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Utilizing naturalistic driving data for in-depth analysis of driver lane-keeping behavior in rain: Non-parametric MARS and parametric logistic regression modeling approaches

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ABSTRACT

It is known that adverse weather conditions can affect driver performance due to reduction in visibility and slippery surface conditions. Lane keeping is one of the main factors that might be affected by weather conditions. Most of the previous studies on lane keeping have investigated driver lane-keeping performance from driver inattention perspective. In addition, the majority of previous lane-keeping studies have been conducted in controlled environments such as driving simulators. Therefore, there is a lack of studies that investigate driver lane-keeping ability considering adverse weather conditions in naturalistic settings. In this study, the relationship between weather conditions and driver lane-keeping performance was investigated using the SHRP2 naturalistic driving data for 141 drivers between 19 and 89 years of age. Moreover, a threshold was introduced to differentiate lane keeping and lane changing in naturalistic driving data. Two lane-keeping models were developed using the logistic regression and multivariate adaptive regression splines (MARS) to better understand factors affecting driver lane-keeping ability considering adverse weather conditions. The results revealed that heavy rain can significantly increase the standard deviation of lane position (SDLP), which is a very widely used method for analyzing lane-keeping ability. It was also found that traffic conditions, driver age and experience, and posted speed limits have significant effects on driver lane-keeping ability. An interesting finding of this study is that drivers have a better lane-keeping ability in roadways with higher posted speed limits. The results from this study might provide better insights into understanding the complex effect of adverse weather conditions on driver behavior.

1. Background

Driver behavior can be considered as the most unpredictable element in the driver, vehicle, and roadway triangle (Zhou et al., 2008). More specifically, while driving, drivers might change their behavior due to different mental and physical conditions, distractions introduced by in-vehicle technologies, or conversing with passengers, etc. (Suzdaleva and Nagy, 2018; Eboli et al., 2017a, 2017b). Driver lane-keeping ability is one of themain behavioral-performance factors that can be used to assess the broader implications of driving tasks (Ghasemzadeh and Ahmed, 2017). One of the basic operations that needs to be performed by each vehicle in the semi-automated or fully automated highway systems is lane keeping (Suryanarayanan and Tomizuka, 2007). Therefore, better understanding of driver lane-keeping behavior drew researchers' attention in recent years.

Lane-keeping performance has been investigated in previous studies from driver inattention standpoint (Harbluk et al., 2002;

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Reed-Jones et al., 2008; Chisholm et al., 2008; Collet et al., 2010; Peng et al., 2013). While findings from these studies indicate the effect of different forms of distractions on driver lane-keeping performance, the impact of adverse weather conditions on lane-keeping ability has not been well researched in previous studies.

Adverse weather conditions have negative impacts on both traffic safety and operations. Based on the National Highway Traffic Safety Administration data, weather contributed to over 22% of the total crashes each year (Hamilton, 2015). More specifically, most of the weather-related crashes occur on wet pavement and during rainfall representing 73% and 46% of weather-related crashes, respectively (Hamilton, 2015). Previous studies revealed that the visibility obstruction caused by rainfall increases crashes by 100% or more (Brodsky and Hakkert, 1988; National Transportation Safety Board, 1980), whereas other studies found more moderate but still significant increase (Andreescu and Frost, 1998; Allen et al., 1996).

In addition, previous studies utilized survey questionnaires and driving simulators to better understand drivers' behavioral and performance factors such as speed and headway selection and lane keeping performance in different adverse weather conditions (Wu et al., 2018; Hamdar et al., 2016; Hassan and Abdel-Aty, 2011; Brooks et al., 2011; Ni et al., 2010). Wu et al. (2018) investigated driver speed adjustments when using real-time fog warning systems in different fog levels in a driving simulator study. While their study concluded that adverse weather and limited visibility have a significant impact on driver performance, they found that warning systems do not impact drivers final speed choice in fog. Hamdar et al., (2016) analyzed the impact of weather conditions and geometric characteristics on driver longitudinal behavior. They claimed that drivers' speed, time/distance headways and time to collision can be affected by both weather conditions and roadway characteristics. In addition, they found that drivers select longer headways in low visibility conditions. Another survey-based study assessed factors affecting drivers' compliance with variable speed limits (VSL) and dynamic message signs (DMS) in various traffic and environmental conditions and found that drivers' satisfaction with VSL/DMS is the most determining factor affecting drivers' compliance with VSL/DMS under reduced visibility conditions (Hassan and Abdel-Aty, 2011). Drivers' speeding behavior and lane-keeping performance under foggy weather conditions were studied by Brooks et al. (2011) using a driving simulator. The results indicated that drivers were not able to reduce their speed efficiently and had poor lane keeping in thick fog conditions.

One of the main contributing factors in run-off-the-road crashes and near-crashes is driver lane-keeping performance. In fact, almost 20% of total crashes are single vehicle roadway departure crashes in the US (Dagan et al., 2004; Pomerleau and Everson, 1999). Lane Departure Warning (LDW) systems can reduce 30–70% of lane departure crashes by alerting driver in different dangerous departure situations, which could be caused by alcohol, drowsiness, and distraction (Xu et al., 2015). Adverse weather conditions might exacerbate poor lane keeping due to poor visibility and slippery surface conditions. Understanding driver behavior and response in adverse weather conditions, specifically when visibility is reduced below a certain level may be helpful not only in mitigating lane-departure crashes, but also in finding a more efficient threshold for LDW systems in adverse weather conditions.

Even though there are many studies that investigated the impact of driver behavior in adverse weather conditions, the studies that investigated the impact of heavy rain on driver behavior and performance on a microscopic scale are few (Yu et al., 2014; Ghasemzadeh and Ahmed, 2017). Therefore, there is a need to analyze driver performance using microscopic data. In recent years, Naturalistic Driving studies (NDS) worldwide are becoming more popular in addressing traffic safety and operation challenges. Utilizing NDS Data has made it possible to study driver behavior and performance at a microscopic level. To be specific, NDS will allow for better understanding of how drivers adjust their behaviors to compensate for increased risk due to reduction in visibility. The main goal of this study is to investigate driver lane-keeping ability using the NDS data obtained from the second Strategic Highway Research Program (SHRP2) in heavy rain and slippery road conditions.

Provided contributions in this paper are emphasized as follows. First, considering the fact that weather data is not readily available in the SHRP2 NDS data, three complementary methodologies were developed to identify weather-related trips from the massive SHRP2 NDS database. Second, drivers speed and lane position offset were compared under the free flow conditions and using matched trips (same driver, vehicle, and traversed routes) in heavy rain and clear weather conditions to provide a better insight into driver behavioral-factors when they are not affected by traffic conditions. Third, a threshold was proposed to eliminate lane-changing events from the dataset using a detailed trajectory analysis at 10 Hz (10 observations per second), considering that the focus of this study is to better understand driver lane-keeping ability not lane-changing. Forth, parametric logistic regression and non-parametric multivariate adaptive regression splines (MARS) models were developed to identify factors affecting drivers' lane-keeping performance.

2. Data source

This study utilized data from the SHRP2 safety data, which is comprised of two main datasets including Naturalistic Driving Study (NDS) data and the Roadway Information Database (RID). NDS refers to the real-time behavioral data that was collected from more than 3400 volunteer drivers in six site locations including New York, Florida, Washington, Indiana, Pennsylvania, and North Carolina. Each driver received an annual incentive of $500 and was asked to provide access to his/her vehicle in order to remove and replace the hard drive with the collected data. Some participants remained in the study for several months and then replaced with new drivers and vehicles, while others remained for the full duration of the study. The project duration was about 39 months (October 2010–December 2013) and during this time drivers' behavior and their vehicle-use were recorded continuously, which made this project one of the largest naturalistic driving studies worldwide.

The Data Acquisition System (DAS) was developed by VTTI (Virginia Tech Transportation Institute), which includes four cameras, forward radar, GPS, vehicle network information, on-board computer vision lane tracking system, as well as other computer vision systems and capability of storing data. The collected NDS data includes but not limited to vehicle kinematics and network