

Investigation of Driver Lane Keeping Behavior in Normal Driving based on Naturalistic Driving Study Data

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ABSTRACT

Lane departure warning (LDW) systems can detect an impending road departure and deliver an alert to allow the driver to steer back to the lane. LDW has great potential to reduce the number of road departure crashes, but the effectiveness is highly dependent upon driver acceptance. If the driver perceives there is little danger after receiving an alert, the driver may become annoyed and deactivate the system. Most current LDW systems rely heavily upon distance to lane boundary (DTLB) in the decision to deliver an alert. There is early evidence that in normal driving DTLB may be only one of a host of other cues which drivers use in lane keeping and in their perception of lane departure risk. A more effective threshold for LDW could potentially be delivered if there was a better understanding of this normal lane keeping behavior. The objective of this paper is to investigate the lane keeping behavior of drivers in normal driving. The study will be based upon data extracted from the Integrated Vehicle-Based Safety Systems (IVBSS) Naturalistic Driving Study conducted by University of Michigan Transportation Research Institute (UMTRI). The study first presents the distributions of DTLB and lateral velocity during normal lane keeping and then examines the relationship between DTLB and lateral velocity as a function of lane width and radius of curvature.

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INTRODUCTION

Road departure crashes are one of the most dangerous crash modes in the United States. When a vehicle departs a roadway, there is a higher potential of impacting less compliant roadside objects, such as trees, poles, as well as other vehicles. In the U.S., road departure crashes account for 10% of all crashes, but are responsible for over 30% of all vehicle occupant fatalities [4]. Lane departure warning (LDW) systems are becoming increasingly common in the U.S. vehicle fleet to help reduce the number of road departures, or at least mitigate the severity of these departures [2]. Previous studies estimate between 11% and 23% of drift out of lane departure crashes could be prevented with these systems if implemented in the entire U.S. vehicle fleet [2]. LDW systems are designed to detect when road departures are imminent. The system can provide the driver with a visual, tactile, or audible warning so they may react and steer the vehicle back into the lane of travel. However, sometimes the LDW system may provide warnings when the driver feels there is no risk of departure. The concern is that drivers may become annoyed by these false-positive warnings and disable the system.

One promising strategy to increase driver acceptance of LDW is to tailor the alert to driver behavior and the driving environment. Naturalistic driving studies provide a foundation for determining driver behavior during lane keeping. By using naturalistic driving behavior data, the influence of road characteristics, such as lane width and road curvature, on driver behavior can be investigated as additional factors to optimize warning delivery time.

Although production LDW systems are proprietary and the algorithms governing warning intervention timing are not publically available, we believe these systems rely on a combination of the lateral distance between the vehicle's leading wheel and the lane edge, or the distance to lane boundary (DTLB), and lateral velocity to determine when a warning should be delivered. These two quantities are defined in [Figure 1](#).

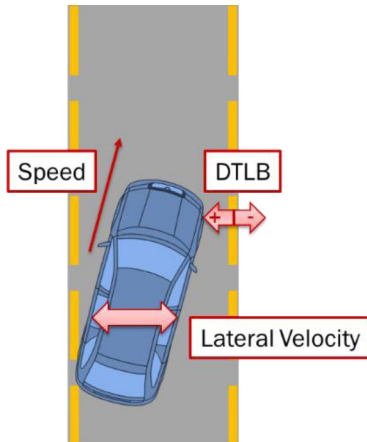


Figure 1. Lane departure parameters

The National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP) has a component that tests the performance of LDW systems. The NHTSA procedure is structured as follows [5]:

- A constant forward speed of 72 kph (45 mph)
- A target lateral velocity of 0.5 m/s
- Two departure directions: left and right
- Three roadway markings: continuous white lines, discontinuous yellow lines, and discontinuous raised pavement markers
- Each combination of test conditions are repeated five times

Each test is performed by a driver who induces a lane departure event by steering the test vehicle towards the lane boundary. Prior to crossing the lane line, the driver releases the steering wheel and the DTLB is recorded when the LDW is received. This procedure is illustrated in Figure 2. The NCAP criteria for a successful test is when a warning is delivered to the driver with a DTLB between -0.3 m and 0.75 m, where positive distance represents a vehicle still in the lane of travel [5].

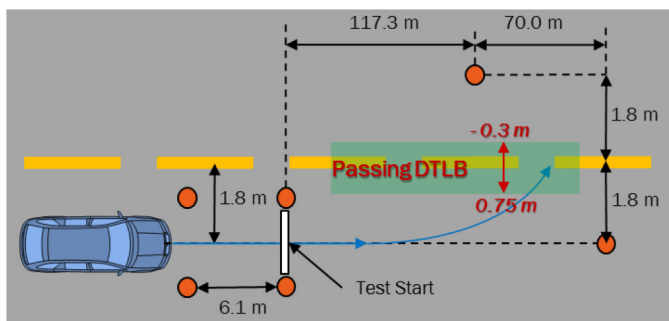


Figure 2. NCAP lane departure test setup

Fujishiro and Takahashi (2015) hypothesized lateral velocity may be a better metric than the NCAP DTLB criteria for determining thresholds for the LDW system to deliver a warning to the driver. The NHTSA method for evaluating LDW systems does not take into account varying lateral departure rates. Fujishiro and Takahashi (2015) studied naturalistic driving behavior in Japan and determined

that in general, drivers have higher lateral velocities when they are near the center of the lane and lower lateral velocities as they approach the lane boundaries. The study also found that departures tended to occur as drivers entered narrower and sharper curved roads. They showed that lateral velocity and these other factors may be a better predictor of when departures may occur. Adjusting LDW thresholds and warning times to better fit natural driving habits could reduce the number of false-positive warnings and increase driver acceptance [1].

The objective of this study was to investigate the lane keeping behavior of drivers in normal driving. The study particularly focused on the distribution of lateral velocity and DTLB and the influence of lane width and radius of curvature upon these two metrics.

APPROACH

This study utilized data extracted from the Integrated Vehicle-Based Safety Systems (IVBSS) Naturalistic Driving Study (NDS) conducted by the University of Michigan Transportation Research Institute (UMTRI) [3]. The aim of the IVBSS Naturalistic Driving Study was to assess the effectiveness of integrated crash safety systems while also monitoring driver behavior. IVBSS evaluated a number of active safety systems including forward collision warning (FCW), lane change/merge (LCM) warning, blind spot monitoring (BSM), curve speed warning (CSW), and lane departure warning (LDW) [3].

The IVBSS-NDS randomly selected a sample of 108 drivers. Each driver was given a 2006 or 2007 model year Honda Accord equipped with a LDW system and instrumented for data collection. The drivers were instructed to drive as they normally would for 40 days. The first 12 days were a baseline period in which data was collected, but the LDW system was disabled and provided no warnings to the driver.

The remaining 28 days were a treatment period where the LDW system was enabled and provided the driver with warnings when a possible lane departure was detected. Data was collected for a total of 147,389 km, in which 12,760 unintentional drift out of lane departure events were recorded. Data was recorded at 10 Hz for the duration of every trip using the following instrumentation [3]:

- Forward facing camera and radar for lane detection, vehicle position, and other roadway characteristics such as lane marking type
- Yaw rate sensor to measure angular velocity
- Tri-axial accelerometer to measure longitudinal and lateral accelerations
- Differential GPS to measure latitude, longitude, and speed

Time series data was provided by UMTRI including the duration of the departure event, plus 30 seconds of normal driving before and 30 seconds after the event occurred. Data elements included key variables such as distance past lane edge, maximum excursion, and lane width for the 12,760 unintentional lane departure events.

UMTRI provided a subset of the IVBSS data which contained unintentional lane departure events. The constraints applied to select the data subset included [3]:

- Lane boundary type known and real (not virtual)
- Maximum lane tracking software confidence level 100%
- Lane tracker enabled
- No braking, lane changes, or turn-signal use during lane departure events
- Buffer time of 5 seconds before and after any intentional maneuver
- Vehicle returned to lane in less than 20 seconds (plus buffer)
- Speed above 40.2 kph (25 mph)
- Valid trip and driver

Note that the restrictions on braking, turn-signal use, and lane changes were only applied to the lane departure event. Some trips had intentional lane changes in the 30 seconds before or after the unintentional departure event. Some of the data also had less than 100% lane tracking confidence or virtual lane boundaries outside of the departure event and buffer window. Additional data quality checks were implemented to verify the data used for this study met the IVBSS criteria at all time points.

For our study, we wanted to focus on purely naturalistic driving behavior without the influence of LDW. We found the ratio of departure events per day for the treatment period was about half the ratio of departure events per day during the baseline period. This shows a significant impact of LDW on driver behavior. The system likely kept drivers out of potential departure situations or encouraged more cautious driving behavior. Therefore, only data collected during the baseline period was used in our analysis. This resulted in a subset of 5,833 lane departure events with no LDW intervention.

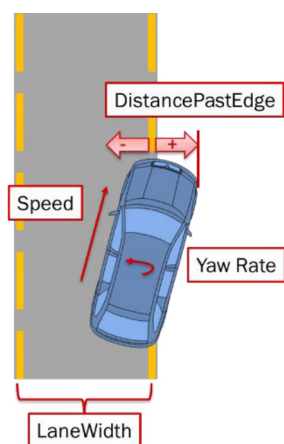


Figure 3. Measurements used from IVBSS database

The IVBSS-NDS variables used in this study are illustrated in Figure 3. A lane departure event is defined by the instant the leading wheel crosses the lane boundary. The end of a lane departure event is defined by the instant the leading wheel fully returns to the lane [3].

The variable *DistancePastEdge* is defined as the distance between the leading wheel and the lane boundary. Note that the sign convention for *DistancePastEdge* is positive out of the lane.

Lateral Velocity

One of the main objectives of this study was to characterize natural driving behavior in terms of lateral velocity and DTLB. Vehicles in the IVBSS Naturalistic Driving Study were equipped with forward facing cameras used to track and record the position of the vehicle with respect to the lane. Specifically, the lateral distance the leading wheel traveled past the lane edge was recorded as illustrated in Figure 3. Our study used a simple time derivative estimate to calculate the lateral velocity as shown in Equation 1. The IVBSS Naturalistic Driving Study variable was called *DistancePastEdge*. The sign convention was positive distance outside the lane of travel. This convention resulted in positive lateral velocities when the vehicle was traveling away from the center of the lane, regardless of departure side.

$$\text{Lateral Velocity} = \frac{d(\text{DistancePastEdge})}{d(\text{Time})} \quad (1)$$

The sign convention for DTLB, on the other hand, is for distances outside the lane of travel to be negative. In our study, we flipped the polarity of the *DistancePastEdge* variable when plotting the lateral velocity - DTLB distribution to be consistent with DTLB convention. The lateral velocity calculation was performed for the entire subset of baseline period events.

Artifacts of Machine Vision

After plotting the normal driving distribution, we found a small subset of the data contained high magnitude lateral velocities (above 5 m/s). These were artifacts of the machine vision and our differentiation method. These unrealistically high lateral velocities occurred when there were large measured changes in lateral DTLB for a single time step of 0.1 seconds. After manually reviewing a sample of these cases, these large DTLB steps were typically found to occur when there were obstacles hindering the lane tracking equipment. Some examples included camera washout from passing under an overpass, changes in pavement contrast, or poor lane markings, especially entering or exiting construction zones. However, the more prominent artifacts were generated when drivers made lane changes, passed through intersections, or approached a highway on or off ramp outside of the unintentional lane departure event window.

Although these high magnitude lateral velocities accounted for less than 0.1% of the time series data and did not significantly skew our results, many of them were removed from our dataset to focus on lane keeping behavior rather than changes in road demographics. Figure 4 illustrates the method used to remove artifacts that could be characterized by a steep spike.