A Preliminary Characterisation of Driver Evasive Manoeuvres in Cross-Centreline Vehicle-to-Vehicle Collisions

Luke E. Riexinger, Rini Sherony, Hampton C. Gabler

Abstract Cross-centreline head-on crashes are one of the most severe crash modes due to the large closing speed between the two opposing vehicles. Two countermeasures, centreline rumble strips and lane departure warning systems, aim to help reduce the frequency of head-on crashes. However, both of these countermeasures rely on proper action by the driver of the encroaching vehicle. The purpose of this paper is to analyse event data recorder information from real-world cross-centreline head-on crashes to help understand how the drivers of the encroaching and impact vehicles react before impact. Most drivers that reacted before the crash simultaneously performed a braking and steering manoeuvre. The driver of the impacted vehicle was more likely to react before the crash than the driver of the encroaching vehicle. Every driver of the encroaching vehicle that performed a steering manoeuvre turned back towards the correct lane of travel.

Keywords *Cross-Centreline, Head-On Crash,* Event Data Recorders, Evasive Manoeuvre, Active Safety Systems, Lane Departure Warning.

I. INTRODUCTION

Cross-centreline head-on crashes are one of the most severe crash modes due to the large closing speed between the two vehicles. In the USA, cross-centreline crashes accounted for only 1.0% of all crashes in 2010-2011 but represented 10.0% of all fatalities [1]. Only 4% of non-intersection crashes were cross-centreline crashes, yet 49% of the fatalities in non-intersection crashes were cross-centreline crashes [2].

A cross-centreline head-on collision occurs when the encroaching vehicle departs from the initial lane of travel into a lane containing oncoming traffic. If another vehicle is on an impact trajectory and neither driver performs a successful evasive manoeuvre, then a head-on crash will occur (Fig. 1).

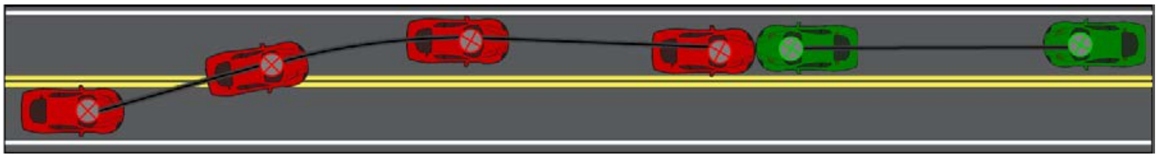

Fig. 1. Example cross-centreline head-on collision

One infrastructure based cross-centreline countermeasure is the centreline rumble strip. Rumble strips are a series of grooves in the pavement on the centreline. When a vehicle travels across the rumble strip, the vehicle vibrates which generates both an auditory and tactile warning of the lane departure. Centreline rumble strips have been estimated to reduce impacts with vehicles travelling to the opposite direction by one quarter [3]. Most drivers would be expected to steer back to the initial lane of travel instead of turning into the oncoming traffic. However, simulator studies showed that between 20-37% of drivers steered away from the initial lane of travel after contacting a centreline rumble strip [4]. A separate study in Texas found that all of the 479 vehicle contacts with the centreline rumble strip resulted in proper trajectory corrections [5]. However, neither of these studies observed any crashes or near-crashes to evaluate driver manoeuvres when a crash is imminent.

One potential vehicle-based countermeasure designed to help prevent both road departure and cross-centreline head-on crashes is lane departure warning (LDW) systems. LDW systems typically use a camera to track the lane position of the vehicle when adequate lane markings are present. When the vehicle begins to depart from the lane of travel, the LDW system delivers an audible or haptic warning to the driver. The driver may then

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react to the warning and attempt to return to the lane of travel (Fig. 2). The effectiveness of LDW systems is largely dependent on the reaction time of the driver assuming the driver steers back towards the initial lane of travel [6,7]. Little has been published on how a driver may react to a LDW especially when a head-on crash is imminent.

Studies of driver manoeuvres during cross-centreline crashes have focused on the driver of the encroaching vehicle [4]. However, the driver of the impacted vehicle may also perform evasive actions in an attempt to avoid a head-on collision. The purpose of this paper is to characterize the evasive actions taken by the drivers of both the encroaching and the impacted vehicles before a cross-centreline head-on crash. This is the first step toward building encroaching and impacted vehicle driver models in cross-centreline head-on crashes. Such driver models can be quite helpful for automakers to design an in-vehicle system that is effective in preventing or mitigating lane departure crashes.

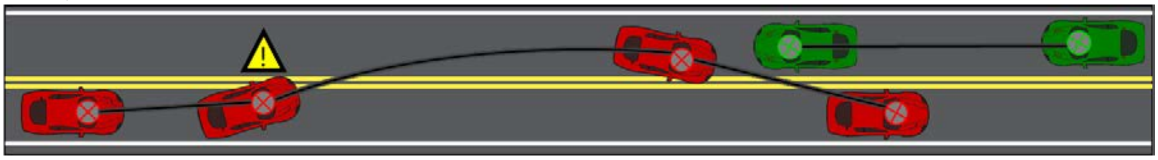


Fig. 2. Example lane recovery after LDW or centreline rumble strip contact

II. METHODS

The study utilized data from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) which contains in-depth crash information for a sample of crashes in the United States in which at least one vehicle was towed away from the scene. Cross-centreline head-on crashes were selected from the most recent five years (2011-2015) of data in NASS/CDS. For some crashes, NASS/CDS also contains data retrieved from a vehicle's event data recorder (EDR). EDRs record basic vehicle information during a crash as well as up to five seconds of pre-crash information such as speed and brake status. To be included in this study, NASS/CDS cases must have had EDR information available for either the encroaching or impacted vehicle. 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 not involving an airbag deployment could occur to overwrite the data [6]. To ensure that the EDR events align with the NASS/CDS events, we selected cases in which the first event in the NASS/CDS case was the largest delta-v of all events. This selection criteria is the same as that used by Scanlon to analyse intersection crashes [8]. The scaled scene diagram of each cross-centreline head-on crash where at least one vehicle had EDR information available, was measured to obtain the trajectory of the encroaching and impacted vehicles. The trajectory of each vehicle's centre of gravity was measured relative to where the centre of gravity of the encroaching vehicle crossed the first lane line. There were four cases in which the encroaching vehicle crossed a centreline rumble strip before the crash. The case selection criteria is summarized in Table I. There were 157 vehicles, 62 encroaching and 95 impacted vehicles, with EDR information available. However, each EDR did not contain all the variables of interest.

TABLE I
Selection Criteria

Criteria	Encroaching Vehicles	Encroaching Vehicles (weighted)	Impacted Vehicles	Impacted Vehicles (weighted)	Total Vehicles	Total Vehicles (weighted)
NASS/CDS 2011-2015	13,826	6,350,944	13,826	6,350,944	317,998	12,701,888
EDR Information and Scaled Scene Diagram Available	181	58,219	183	58,222	364	116,441
Airbag Deployment or delta-v > 8kph	62	15,971	95	33,974	157	49,945
Pre-crash Speed Available	62	15,971	94	33,540	156	49,511
Pre-crash Braking Available	61	15,710	95	33,974	156	49,684
Pre-crash Yaw Rate Available	10	2,394	17	5,043	27	7,437

The departure angle was measured from the scene diagram and was defined as the angle between the path of the vehicle centre of gravity and the line tangent to the lane line at the first lane departure. For example, if the encroaching vehicle crosses multiple lanes before the centreline, the departure angle was measured at the first lane departure not at the centreline. The distance to impact from the first lane departure was measured as the straight-line distance from the point of departure to the point of impact.

The information recorded by EDRs vary by manufacturer and module type. All EDRs record five seconds of pre-crash information. However, the resolution of the measurements can vary from one sample to ten samples a second. Since the EDR module takes measurements at a specified interval, it likely does not record a measurement exactly at the time of impact [8]. A few EDRs do record a measurement at the moment of impact but it is not necessarily measured at the same period as the rest of the measurements. In our study, the impact speed was assumed to be the last measurement taken by the EDR. Therefore, the assumed impact time was no more than one sampling period from the actual impact time. The travel speed was assumed to be the first measured speed.

Each case was examined for evidence of braking or steering manoeuvres. For the EDRs which recorded brake activation, the brake activation was used to determine whether the driver braked before the crash. However, brake activation does not indicate the magnitude of the deceleration. Therefore, the change in speed was divided by the brake duration to estimate the deceleration. The average deceleration was determined for both encroaching and impacted vehicles using a linear regression relating the change in velocity to the time spent braking. The deceleration was only computed during the consecutive measurements where the driver activated the brake leading up to the crash. For the EDRs which recorded the vehicle yaw rate, evasive steering was defined as a yaw rate greater than 4 deg/s based on naturalistic driving studies [9].

One specific case we analysed was case number 550017440. In this case a 73 year old female was driving a 2011 Chevrolet HHR (vehicle 1) through a construction zone on a rural two lane highway (Fig. 3). The vehicle departed the lane and impacted a 2010 Ford E-Series van (vehicle 2) driven by a 25 year old female travelling in the opposite direction. The driver of the encroaching vehicle had an injury of MAIS 4 severity and the other driver had an injury of MAIS 2 severity. The EDR in vehicle 1 did not take a measurement at the time of impact but the EDR in vehicle 2 did include a measurement at the time of impact (Fig. 4). The EDR information indicates that both vehicles were travelling about 66 km/hr prior to the crash. The impacted vehicle saw the encroaching vehicle and reacted by both steering and braking simultaneously.

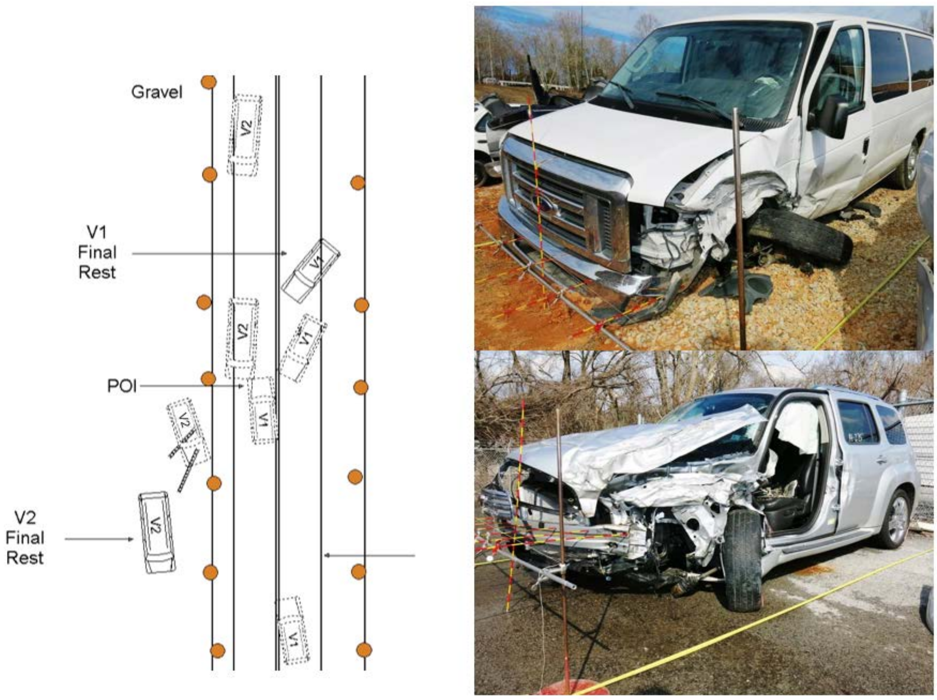


Fig. 3. Case number 550017440. Chevrolet HHR (V1, bottom) departs lane and impacts a Ford E-Series van (V2, top)

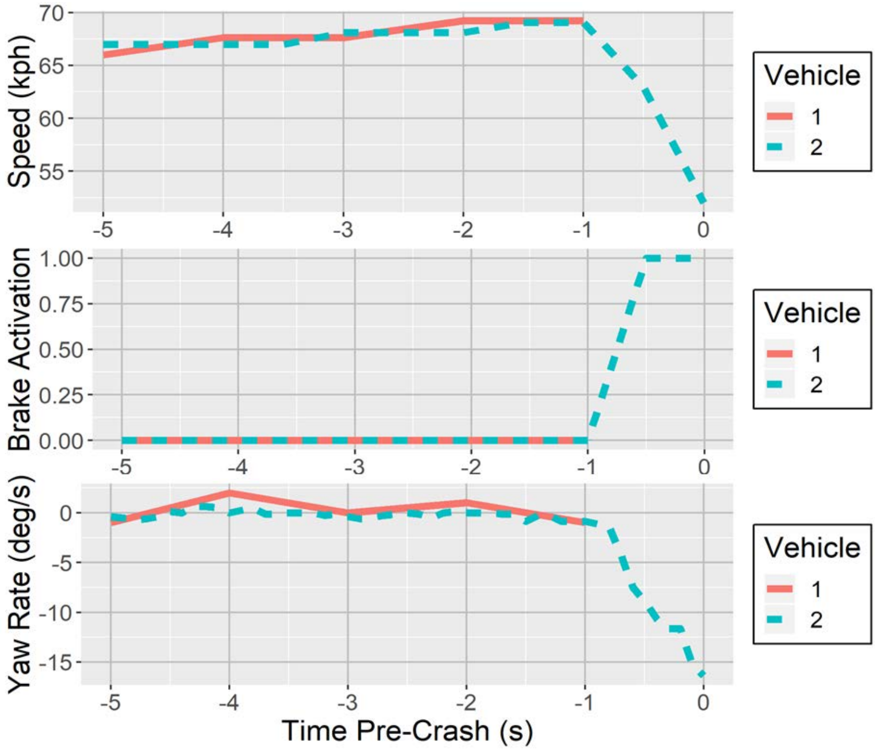


Fig. 4. The EDR speed, braking, and yaw rate information for both vehicles

III. RESULTS

The evasive manoeuvres performed by the drivers and their frequency are summarized in Table II. Both the encroaching and impacted vehicle drivers performed steering and braking manoeuvres with a similar frequency.

TABLE II
Evasive Manoeuvres Distribution

Evasive Action	Role	Action Performed	Cases Available	Percent of Cases	Action Performed (weighted)	Cases Available (weighted)	Percent of Cases (weighted)
Brake	Encroaching	29	61	47.5%	7,229	15,710	46.0%
	Impacted	76	95	80%	26,230	33,974	77.2%
	Total	105	156	67.3%	33,458	49,684	67.3%
Steering	Encroaching	5	10	50.0%	1,878	2,394	78.4%
	Impacted	13	17	76.5%	4,056	5,043	80.4%
	Total	18	27	66.7%	5,934	7,437	79.8%

Our dataset included one case in which both the encroaching and impacted vehicles had yaw rate information from the EDRs. However, there were 11 cases in which both vehicles had EDR data with braking information. The majority of the impacted vehicles did perform a braking manoeuvre before the crash (Table III). In contrast, the majority of encroaching vehicles did not brake before the impact.

TABLE III
Contingency Table of Braking Manoeuvres

		Encroaching Vehicle Braked		
		Yes	No	Total
Impacted Vehicle Braked	Yes	3	6	9
	No	0	2	2
	Total	3	8	11

There were 27 EDRs representing 7,433 vehicles with both steering and braking data. The majority of encroaching and impacted drivers responded by both steering and braking simultaneously (Table IV). This is likely why they had similar frequencies in Table I.

TABLE IV
Combination of Evasive Manoeuvres

Evasive Action	Role	Action Performed	Cases Available	Percent of Cases	Action Performed (weighted)	Cases Available (weighted)	Percent of Cases (weighted)
No Avoidance	Encroaching	4	10	40.0%	394	2,392	16.5%
	Impacted	0	17	0.0%	0	5,041	0.0%
	Total	4	27	14.8%	394	7,433	5.3%
Brake and Steer	Encroaching	3	10	30.0%	1,333	2,392	55.7%
	Impacted	11	17	64.7%	3,731	5,041	74.0%
	Total	14	27	51.8%	5,065	7,433	68.1%
Steer Only	Encroaching	2	10	20.0%	544	2,392	22.7%
	Impacted	2	17	11.8%	323	5,041	6.4%
	Total	4	27	14.8%	868	7,433	11.7%
Brake Only	Encroaching	1	10	10.0%	121	2,392	5.1%
	Impacted	4	17	23.5%	987	5,041	19.6%
	Total	5	27	18.5%	1,108	7,433	14.9%

In the majority of cross-centreline crashes – 49.3% of the encroaching vehicles and 31.2% of the impacted vehicles – the vehicle was travelling faster than the speed limit (Fig. 5). In 26 of the 62 cases, the encroaching vehicle was travelling more than 8 kph (5 mph) over the speed limit. The median travel speed was 59.6 kph for the encroaching vehicle and 46.7 kph for the impacted vehicle (Fig. 6).

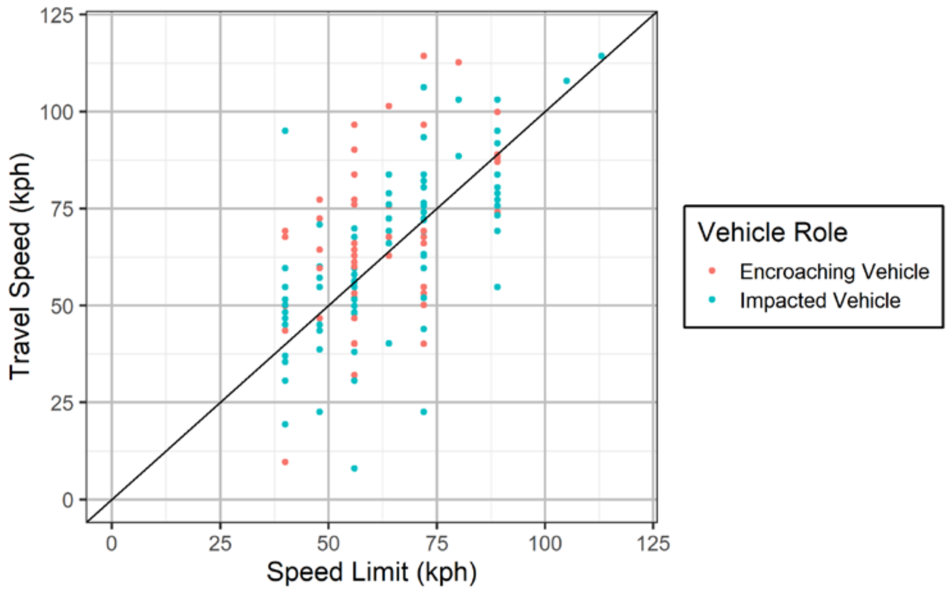


Fig. 5. Vehicle speed compared to the posted speed limit. Cases above the line represent vehicles travelling faster than the posted speed limit

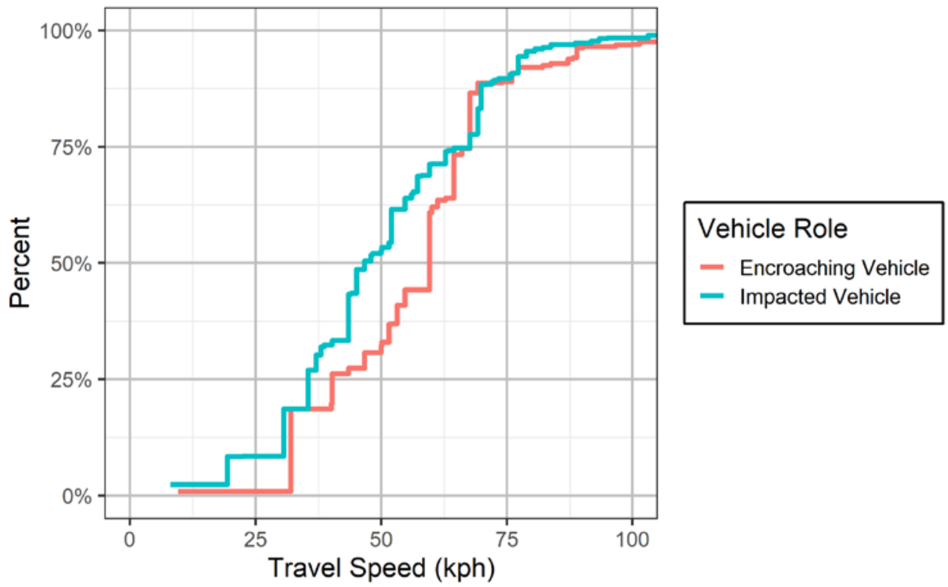


Fig. 6. Distribution of travel speeds

The median departure angle was 9° (Fig. 7). The median departure angle was larger than the 0.4 to 0.6° reported from naturalistic driving studies [10]. This is likely due to the fact that all cases in NASS/CDS are crashes, so the departure angles were significantly higher, whereas in the naturalistic data sets, there were no crashes, so the departure angles were much lower and the driver was able to manoeuvre the vehicle back in the lane

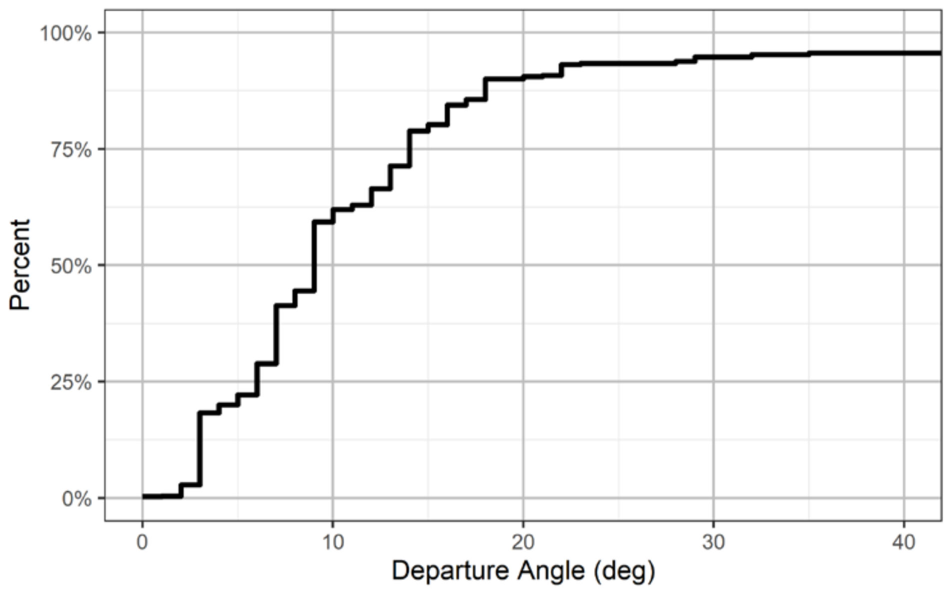


Fig. 7. Distribution of departure angles

The median impact speed was 40.3 kph for the encroaching vehicle and 38.0 kph for the impacted vehicle (Fig. 8). The median change in velocity during the crash (delta-v) was 17.2 kph for the encroaching vehicle which is about half of the impact speed (Fig. 9). The median delta-v was lower for the impacted vehicle at 12.4 kph. This suggests that the impacted vehicle tended to experience a lower crash severity than the encroaching vehicle.

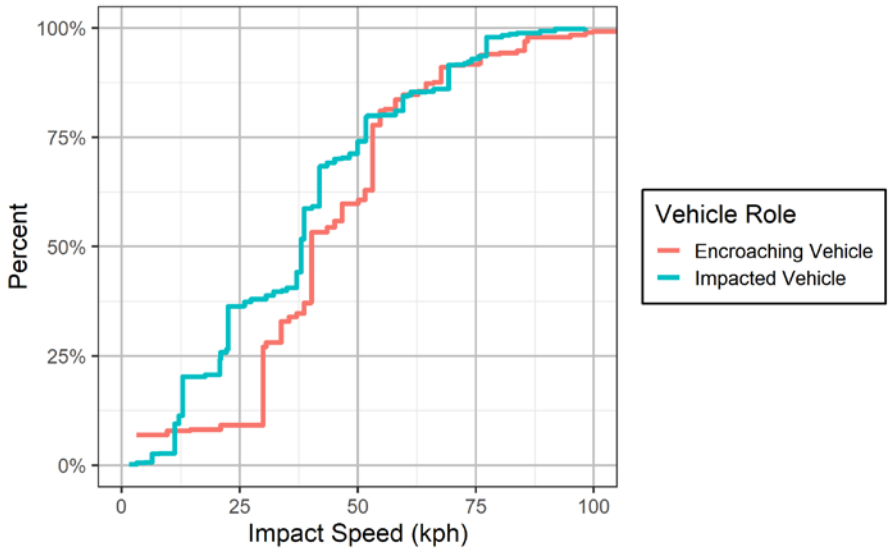


Fig. 8. Distribution of impact speeds

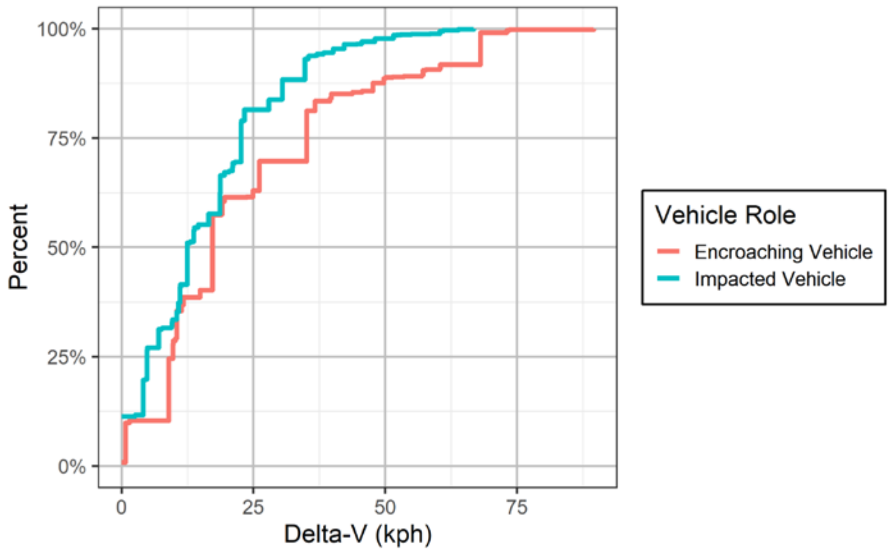


Fig. 9. Distribution of crash impact delta-v

Over 25% of cross-centreline crashes occurred within 1m of the point of lane departure (POD) (Fig. 10). Because the cross-centreline head-on crashes occurred very close to when a LDW would trigger, it may be difficult for even a warned driver to avoid this crash type.

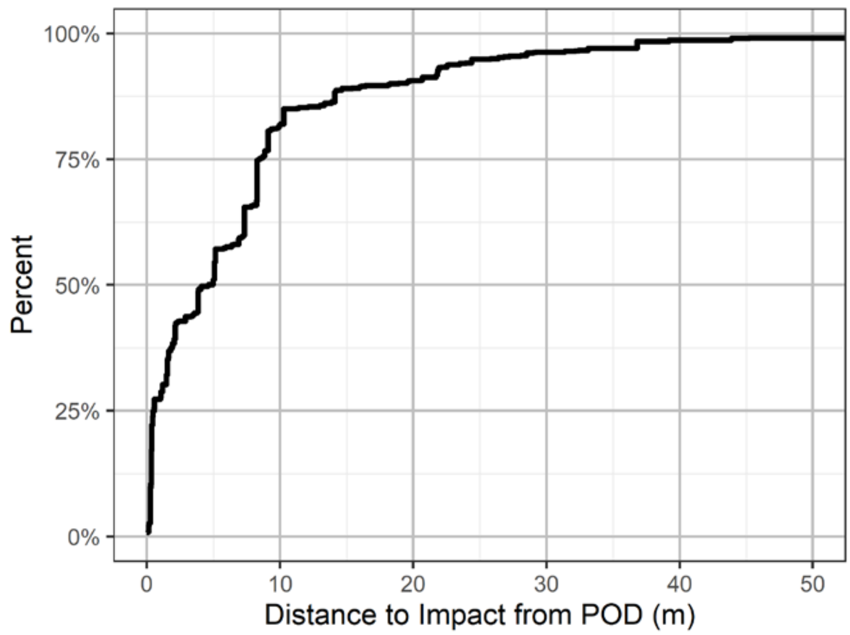


Fig. 10. Distance from the point of lane departure to the impact location for the encroaching vehicle

IV. DISCUSSION

Development of Driver Model in Cross-Centreline Crashes

Based on the driver response information from the EDR data, a probabilistic driver response model was developed. The frequency of braking, steering, and combination manoeuvres were discussed in Table IV. However, in order to develop a meaningful model for both the encroaching and impacted vehicle drivers, first it was important to understand the magnitude of the braking and steering manoeuvres.

Braking Model

The average deceleration of the encroaching vehicle due to braking was greater than the average deceleration of the impacted vehicle due to braking (Fig. 11). The impacted vehicle decelerated at about half the magnitude of evasive braking observed in intersection crashes (0.58 g) [8]. The evasive braking deceleration was much lower for cross-centreline crashes than road departure crashes which may indicate less time to react. There was very little difference in the deceleration between the encroaching and impacted vehicles.

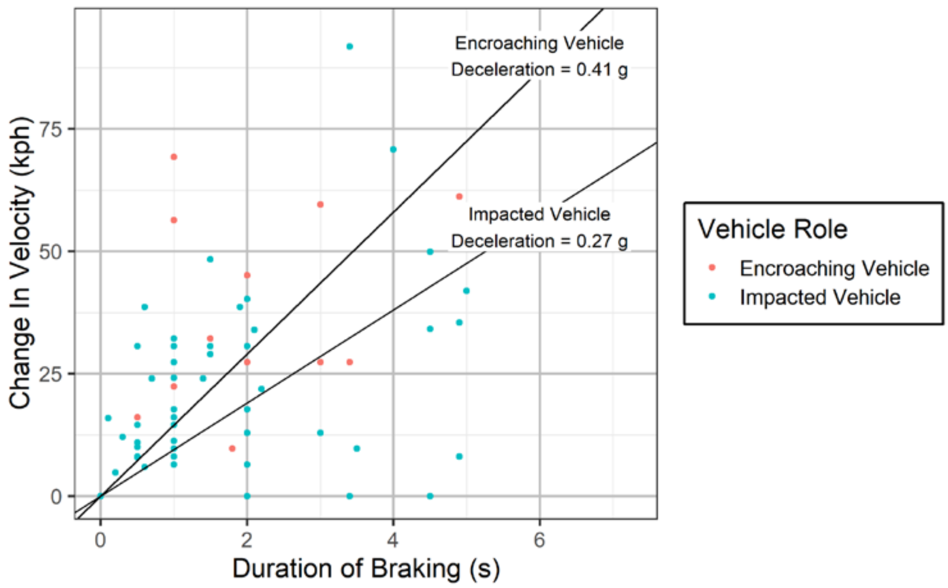


Fig. 11. Vehicle deceleration from braking before impact

Of the vehicles which performed a braking manoeuvre before the impact, the median brake duration was 1.0s for the encroaching vehicle and 0.6 s for the impacted vehicle (Fig. 12).

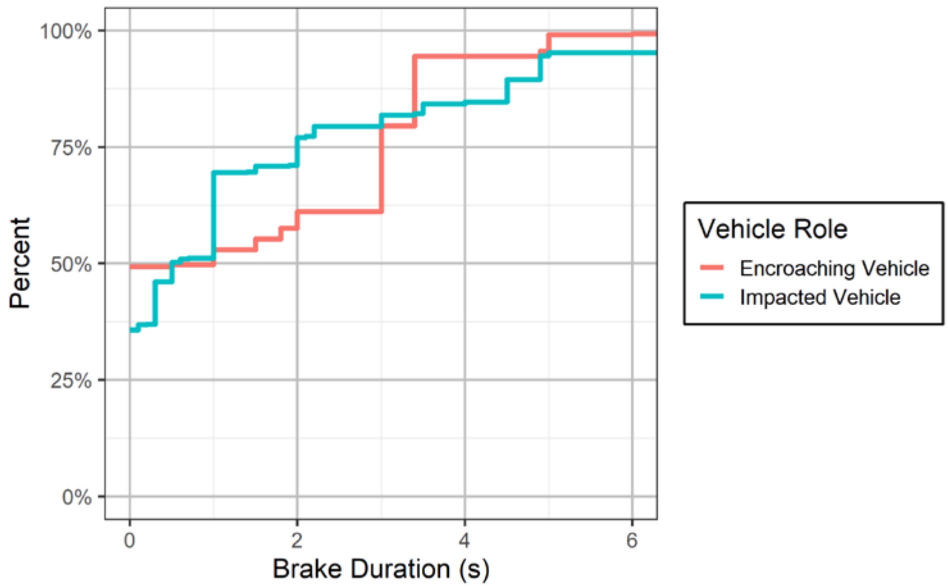


Fig. 12. The distribution of braking duration for vehicles which performed a braking manoeuvre before impact

The distribution of vehicle decelerations before impact is shown in Fig. 13. The median deceleration was 0.56g for the encroaching vehicle and 0.32g for the impacted vehicle. The decelerations were computed as the change in velocity divided by the duration of braking. This method led to a total of six cases with a deceleration greater than 1g, which is not possible from braking alone. Four of these cases were travelling uphill before the crash and one jumped a small median before the crash. For the last case, the measured brake duration may be shorter than the actual brake duration due to the low sampling frequency of the EDRs. The average vehicle deceleration for the encroaching vehicle (0.41g) and impacted vehicle (0.27g) was used to represent the braking manoeuvre of each vehicle.

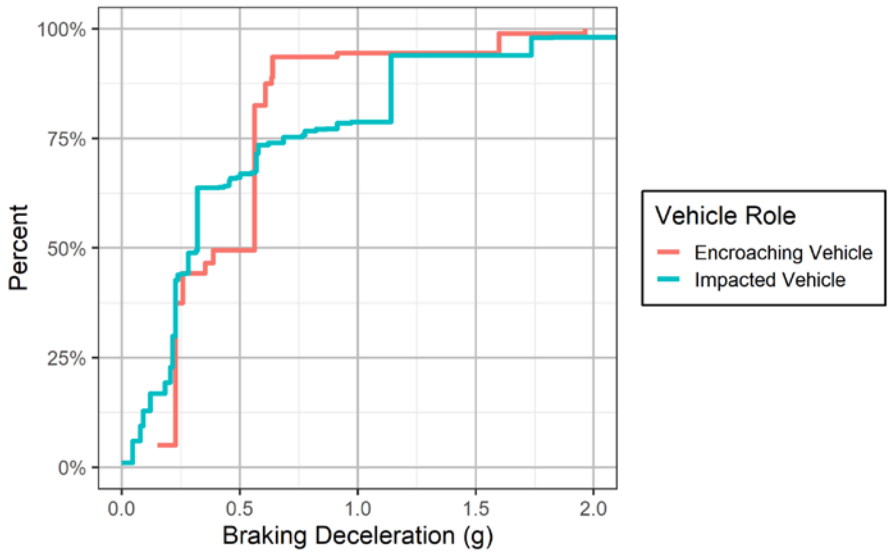


Fig. 13. The distribution of deceleration for vehicles which performed a braking manoeuvre before impact

Steering Model

As a group, the encroaching vehicle typically performed a harder evasive steering manoeuvre than the impacted vehicle. The median magnitude of steering was 25 deg/s for the encroaching vehicle compared to only 11.7 deg/s for the impacted vehicle (Fig. 14). The median yaw rate for the encroaching vehicle and impacted vehicle was used as a surrogate for the steering magnitude. Every encroaching vehicle which performed a steering manoeuvre before the impact, steered to the right, back toward their original lane of travel (Table V). The impacted vehicle was more likely to steer but the direction of steering was not consistent. The impacted vehicle most commonly steered to the right, away from the centreline. One impacted vehicle (Case ID 717018033) crossed the centreline in an attempt to avoid the crash. If the impacted vehicle driver model performed a steering manoeuvre, then 71.7% of the time it turned left, and 28.3% of the time it turned right.

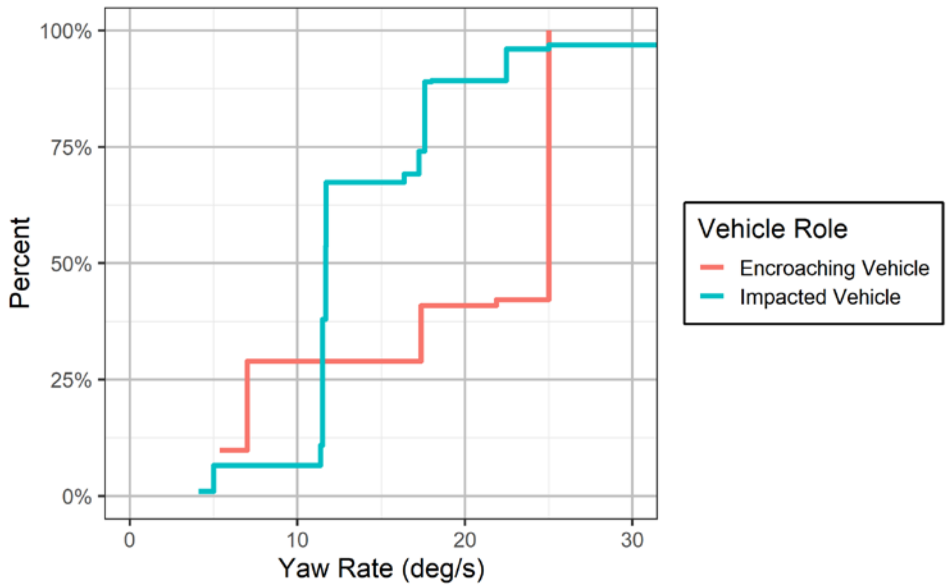
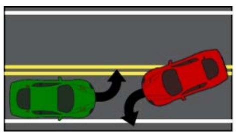
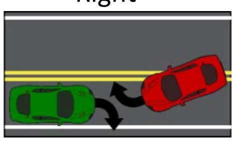


Fig. 14. Distribution of the maximum yaw rates for vehicles which performed a steering manoeuvre

TABLE V
Distribution of Steering Manoeuvre Direction

Steering Direction	Role	Action Performed	Cases Available	Percent of Cases	Action Performed (weighted)	Cases Available (weighted)	Percent of Cases (weighted)
Left 	Encroaching	0	5	0.0%	0	1,877	0.0%
	Impacted	5	13	38.5%	1,149	4,054	28.3%
Right 	Encroaching	5	5	100.0%	1,877	1,877	100.0%
	Impacted	8	13	61.5%	2,905	4,054	71.7%

Driver Model in Cross-Centreline Crashes

Two separate models for the encroaching and impacted vehicle were developed using EDRs which recorded both steering and braking information. The predicted evasive steering manoeuvre in the driver model was a yaw rate of 25 deg/s for the encroaching vehicle and 11 deg/s for the impacted vehicle based on the median yaw rate. The predicted braking manoeuvre in the driver model was 0.41g for the encroaching vehicle and 0.27g for the impacted vehicle based on the average vehicle deceleration. The evasive actions by the impacted vehicle driver are less extreme than the encroaching vehicle driver. The most common evasive action by the encroaching vehicle driver was braking and steering to the right (Table VI). In the analysed cases the encroaching vehicle driver never performed a steering manoeuvre to the left which is reflected in the model. This model provides insight into how encroaching vehicle drivers may react when given a warning in cross-centreline departures.

TABLE VI
Encroaching Vehicle Driver Model

Evasive Action	No Braking (0.0g)	Braking (0.41g)
No Steering (0 deg/s)	16.5%	5.1%
Steering Left (25 deg/s)	0.0%	0.0%
Steering Right (25 deg/s)	22.7%	55.7%

Unlike the encroaching vehicle driver model, the impacted vehicle driver always performs an evasive manoeuvre (Table VII). Similar to the encroaching vehicle, the impacted vehicle driver most frequently performs a braking and steering manoeuvre. Occasionally, the impacted vehicle driver performs a steering manoeuvre to the left. This was an important finding since the impacted vehicle would be travelling toward the encroaching vehicle which could result in a more severe crash than if the vehicle had travelled to the right.

TABLE VII
Impacted Vehicle Driver Model

Evasive Action	No Braking (0.0g)	Braking (0.27g)
No Steering (0 deg/s)	0.0%	19.6%
Steering Left (11 deg/s)	1.8%	20.9%
Steering Right (11 deg/s)	4.6%	53.1%

Limitations

This study analysed only those centreline departures that resulted in vehicle-to-vehicle collisions with EDR data available. Accordingly, conclusions cannot be made about what driver manoeuvres were successful in avoiding a crash. Additionally, the resolution of the measurements was limited by the recording frequency of the EDR. A more detailed driver model could be developed further with additional cases.

V. CONCLUSIONS

Overall, the impacted vehicle driver was found to be more likely to attempt an evasive manoeuvre than the encroaching vehicle. Among the crashes where EDR information was available, all impacted vehicles attempted to perform an evasive action. The most common manoeuvre was braking and steering simultaneously. However, the drivers did not brake as hard as was possible. The encroaching vehicle tended to be travelling faster than the impacted vehicle. Additionally, over one quarter of cross-centreline vehicle-to-vehicle crashes occur within 1 m of the centreline. Two separate models for the encroaching and impacted vehicle were developed using EDRs to predict whether a driver would brake, steer left, steer right, both braking and steering, or not react. This model provides insight into how encroaching vehicle drivers may react when given a warning in cross-centreline departures.

VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Toyota Collaborative Safety Research Center (CSRC) and Toyota Motor Corporation for funding this study.

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