A Preliminary Characterisation of Driver Manoeuvres in Road Departure Crashes

Luke E. Riexinger, Hampton C. Gabler

Abstract Road departure crashes are one of the most dangerous crash modes in the USA. Lane departure warning (LDW) systems have been designed as an attempt to mitigate these crashes. Understanding the evasive manoeuvres employed by the driver is crucial to the development of an accurate model of a driver reacting to a LDW. Event data recorders (EDRs) were used to characterise recorded driver manoeuvres in road departure crash scenarios. Steering was the most common evasive action, followed by braking. On average, the evasive braking resulted in a deceleration of 0.41 g. Based on typical human reaction times to LDW, between 23% and 71% of crashes occurred before the driver could react and perform an evasive manoeuvre.

Keywords Road Departure Crashes, Event Data Recorders, Evasive Manoeuvre, Active Safety Systems, Lane Departure Warning.

I. INTRODUCTION

Road departure crashes are one of the most dangerous crash modes. From 2007 to 2011, these crashes accounted for fewer than 10% of crashes but one-third of all crash fatalities in the USA [1]. The high severity of this crash mode has been a key motivation for the development of active safety systems, such as lane departure warning (LDW) systems. LDW systems are designed to alert the driver, through audible, visual or haptic signals, that the vehicle has inadvertently left the lane of travel. Ideally, the driver reacts to the warning and returns to the lane, preventing an impact (Fig. 1). However, the effectiveness of a warning system is limited by the reaction time of the driver and the ability of the driver to return to the road without impacting any roadside objects. While driver reaction time has been extensively investigated, little has been published on the magnitude or type of evasive manoeuvres taken by the driver to recover from a road departure. The purpose of this study is to understand what evasive manoeuvres drivers perform while attempting to avoid roadside obstacles after a road departure.

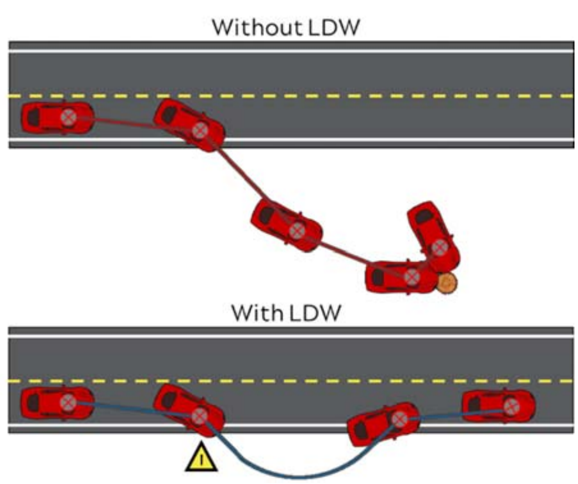

Fig. 1. Example of a LDW system preventing a road departure crash by inducing a driver manoeuvre.

The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) data set is a representative sample of all crashes in the USA that requires at least one vehicle to be towed away. Each case in

L. E. Riexinger (e-mail: luker7@vt.edu) is a PhD student and H. C. Gabler is Professor of Biomedical Engineering in the Department of Biomedical Engineering and Mechanics, both at Virginia Tech, Blacksburg, Virginia, USA.

the data set includes a scaled scene diagram with the vehicle trajectory and impact locations. If possible, the vehicle delta-v is calculated from an energy reconstruction based on the crush profile of the vehicle using Win-Smash [2-4]. Detailed information about the vehicle, driver and environment is also recorded. However, NASS/CDS provides little data on the vehicle's trajectory once leaving the road edge. The National Cooperative Highway Research Program (NCHRP) 17-43 database provides supplemental data for NASS/CDS road departures, including numeric trajectory information and the estimated departure and impact speeds.

Most recently manufactured vehicles have an event data recorder (EDR) installed, which records basic vehicle information in the event of a crash. The EDR records data during the crash, such as delta-v, to capture the crash pulse. Additionally, five seconds of pre-crash information, such as vehicle speed, throttle position, brake activation and engine RPM, are recorded. Some advanced EDRs also record information such as the steering-wheel position, the activation of electronic stability control (ESC) and the activation of the antilock brakes system (ABS). EDRs are a unique data source, capable of providing information on human evasive actions in emergency situations.

II. METHODS

Crash Scenario Categorisation

All NASS/CDS 2011–2015 cases were categorised into 44 different crash scenarios according to the methodology established by Kusano [1]. The categorisation is based on the crash type, critical pre-crash event and any pre-crash movements. LDW applicable crashes were crash scenarios that involved an unintentional lane departure, not due to loss of control. There were a total of four LDW applicable scenarios: single vehicle, lane departure crash; impact with vehicle travelling in the opposite direction; impact with vehicle travelling in the same direction; and impact with a parked vehicle.

Case Selection Criteria

NCHRP 17-43 only contains records of single vehicle, road departure crashes, therefore, all of the cases analysed are LDW applicable crash scenarios. To be included in the study, NASS/CDS cases with supplemental NCHRP 17-43 data must have EDR information available. In order to ensure that the EDR event recorded corresponds to the impact described in the NASS/CDS case, we selected only those cases in which the EDR either recorded an airbag deployment or had a delta-v greater than 8 kph. When an airbag deploys, the data is locked into the EDR and cannot be overwritten by lower severity impacts. A delta-v of 8 kph is a significant crash, and it is unlikely that a more significant event could occur to overwrite the data. To ensure that the EDR events align with the NASS/CDS events, the first event in the NASS/CDS case must have the largest delta-v. This selection criteria is the same as that used by Scanlon to analyse intersection crashes [5] and is summarised in Table I.

TABLE I
SELECTION CRITERIA

Criteria	Cases	Weighted Cases
NCHRP 17-43	992	343,494
EDR Information Available	252	92,241
Airbag Deployment or Delta-V > 8 kph	239	88,422
First Impact Most Severe	123	53,660
Pre-crash Information Available	97	44,439

EDR Reconstruction Methodology

To understanding the evasive actions attempted by the driver, only the pre-crash data recorded after the initial lane departure is relevant. The time of lane departure is determined by the method described in one of our earlier studies [6]. The distance the vehicle travelled after departing the road is determined based on the trajectory of the vehicle. Additional distance was added for cases in which the vehicle crossed at least one lane before departing the road. The additional distance was computed by assuming a straight path from the point of lane departure to the point of road departure and that the vehicle departed the lane with the same angle as it departed the road (Eq. 1).

$$\text{Lane Distance} = \frac{\text{Lane Width}}{\cos(90 - \text{Road Departure Angle})} \quad \text{(Eq. 1)}$$

Assuming constant acceleration between EDR velocity measurements, the distance travelled by the vehicle is computed. The time of the initial lane departure was calculated at the moment when the EDR-computed distance is greater than the trajectory distance (Fig. 2).

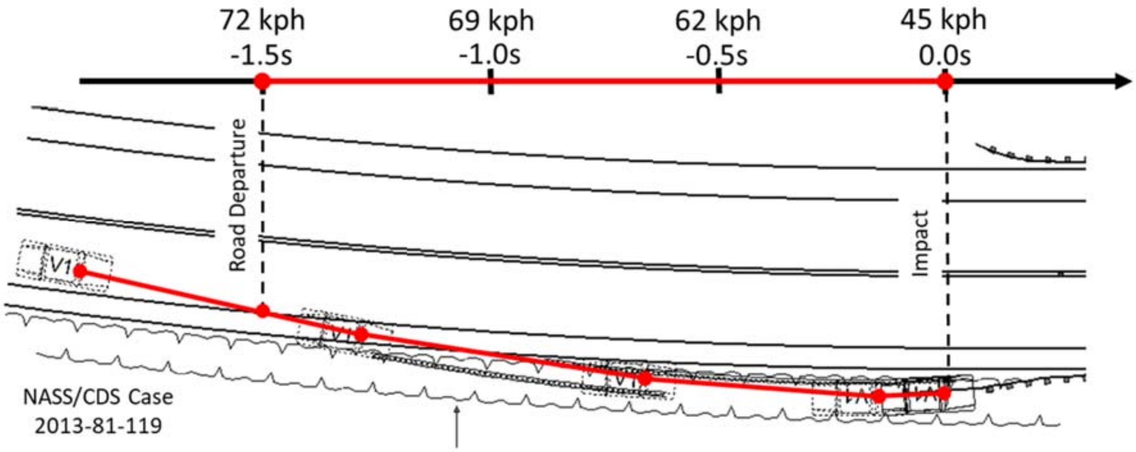

Fig. 2. Example alignment of EDR pre-crash velocity with the trajectory information to determine the time of initial lane departure. The red segment represents the time travelled after departing the lane but before impacting the guardrail.

Steering Angle

In this study, evasive steering was defined as a yaw rate greater than 4 deg/s, using a convention consistent with earlier NDS studies [7]. A criterion for evasive steering based on the steering wheel angle was computed by relating the steering wheel angle to the yaw rate. EDR pre-crash data with both yaw rate and steering-wheel angle were used to determine the relationship between the two parameters. This excluded rollover crashes because they often are not tracking before tripping. Ten cases in NASS/CDS and NCHRP 17-43 met this criteria and a linear model was used to relate the yaw rate to steering wheel angle before the crash. The steering-wheel angle is proportional to the yaw rate by a factor of 4.4 (Fig. 3). The threshold for evasive steering based on steering-wheel angle was, therefore, 17.5^{o}.

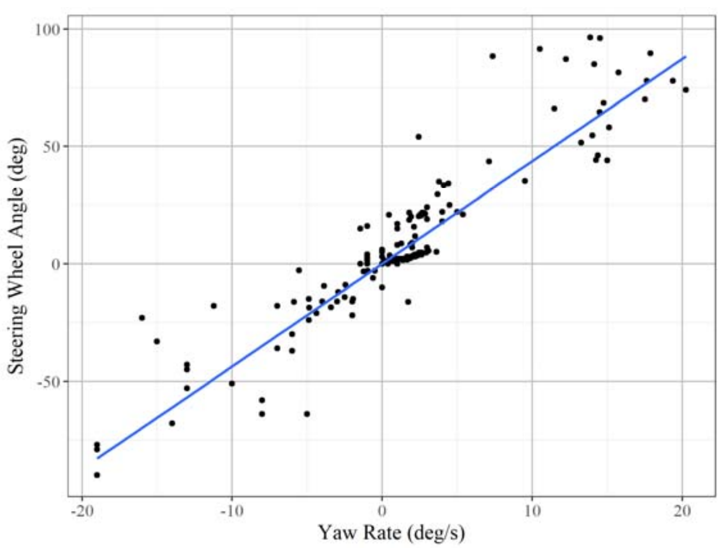

Fig. 3. Average relationship between steering-wheel angle and yaw rate.

III. RESULTS

The distribution of the crash scenarios in 7,142 NASS/CDS 2011–2015 cases, representing 3,543,219 crashes, are summarised in Fig. 4. About one-quarter of crashes in the USA are lane departure crashes, of which 65% are single vehicle road departure crashes.

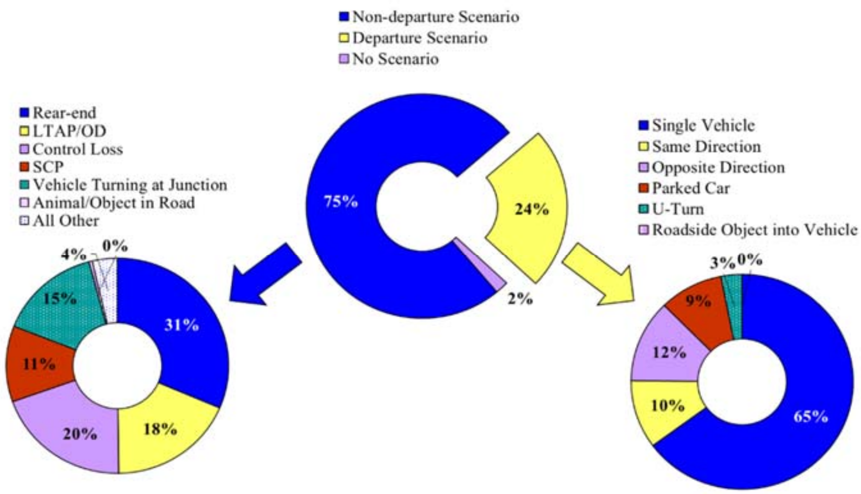

Fig. 4. Distribution of NASS/CDS 2011–2015 crash scenarios.

There were 1,512 LDW applicable crashes in NASS/CDS, representing 563,809 crashes. LDW applicable crashes accounted for only 12% of occupants involved in crashes but for nearly half of all MAIS3+Fatal crashes (Fig. 5). Therefore, LDW applicable crash scenarios tend to have more serious injuries than other crash scenarios.

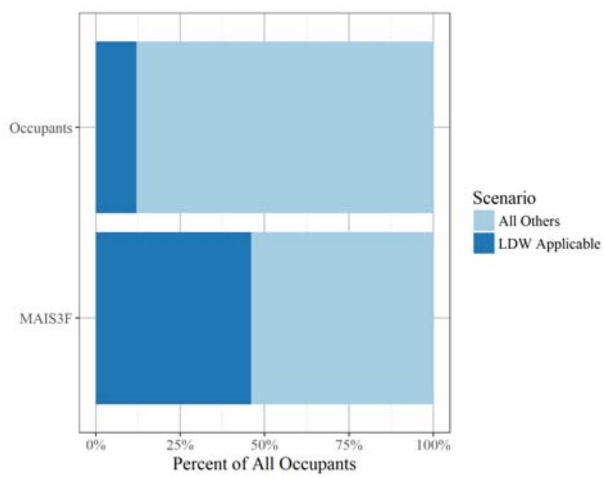

Fig. 5. Comparison of the proportion of occupants and serious injuries of LDW applicable scenarios to all other scenarios.

Table II summarises the number of cases available for characterisation of evasive manoeuvres. The evasive manoeuvres performed by the drivers and their frequency are summarised in Table III. Steering was the most common driver response, followed by braking.

TABLE II
COMPOSITION OF EDR DATA SET BY PRE-CRASH PARAMETERS

Parameter	Cases	Weighted Cases
Travel Speed	96	43,891
Departure Speed	96	43,891

Braking	92	40,849
Accelerator	52	21,307
Steering	17	8,985
Yaw	15	4,671
ABS	16	9,029
ESC	12	3,680

TABLE III
EVASIVE MANOEUVRES

Parameter	Action Performed	Cases Available	Percent of Cases	Action Performed (weighted)	Weighted Cases	Percent of Weighted Cases
Brake	40	92	43.4%	20,556	40,849	50.3%
Accelerate	27	52	51.9%	8,829	21,307	41.4%
Steer	15	17	88.2%	7,813	8,985	87.0%
Yaw	10	15	66.7%	2,493	4,671	53.4%
ABS	4	16	33.3%	329	9,029	3.6%
ESC	4	12	25.0%	752	3,680	20.4%

There were 16 cases with both steering and braking data. The majority of drivers responded by only steering (Table IV). There was no trend in the order of braking and steering for the five cases that performed both actions.

TABLE IV
COMBINATION OF EVASIVE MANOEUVRES

Parameter	Action Performed	Percent of Cases	Action Performed (weighted)	Percent of Weighted Cases
No Avoidance	1	6.3%	1,111	17.5%
Brake and Steer	5	31.3%	485	7.6%
Steer Only	9	56.3%	4,694	73.9%
Brake Only	1	6.3%	60	0.9%

IV. DISCUSSION

NASS/CDS is inadequate for drawing conclusions about driver evasive manoeuvres because in over 50% of the cases, the response was unknown (Fig. 6). The driver manoeuvre was determined by the crash investigator based on physical evidence, such as tyre marks. However, as the scene was investigated up to two weeks after the crash, much of the visible evidence was likely missing. Therefore, NASS/CDS is not an adequate source for understanding driver manoeuvres. Unlike NASS/CDS, the use of supplementary EDR information provides a direct measurement of the driver response to road departure. This is why more cases in NASS/CDS record the driver as performing no evasive manoeuvre before the crash than what was recorded in the EDR. Both the EDRs and NASS/CDS determine steering and braking as the most common evasive manoeuvres.

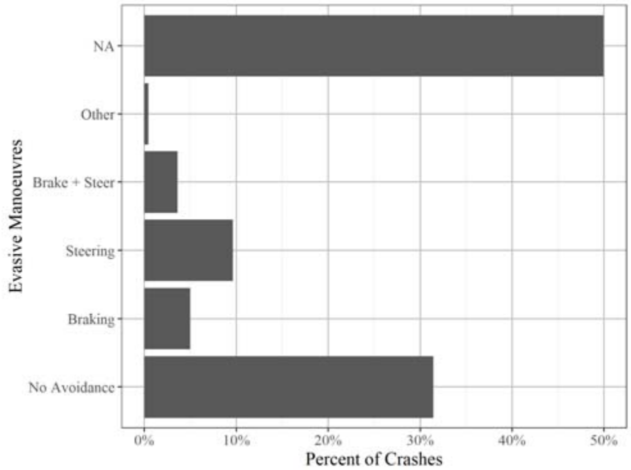

Fig. 6. Distribution of NASS/CDS investigator-reported driver action.

In the majority of road departure crashes – 67.1% of cases and 56.2% of weighted crashes – the vehicle was travelling faster than the speed limit (Fig. 7). In 43 of the 82 cases, the vehicle was travelling more than 8 kph (5 mph) over the speed limit. The median departure speed was determined to be 54.7 kph. Very few road departure crashes occurred at speeds below 25 kph (Fig. 8).

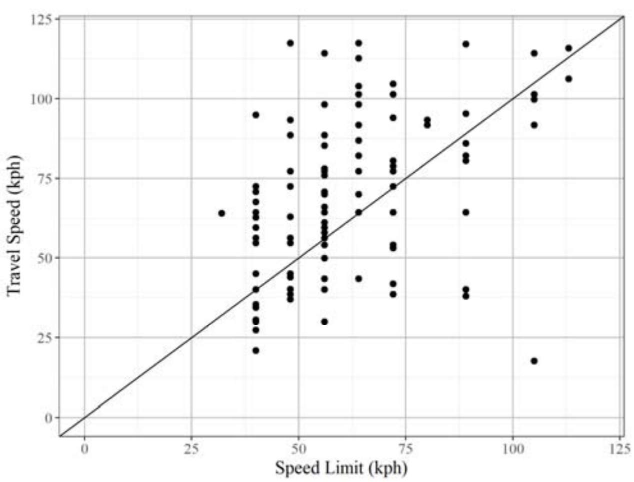

Fig. 7. Vehicle speed compared to the posted speed limit. Cases above the line represent vehicles travelling faster than the posted speed limit.

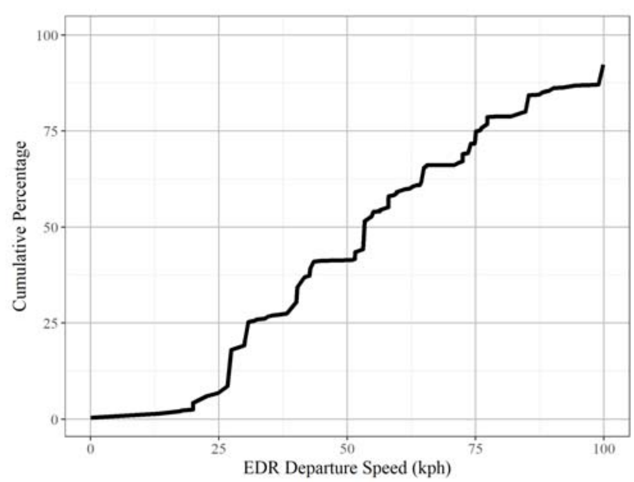

Fig. 8. Cumulative distribution of the departure speed.

The distance travelled to the site of impact from the initial lane departure is related to the time from the departure to the impact (Fig. 9). This is closely correlated with the departure speed, as expected. Within each time to impact, vehicles travelling faster will cover more distance before impact than slower vehicles. The difference between the distance travelled by slow- and fast-moving vehicles increases with time. Thus, the variation in distance travelled to impact is larger with a longer time to impact.

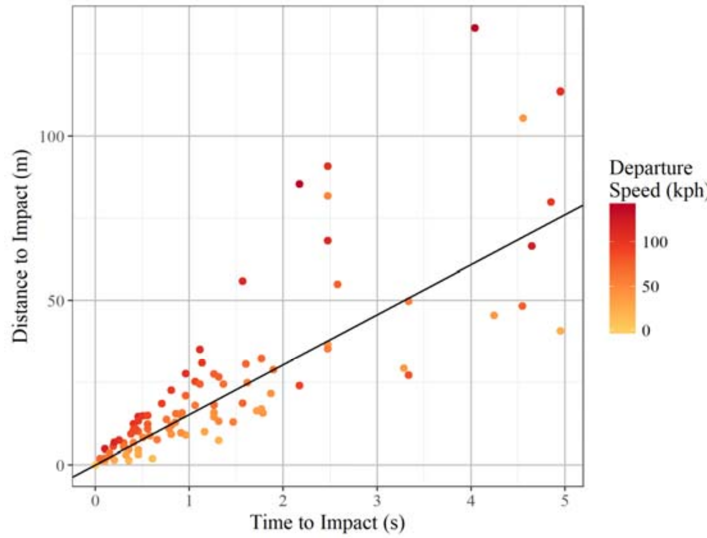

Fig. 9. Relationship between the distance travelled and the time to impact. The slope of the line represents the median departure speed of 54.7 kph.

As many of the crashes occurred close to the road and at high speeds, many drivers did not have sufficient time to react. Typical reaction times to LDW systems are between 0.38 s and 1.36 s [8]. Therefore, individuals with a fast reaction time of 0.38 s could not respond to an LDW in 23.4% of crashes. Individuals with a slow reaction time of 1.36 s could not respond to an LDW in 71% of crashes (Fig. 10). LDW systems require sufficient time for the driver to react to the warning and perform an evasive manoeuvre. A lane departure prevention (LDP) system may be more effective in avoiding these crashes by providing a steering input immediately when the vehicle begins to leave the lane.

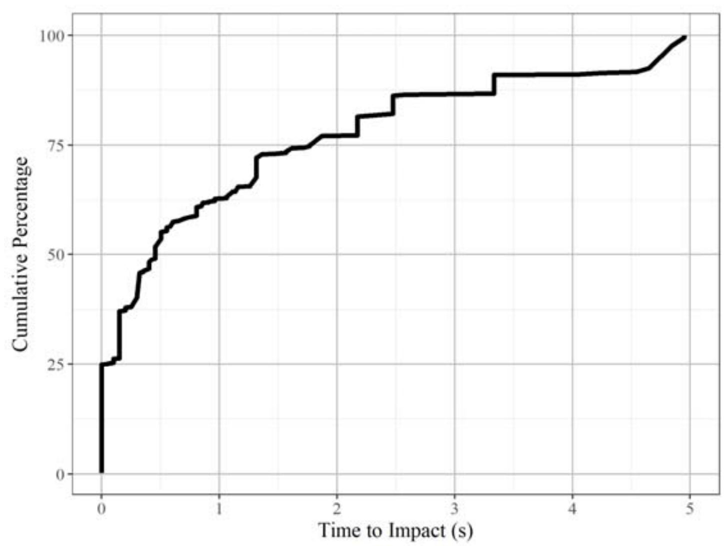

Fig. 10. Distribution of time from road departure to time of impact.

The deceleration was computed using a linear regression of the amount of time the driver was braking as a function of the change in velocity. The average deceleration of the vehicle due to braking was 0.41 g (Fig. 11). This is less than the 0.58 g evasive braking present in intersection crashes [5]. This is likely due to the lower coefficient of friction between the tires and the ground when off the road compared to when the vehicle is on pavement.

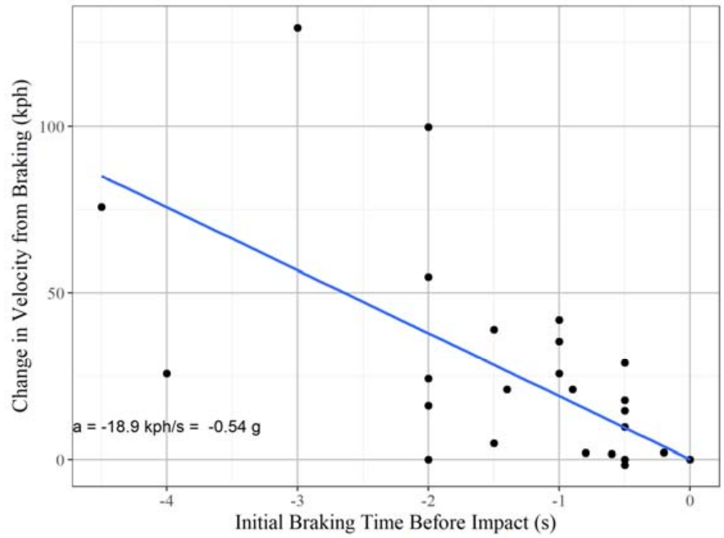

Fig. 11. Vehicle deceleration from braking before impact.

The majority of drivers responded to the road departure by performing some steering manoeuvre. In over 70% of the cases in which the driver performed an evasive steering action, the driver turned in the direction of the road. These results are limited by the small number of cases that had the EDR steering or yaw rate data available. The same limitation applies to the activation of ABS and ESC before the crash.

This study analysed only those road departures that resulted in crashes. Accordingly, conclusions cannot be made about what driver manoeuvres are successful in avoiding a crash in road departure scenarios. However, the purpose of LDW systems is to reduce the number of road departure crashes, which is represented in these data.

V. CONCLUSIONS

LDW applicable crashes account for a small portion of crashes but comprised almost 50% of all MAIS3+F injuries. Drivers tend to react to a road departure with an evasive steering action back in the direction of the road. The second most frequent manoeuvre was braking, which had an average deceleration of 0.41 g. Future work will include the development of driver behaviour models to estimate the number of road departure crashes that are preventable with LDW.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Toyota Collaborative Safety Research Center (CSRC) and Toyota Motor Corporation for funding this study. Our special thanks to Rini Sherony of Toyota for sharing her technical insights and expertise throughout this study. The research team would like to acknowledge Taylor Johnson and Virginia Tech students Yvonne Teng, Katelyn Kleinschmidt and Sydney Lavery for their assistance in developing the NCHRP 17-43 database, and Dong Lee for his assistance in developing the EDR database.

VII. REFERENCES

[1] Kusano, K.D. and Gabler, H.C. (2014) Comprehensive target populations for current active safety systems using national crash databases. *Traffic Injury Prevention*, **15**(7): pp. 753-761

[2] Sharma, D., Stern, S., Brophy, J., and Choi, E. (2007) An overview of NHTSA's crash reconstruction software WinSMASH. *Proceedings of Proceedings of the 20th International Technical Conference on Enhanced Safety of Vehicles*, 2007. Lyon, France

[3] Hampton, C.E. and Gabler, H.C. (2010) Evaluation of the accuracy of NASS/CDS Delta-V estimates from the enhanced WinSmash algorithm. *Proceedings of Annals of Advances in Automotive Medicine/Annual Scientific Conference*, 2010. Las Vegas, USA

[4] Gabler, H.C., Hampton, C., and Johnson, N., (2012) "Development of the WinSMASH 2010 Crash Reconstruction Code". U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA).

[5] Scanlon, J.M., Kusano, K.D., and Gabler, H.C. (2015) Analysis of driver evasive maneuvering prior to intersection crashes using event data recorders. *Traffic Injury Prevention*, **16**(sup2): pp. S182-S189

[6] Riexinger, L.E., Sherony, R., and Gabler, H.C. (2018) Methodology for Estimating the Benefits of Lane Departure Warnings Using Event Data Recorders, *SAE World Congress Experience*. SAE International: Detroit, USA. doi: 10.4271/2018-01-0509.

[7] Dingus, T.A., Klauer, S.G., et al. (2006) The 100-car naturalistic driving study, Phase II-results of the 100-car field experiment.

[8] Suzuki, K. and Jansson, H. (2003) An analysis of driver's steering behaviour during auditory or haptic warnings for the designing of lane departure warning system. *JSAE review*, **24**(1): pp. 65-70