ABSTRACT

Naturalistic Driving Study (NDS) data are an important source for driver behavior data to design and evaluate autonomous vehicles and driver assistance systems. The number of serious crash events in NDS, however, is often small. As a result, surrogates such as “near crashes” or events identified using vehicle instrumentation are used with the assumption that they are relevant to real crash events. The objective of this study is to determine if NDS crash and near-crash data are indeed representative of crash events. To examine this issue, we focused on one subset of crash events, lane departure events where the vehicle drifts out of its lane. These are the events most likely to be mitigated by lane departure warning systems.

Four naturalistic datasets that covered the full range of events from lane departures during normal driving, to near-crashes, to crashes were compared to data from a crash database. Our hypothesis is that the crash and near-crash NDS events will have the most similar vehicle kinematics compared to the crash database. Normal driving departure events were extracted from the Integrated Vehicle-Based Safety Systems (IVBSS) field operation test. Two departure event datasets from IVBSS were identified using the lane tracking cameras. The first dataset consisted of 12,760 cases of the vehicle departing and returning to its lane and the second consisted of 7,750 events where the equipped LDW systems were triggered. Thirty-two (32) near-crash lane departure events were analyzed from the 100-Car NDS. Finally, 49 curb strike events were analyzed from the SHRP-2 NDS. Data from lane departure crashes was extracted from the National Automotive Sampling System, Crashworthiness Data System (NASS/CDS). Event Data Recorders (EDRs) downloaded from 482 NASS/CDS crash investigations were analyzed.

There were important sampling differences between datasets. Younger drivers were overrepresented in the 100-Car near-crash and SHRP-2 curb strike events and crash data while the IVBSS participants were uniformly distributed over age and gender groups. The vehicle speeds from IVBSS were restricted to over 42 kph (25 mph), whereas the crash data had vehicles speed that contained both low and high speed events. The 100-Car near-crash and SHRP-2 curb strike departures had larger departure angles (2.6° and 14.1° median, respectively) and lateral excursion (0.63 m and 0.50 m median, respectively) compared to the IVBSS data (0.6° and 0.7° departure angle and 0.19 m and 0.10 m excursion for LDW and lane departure datasets, respectively). The differences in departure conditions may have also affected driver maneuvers after the departure. In 52% of crashes with EDRs there was a brake application in the last second before the crash compared with 38% of 100-Car near-crash and 33% of SHRP-2 curb strike events. The selection criteria for the IVBSS departures excluded almost all brake application, with only 4% of the IVBSS LDW events having brake application. Steering wheel input was also substantially larger in the 100-Car near-crashes (48°) compared to the IVBSS (4°-5°).

These results show that crash and near-crash events from NDS produce datasets that are most consistent with crash data compared to datasets generated using lane tracking information. If the research question involves replicating conditions relevant to departure crashes, such as in the design of test track experiments, crash and near-crash events should be used over less severe NDS departure events.

INTRODUCTION

Naturalistic Driving Studies (NDS) have become an important data source for studying driver behavior to design and evaluate active safety systems, such as lane departure warning (LDW) systems. NDS involve instrumenting drivers’ personal vehicles and recording all normal driving for a period of months or years. Participants are given no
special instructions and researchers are not present during driving. The result is often thousands to millions of vehicle miles of instrumented driving. The instrumentation, including cameras and vehicle sensors, provide a high level of detail to study driver behavior in a variety of driving scenarios. LDW systems will mostly likely mitigate crashes caused by the driver inadvertently drifting out of the vehicle’s lane, i.e. not changing lanes or turning. This study focuses on examining lane departure events where the driver drifted out of their lane. These drift out of lane events are important for developers of LDW systems because they represent the scenarios where LDW will most likely activate.

Because crashes are extremely rare in NDS, analysis is often based on near-crashes or other crash surrogates that are correlated with crash risk (Guo et al. 2010). The assumption of researchers is that these NDS critical events, whether identified through manual review or aggregated from vehicle sensor data, are representative of crashes and crash risk. The validity of this assumption is on open research question (Ljung Aust 2013), but is difficult to evaluate because the type of driver behavior data obtained from NDS are not available in most crash datasets. Using critical event data may be appropriate for some research questions, such as exposure to lane departures, but not for other research questions, such as how drivers steer to avoid serious departure events. Although a researcher’s choice of dataset may affect the results of studies, little previous work has been done to directly compare different NDS data sources.

Most crash databases are investigated retrospectively and do not contain detailed pre-crash information that is available in most NDS. One promising data source for obtaining driver behavior from crashes are Event Data Recorders (EDRs). EDRs are able to record data both after a crash occurs as well as pre-crash vehicle data in some modules. This study uses a set of EDR modules downloaded from investigated crashes from a nationally representative crash database. In addition to the vehicle speed and brake pedal data recorded on the EDR, supplemental analysis of the scene diagrams prepared by investigators was performed to measure the approximate departure angle and impact location.

Even between different NDS, the selection criteria to generate lane departure event datasets may affect the composition of the lane departure datasets. Some selection criteria may result in a dataset of more severe driver corrective action than other selection criteria, for example. Where along the continuum of departure severity a departure dataset falls, from moderate departures requiring little driver intervention to near-crashes involving emergency maneuvers, may have implications for the study of active safety systems. For example, selecting a dataset that has only small driver steering input may result in evaluations that do not include departure conditions relevant to crashes.

The objective of this study was to determine how representative lane departure event datasets extracted from NDS are of real crashes investigated in crash databases. This study is unique in that it directly compares the completely different NDS to real-world crash data.

**METHODS**

**Comparison of Datasets**

The data sources for this study were the 100-Car NDS, the Integrated Vehicle-Based Safety Systems (IVBSS) NDS, the SHRP-2 NDS, and EDRs downloaded from crashes in the National Automotive Sampling Systems, Crashworthiness Data System (NASS/CDS). A description of each data source and selection criteria of departure events are described in the following sections. This first section describes how data sources were compared.

Figure 1 shows the relationship of the data sources examined for this study. The NDS and crash data sources are arranged in increasing severity. The hypothesis that will be examined in this paper is that the more severe NDS lane departure events are most similar to crash events. The crash data from the NASS/CDS was used as the “gold standard” that represents serious crashes that result in tow-away damage to vehicles.
Figure 1. Comparison of Lane Departure Events from NDS and Crash Databases.

The data sources will be compared in two ways: 1) the drivers and vehicles that make up each data source and 2) the characteristics of the vehicle during the departure events. The first comparison of participant and vehicle makeup will determine how selection criteria may bias the observed behavior. Age and gender can affect driver behavior (Montgomery et al. 2014). The age of the vehicle may also affect handling and the availability of safety equipment such as electronic stability control. The second comparison of the departure events will determine how the departure characteristics differ between critical events and crashes. These characteristics include departure angle and vehicle speed, brake application, steering wheel angle, and maximum lateral excursion.

100-Car NDS

The 100-Car NDS was a landmark study of approximately 100 vehicles instrumented between 2002 and 2004 in the Washington D.C. metropolitan area (Dingus et al. 2006). There were 108 primary drivers that enrolled in the study. A primary driver was the owner(s) or lessee(s) of the vehicles who most often drove the vehicle. These primary drivers drove approximately 1.1 million miles during the study and drove an average of 224 unique days while their vehicles were instrumented (McClafferty and Hankey 2010). The instrumentation on the vehicles included cameras, inertial sensors, and monitoring of the vehicle network (CAN) data. Some vehicles were fitted with a prototype lane detection system, but not in sufficient numbers to identify a representative sample of departure events. Participants that were new drivers and that had high self-reported driving mileage were oversampled in the study design.

Lane departure crash and near-crash events from the 100-Car study were first identified by McLaughlin et al. (2009). They identified 121 lane departure events, 28 of which were crashes and the remaining 93 were near-crashes. Crashes included any physical contact with objects, including vehicles striking curbs. A near-crash was defined as the vehicle leaving the road or a vehicle leaving the lane and having to take emergency maneuvers to avoid impacting another vehicle or object. Near-crashes were found by first identifying potentially dangerous events using lateral acceleration and yaw rate sensors and then by a manual review of events. Of these 121 lane departure events, many were scenarios that LDW systems will likely not mitigate, such as leaving the road after avoiding a stopped lead vehicle, changes in road geometry in or around intersections, or as the result of turning maneuvers. Our study examined the video and instrumentation data for the 121 departure events. Our analysis identified 32 events were the driver unintentionally drifting out of their lane, which is the scenario most applicable to LDW systems. Of these events, 5 were classified as crashes and 27 as near-crashes. All 5 crash events were curb strikes that did not result in vehicle damage. These 32 events are the basis for the 100-Car events analyzed for this study. These events will be referred to as the “100-Car near-crash events” in this study. Even though 5 events were classified as crashes, these curb strikes do not rise to the same severity as tow-away crashes extracted from NASS/CDS.

Integrated Vehicle-Based Safety Systems Field Operational Test

The IVBSS NDS was conducted by the University of Michigan Transportation Research Institute (UMTRI) (Sayer et al. 2008, Sayer et al. 2011a, Sayer et al. 2011b, Nodine et al. 2011). IVBSS was designed to assess the effectiveness of prototype crash warning systems designed to mitigate the risk of rear-end, roadway departure, and lane change-merge crashes. In the light vehicle portion of IVBSS, vehicles were installed with forward collision warning (FCW), lane departure warning (LDW), lane-change/merge warning (LCM), and curve speed warning (CSW).
Participants of the program included 108 drivers randomly selected and stratified by age and gender. State driving records were used to identify an equal proportion of males and females in the age groups of 20 to 30 years, 40 to 50 years, and 60 to 70 years. Participants were equally distributed over the three age groups, but the exact number of participants by age and gender was not disclosed by the study designers. The drivers were given a 2006 or 2007 model year Honda Accord equipped with retrofitted prototype crash warning systems. The instrumented test vehicles recorded driving during a 40 day period. During the first 12 days, or the “baseline period”, the system gave no warnings from the crash avoidance systems. The activation of the systems, however, was recorded during the baseline period. During the “treatment period”, or the last 28 days of data collection, the system provided audible, visual warnings, and tactile warnings. Instrumentation in the study included video, inertial sensors, lane tracking information (lane width, vehicle position in lane, lane marking type), and LDW system activation.

Two datasets from the IVBSS were examined for this study: 1) lane departure events as identified by the lane tracking cameras and 2) lane departure events that triggered the LDW system (Sayer et al. 2011a). The selection criteria, number of events, and human review status is summarized in Table 1. Vehicle instrumentation and forward video data were provided to the authors by UMTRI.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Lane Departure Event</th>
<th>Valid LDW Triggered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition for Inclusion</td>
<td>Vehicle leaves and returns to lane; no lane change, braking, or large steering input activity 5 seconds before, after, or during departure; no braking during event; speed above 25 mph</td>
<td>LDW delivered, reviewer confirmed system operated correctly, and driver had steering reaction to return to lane</td>
</tr>
<tr>
<td>Number of Events</td>
<td>12,760</td>
<td>7,750</td>
</tr>
<tr>
<td>Generated by Human Review</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The IVBSS lane departure event dataset was collected by selecting driving where the lane tracking system had high confidence of lane tracking and the vehicle was traveling above 42 kph (25 mph). A departure event was defined as one of the vehicle’s wheels crossing the lane boundary followed by the vehicle returning to the lane within 20 s of the departure. Any events that had intentional maneuvers (e.g., lane changing or turning) within 5 s of the start or end of the departure event were excluded. Any departure events with braking during the departure were also excluded. The result was a dataset of 12,760 lane departure events generated automatically without manual review of events.

The LDW triggered event dataset was constructed from LDW warnings that were triggered during the study. These events included LDW activation during both the baseline period, where no warnings were delivered to the drivers, and the treatment period, where warnings were delivered. There were two levels of LDW alerts: 1) a “cautionary” alert (LDW-C) and 2) an “imminent” alert (LDW-I). The LDW-C was delivered when the driver was drifting out of their lane into an unoccupied space, such as a clear lane or the shoulder. The LDW-I alert was delivered when the side-looking sensors detected a hazard, such as another vehicle or roadside object. The LDW-C alert presented only a seat vibration in the direction of the lane departure and the LDW-I alert delivered seat vibrations as well as audio and visual warnings. All warnings were suppressed at vehicle speeds less than 40.2 kph (25 mph). In total there were 20,005 LDW-C and LDW-I warnings triggered. Of these, a video review performed by UMTRI found that 94% of warnings were valid (Sayer et al. 2011a). A valid LDW was defined as a warning that was delivered as intended by the design of the system. Many warnings, however, were delivered when a driver changed lanes without using a turn signal or intentionally left the lane, for example to avoid construction equipment. A video review performed by UMTRI researchers found that 7,385 LDW events had a driver reaction to steer back toward the lane.

The lane departure event and LDW triggered event datasets had little overlap. Out of the 12,760 departure events, only 2,165 (17% or departure events) had an LDW during or within 1 second of the departure. Of the 7,750 LDW events with driver correction that were validated by manual review, 1,343 were on the departure data set (17.3% of valid LDW events). The design of LDW used in IVBSS was proprietary. The result that many drift out of lane
events did not trigger an LDW may suggest that the design of the LDW was dependent on other vehicle dynamics, such as lateral speed, other than lateral distance to the lane line.

**SHRP-2 NDS**

The Strategic Highway Research Program 2 (SHRP-2) NDS was a follow-on to the 100-Car study and was funded by the Transportation Research Board of the National Academies. A total of 3,362 vehicles were instrumented in 6 study locations throughout the U.S. Collection of the field data was completed in 2013. The analysis of the data is ongoing. In total 6.7 million trips were recorded resulting in 49.7 million miles traveled, which is approximately 45 times more distance traveled than was recorded during the 100-Car study.

Part of the initial analysis of the SHRP-2 NDS was identifying all crash and near-crash events that occurred. Identification of crash and near-crash events followed a protocol similar to the 100-Car study. First, risky driving events were identified by using the instrumentation signals. Second, risky events were manually reviewed by data reductionists to classify the events as crashes, near-crashes, or non-critical events. For this study, all crash events with a precipitating event of the vehicle departing its lane were analyzed. Crashes were defined as any physical contact between the vehicle and its surroundings. The lowest severity crashes, as defined by the SHPR-2 analysis, involved the tires of the vehicle striking a curb. The most severe event was a vehicle departing the road into a ditch resulting in a rollover.

A total of 49 lane departure crash events were extracted from the data reduction performed for the SHRP-2 study. Events were selected by extracting all events that had an event severity of “crash” (i.e., not near-crash) and an incident type of “lane departure – left or right.” At the time of writing, there were 264 such events in the SHRP-2 database. The data reduction is ongoing and it is expected that more events will be added to the database as analysis is completed. Some lane departure crash events were associated with turning or other another vehicle maneuver (163), occurred in a parking lot (107), and/or were caused by control loss (33). These departure crash events which included maneuvers, parking lots, and control loss were excluded from this analysis because these scenarios would not likely be mitigated by LDW systems. The final dataset of SHRP-2 lane departure crashes consisted of 49 events. From the event narratives, all crash events from SHRP-2 involved minor impacts with a curb and none were police reported.

**Event Data Recorders from NASS/CDS**

In a growing number of NASS/CDS crashes, investigators are able to download the EDR data from the involved vehicles. Since calendar year 2000 NASS/CDS investigators have downloaded over 8,000 EDRs from General Motors (GM), Ford, Chrysler, and Toyota vehicles. Some EDR are able to store vehicle data up to 5 seconds before the crash occurred.

An example of the pre-crash data that is available from some EDRs is NASS/CDS crash 2013-11-049. This crash involved a 2003 GMC G-Series van departing a two-lane undivided road and striking a large tree resulting in the driver being fatally injured. There was no police reported alcohol involvement and the crash occurred during daylight, clear weather, and dry pavement conditions. Figure 2 shows the pre-crash data downloaded from the EDR. The throttle application was constant at 31% prior to the crash, resulting in the vehicle accelerating from 68 to 76 kph (42 to 47 mph). There was no brake application recorded by the EDR prior to the crash. This EDR sampled pre-crash data once every second. Newer modules sample pre-crash data more frequently at 2 or 10 samples per second.
Figure 2. Example of EDR Pre-Crash Data from NASS/CDS Case 2013-11-049.

Table 2 summarizes the number of crashes and vehicles from NASS/CDS involved in single vehicle, drift out of lane crashes with an EDR download. From 2000 to 2013, the years EDRs were downloaded in NASS/CDS, there were 3.8 million weighted single vehicle lane departure crashes, which accounted for 12% of all NASS/CDS crashes. Drift out of lane crashes were identified using pre-crash scenarios developed in a previous study and excluded single vehicle crashes where the vehicle lost control before departing the lane (Kusano and Gabler 2014). Of these lane departure crashes, 249,572 weighted crashes, or 6%, had an EDR downloaded. Some EDRs are able to store events that did not result in a deployment of an air bag, also called non-deployment events. Non-deployment events are not locked in the memory of the EDR and can be overwritten by subsequent events. As a result of the volatile storage of non-deployment events, only EDRs with locked deployment events were analyzed. This final sample of EDRs from drift out of lane departure crashes consisted of 482 modules corresponding to 126,532 crashes or 3% of all drift out of lane crashes in NASS/CDS.

Table 2.
Selected Lane Departure Crashes with EDRs from NASS/CDS Years 2000-2010.

<table>
<thead>
<tr>
<th>Group</th>
<th>Cases</th>
<th>Weighted Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>All NASS/CDS Crashes (2000-2013)</td>
<td>64,189</td>
<td>31,487,174</td>
</tr>
<tr>
<td>All Vehicles with EDRs (2000-2013)</td>
<td>8,426</td>
<td>3,895,698</td>
</tr>
<tr>
<td>Single Vehicle, Lane Drift Crashes</td>
<td>10,808</td>
<td>3,898,012</td>
</tr>
<tr>
<td>Lane Drift Crash with EDR</td>
<td>808</td>
<td>249,572</td>
</tr>
<tr>
<td>Lane Drift with locked EDR Record</td>
<td>482</td>
<td>126,532</td>
</tr>
</tbody>
</table>

RESULTS

Comparison of Drivers and Vehicles

Table 3 shows the distribution of age groups in each of the datasets. Proportions are shown for all departure crashes in NASS/CDS (3.9 million crashes) and for NASS/CDS crashes with EDR downloads (126,532 crashes). The 32 departure near-crash events from the 100-Car study involved 19 drivers, 5 of which were non-primary drivers who did not have age information collected as part of the study. Non-primary drivers were those who did not enroll formally in the study but were recorded driving the instrumented vehicles. The final distribution of demographics from the IVBSS study was not published, but the study design stated that subjects were selected to balance participants in three age groups (20-30, 40-50, and 60-70 years). In the crash data, there were more young drivers under age 21(23.7%) and fewer drivers with age over 60 (8.2%) compared to departures with EDR downloads (17% young driver and 17.5% 60+ drivers). The difference in driver age between NASS/CDS crashes with EDR downloads and all NASS/CDS departure crashes was statistically significant according to a Wald chi-squared test (p = 0.0181). The IVBSS drivers were equally distributed and thus contained more older drivers compared to the crash
data. The 100-Car drivers followed the same trend as the crash data with 64% of drivers under the age of 31, however fewer were under the age of 21. The SHRP-2 curb strike events had more drivers over the age of 60 (22.9%) compared to the crash data, but also had a large proportion of young drivers.

Table 3.
Distribution of Driver Age Group for Crash, EDR, 100-Car, and IVBSS Lane Departure Datasets.

<table>
<thead>
<tr>
<th>Age Group</th>
<th>NASS/CDS Departure Crashes</th>
<th>NASS/CDS Departure Crash EDRs</th>
<th>IVBSS* Normal Driving</th>
<th>100-Car Near-Crashes</th>
<th>SHRP-2 Curb Strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 21</td>
<td>23.7%</td>
<td>17.0%</td>
<td>0%</td>
<td>14.3%</td>
<td>27.1%</td>
</tr>
<tr>
<td>21-30</td>
<td>30.9%</td>
<td>30.0%</td>
<td>33%</td>
<td>50.0%</td>
<td>27.1%</td>
</tr>
<tr>
<td>31-40</td>
<td>16.3%</td>
<td>13.0%</td>
<td>0%</td>
<td>7.1%</td>
<td>6.3%</td>
</tr>
<tr>
<td>41-50</td>
<td>13.6%</td>
<td>10.8%</td>
<td>33%</td>
<td>0%</td>
<td>10.4%</td>
</tr>
<tr>
<td>51-60</td>
<td>7.4%</td>
<td>11.6%</td>
<td>0%</td>
<td>28.6%</td>
<td>6.3%</td>
</tr>
<tr>
<td>60+</td>
<td>8.2%</td>
<td>17.5%</td>
<td>33%</td>
<td>0%</td>
<td>22.9%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

* Demographic information for IVBSS drivers was not disclosed, but the study design attempted to equally distributed among age groups.

Table 4 summarizes the distribution of gender in the crash, EDR, 100-Car, and IVBSS lane departure datasets. Real-world crashes involved more male than female drivers with approximately 59%-65% of drivers being male. The 100-Car near-crashes follow this trend with 58% male. The gender of IVBSS participants was assumed to be equally distributed. The SHRP-2 curb strike events were reversed, with almost two-thirds (65%) of drivers being female.

Table 4.
Distribution of Driver Gender for NASS/CDS, EDR, 100-Car, and IVBSS Lane Departure Datasets.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASS/CDS Departure Crashes</td>
<td>65%</td>
<td>35%</td>
</tr>
<tr>
<td>NASS/CDS Departure EDRs</td>
<td>59%</td>
<td>41%</td>
</tr>
<tr>
<td>IVBSS*</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>100-Car Near-Crashes</td>
<td>58%</td>
<td>42%</td>
</tr>
<tr>
<td>SHRP-2 Curb Strike</td>
<td>35%</td>
<td>65%</td>
</tr>
</tbody>
</table>

* Demographic information for IVBSS drivers was not disclosed, but the study design attempted to equally distributed among gender.

Figure 3 shows the cumulative distribution of vehicle model year for departure events. The CDS departure events were shown for the entire dataset (2000 – 2013), a subset of CDS departures with vehicle model year 1995 and greater (the first year EDRs were downloaded using a public tool, MY1995+), and CDS departures with EDR downloads. All vehicles from the IVBSS were either 2006 or 2007 model year vehicles and were not included in Figure 3. The vehicles with EDR downloads had a higher model year than all CDS crashes and near-crash events from the 100-Car database. When the CDS departure crashes are restricted to those involving model year 1995 and great vehicles (MY1995+), the distributions of model year was more similar to the EDR sample. However, all three CDS samples were statistically different from one another according to a simultaneous test using Tukey contrasts (p < 0.0001). This result suggests that vehicles with EDR data downloaded are newer than the general departure crash population. The newest vehicle population was from the SHRP-2 study.
Comparison of Departure Characteristics

Figure 4 shows the cumulative distribution of vehicle speed in departure events. Not all EDR modules were equipped to record pre-crash vehicle speed. In the sample of lane departures with EDRs, 109 had valid pre-crash speed data. The time that the vehicle departed the road is not known in the EDR data and here we used maximum pre-crash speed as a surrogate for departure speed. The maximum pre-crash speed recorded by the EDR was plotted in Figure 4 using the national weighting factors included in NASS/CDS. In IVBSS, the LDW system was suppressed at travel speeds under 42 kph (25 mph). The SHRP-2 curb strike events occurred at the lowest speeds with a median speed of 44.8 kph (27.8 mph), followed by the 100-Car near-crashes with a median speed of 69.7 kph (43.3 mph). The IVBSS LDW dataset had a median of 86.5 kph (53.7 mph), which was close to the EDR dataset median speed of 85.3 kph (53.0 mph). The IVBSS lane departure events had the highest median speed at departure with 113.4 kph (70.5 mph). The mean departure speeds for the IVBSS lane departure, and IVBSS LDW, 100-Car near-crash, and SHRP-2 curb strike sets were significantly different according to an Analysis of Variance (ANOVA, \( p < 0.0001 \)). The EDR data was not included in the ANOVA because the sample design variables (clustering, stratification, and weighting) cannot be combined with the other data. This limitation of the data is discussed further in the Discussion section.
Table 5 lists events with and without brake application. The pre-crash EDR records display brake switch status, i.e. ON or OFF, but not brake magnitude. In 60% of crashes with EDRs, there was braking during the pre-crash record. This estimate may include some non-event related braking, because most EDR pre-crash records span up to 5 seconds prior to the crash. If restricted to the last second of the pre-crash record, 52% of crashes with EDRs had brake application. This result shows that much of the braking recorded by the EDR in departure crashes is in the last second before the crash. In the IVBSS event datasets, brake application was rare. A condition of selection for the lane departure events was that there was no brake application. In IVBSS LDW events, only 4% of events had brake application. In the 100-Car near-crash events, approximately 38% of events had brake application between 0.5 s before and 2 s after the start of the departure events. Similarly, the SHRP-2 curb strike events had approximately one-third of drivers apply the brakes (32.7%) between 0.5 s before and 2 s after the curb strike.

Table 5. Brake Application in EDR, 100-Car, and IVBSS Departure Events

<table>
<thead>
<tr>
<th>Group</th>
<th>Brake Application</th>
<th>No Brake Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDR (Any Braking)</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>EDR (Any Braking 1 second before crash)</td>
<td>52%</td>
<td>48%</td>
</tr>
<tr>
<td>IVBSS Lane Departure*</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>IVBSS LDW</td>
<td>4.2%</td>
<td>95.8%</td>
</tr>
<tr>
<td>100-Car Near-Crashes</td>
<td>37.5%</td>
<td>62.5%</td>
</tr>
<tr>
<td>SHRP-2 Curb Strike</td>
<td>32.7%</td>
<td>67.4%</td>
</tr>
</tbody>
</table>

* Lack of brake application was a condition of selection for LDW lane departure events

Comparison of NDS Departure Characteristics

The instrumentation available on NDS allow for examination of additional departure conditions, such as departure angle, maximum lateral excursion, and steering wheel input, which are not available on most EDR modules. This section compares these additional departure conditions in the IVBSS LDW, and IVBSS lane departure, 100-Car near-crash, and SHRP-2 curb strike datasets. Only IVBSS LDW departures that did not occur within 5 seconds of a lane change event were included in this analysis because characteristics due to correcting the lane drift were difficult to discern from the lane change. This lane change exclusion eliminated 1,569 (20.2%) of the IVBSS LDW events. The 49 SHRP-2 curb strike events occurred mostly on roads without road markings and as a result the lane tracking
cameras used to calculate departure angle and excursion were not available. This section includes 9 departure events that had high lane tracking confidence during the departure.

Figure 5 shows the cumulative distribution of maximum lateral distance vehicles traveled out of the lane for the IVBSS LDW dataset, and the IVBSS lane departure dataset, 100-Car near-crashes, and SHRP-2 curb strike events. Lateral excursion from the IVBSS and SHRP-2 vehicles was estimated using the lane width and vehicle positioning provided by the lane tracking camera. The 100-Car vehicles were not all instrumented with lane tracking cameras. Trajectories for the 100-Car departures were computed using the vehicle forward speed and yaw rate to estimate the vehicle’s position. The methodology used to reconstruct trajectories in the 100-Car near-crashes is detailed in the appendix. The median lateral distance was 0.10 m for the IVBSS departure dataset, 0.19 m IVBSS LDW dataset, 0.63 m for the 100-Car dataset, and 0.50 m for the SHRP-2 curb strikes. The vehicle did not leave the lane (negative maximum excursion) in approximately 10% of the IVBSS LDW events. Excluding these negative events, the median maximum excursion was 0.20 m. Most of the curb strikes from the SHRP-2 data redirected the vehicles, limiting the maximum excursion. The higher excursions, i.e., those above 0.5 m were mostly the result of vehicles overriding the curb before the driver steered back into the lane. The mean excursions were significantly different from each other using a post-hoc Tukey’s test (all p < 0.0001).

Figure 5. Cumulative Distribution of Maximum Lateral Excursion in NDS Events. SHRP-2 curb strike data includes 9 events with lane tracking during departure.

Figure 6 shows the distribution of departure angle in the NDS events. The departure angle from the 100-Car near-crash events was found in the reconstruction of the vehicle trajectory used to determine the lateral excursion. The IVBSS and SHRP-2 departure angle was estimated using the distance to the lane line 0.1 s prior to the lane departure and the vehicle forward speed at departure. Like lateral distance traveled outside of the lane, the 100-Car near-crash events had higher departure angle (median 2.6°) compared to the IVBSS departure (median 0.6°) and IVBSS LDW (median 0.7°). The SHRP-2 curb strike events (median 14.1°) had several high angle departures. One possible explanation for the high departure angles could be the tires entering the gutter portion near the curb causing the vehicle to rotate before striking the curb. Steering wheel angle was only available for 4 of the 9 SHRP-2 events. Two of these events had high angles and showed evidence of driver steering prior to the departure event. The mean departure angles were significantly different from each other using a post-hoc Tukey’s test (all p < 0.0001).
Figure 6. Cumulative Distribution of Departure Angle in NDS Departure Events. SHRP-2 curb strike data includes 9 events with lane tracking during departure.

Figure 7 shows the cumulative distribution of steering magnitude for the IVBSS LDW, IVBSS lane departure, and 100-Car near-crash datasets. Steering magnitude was defined as the largest absolute change in steering wheel angle from the steering wheel angle at departure. Data from the SHRP-2 curb strikes was excluded from the figure because few vehicles were equipped with steering wheel sensors. The instrumentation from the 100-Car study did not include a steering wheel sensor. Steering wheel angle was estimated for the 100-Car departure events by video tracking analysis using the over shoulder video view. Of the 32 departures, 18 had the steering wheel visible for video tracking analysis. Reasons for a non-visible steering wheel were dark conditions in the vehicle or the steering wheel being blocked by objects, e.g. papers or a book. The IVBSS vehicle instrumentation reported steering wheel angle to the nearest degree. The median steering magnitude was 5° for the IVBSS LDW events, 4° for the IVBSS lane departure events, and 48° for the 100-Car near-crashes. Because near-crashes often included emergency maneuvers to return to the lane to avoid a crash, the steering magnitudes were substantially higher than in the IVBSS datasets, where non-emergency maneuvers were taken to return to the lane. The mean steering wheel angle from the lane departure and LDW departures from IVBSS were statistically different according to an ANOVA.
DISCUSSION

This study compared several NDS lane departure event datasets to crash data with EDR downloads with the goal of determining how representative NDS events are of serious, tow-away severity crashes. This comparison was accomplished in two ways: 1) by comparing the sample of drivers and vehicles in each dataset and 2) by comparing the departure conditions and driver reactions after departure. The results showed that the populations included in each NDS dataset were different and therefore it is not surprising that the characteristics of these departures were also different.

The near-crash events from the 100-Car study and the SHRP-2 curb strike events more closely matched the conditions of the crash data than did the normal driving datasets from IVBSS. Younger drivers were overrepresented in the crash data, which was true for both the 100-Car and SHRP-2 samples, while IVBSS had a uniform distribution of ages by design. Males were also overrepresented in the crash data, which was true for the 100-Car near-crash events. The SHRP-2 curb strikes had a majority of female drivers. The IVBSS sampled was evenly distributed between males and females. Driver demographics may play an important role in driver behavior, as risk evaluation differs by both age and gender (Harris et al. 2006, Charlton et al. 2006). The datasets also differed in how lane departures were selected. The IVBSS events were selected using the lane tracking cameras, and as a result were restricted to highway driving at high speeds. The 100-Car near-crash and SHRP-2 curb strikes occurred at a larger range of speeds, similar to the crash data.

The differences in departure conditions between the crash/near-crash NDS and IVBSS were also reflected in the severity of departures and driver reactions to the departures. The near-crash and crash datasets had much higher departure angles and maximum lateral distance out of the lane. There was brake application before over half (52%) of departure crashes. By design, the IVBSS data excluded events with brake application, while the near-crash and curb strike data had 38% and 33% of events with brake application, respectively. Steering wheel input was also much larger in the 100-Car near-crashes compared to the IVBSS data (SHRP-2 near-crashes did not have sufficient steering wheel data to evaluate).

The differences in departure conditions in the NDS data may be important if the goal of the research is to replicate departure conditions and driver input in lane departure crashes. For example, designing a test track evaluation using the IVBSS data may produce departure conditions that are not representative of crash events. The moderate departure events, however, may still be correlated with crash risk (Guo et al. 2010) and thus are appropriate to use to evaluate the overall impact of LDW on drivers’ lane keeping safety. The results of two previous analyses of the IVBSS LDW data found a statistically significant improvement in lane keeping safety metrics. One study found that the presence of LDW improved driver’s lane keeping ability and decreased the number of departures per mile driven.

![Figure 7. Cumulative Distribution of Steering Input Magnitude after Departure in NDS Events.](image-url)
An independent analysis of the IVBSS also found a decreased rate of departure events with LDW active (Nodine et al. 2011). These trends are likely correlated with a driver’s risk for involvement in serious departure crashes.

The NDS had different purposes and subject recruitment strategies. The 100-Car and IVBSS recruited drivers from a single geographical area (Washington D.C. and Ann Arbor, MI, respectively), while SHRP-2 was conducted in 6 study areas. IVBSS, however, had the purpose of evaluating prototype safety equipment while 100-Car and SHRP-2 had the sole purpose of monitoring normal driving in unmodified vehicles. It is possible the subjects recruited for IVBSS were early adopters of safety technology and as a result safer drivers than the subjects in the 100-Car and SHRP-2 studies. A limitation of the current study is that it is difficult to address subject recruitment differences in the post-hoc fashion used for this study.

From a statistical perspective, comparing the NASS/CDS data to the NDS datasets is a challenge. A standard technique to compare variables across multiple datasets is to perform an ANOVA on all data. The response in the model is the variable of interest and the main effect is the data source. This ANOVA will determine if there are significant differences in the mean of the variable across data sources. The NASS/CDS data are collected using a probability weighted complex survey design, not a random sample. In order to estimate variance, the survey design variables (clustering and strata) must be taken into account. The result is that traditional statistical analyses techniques, such ANOVA, cannot be performed on the NASS/CDS data.

Another statistical challenge is analyzing the large volume of events in the modern NDS datasets like IVBSS. Because traditional statistical methods like ANOVA are highly dependent on sample size, the massive number of samples makes almost all tests significant to the 95% confidence level. Another statistical challenge is modeling within- and between-driver variability. Research on appropriate statistical techniques for NDS data is ongoing (Kim et al. 2013; Zhang et al. 2012). There is a need for consensus on the methods that researchers should use when analyzing NDS data.

CONCLUSIONS

The objective of this study was to compare departure events where LDW could have intervened that were extracted from crash and NDS data in order to determine if NDS data are representative of the crash data. The departure events examined were extracted from the NASS/CDS crash database, the IVBSS (two separate instrumentation triggered events), the 100-Car NDS (near-crash events), and the SHRP-2 NDS (curb strike events). The 100-Car and SHRP-2 NDS had a distribution of driver age and gender more similar to the crash data than the IVBSS subjects, who were equally distributed by design. Age and gender may affect risk of a departure occurring as well as driver response once a departure occurs. These differences in demographics may help explain why there were large differences in the departure characteristics between NDS and crash data. The IVBSS departure datasets had almost no brake application while the crash, 100-Car, and SHRP-2 data had 52%, 38%, and 33% of drivers applying the brakes, respectively. The IVBSS data were also selected using the lane tracking cameras, which restricted vehicle travel speeds above 42 kph (25 mph). The 100-Car and SHRP-2 events were selected by manual review of risky driving events identified from the instrumentation data. The near-crash and curb strike occurred at a wide range of travel speeds, although the median speeds were lower than the crash data. The differences in conditions may have also affected the severity of departure. The 100-Car near-crash and SHRP-2 curb strike departures had larger departure angles (2.6° and 14.1° median, respectively) and lateral excursion (0.63 m and 0.50 m median, respectively) compared to the IVBSS data (0.6° and 0.7° departure angle and 0.19 m and 0.10 m excursion for LDW and lane departure datasets, respectively). The results of this study suggest that both driver composition and event selection criteria in NDS datasets affect the evaluation of departure characteristics. Near-crash and crash severity NDS events are more representative of crash events compared to the normal driving used to create the IVBSS departure datasets. These differences are important when answering research questions where replicating conditions similar to crashes are important.

ACKNOWLEDGEMENTS

The research team would like to acknowledge the Toyota Collaborative Safety Research Center (CSRC) and Toyota Motor Corporation for funding this study. The authors would like to thank Rini Sherony, Hiroyuki Takahashi, and Katsuhiko Iwazaki from Toyota for their helpful feedback to improve this research. The team would also like to
acknowledge the University of Michigan Transportation Research Institute (UMTRI) for providing access to the IVBSS data. We would also like to thank Jonathan Rupp, Scott Bogard, David LeBlanc, and Jim Sayer from UMTRI for their assistance in accessing and analyzing the IVBSS data. The research team would like to acknowledge the Virginia Tech Transportation Institute (VTTI) for providing access to the 100-Car and SHRP-2 data. The authors would like to thank Miguel Perez, Shane McLaughlin, Julie McClafferty, and Joel Kady from VTTI for their assistance.

REFERENCES


APPENDIX: METHODOLOGY FOR RECONSTRUCTING DEPARTURE TRAJECTORIES FROM VEHICLE INSTRUMENTATION

The method for reconstructing the departure events is summarized in Figure 8. First, the yaw rate and forward vehicle speed were integrated to determine the change in heading angle and curvature of the vehicle’s path. These two signals were used to reconstruct the vehicle’s X-Y position. If the road was curved, satellite imagery of the event site was used to determine the radius of curvature of the road. The vehicle GPS location data was used to locate the sites and the radius of curvature of the road was estimated using publically available satellite imagery and tools, Google Earth. The forward video view was used to approximate when the vehicle departed its lane and when it returned to its lane. The departure point was defined as when the vehicle’s leading wheel first touched the lane line or road edge if there was no lane line. The end of the departure event was when the same wheel crossed the same lane line or road edge. Using the X,Y trajectory from the vehicle data, the road data, and the time off the road the departure angle of the trajectory was iteratively varied until it matched the recorded time off road. The departure angle was iterated by 0.05°. The departure angle that had the lowest error to the observed time out of lane was chosen as the departure angle.

\[ r_j = \frac{v_j}{\omega_j} \]  

(1)

The change in angle between point \( j \) and \( j + 1 \) is the difference between heading angles

\[ \epsilon_j = \theta_{j+1} - \theta_j \]  

(2)

Figure 8. Procedure for Determining Vehicle Trajectory from Naturalistic Driving Data.

Consider a vehicle trajectory that has discrete points corresponding to each successive instrumentation measurement, shown in Figure 9. At time \( j \) the vehicle has a heading angle \( \theta_j \) and speed \( v_j \). At the next time point, \( j + 1 \), the vehicle has a heading \( \theta_{j+1} \) and speed \( v_{j+1} \).

Figure 9. Schematic of Determining Vehicle X-Y Trajectory from Vehicle Data.
Next, the chord length can be found using the geometric relationship

\[ l_j = 2r_j \sin \frac{\theta_j}{2} \]  

(3).

Finally, the coordinates of the next point can be found as

\[ x_{j+1} = x_j + l_j \cos \theta_j \]  

(4)

and

\[ y_{j+1} = y_j + l_j \sin \theta_j \]  

(5).