To select only the relevant subset of road departure crashes from the SHRP-2 NDS the analysis of the road departure crash only included events that satisfy the following criteria.

- Event Severity = Crash
- Incident Type = Left or Right Road Departure
- Crash Severity = Most Severe, or Police-Reportable Crash

4.1.4.2 Lane Departure Definition

In this analysis lane excursions are defined as minor lane departures that occur as a result of normal lane keeping behavior, and do not result in crashes. Figure 25 shows the phases of a typical lane excursion event. While most normal lane excursions do not result in crashes; in certain instances such as driver inattention these lane excursions can lead to road departure crashes if the driver does not initiate corrective measures in time. Therefore, a characterization of normal lane excursion duration provides a guideline to establish sufficient EDR recording duration to capture driver lane keeping behavior prior to road departure crashes.

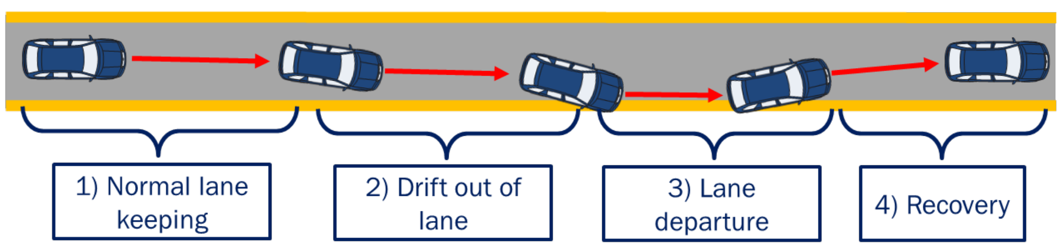


Figure 25. Phases of a Typical Lane Excursion Event

One of the major challenges in determining the duration of normal lane excursion is defining the beginning of the lane excursion event. One metric of defining the excursion duration is to measure the total vehicle out of lane time, defined as the total time between when the vehicle's leading edge touches the lane line to when the vehicle returns to the lane, as shown in Phase 3 in Figure 25. However, the duration of vehicle out of lane does not capture the entire lane excursion event, as the driver typically begins to drift out of the lane before the vehicle's edge crosses the lane boundary.

To fully capture the lane excursion event, we will take advantage of an automated tool that we developed to characterize lane departures using the 100-Car NDS data in an earlier project (Johnson et al., 2016). Using the lane marking proximity data element of the 100-Car NDS dataset, both the distance to lane crossing and the lateral velocity of the vehicle can be computed, as shown in Figure 26. "Distance to lane boundary" (DTLB) measures the distance between the vehicle edge and the lane edge, while lateral velocity measures the rate of change of the distance to lane boundary. Combining distance to lane crossing and lateral velocity, we can identify the occurrence of a lane departure event along with the driver's efforts to recover. To identify the point at which the driver began to drift out of the lane, we will work backwards in time from the time of departure to the time point where the driver was exhibiting normal lane keeping. Because lane keeping exhibits some variability within the lane, the point of normal lane keeping will be determined using a stochastic approach that we have successfully used in our analysis of lane keeping and overtaking using 100-Car NDS data (Chen et al., 2015a, 2015b).

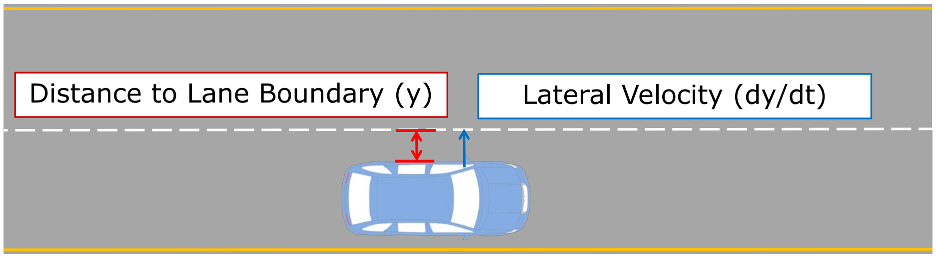


Figure 26. Vehicle Kinematic Parameters Used to Estimate Start of Lane Change

Another challenge associated with determining the start of the lane excursion event is that there are a wide variety of driving scenarios and lane keeping behaviors. Different drivers may exhibit different lane keeping preferences, and different scenarios may prompt the drivers to adjust their lane keeping behavior. Therefore, our algorithm for finding the start of driver drift out of lane must be dynamic and capable of adapting to different scenarios.

Our solution to developing an adaptive driver drift out of lane detection algorithm is based on the idea that if we observe the driver's "normal" lane keeping behavior for a period of time, then we may be able to detect when driver lane keeping behavior falls outside of what is "normal" for each specific event. We defined normal driving behavior in this study using a technique adapted from Fujishiro and Takahashi (2015). Figure 27 shows an example from the Fujishiro and Takahashi study, in which driver lane keeping behavior was characterized as a function of distance to lane boundary and lateral velocity. In the Fujishiro and Takahashi study, a bivariate normal distribution was constructed using the DTLB and lateral velocity time series data, and normal driving behavior was defined as any data within the contour line representing 99 percent probability, as shown by the magenta circle.

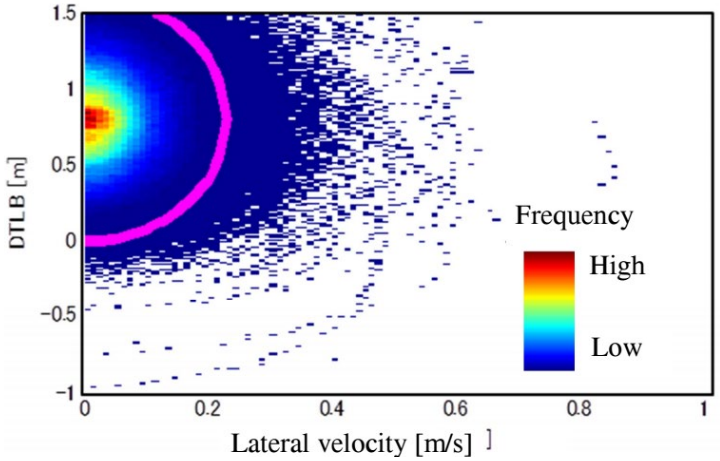


Figure 27. Lateral Velocity and Distance to Lane Boundary (DTLB) Distribution From Fujishiro and Takahashi (Reproduced With Permission From Authors)

4.1.4.3 Bivariate Normal Distribution

The bivariate normal distribution is an extension of the univariate normal distribution. Similar to univariate normal distribution, the bivariate extension computes the probability distribution as a function of two variables, and has a probability of density function of the following form:

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}\exp(-\frac{1}{2}Q(x,y)) \qquad \textit{Equation 3}$$

where the function Q takes the form:

$$Q(x,y) = \frac{1}{1-\rho^2}[(\frac{x-\mu_x}{\sigma_x})^2 + (\frac{y-\mu_y}{\sigma_y})^2 - 2\rho\frac{(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}] \qquad \textit{Equation 4}$$

The parameters σ_x σ_y and μ_x μ_y represents the standard deviation and mean of the variable x and y, respectively. The parameter ρ is the population correlation coefficient, which measures the dependence of two variables and is computed based on the covariance of the variables x and y and their respective standard deviation, as shown in Equation 5.

$$\rho(x,y) = \frac{COV(x,y)}{\sigma_x\sigma_y} \qquad \textit{Equation 5}$$

The probability of each x and y combination is calculated by taking a surface integral of Equation 5, as shown in Equation 6. The desired contour boundary is determined by finding x and y values of the same probability.

$$P(x,y) = \iint_S f(x,y)dS \qquad \textit{Equation 6}$$

4.1.4.4 Steering Maneuver Detection Algorithm

The driver drift out of lane detection algorithm follows the 3 steps shown in Figure 28. The algorithm first detects instances when the vehicle departs the lane line, as shown in Figure 28 (a). The next step of the algorithm takes available time series data, up to 60 seconds before vehicle lane crossing to 5 seconds before vehicle lane crossing, and models normal driver lane keeping behavior by DTLB and lateral velocity, as shown in Figure 28 (b). Similar to the Fujishiro and Takahashi study, we defined normal driving behavior by creating a bivariate normal distribution of the DTLB and lateral velocity data prior to vehicle lane crossing and an associated 95 percent probability contour line. If less than 60 seconds of quality lane tracking data is available, then the algorithm uses any available data to model normal driving behavior. If the lane crossing occurred less than 5 seconds from the start of the trip, then the particular event is omitted from the analysis, as not enough data is available to model driver lane keeping behavior.

The last step of the algorithm, shown in Figure 28 (c), takes the available time series data from 5 seconds before vehicle lane crossing to time of vehicle lane crossing to determine the earliest time at which the lane keeping behavior is outside of the 95 percent boundary established in step (b). The process shown in Figure 28 was repeated for each lane change event to create a unique "normal" lane keeping threshold for each event.

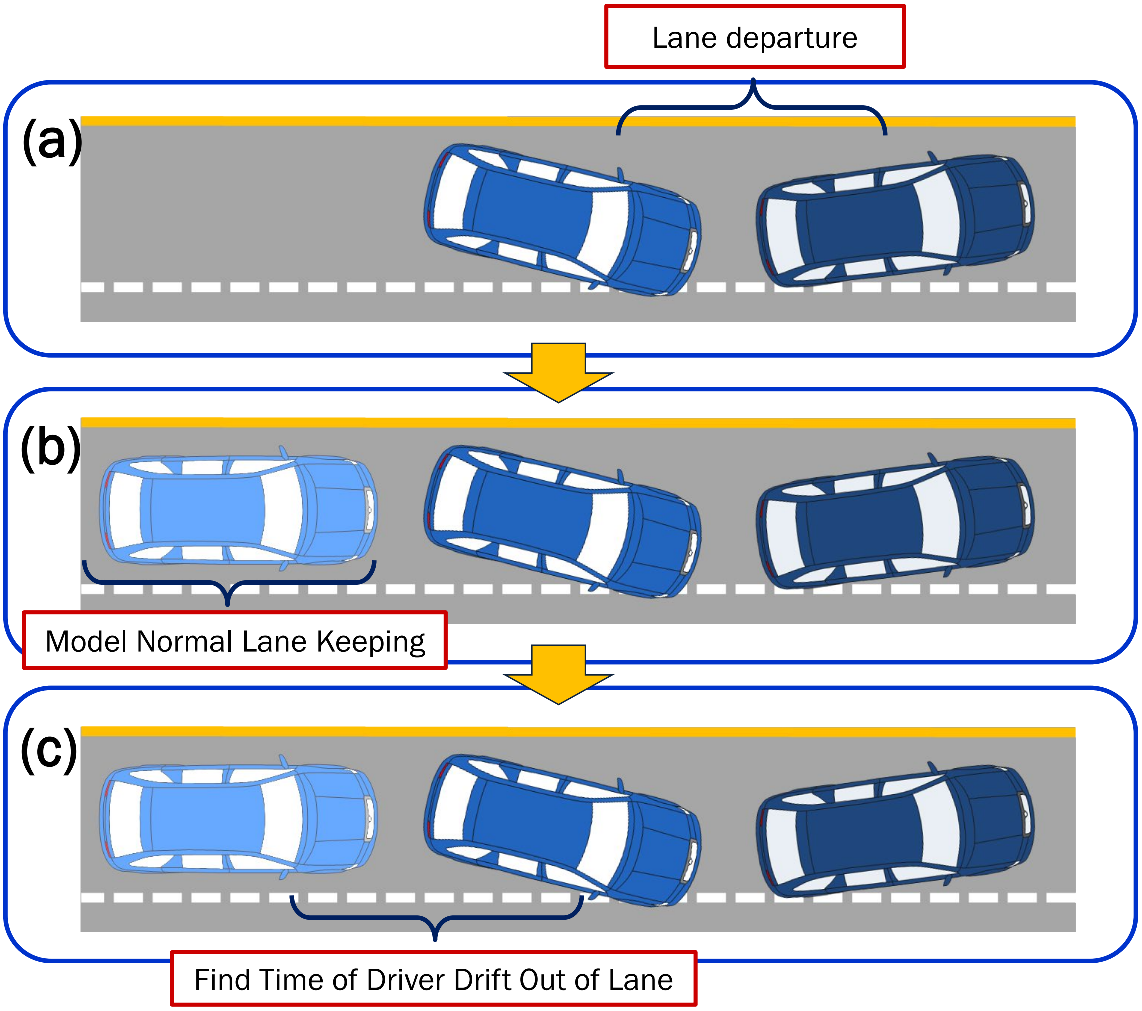


Figure 28. Steering Maneuver Detection Algorithm Procedure

4.1.4.5 Data Signal Processing

To select only the reliable lane tracking data, the following selection criteria were enforced.

- Lane tracking confidence = 100 percent
- Lane departure event is not a part of a lane change
- Lane tracking reports positive lane width
- Vehicle speed greater than 40.2 kph (25 mph)
- Exclude potential outliers by Cook's Distance

The 100-Car NDS provides confidence levels for both left and right lanes in the on-board lane tracking software. For the current study, to include sufficient data to model normal lane keeping behavior while retaining reasonable data quality, we required 100 percent lane tracking confidence and positive lane width for all data points included in the analysis.

After filtering out the unreliable lane tracking data points, we created a multilinear regression model based on the remaining DTLB and lateral velocity data and calculated the Cook's

Distance for each data point. Cook's Distance measures the influence of each point on the regression model if the data point was excluded from the model, higher Cook's Distance indicates significant influence on the regression and may be used to identify potential outliers. Previous studies have used Cook's Distance greater than 3 times the average Cook's Distance of the sample as an indication of an outlier (Stevens, 2009). The following study excludes data points with Cook's Distances that are greater than 5 times the average Cook's Distance to exclude extreme data points and retain sufficient information.

4.1.4.6 Algorithm Validation

To validate the results reported by our algorithm, we compared the algorithm results to manual inspection of video footage of selected lane change events in the 100-Car NDS.
A total of 131 randomly selected lane change events from 112 trips were extracted as the validation sample. For each lane change event, the over-the-shoulder camera view was reviewed to determine the time stamp when the driver begins to initiate steering maneuver. In certain low lighting lane change events, such as nighttime or shadows created by nearby objects, time of steering initiation could not be determined by manual inspection, and therefore was not included in the validation sample.

Figure 29. Algorithm Validation With Manual Video Review

4.1.5 Intersection Approaches and Traversals

As seen in Figure 30, each intersection event was broken down into two phases – approach and traversal. In this study the approach phase was considered to be the vehicles' travel from the point the vehicle began decelerating from steady state velocity, to the point it reached minimum velocity. The traversal phase was considered to be the distance in which the vehicle was exposed in the intersection.

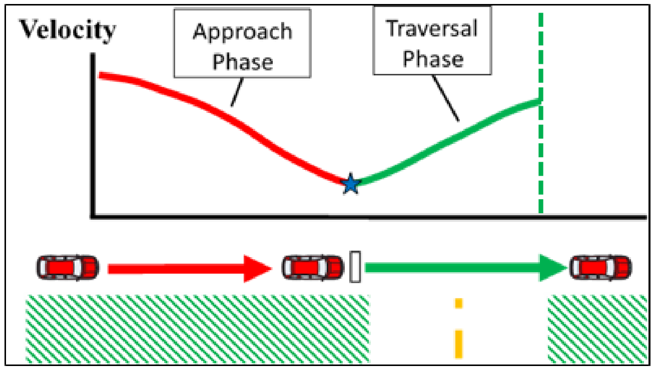


Figure 30. Breakdown of Intersection Event Into Approach Phase and Traversal Phase

Because the objective of this task was to evaluate the entire time of both the approach and traversal phase, incomplete intersection data was eliminated from the original data set. To ensure completeness, intersection approach and traversals were captured for each event analyzed, intersection events that met the following criteria were selected.

- Max approach speed must be > 15 mph
- Max approach and traversal speed must be within 15 mph of each other
- Approach and traversal recording time each must be > 5 seconds

Possible scenarios that may have caused an event to be incomplete or fall outside of the desired parameters include: an incomplete recording/transmission of vehicle data during an intersection event, or a vehicle approaching or traversing a congested intersection, causing the vehicle to slow down and speed up, artificially simulating the approach/traversal of an intersection.

The 100-Car NDS categorized each intersection event by traffic control device (TCD). Each intersection was controlled by either a stop light (signalized) or stop sign. For this study signalized controlled intersections heavily outnumbered stop-sign controlled intersections.

Each intersection event was further separated based on the driver's action approaching the intersection. These actions were broken down into complete stop, rolling stop/start, or straight through. The vehicle was considered to reach a complete stop if a minimum velocity of 3 mph or less was reached. There were very few events in which the vehicle came to a true complete stop of 0 mph, thus 3 mph was chosen as a speed slow enough to be considered completely stopped. A vehicle was considered to come to a rolling stop (for stop sign intersections) or to a rolling start (for signalized intersections) if the vehicle slowed down, but did not reach a complete stop. The reason the term "rolling stop" is used for a stop sign is that a vehicle is required by law to come to a complete stop at stop sign. The reason the term "rolling start" is used for a signalized intersection is that the driver may not have been required to come to a complete stop depending on the light signal. For example, a vehicle may be approaching a red light that turns green, causing the vehicle to slow down and start speeding back up legally without coming to a complete stop. Rolling stops and rolling starts were broken down into low speed (minimum speed of 10 mph or less and greater than 3 mph), and high speed (minimum speed of 20 mph or less and greater than 10 mph). In all other events, the drivers were considered to drive straight through the intersections, taking no action during the approach phase. Due to the fact that there was no action taken by the driver, straight-through events were excluded from the intersection events analyzed in this study.

Events were also separated by traversal action through the intersection. The actions analyzed in this study consisted of straight traversals and left turn traversals. The traversal action was determined through manual visual review of each intersection event by VTTI.

4.1.5.1 Determining Approach Time Span

To find the point that the vehicle began decelerating during the approach, the difference in velocity (dv) over a span of 5 seconds (dt) was evaluated. Starting at the point of minimal velocity, the acceleration (dv/dt) between that data point and the data point 5 seconds prior was calculated. If the acceleration (dv/dt) was greater than 0.002 g the vehicle was considered to be decelerating and the algorithm stepped a data point back in time (1/10th of second) from the previous starting point and evaluated the acceleration from that point to a point 5 second prior. The algorithm continued until the acceleration was 0.002 g or less, at which point the vehicle was considered to be at steady-state velocity. Within this span of 5 seconds, the latest point of maximum velocity was considered to be the approach starting point. This procedure ensures that the last point of steady state velocity before the vehicle began decelerating was chosen as the approach starting point. The difference in time between this point and the point of minimum velocity was defined as the approach time. Figure 31 is a simplified representation of how the algorithm picks the starting approach point.

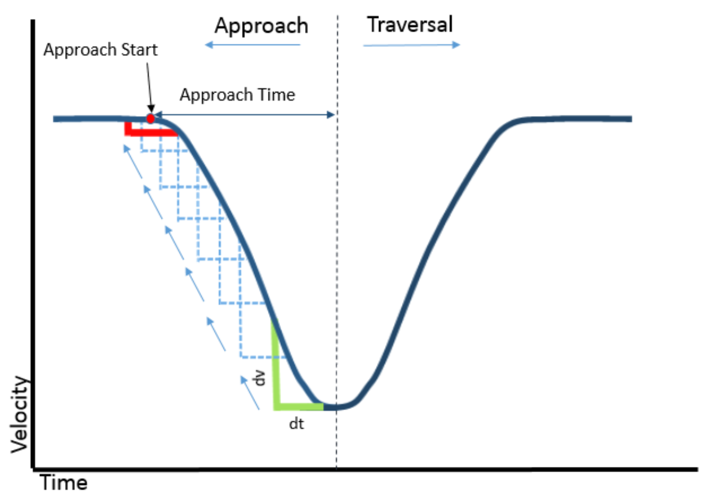


Figure 31. Simplified Representation of Algorithm in Determining Approach Starting Point

4.1.5.2 Determining Traversal Distance

To estimate the distance that the vehicle was exposed in the intersection, we assumed each intersection was a perfectly symmetrical four-way intersection with a lane width of 3.6 meters. The traversal distance depended upon the number of lanes as well as the traversal action (left turn vs straight). For a straight traversal, the traversal distance was calculated by multiplying the number of lanes by the lane width. When turning left, the driver was assumed to always turn from far-left lane to the far-left lane. Therefore, left-turn traversal distance through intersections with an even number of lanes was calculated as a quarter of a circle with the radius being the distance from the far-left boundary of the intersection to the center of the left lane as depicted in Figure 32. For left turning traversals through intersection with an odd number of lanes the distance was calculated as a quarter of an ellipse due to the turning lane. To calculate a minimal, moderate, and maximum traversal time for each intersection event, we calculated the traversal time for each event with assumed number of lanes of 2, 5, and 7. Table 17 displays the calculated distance for each intersection size. Since the vehicle was assumed to turn from the left lane to the left lane, as the number of lanes increased the turning distance became less than the straight traversal distance. The traversal time for each intersection event was considered to be the time the vehicle traveled from a minimal velocity until it reached the calculated traversal distance.

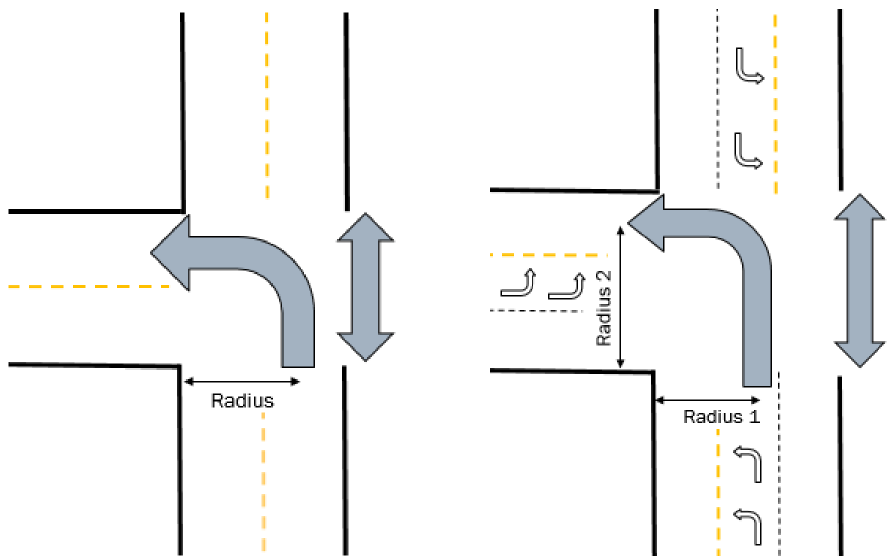


Figure 32. Diagram of Intersection Traversal Distances Used to Approximate the Time a Vehicle Is Exposed in the Intersection

Table 17. Calculated Distances for Two-, Five-, and Seven-Lane Intersection Traversals

	Traversal Distance (meters)		
	Two Lanes	Five Lanes	Seven Lanes
Left Turn	8.48	17.20	22.80
Straight	7.20	18.00	25.20

4.2 Analysis of the Required Recording Duration for Rear Crashes

4.2.1 100-Car NDS Analysis

4.2.1.1 Dataset Summary

Table 18 shows the summary of drivers and trips that contained valid sensor data. Our study extracted a total of 868,151 braking events with closing lead vehicles from 72,380 trips taken by 64 drivers. Braking events with closing lead vehicles were specifically targeted in this study due to their likelihood or resulting in rear-end crashes.

Table 18. Dataset Summary

Group	Count
Drivers	64
Trips	72,380
Braking Events With Closing Lead Vehicle	868,151

Figure 33 shows the distribution of stopped and traveling lead vehicle during the braking events. As shown by the figure, the dataset consisted of predominantly braking events with traveling vehicles, amounting to a total of 868,151 braking events and approximately 84 percent of the total braking events in the dataset.

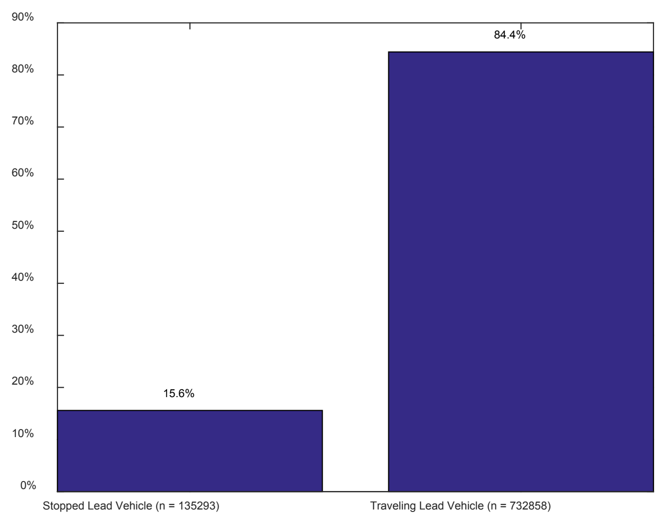


Figure 33. Distribution of Stopped and Traveling Lead Vehicles

4.2.1.2 Braking Event Duration Distributions

Figure 34 shows the distribution of brake event duration in all events. In this study brake event duration was calculated as the total "ON" duration of the brake light switch, or the time duration between when drivers depressed the brake pedal to the time when the brake pedal was released. As shown in Figure 34, the median braking duration for all the braking events in the study was approximately 2.2 seconds, and the 90th percentile was approximately 8.1 seconds.

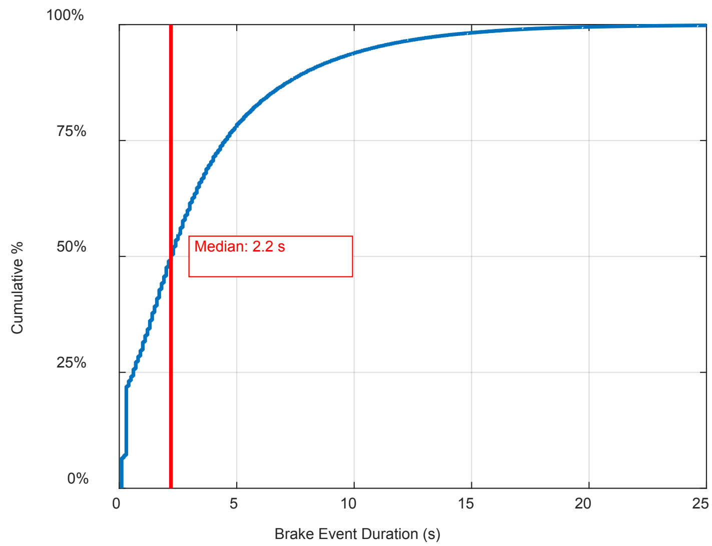


Figure 34. Distribution of All Brake Event Duration

We hypothesized that braking duration might differ by whether the lead vehicle was stopped or moving. Figure 35 shows the distribution of brake event duration for the “Stopped Lead Vehicle” and “Traveling Lead Vehicle” scenarios. As shown by the figure, braking events duration are dramatically different for the two different lead vehicle scenarios. The median duration for braking events with stopped lead vehicles was approximately 12.7 seconds, while the median duration for braking events with traveling lead vehicles was only 1.9 seconds. The large difference between the duration for the two types of braking events largely stemmed from the fact that braking events with stopped lead vehicles were likely associated with stopping for stops signs, traffic lights, or congested traffic. In this study braking event duration is considered to be from the time when brake switch is “ON” to the time when brake switch is “OFF,” therefore a portion of the event duration with stopped lead vehicle includes the time when the vehicle is stopped in traffic.

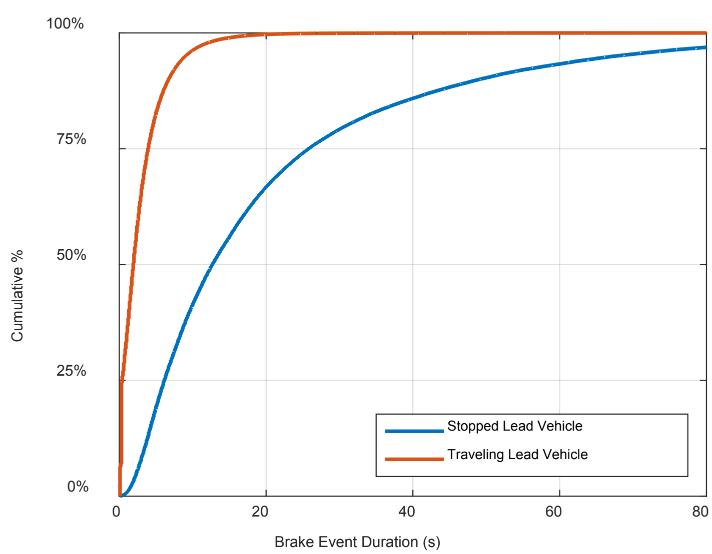


Figure 35. Distribution of Brake Event Duration

An alternative method of quantifying brake event duration is to characterize the time to closest approach. For a braking event with a stopped lead vehicle, the time to closest approach is approximately the time between brake switch "ON" to the first time point when the vehicle speed reaches zero. Figure 36 shows the distribution of time to closest approach during the braking events. Similar to the distribution of brake event duration, events with stopped lead vehicle are associated with longer time to closest approach. The median time to closest approach for braking events with stopped lead vehicles was approximately 4.3 seconds, while the median time to closest approach for braking events with traveling lead vehicles was approximately 1.5 seconds.

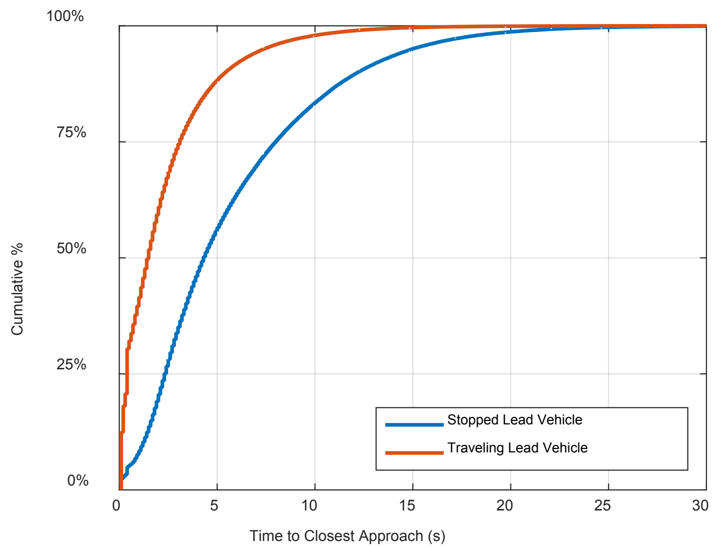


Figure 36. Distribution of Time to Closest Approach

In addition to time to closest approach, we also examined the time to minimum TTC in braking events. Figure 37 shows the distribution of time to minimum TTC for both stopped and traveling lead vehicle. As shown by the figure, braking events with stopped lead vehicles were once again associated with the longer time to minimum TTC. The median time to minimum TTC for braking events with stopped lead vehicles was approximately 2.0 seconds, while the median time to minimum TTC for braking events with traveling lead vehicles was approximately 0.3 seconds.

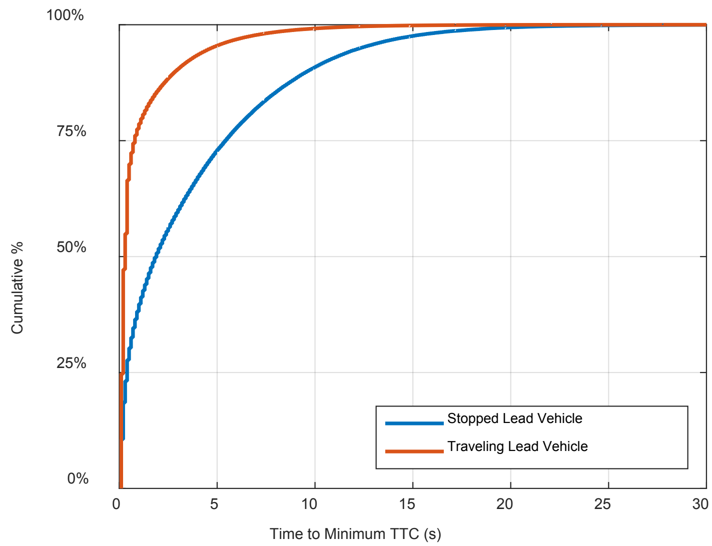


Figure 37. Distribution of Time to Minimum TTC

One hypothesis of the difference in duration between braking events with traveling and stopped lead vehicle is the nature of the two types of braking events. Drivers may recognize stopped lead vehicles well in advance and plan to brake at an earlier time, while braking events with traveling lead vehicles are likely minor speed changes or drivers braking to increase or maintain following distance. To test this hypothesis, Figure 38 shows the distribution of vehicle change in velocity during the braking event. As expected, the distribution shows that braking events with a lead vehicle experiences greater reduction in vehicle speed, the median change in vehicle velocity for braking events with stopped lead vehicles was approximately 12.4 mph, while the median change in vehicle velocity for events with traveling lead vehicle was approximately 2.5 mph. This result supports the hypothesis that drivers need longer time to achieve greater speed reduction in braking events with stopped lead vehicles.

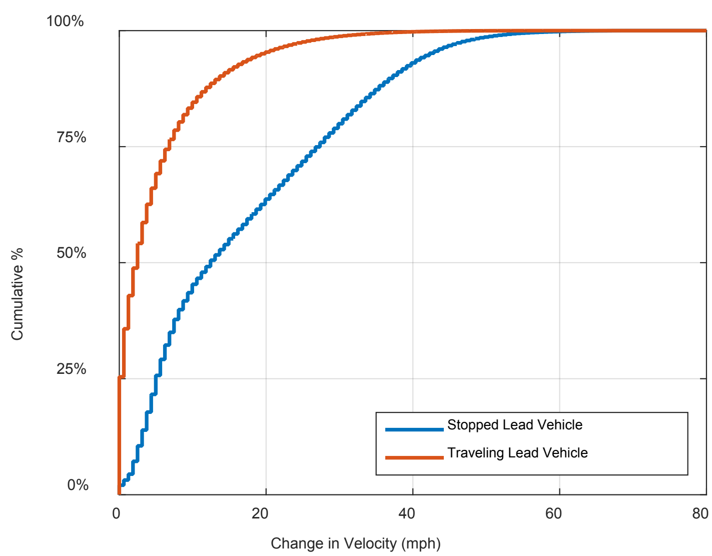


Figure 38. Distribution of Vehicle Change in Velocity

4.2.1.3 Braking Time to Collision Distributions

In addition to the characteristics of time durations during the braking events, we also characterized the distribution of TTC during braking events. Figure 39 shows the distribution of TTC at brake application with a stopped and traveling lead vehicle. As shown by the figure, braking events with stopped lead vehicles was associated with lower TTC as compared to braking events with traveling lead vehicle. The median TTC at brake application with a stopped lead vehicle was approximately 4.1 seconds, while the median TTC for braking events with traveling lead vehicles was approximately 7.8 seconds.

The distribution of braking event duration, presented in the previous subsection shows that braking events with stopped lead vehicles are generally associated with longer event duration. In contrast, the TTC distribution shown in Figure 39 shows shorter TTC for braking events with stopped lead vehicles. One potential reason for the differing trend is the effect of vehicle speed. Previous studies have shown that TTC in car-following events generally increases with increasing vehicle speed (Chen et al., 2015b; Kusano et al., 2015b, 2015a). Braking events with stopped lead vehicles, such as approaching intersections or stopped lights, are therefore more likely to be associated with lower vehicle speeds.

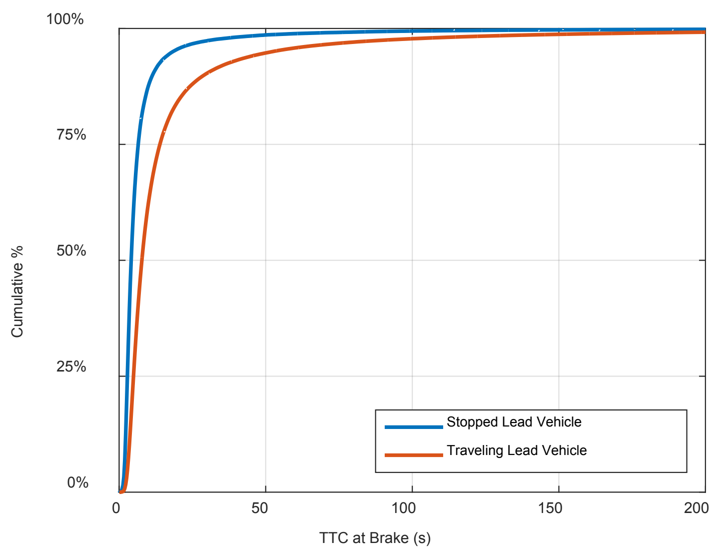


Figure 39. Distribution of TTC at Brake Application

Figure 40 shows the distribution of vehicle speed at the start of the braking event with stopped and traveling lead vehicle. As shown by the figure, median vehicle speed for braking events with stopped lead vehicles was approximately 14 mph, while the median vehicle speed for braking events with traveling lead vehicles was approximately 31 mph.

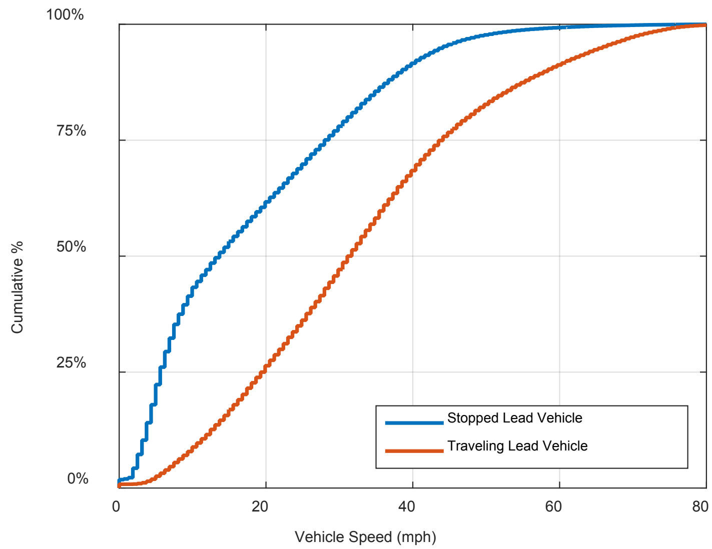


Figure 40. Distribution of Vehicle Speed at Brake Application

In addition, the difference in TTC can also be attributed to the nature of the brake applications in both scenarios. Braking with a moving lead vehicle will likely occur with a large TTC as both vehicles are moving and the driver maintains a safe following distance. These braking events with a moving lead vehicle are largely minor speed corrections and therefore are typically associated with a shorter duration. On the other hand, braking events with stopped lead vehicles occurs with a shorter TTC since the lead vehicle is stopped and the following vehicle is quickly approaching the lead vehicle. However, the duration of braking events with stopped lead vehicles is typically longer than that of similar braking events with a moving vehicle, as the driver takes longer to completely stop the vehicle in response to the stopped lead vehicle in front.

Figure 41 shows a distribution of the ratio of TTC at the onset of brake application and the time to closest approach. For each braking event, the ratio was calculated as the TTC at brake application divided by the time to closest approach. A ratio less than 1 would indicate that the time to closest approach was greater than the TTC for a particular event, and the opposite is true for ratio greater than 1. As shown in Figure 41, more than 50 percent of the braking events with stopped lead vehicles have a ratio less than 1, indicating that, while the TTC is lower for these braking events, drivers are typically prepared to stop and take a longer time to fully stop the vehicles.

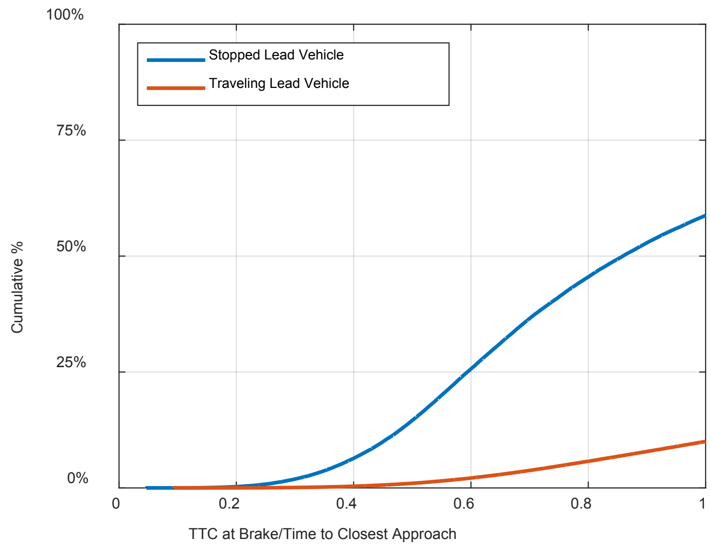


Figure 41. Distribution of Ratio of TTC at Brake and Time to Closest Approach

4.2.1.4 Discussion and Conclusions

The overall objective of this subtask was to characterize the time duration and TTC of car-following braking events, to investigate the need for an EDR recording duration longer than the current minimum requirement. The approach was to use normal braking events from the 100-Car NDS to provide a threshold to determine the required time duration to fully capture driver braking behavior.

The results show that the current standard of 5-second minimum recording duration for EDRs is not sufficient to fully capture driver behavior during braking events. Table 19 shows a tabulation of the medians and 90th percentile of the time duration distributions and TTC distributions presented in the results. The results are divided into braking events with a stopped lead or traveling lead vehicle. A braking event with stopped lead vehicle is associated with longer overall event duration, time to closest approach, and time to minimum TTC. The distribution of vehicle change in speed, shown in Figure 38, suggest that the large difference in event duration may be attributed to a driver braking to a full stop with a stopped lead vehicle, while only performing minor speed adjustments with a traveling vehicle.

The distribution of braking event types shows that braking events with stopped lead vehicles only account for 16 percent of the braking events in the sample. An argument, then, can be made that the EDR recording duration standard only needs to accommodate braking events with traveling lead vehicles to include the majority of braking events. However, previous studies on rear-end crashes in the 100-Car NDS has shown that over 81 percent rear-end crashes were associated with stopped lead vehicles (Lee et al., 2007), suggesting that a braking event with a stopped lead vehicle, although less frequent, cannot be neglected in the characteristic of pre-crash driver behavior.

Based on the distribution of brake event duration, shown in row 1 of Table 19, EDRs would need to record nearly 50 seconds to capture 90 percent of all normal braking events with stopped lead vehicles. In contrast, a recording duration of 7 seconds can capture a similar percentage of braking events with traveling lead vehicles. However, braking events with stopped lead vehicles were likely associated with long periods of standing in traffic, such as stopping in intersections or congested traffic; therefore the time to closest approach is a more practical metric of quantifying event duration. For braking events with stopped lead vehicles, the time to closest approach is approximately the time between brake switch "ON" to the time when the instrumented vehicle is stopped. For braking events with traveling lead vehicles, the time to closest approach describes the duration when the two vehicles are closing, i.e., the portion of the braking event relevant to rear-end crashes. As shown in Table 19, 90 percent of the braking events with stopped lead vehicles has a time to closest approach of less than 12 seconds.

In addition to characterizing the duration of the braking event, the current study also analyzed the distribution of TTC during the braking event. As evidenced by the median and 90th percentile TTC shown in Table 19, braking TTC in a normal driving scenario decreases from the time of initial brake application to the minimum, and then increases as the vehicle comes to a stop or the two vehicles begin to separate. Braking events with stopped lead vehicles have lower TTC, at both the start of braking and minimum, as compared to braking events with traveling lead vehicles. The difference in TTC can be attributed to the relative velocity between the lead and following vehicle in the two scenarios. Braking events with stopped lead vehicles are typically associated with greater relative velocity, as the lead vehicle is stopped and the following vehicle is quickly approaching the lead vehicle. On the other hand, when the two vehicles are both in transit, the relative velocity is lower than in stopped situations, therefore we expect higher TTC for braking events with traveling lead vehicles.

In this study TTC at the start of the braking event is especially interesting, because it signifies the time remaining until impact at the onset of the braking event. In other words, if the driver had not applied the brake, and the two vehicles continue at the current acceleration and path, how long would it take for the two vehicles to collide? In pre-crash scenarios, drivers are likely to apply the brake much later and therefore have lower TTC values as compared to normal driving braking events. As shown in Table 19, the 90th percentile TTC at brake for events with stopped lead vehicles was approximately 11 seconds. In the context of analyzing pre-crash driver behavior using EDR data, if the EDR was able to record 11 seconds of pre-crash data, this would then allow researchers to compare driver behavior during pre-crash rear-end crashes against driver behavior during normal driving scenarios for approximately 90 percent of the braking events with stopped lead vehicles.

Based on the results presented in the current study, a time duration of 11 or 12 seconds may provide sufficient time to record key elements of driver behavior during a braking car-following event.

Table 19. Distribution Medians and 90th Percentile

Distribution	**Stopped Lead Vehicle**		**Traveling Lead Vehicle**	
	Median	90th Percentile	Median	90th Percentile
Brake Event Duration (s)	12.7	49.1	1.9	6.7
Time to Closest Approach (s)	4.5	12.3	1.5	5.4
Time to Minimum TTC (s)	2.0	9.8	0.3	2.9
TTC at Brake (s)	4.0	10.7	7.7	29.0

4.2.2 SHRP-2 NDS Analysis

In this phase of the project, the research team extracted rear-end crashes from the SHRP-2 NDS to validate the time duration determined from the previous task. Individual driver inputs, such as brake initiation, steering input, and accelerator input, were examined to determine the recording time necessary to capture each unique driver input prior to a crash.

4.2.2.1 Dataset Summary

Table 20 shows the summary of SHRP-2 crashes that contained valid sensor data. Our study extracted 111 rear-end striking vehicle crashes.

Table 20. SHRP-2 Rear-End Striking Crash Event Dataset Summary

Group	Count
Valid Accelerator Status	64
Valid Brake Status	90
Valid Steering Position	9

Figure 42 shows the distribution of stopped and traveling lead vehicles during the crashes. As shown by the figure, the dataset consisted predominantly of crashes with stopped lead (struck) vehicle, amounting to approximately 79 percent of the total crashes in the dataset.

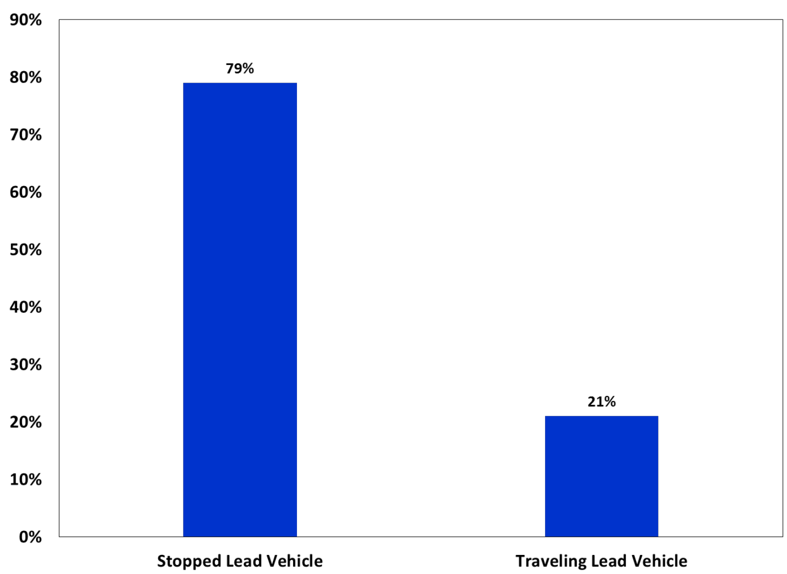


Figure 42. Distribution of Stopped and Traveling Struck Lead Vehicles

4.2.2.2 Accelerator Release Distribution

Figure 43 shows the distribution of final accelerator release time. At 5 seconds pre-crash, approximately 79 percent of drivers had released the accelerators for the final time pre-impact. Based on this SHRP-2 dataset, the median and 90th percentile of the accelerator release distribution are approximately 2 and 12 seconds, respectively.

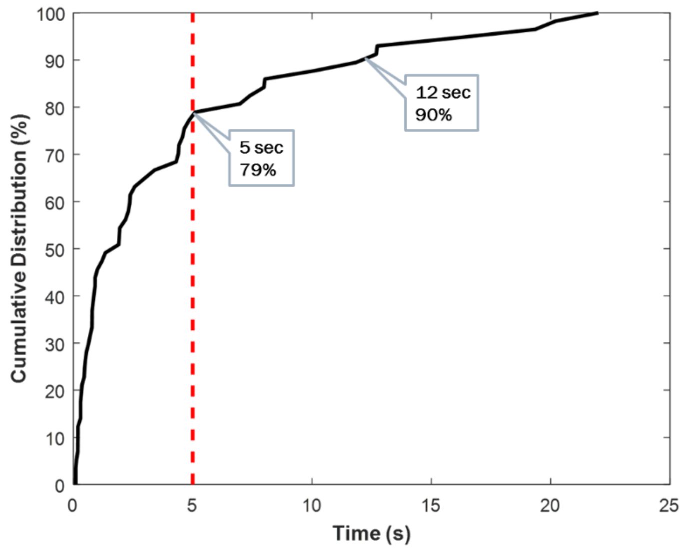


Figure 43. Distribution of Accelerator Release

4.2.2.3 Brake Initiation Distribution

In addition to the characteristics of accelerator release prior to crashes, we also characterized the distribution of brake initiation prior to crashes. Figure 44 shows the distribution of final brake initiation time. As shown by the figure, at 5 seconds pre-crash, approximately 82 percent of drivers had initiated braking for the final time pre-impact. The median and 90th percentile of the brake initiation distribution are approximately 1 and 10 seconds, respectively.

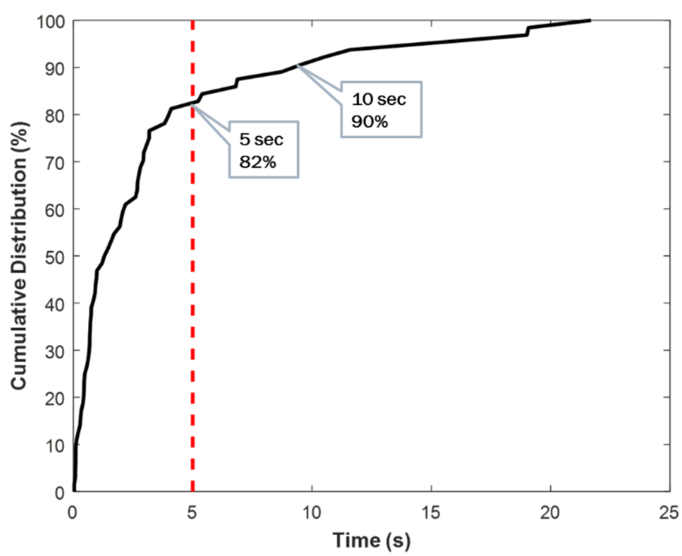


Figure 44. Distribution of Brake Initiation

4.2.2.4 Evasive Steering Distribution

Figure 45 shows the distribution of evasive steering initiation time. The beginning of all evasive steering maneuvers in this dataset were captured within 5 seconds pre-crash.

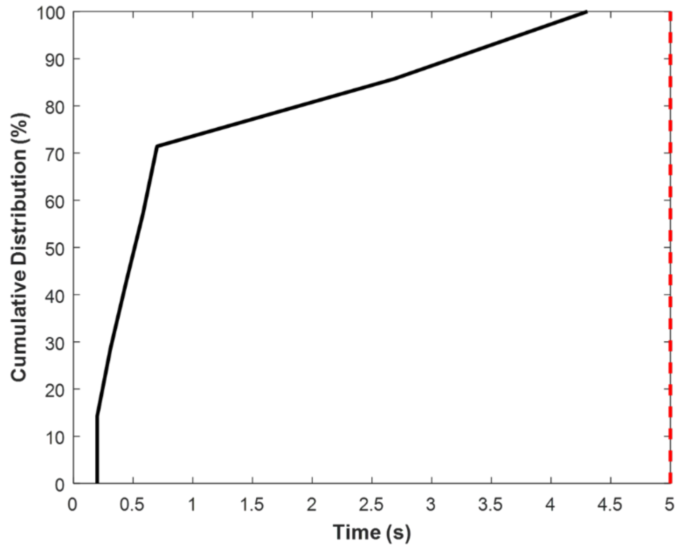


Figure 45. Distribution of Evasive Steering Initiation

4.2.2.5 Discussion and Conclusions

The SHRP-2 dataset was used to characterize driver pre-crash behavior in striking rear-end crashes to investigate the potential need for a longer EDR recording duration standard. The approach was to use striking rear-end crashes from the SHRP-2 NDS to provide a threshold to determine the required time duration to fully capture driver pre-crash behavior.

The results show that the current standard of 5-second recording duration for EDRs is not sufficient to fully capture driver pre-crash behavior during striking rear-end crashes. Table 21 shows a tabulation of the medians and 90th percentiles of the final accelerator release, final brake initiation, and evasive steering initiation presented in the results.

Based on the distribution of final accelerator release, shown in row 1 of Table 21, EDRs would need to record nearly 12 seconds to capture 90 percent of all accelerator maneuvers during a pre-crash event. In addition to characterizing final accelerator release, the current study also analyzed the distribution of final brake initiation pre-crash. As shown in Table 21, the 90th percentile time of final brake initiation for striking rear-end crashes was approximately 10 seconds. While all driver pre-crash evasive steering maneuvers were captured within 5 seconds pre-crash, this particular data sample was small and should be revisited when more data is available.

Based on the results presented in the current study, a time duration of 10 to 12 seconds may provide sufficient time to record key elements of driver behavior during a striking rear-end crash. This supports the time durations determined from the previous task (11 to 12 seconds), determining required recording duration for rear-end crashes using an analysis of 100-Car NDS data.

Table 21. Rear-Crashes in SHRP-2: Median and 90th Percentile of Distributions

Distribution	Median	90th Percentile
Final Accelerator Release (s)	1.6	11.8
Final Brake Initiation (s)	1.3	9.6
Evasive Steering Initiation (s)	0.5	2.7

4.3 Analysis of the Required Recording Duration in Lane Departures

4.3.1 100-Car NDS Analysis

4.3.1.1 Dataset Summary

Table 22 summarizes the subset of drivers and trips extracted from the 100-Car NDS that contained valid sensor data. Using the lane tracking information on-board the 100-Car NDS vehicles, we detected a total 2,548 lane excursion events from a total of 961 trips and 52 drivers.

Table 22. 100-Car NDS Dataset Summary

Group	Count
Drivers	52
Trips	961
Lane Departure Events	2,548

4.3.1.2 Lane Excursion Duration Characterization

Figure 46 shows the distribution of left-side and right-side departures in the sample. As shown in the figure, the majority of the departure events (60%) occurred on the left side of the lane/road. One rationale for the predominantly left-side departures is the availability of lane lines for the lane tracking software. On U.S. roadways, left-side road markings are typically more prominent, these include double yellow median lines and solid lane dividers. However, right-side lane lines, especially lines close to the road edge, are less likely to be painted due to the presence of sidewalks and dirt road edges.

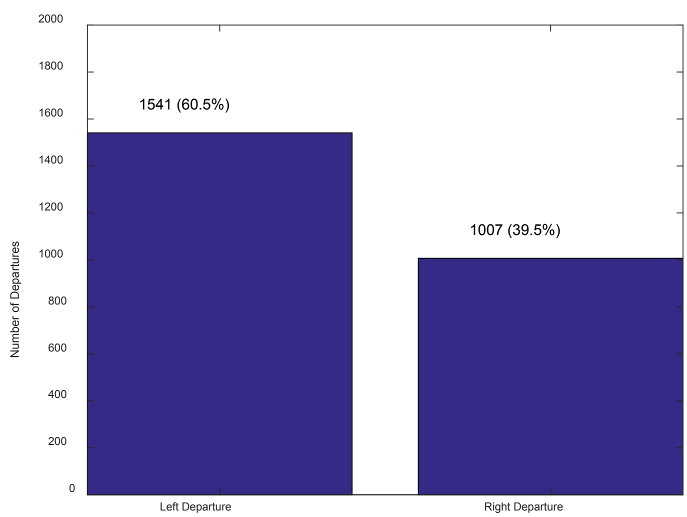


Figure 46. Distribution of Left-Side and Right-Side Departures

Figure 47 shows the distribution of duration of lane excursion, from the moment of vehicle lane crossing (departure), to the time when the vehicle is back within the lane line (recover). As shown in the figure, the median departure to recover time is approximately 1.5 seconds, and the 90th percentile was approximately 4 seconds.

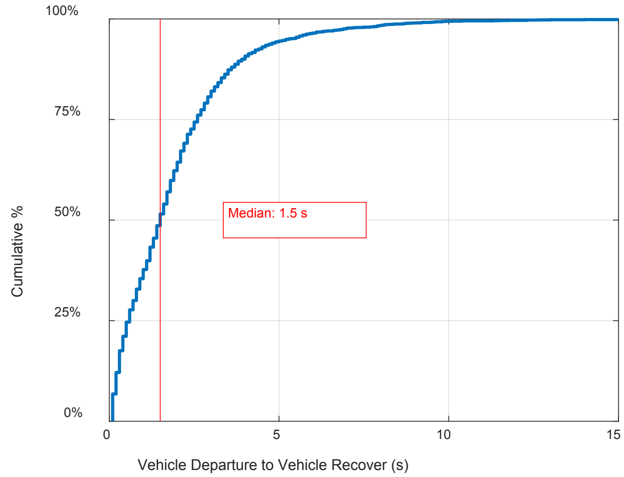


Figure 47. Distribution of Duration of Vehicle Departure to Recovery

Figure 48 shows the distribution of time of drift out of lane to vehicle departure. Time at which the driver begins to drift out of the lane was calculated using the bivariate distribution method described in the Methods sections, and the time of vehicle departure denotes the time at which the vehicle's leading edge crosses the lane line. As shown in the figure, the median time between driver drift out of lane to vehicle departure was approximately 1.4 seconds.

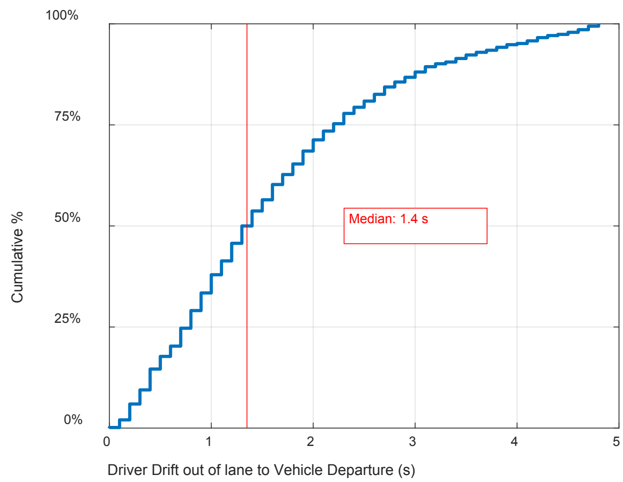


Figure 48. Distribution of Time of Drift out of Lane to Vehicle Departure

Figure 49 shows the distribution of driver drift out of lane to vehicle recovery. This distribution combines the time duration shown in Figure 47 and Figure 48, and presents the entire duration of vehicle lane excursion from the time when driver begins to drift out of lane to the time when the vehicle fully recovers back within the lane lines. As shown in the figure, the median time duration for all lane excursion events was approximately 3.2 seconds, and the 90th percentile of the distribution was approximately 6 seconds.

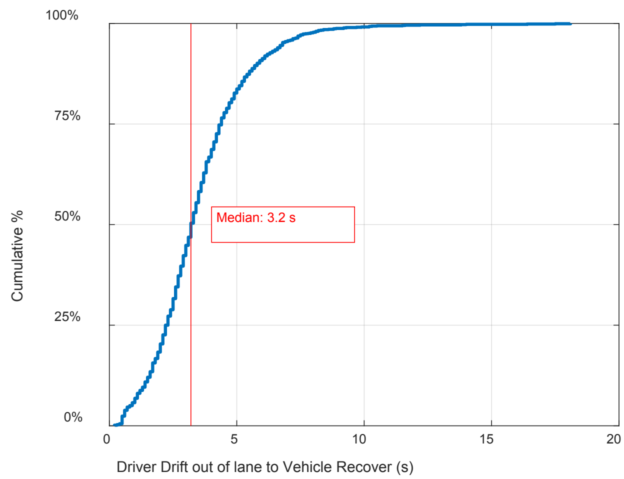


Figure 49. Distribution of Time of Driver Drift out of Lane to Vehicle Recovery

4.3.2 SHRP-2 NDS Analysis

4.3.2.1 Dataset Summary

Table 23 shows the dataset summary of the subset of road departure crashes from the SHRP-2 NDS. Twenty-six police reportable road departure crashes were extracted from the database.

Table 23. SHRP-2 Dataset Summary

Group	Count
Drivers	24
Trips	26
Road Departure Crashes	26

4.3.2.2 Road Departure Crash Duration Characterization

Figure 50 shows the distribution of brake application to road departure times. Negative values in the distribution denotes that the driver applied the brake after the vehicle departed the roadway, while positive values denotes that the driver applied brakes prior to departing the roadway. If there were multiple brake applications prior or after departure, the distribution in Figure 50 only shows the brake application time closest to the time of departure. As shown in the figure, a total of 19 events recorded valid braking information and the median time of brake application was approximately 1.9 seconds. In certain instances, the driver applied the brake as early as 21 seconds prior to departure.

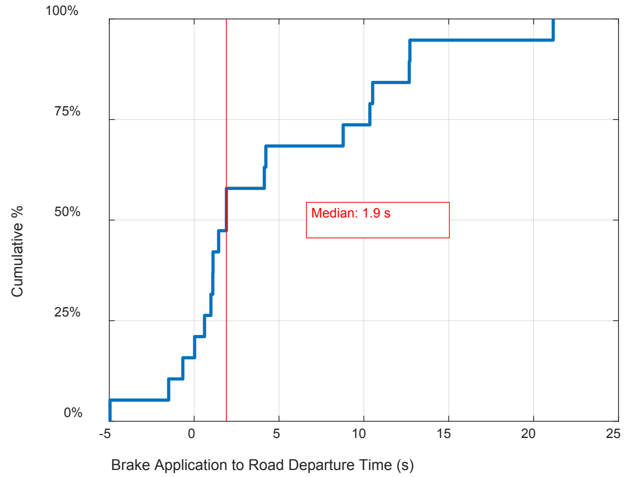


Figure 50. Distribution of Brake Application to Road Departure Time (n = 19)

Figure 51 shows the distribution of throttle release to road departure time. This distribution only shows the throttle release time closest to the time of departure. In other words, if the driver repeatedly depressed and released the throttle, the distribution in Figure 51 only considers the last throttle release prior to departure. As shown in the figure, 14 events recorded valid throttle information, and all drivers in the 14 events released the throttle more than 5 seconds prior to departure. The median throttle release time prior to departure was approximately 23 seconds.

In addition to brake and throttle input, we also examined possible evasive steering maneuver prior to departure. In this analysis, evasive steering begins with the first instance that the driver steering rate is greater than 500 degrees per second. However, only 1 road departure crash recorded valid steering data. For the single case of road departure event with valid steering wheel data, the driver initiated evasive steering maneuver at 4.8 seconds prior to departure.

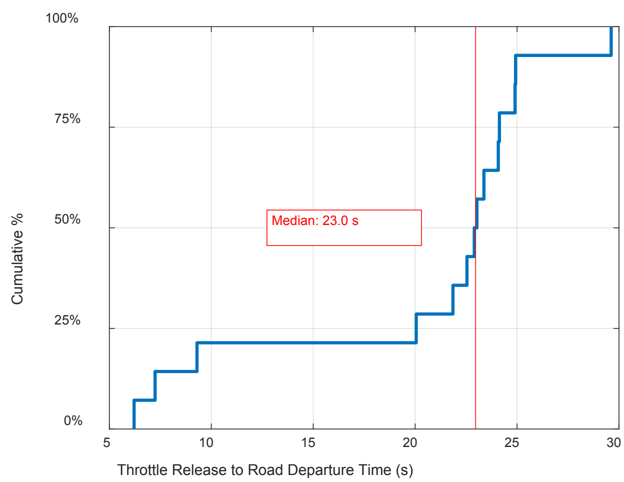


Figure 51. Distribution of Throttle Release to Road Departure Time (n = 14)

Last, this analysis also analyzed the distribution of safety systems, specifically ABS and ESC activation time prior to departure. Figure 52 shows the distribution of ABS activation time. A total of 4 events recorded ABS activation time, and in these 4 events, the system activated as early as 9 seconds prior to departure, to as late as nearly 2 seconds prior to departure.

In addition to ABS activation, we also analyzed ESC activation time prior to departure. However, none of the road departure crashes from SHRP-2 recorded valid ESC activation times.

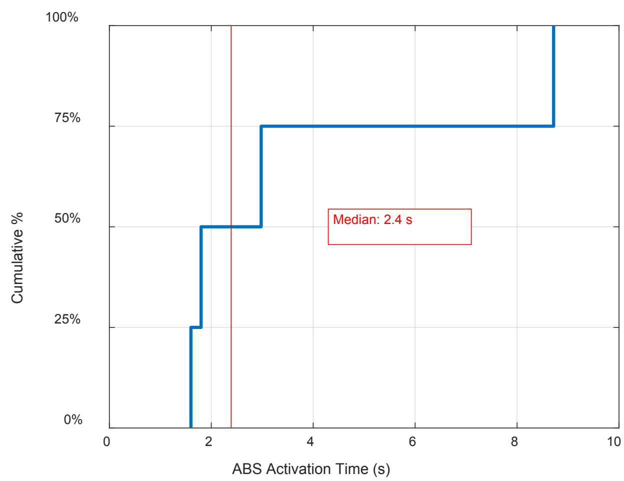


Figure 52. Distribution of ABS Activation Time (n = 4)

4.4 Analysis of the Required Recording Duration in Intersection Approaches and Traversals

4.4.1 Dataset Summary

Table 24 displays the number of intersection events characterized by TCD type and driver approach/traversal action in the 100-Car NDS.

Table 24. Intersection Events Grouped by TCD Type and Approach/Traversal Action

Movement Group	**Minimum Speed Threshold**	**Stop Sign Num. of Events**		**Signalized Num. of Events**	
		Left Turn	Straight	Left Turn	Straight
Complete Stop	Minimum Speed <= 3 mph	40	51	1,560	7,336
Rolling Stop/Start – Low Speed	3 mph < Minimum Speed <= 10 mph	63	138	220	502
Rolling Stop/Start – High Speed	10 mph < Minimum Speed <= 20 mph	48	143	775	806
Travelling Through	All Remaining Events	8	0	343	26,639

4.4.2 Results Overview

Cumulative distributions for the approach, traversal, and total (approach plus traversal) times were analyzed for each TCD type, approach action, traversal action, and lane size. We found that between stop signs and signalized intersection there was no significant difference in total intersection timing. However, from complete stops to rolling stops/starts there was a significant reduction in both approach time and traversal times. There was also a significant increase in traversal time from left turns to straight traversal for small lane intersections, while there was not a significant difference for larger intersections. We also found there to be a 50 percent increase in traversal times from two-lane intersections to seven lane intersections. From these results, we were able to determine that the current 5-second duration of recording would have captured less than 1 percent of the total intersection timing, while a duration of 15 seconds would be sufficient in capturing 50 percent of all intersection events, and a duration of 20 seconds would capture 99 percent of all intersection events.

Table 25. Distribution Data of Approach, Traversal, and Total Time for All stop sign intersections

Approach Action	**Traversal Action**		**50th Percentile (seconds)**			**90th Percentile (seconds)**			**Percent Captured by 5s Duration**		
		Number of Lanes	2	5	7	2	5	7	2	5	7
Complete Stops	Straight	Approach	9.3	9.3	9.3	12.9	12.9	12.9	2.0%	2.0%	2.0%
		Traversal	2.8	4.6	5.4	3.6	5.5	6.4	100.0%	76.5%	35.4%
		Total	12	13.7	14.4	15.3	17	18.8	0.0%	0.0%	0.0%
		Data Count	51 Events								
	Left Turn	Approach	8.1	8.1	8.1	11.4	11.4	12.9	0.0%	0.0%	0.0%
		Traversal	3.6	4.3	4.95	4.6	5.45	6.03	95.0%	80.0%	54.0%
		Total	11.8	12.5	13.4	14.8	15.4	16.1	0.0%	0.0%	0.0%
		Data Count	40 Events								
Low-Speed Rolling Stops/Starts	Straight	Approach	9.2	9.2	9.2	13	13	13	10.0%	10.0%	10.0%
		Traversal	2.3	3.9	4.8	2.7	4.6	6	100.0%	97.2%	70.3%
		Total	11.3	13	13.9	15.1	16.9	17.8	0.0%	0.0%	0.0%
		Data Count	138 Events								
	Left Turn	Approach	8	8	8	11.8	11.8	11.8	4.7%	4.7%	4.7%
		Traversal	3.1	3.8	4.5	3.7	4.3	5.1	99.0%	98.0%	80.0%
		Total	10.8	11.4	12	15	15.8	16.6	0.0%	0.0%	0.0%
		Data Count	63 Events								
High Speed Rolling Stops/Starts	Straight	Approach	7.3	7.3	7.3	8.5	8.5	8.5	23.0%	23.0%	23.0%
		Traversal	1.2	2.7	3.5	1.4	3	3.9	100.0%	100.0%	100.0%
		Total	8.5	9.9	10.7	11.3	12.8	13.7	9.3%	0.0%	0.0%
		Data Count	143 Events								
	Left Turn	Approach	7.4	7.4	7.4	9.3	9.3	9.3	16.7%	16.7%	16.7%
		Traversal	2.1	2.7	3.4	2.4	3.1	3.9	100.0%	100.0%	100.0%
		Total	9.4	10	10.7	11.5	12.14	12.9	1.0%	0.0%	0.0%
		Data Count	48 Events								

Table 26. Distribution Data of Approach, Traversal, and Total Time for All signalized intersections

Approach Action	**Traversal Action**		**50th Percentile (seconds)**			**90th Percentile (seconds)**			**Percent Captured by 5s Duration**		
		Number of Lanes	2	5	7	2	5	7	2	5	7
Complete Stops	Straight	Approach	10.5	10.5	10.5	13.5	13.5	13.5	1.0%	1.0%	1.0%
		Traversal	2.4	4	4.9	3.1	5	5.9	100.0%	90.0%	60.0%
		Total	13.1	14.7	15.6	16.2	18	18.9	0.0%	0.0%	0.0%
		Data Count	7,336 Events								
	Left Turn	Approach	11	11	11	14.1	14.1	14.1	1.7%	1.7%	1.7%
		Traversal	3.4	4.1	4.8	4.6	5.4	6.3	93.2%	85.0%	58.7%
		Total	12.4	13.1	13.9	15.4	16.2	17	0.0%	0.0%	0.0%
		Data Count	1,560 Events								
Low-Speed Rolling Stops/Starts	Straight	Approach	8.2	8.2	8.2	10.7	10.7	10.7	7.0%	7.0%	7.0%
		Traversal	2.1	3.9	4.9	2	4.9	6	100.0%	92.6%	56.0%
		Total	10.4	12.2	13.2	13.3	15.2	16.2	2.4%	0.0%	0.0%
		Data Count	502 Events								
	Left Turn	Approach	9.2	9.2	9.2	11.8	11.8	11.8	5.5%	5.5%	5.5%
		Traversal	3.2	4	4.8	4.1	4.9	5.9	100.0%	94.0%	58.1%
		Total	11.1	12.7	13.5	14	15.7	16.6	2.3%	0.0%	0.0%
		Data Count	220 Events								
High-Speed Rolling Stops/Starts	Straight	Approach	5.7	5.7	5.7	8.4	8.4	8.4	36.6%	36.6%	36.6%
		Traversal	1.3	2.4	3.2	1.4	3	4	100.0%	100.0%	99.0%
		Total	6.7	8.1	8.9	9.5	11	11.9	23.2%	11.0%	7.7%
		Data Count	806 Events								
	Left Turn	Approach	5.7	5.7	5.7	9.6	9.6	9.6	37.7%	37.7%	37.7%
		Traversal	1.6	2.1	2.7	1.9	2.6	3.3	100.0%	100.0%	100.0%
		Total	9.6	7.2	7.8	10.8	11.3	11.9	27.0%	25.0%	22.0%
		Data Count	775 Events								

4.4.3 TCD – Stop Signs Versus Signalized Intersections

Overall, the type of TCD did not have a significant effect on intersection event duration. As indicated by Figure 53, the approach, traversal, and total times remain relatively consistent between stop sign and signalized intersections. While the data displayed in Figure 53 contains only data from the assumed seven lane intersections, the analyses holds true for two- and five-lane intersection evaluations as well.

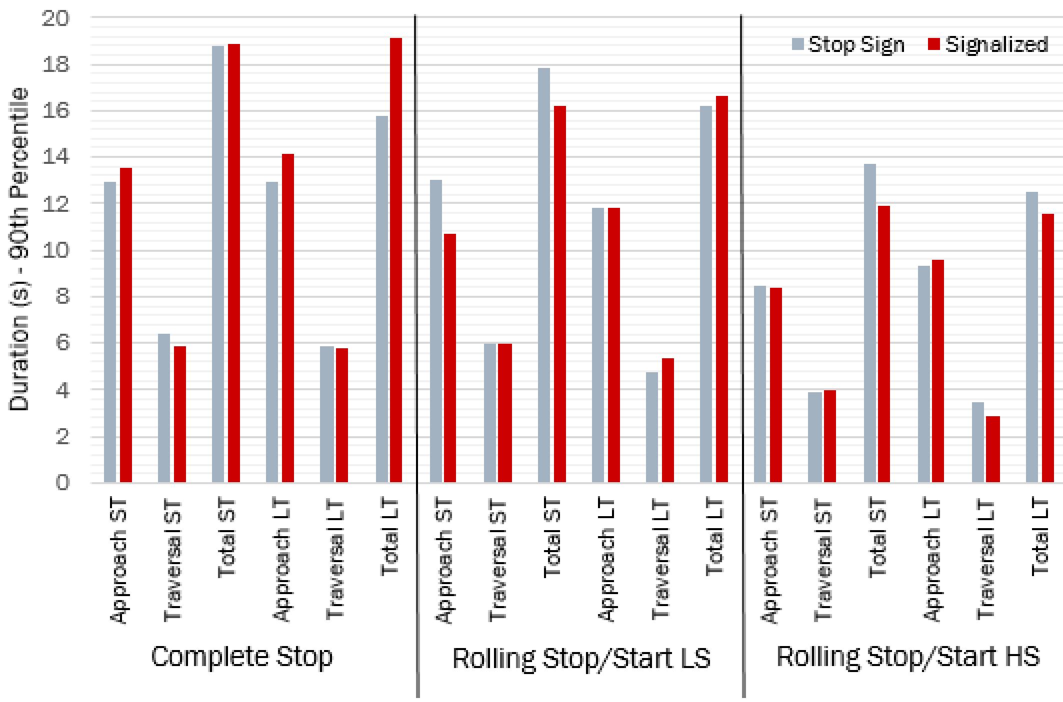


Figure 53. 90th Percentile Approach, Traversal, and Total Times of All Seven-Lane Intersection Events. In the diagram, ST Indicates Straight Through While LT Indicates Left Turn.

4.4.4 Approach Action – Complete Stop Versus Rolling Stop/Start

As indicated by Figure 54 to Figure 56, the approach action has a very significant effect on the intersection event duration time. The figures display the cumulative distribution of approach, traversal, and total times for complete stops, rolling starts at low speed, and rolling starts at high speeds. Each figure contains data for signalized five-lane intersections in which the driver traversed straight through. As indicated by these figures, the approach, traversal and thus the total times all decreased significantly from complete stops to rolling start. For this specific scenario, there was a 60 percent, 40 percent, and 39 percent decrease in the 90th percentile of approach, traversal, and total times from complete stops to high-speed rolling starts. Across all intersection scenarios, the decrease in total intersection event duration from complete stops to high-speed rolling stops/starts ranged from 20 percent up to 56 percent.

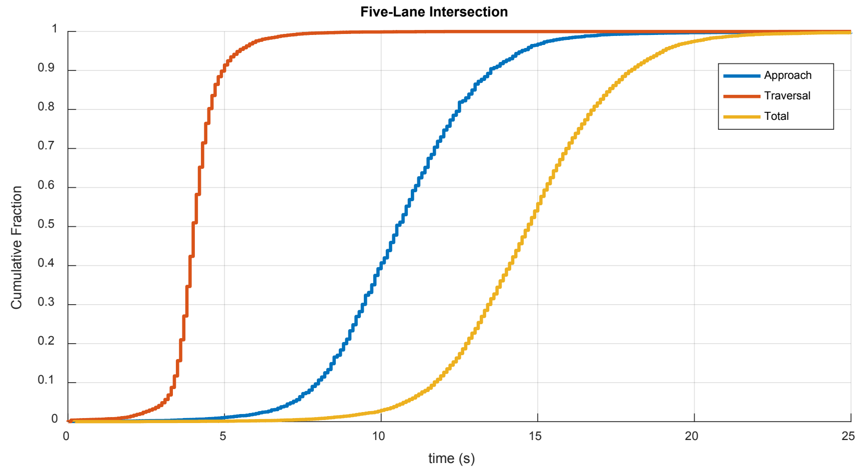


Figure 54. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Five-Lane Signalized Intersection in Which the Driver Came to a Complete Stop and Traversed Straight Through

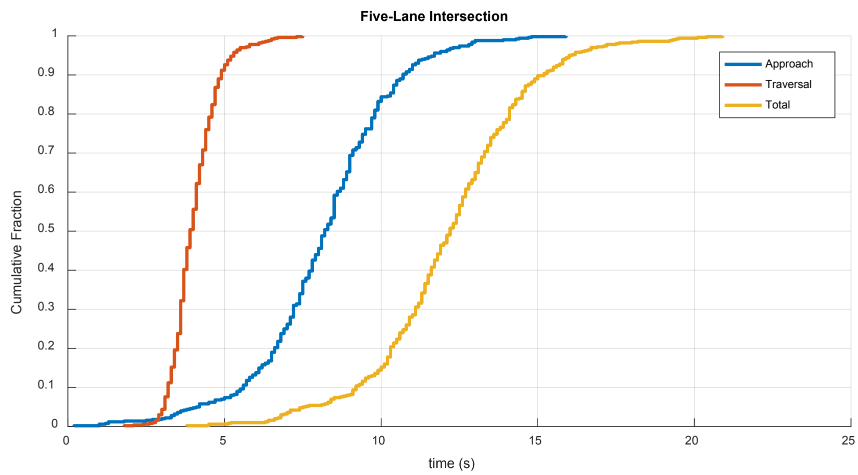


Figure 55. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Five-Lane Signalized Intersection in Which the Driver Came to a low Speed Rolling Start, and Traversed Straight Through

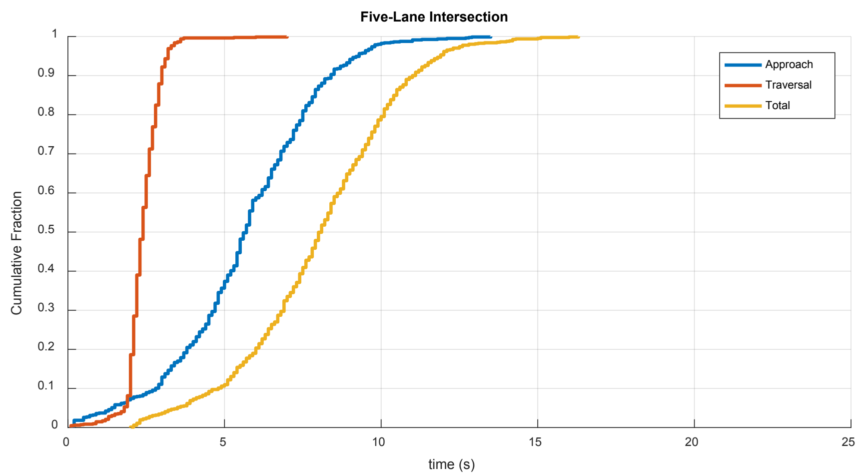


Figure 56. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Five-Lane Signalized Intersection in Which the Driver Came to a High-Speed Rolling Start, and Traversed Straight Through

Table 27. Cumulative Distribution Data Summary of Approach, Traversal, and Total Times of Each Approach Action. This Data Is Based on a Five-Lane Signalized Intersection in Which the Driver Traversed Straight Through.

	50th Percentile (seconds)			**90th Percentile (seconds)**			**Percent Captured by 5s Duration**		
	Complete Stop	Rolling Start LS	Rolling Start HS	Complete Stop	Rolling Start LS	Rolling Start HS	Complete Stop	Rolling Start LS	Rolling Start HS
Approach	10.5	8.2	5.7	13.5	10.7	8.4	1.0%	7.0%	36.6%
Traversal	4	3.9	2.4	5	4.9	3	90.0%	92.6%	100.0%
Total	14.7	12.2	8.1	18	15.2	11	0.0%	0.0%	11.0%

4.4.5 Traversal Action – Straight Versus Left Turn

As seen in Figure 57, two-lane intersection traversal time was significantly greater for left turns compared to straight traversals, while there was not as much of a difference for five- and seven-lane intersections. The reason the difference in traversal times decreased as lane size increases is due to the fact that the calculated left turn traversal distance in smaller intersections was proportionally larger than straight traversals. Whereas, for larger intersections, straight traversal distance was larger than left turn distance. From Table 17 the calculated left turn and straight traversal distance for a two-lane intersection are 8.48 meters and 7.20 meters, respectively. The calculated distance for left turn and straight traversal distance for a seven-lane intersection are 22.80 meters and 25.20 meters, respectively. However, for some larger intersection cases the traversal time was still longer for left turns than straight traversals even though the left turn distance was shorter. This perhaps indicates that drivers accelerated through intersections at lower speeds when turning left compared to when traversing straight through.

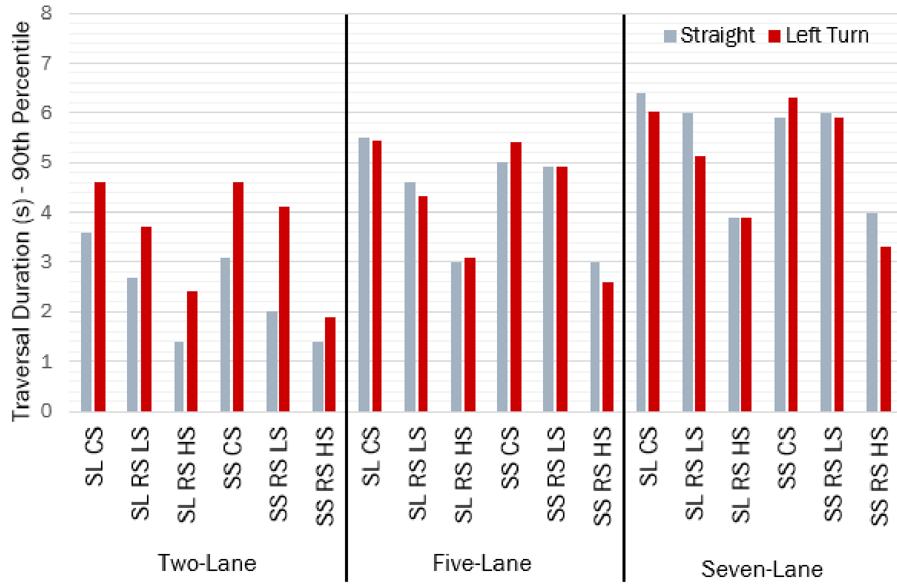


Figure 57. 90th Percentile Durations for Straight and Left Turn Traversals. SL and SS Stand for Signalized and Stop Sign. CS Stands for Complete Stops, RS LS and RS HS stand for Rolling Start/Stop Low Speed and Rolling Start/Stop High Speed.

4.4.6 Intersection Size

Because we calculated the traversal length through assuming the intersection size and lane size, the traverse and total times increased as the size of the intersection increased, while the approach time remained constant. Figure 58 to Figure 60 demonstrate the change in traversal and total time distributions with intersection size for a signalized intersection in which the driver came to a complete stop and traversed straight through. Over all intersection events, the total intersection event duration ranged from 10 to 16.5 seconds for two-lane intersections, 11 to 18 seconds for five-lane intersections, and 11.6 to 19.3 seconds for seven-lane intersections.

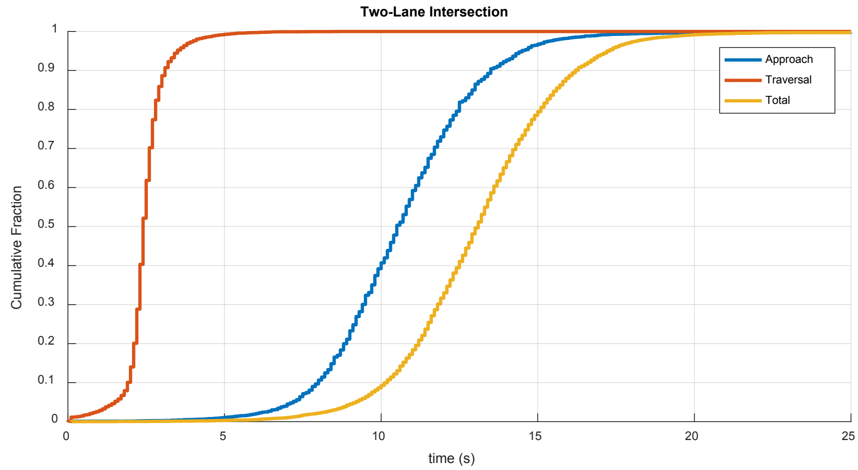


Figure 58. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Two-Lane Signalized Intersection in Which the Driver Came to a Complete Stop and Traversed Straight Through

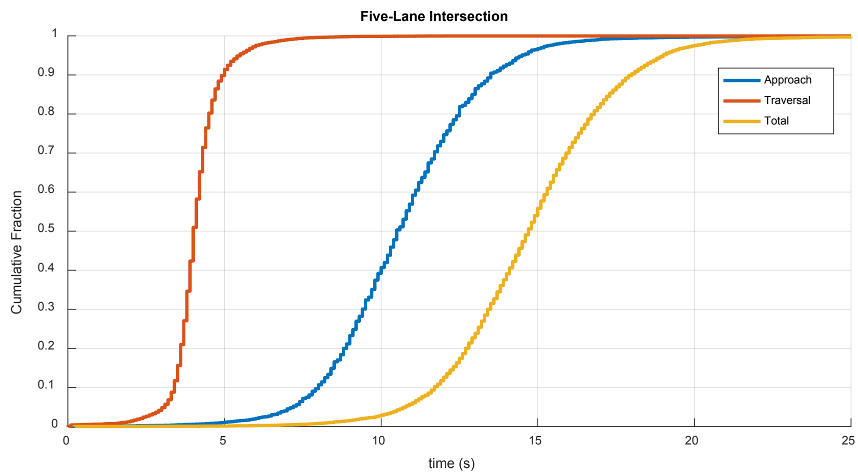


Figure 59. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Five-Lane Signalized Intersection in Which the Driver Came to a Complete Stop, and Traversed Straight Through

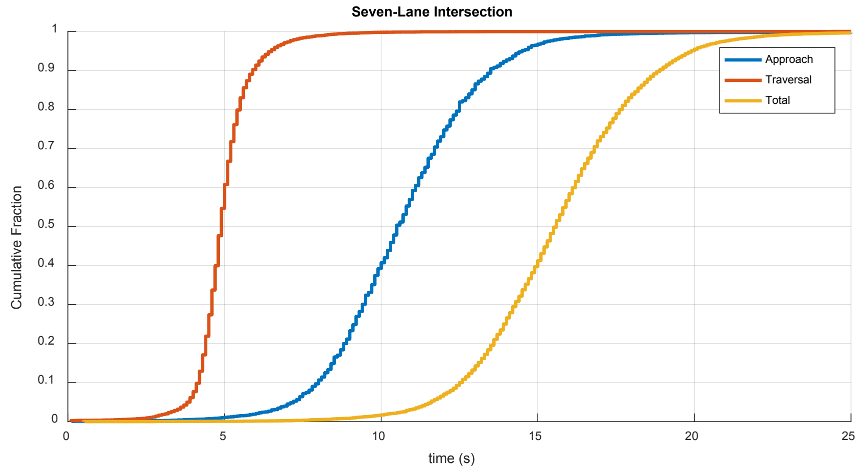


Figure 60. Cumulative Distribution Plot of Approach, Traversal, and Total Times for Seven-Lane Signalized Intersection in Which the Driver Came to a Complete Stop and Traversed Straight Through

4.4.7 Current Duration Comparison

As indicated by Table 28, if all intersections were approximated as two-lane intersections, the 5 second recording time would only capture 1.8 percent of the total event time, and 0 percent of the total time if all intersections were seven-lane intersections. A recording time of 15 seconds would capture approximately 50 percent of all intersections event time, while a recording time of 20 seconds would capture approximately 95 percent of the total time.

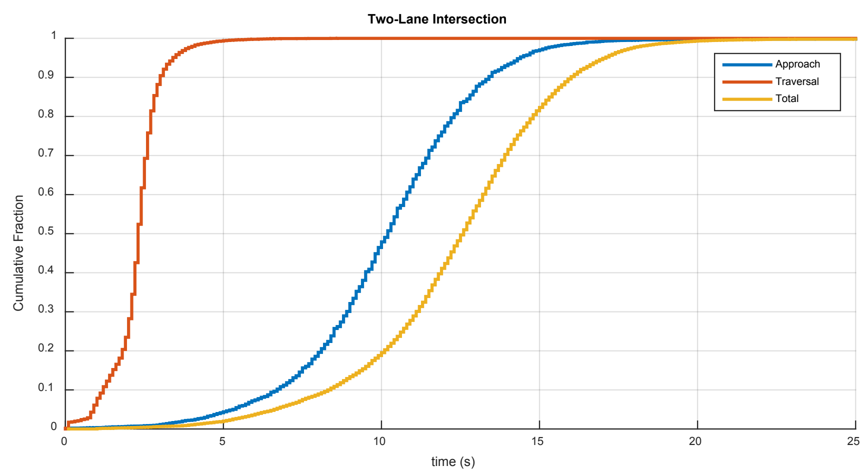


Figure 61. Cumulative Distribution Plot of Approach, Traversal, and Total Times for All Two-Lane Intersection Events

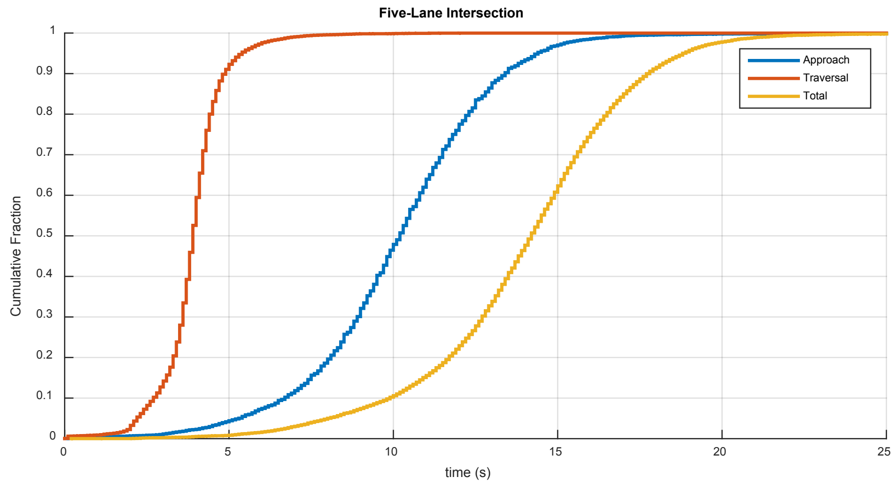


Figure 62. Cumulative Distribution Plot of Approach, Traversal, and Total Times for All Five-Lane Intersection Events

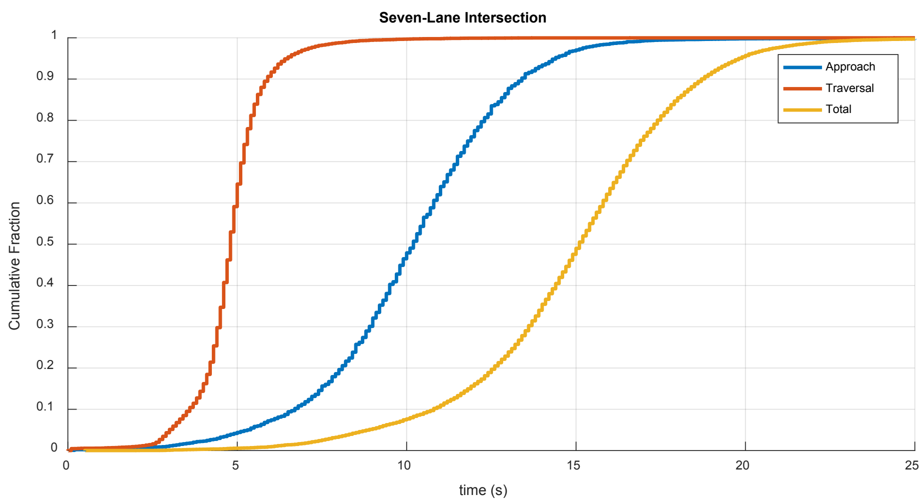


Figure 63. Cumulative Distribution Plot of Approach, Traversal, and Total Times for All Seven-Lane Intersection Events

Table 28. Distribution Data for All Intersection Events

	50th Percentile (seconds)			**90th Percentile (seconds)**			**Percent Captured by 5s Duration**		
Number of Lanes	2	5	7	2	5	7	2	5	7
Approach	10.2	10.2	10.2	13.4	13.4	13.4	4%	4%	4%
Traversal	2.5	4.0	4.8	3.6	4.9	5.9	100%	92.3%	63.3%
Total	12.6	14.2	15.1	16.0	17.8	18.6	1.8%	0.8%	0.0%
Data Count	11,682 Events								

4.4.8 Discussion and Conclusions

The objective of this subtask was to evaluate the duration in which drivers approach and traverse through an intersection during normal driving, and to evaluate the effectiveness of the EDR pre-crash recording time of 5 seconds. The analysis focused on 11,682 intersection events over 143 stop-sign-controlled intersections and 163 signalized intersections recorded by VTTI's 100–Car NDS.

The cumulative distribution for all intersection events reveals that the current EDR pre-crash recording time of 5 seconds captures less than 1 percent of the total intersection event time. The distribution for all events also supports that a recording time of 15 seconds would capture approximately 50 percent of the total intersection event time, and a recording time of 20 seconds would capture approximately 95 percent of the total time.

5 Conclusions and Discussions

The goal of this project was to determine the EDR recording duration needed to investigate crash causation. The first phase of the study sought to identify crash modes that would benefit from more than 5 seconds of EDR pre-crash recording. The analysis used EDR data contained in the NASS/CDS and the NMVCCS databases. The overall approach was to analyze the capability of EDRs to record the initiation of driver braking, steering, and accelerator pedal input during the pre-crash period of rear-end, intersection, and road departure crashes. A total of 1,616 EDR downloads were extracted from NASS/CDS from case years 2000 to2015, and 50 EDRs were extracted from NMVCCS from 2005 to 2007.

The analysis of driver pre-crash maneuver in NASS/CDS crashes showed that the current 5-second EDR recording duration was not sufficient to capture all driver pre-crash maneuver initiations in rear-end, intersection, as well as road departure crashes. The result showed that EDRs failed to capture driver pre-crash braking initiation in approximately 35 percent of the rear-end, intersection, and road departure crashes in a subset of NASS/CDS crashes. In addition, current EDR recording duration failed to capture driver pre-crash steering maneuver initiation in 64 to 88 percent of all rear-end, intersection, and road departure crashes, in NASS/CDS. Similarly, the analysis of EDRs extracted from NMVCCS crashes shows that current EDRs failed to capture up to nearly 56 percent of all driver pre-crash braking initiation in rear-end crashes. Table 29 shows a summary of the percentage of EDRs, which did not capture driver pre-crash maneuver during the 5-second recording duration.

Table 29. Summary of EDR Recorded Driver Pre-Crash Maneuver at t = -5 Seconds

Driver Pre-Crash Maneuver		**EDR Failed to Record Maneuver Initiation (%)**
Rear-End	Braking Input	35%
	Steering Input	80%
	Accelerator Release	9%
Intersection	Braking Input	35%
	Steering Input	64%
	Accelerator Release	5%
Road Departure	Braking Input	35%
	Steering Input	88%
	Accelerator Release	8%

In addition to driver pre-crash maneuver, current EDR capabilities were investigated to capture the vehicle traversal phase during intersection and road departure events. The analysis of vehicle traversal time was based upon reconstructions of select intersection and road departure crashes from NASS/CDS. The result showed that in approximately 13 percent of the sample of intersection crashes, the driver entered the intersection more than 5 seconds prior to impact. In other words, the current 5-second EDR recording duration failed to capture intersection entry in approximately 13 percent of intersection crashes. On the other hand, the analysis of road departure traversal time shows that, in nearly all road departure events, the time period between initial road departure to final rest was less than 5 seconds.

The second phase of the research program sought to determine the complete duration of driver pre-crash actions. This part of the study was based on driver actions extracted from two naturalistic driving studies, the 100-Car NDS, and the SHRP-2 NDS. The analysis of driver pre-crash maneuvers in the 100-Car NDS and SHRP-2 showed that the current 5-second EDR recording duration was not sufficient to capture all driver pre-crash maneuver initiations in rear-end, intersection, and road departure crashes. The longest needed recording durations were in intersections where complete recording of the approach and traversal phases would require over 18 seconds to capture the complete maneuver.

Table 30 shows a summary of the time needed to capture driver maneuvers during normal driving in car following (the precursor to rear crashes), intersection traversals, and road departures.

Table 30. Summary of Typical Driver Maneuver Time

Driver Pre-Crash Maneuver		**Duration of Driver Action (seconds)**	
		50th Percentile	90th Percentile
Rear-End	Time to Closest Approach	4.5	12.3
Intersection	Approach + Traversal	12.6-15.1	16.0-18.6
Road Departure	Drift out of Lane to Recovery	3.2	6.0

These findings suggest that an EDR recording duration of 20 seconds would adequately capture driver pre-crash inputs to the vehicle, i.e., braking, steering, and acceleration, in rear crashes, intersection crashes, and road departures.

6 Acknowledgements

The authors gratefully acknowledge John Scanlon and Taylor Johnson of Virginia Tech for their contribution in the data collection efforts for the intersection and lane departure traversal analysis.

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DOT HS 813 082B
March 2022

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14682b-021522-v1b