Final Report

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

On

NCHRP Project 20-07(368)

Development of a Roadmap for Use of SHRP2 Safety Data to Enhance Existing Publications

Submitted by:

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LIST OF ABBREVIATIONS / ACRONYMS

Abbreviation / Acronym	Definition
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADAS	Automated Driver Assistance Systems
ALD	Adaptive Lighting System
CAV	Connected and Automated Vehicle
CMF	Crash Modification Factor
DOT	Department of Transportation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FL	Florida
GPS	Global Positioning System
HCM	Highway Capacity Manual
HFG	Human Factors Guide
HOV	High Occupancy Vehicle
HSM	Highway Safety Manual
IAP	Implementation Assistance Program
IN	Indiana
ITE	Institute of Transportation Engineers
LED	Light-emitting diode
MASH	Manual for Assessing Safety Hardware
MIRE	Model Inventory of Roadway Elements
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials
NC	North Carolina
NCHRP	National Cooperative Highway Research Program
NDS	Naturalistic Driving Study
NY	New York
PA	Pennsylvania
PII	Personal Identifiable Information
RDG	Roadside Design Guide
RID	Roadway Information Database
RSAP	Road Safety Analysis Program
RwD	Roadway Departure
SHRP2	Strategic Highway Research Program 2
SPFs	Safety Performance Functions
TDM	Travel Demand Management
TRB	Transportation Research Board
TSMO	Transportation Systems Management and Operations
VTTI	Virginia Tech Transportation Institute
WA	Washington
XGB	eXtreme Gradient Boosting

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CHAPTER 1. INTRODUCTION

Background

The Strategic Highway Research Program 2 (SHRP2) safety research collected important driver behavior data through the Naturalistic Driving Study (NDS) with accompanying roadway information database (RID). Upon completion of data collection, the American Association of State Highway and Transportation Officials (AASHTO) sponsored a number of projects utilizing this dataset through the Implementation Assistance Program (IAP) in cooperation with the Federal Highway Administration (FHWA). The current project, National Cooperative Highway Research Program (NCHRP) Project 20-07 Task 368, establishes a research roadmap for future projects to make use of these data to inform future editions of key transportation policy and guidance documents.

The project was accomplished through the following tasks:

- **Task 1. Develop Amplified Work Plan.** The objective of this task was to provide NCHRP with a detailed work plan that expanded on the proposed work presented in the proposal.
- **Task 2. Conduct Literature Review.** The objective of this task was to identify previous studies which have used the SHRP2 data.
- **Task 3. Identify the Potential Opportunities for Using SHRP2 NDS Data and Develop a Roadmap for Enhancing the Existing Publications.** The objective of this task was to identify gaps and opportunities for research to inform future editions of key transportation publications.
- **Task 4. Develop Draft and Final Report.** In this task, the research team prepared this report detailing the methods and findings of the research. The report includes recommendations for future research.

This *Final Report* contains the following chapters and appendices:

- **Chapter 1. Introduction**. This chapter provides an overview of the research problem and the approaches used in the research. It also presents the objectives of the research project and an overview of each chapter and appendix contained in this report. This chapter also includes a brief overview of the SHRP2 Safety research program.
- **Chapter 2. Literature Review**. The research team conducted a review of the literature where the researchers used some component of the SHRP2 data: the NDS alone, the RID alone, or both datasets together. The content in Chapter 2 highlights the key findings from the literature review with the detailed findings summarized in Appendix A.
- **Chapter 3. Subject Matter Expert Interviews**. The research team conducted interviews with seventeen subject matter experts to identify research needs pertaining to the document(s) within their area of expertise. The interviews are summarized in Chapter 3 and the interview script is presented in Appendix B.
- **Chapter 4. Research Themes and Roadmap.** Using information gathered through the literature review and subject matter expert interviews, this chapter presents the identified research themes. This chapter also reviews the rationale for the research questions. A

research roadmap is presented that ties to the key AASHTO documents, as well as other safety-related documents used frequently in the traffic safety profession.

- **Chapter 5. Research Problem Statements and Conclusions.** The research team developed research problem statements for the priority projects in the roadmap to provide to key AASHTO committees for consideration.
- **References.** This section provides a list of cited documents contained in this report.
- **Appendix A. Literature Review Results.** References reviewed by the research team but not needed for the Chapter 2 literature review are summarized in this Appendix.
- **Appendix B. Interview Script.** This appendix provides details of material used in the subject matter expert interviews.

SHRP2 Summary

As part of the SHRP2 study, researchers collected data from six states: Florida (FL), Indiana (IN), New York (NY), North Carolina (NC), Pennsylvania (PA), and Washington (WA). This extensive data set consisted of two large separate databases, the NDS and RID data. These data sets include common identifiers that enable them to be linked together. After collecting the NDS data from the participants, a data collection team collected companion roadway data from the locations traveled by the NDS drivers using the Mobile Van. Table 1 shows the total miles for data collected by the Mobile Van.

Table 1. Miles Covered by Mobile Van

State	Miles Collected
Florida	4,366 miles
Indiana	4,635 miles
New York	3,570 miles
North Carolina	4,558 miles
Pennsylvania	3,670 miles
Washington	4,277 miles

To link the two databases, the Virginia Tech Transportation Institute (VTTI) team assigned Link IDs to each roadway segment included in the RID database. The Link IDs can be obtained from the "Links" shapefile available is the RID database. There are two methods for obtaining and linking the NDS and RID data. The first and most common method is to request the NDS events of interest (i.e., crash, near-crash, or baseline driving event) through the query available at the Insight website (available at: https://insight.shrp2nds.us/). When making a data request, the researcher requesting the data must also request the Link IDs for the requested locations. This information can then be used to link the NDS data to the RID database and therefore enable access to the associated roadway data elements. Alternatively, prospective data users can select the sites of interest from the RID database and provide the Link ID of these sites to VTTI in order to obtain the NDS events. Access to crash event data is limited to a secure data enclave.

Naturalistic Driving Study

NDS information indicates actual driver behavior during every trip traversed by one of 3,500 volunteer drivers (ages 16-90+) and the data duration extended over a one-year or two-year period. The NDS study research team compiled 5.4 million trips from passenger cars, vans, SUVs, and pickup trucks. This was equivalent to more than 30 million miles of data. Of this data, there were 1933 events that were identified as a crash or potential crash events.

The NDS study included four types of data. With the exception of time series data, example data can be viewed at the Insight website. To request in-depth data, a prospective user should refer to instructions provided on the SHRP2 website.

- *Time series or vehicle kinematics* data include the data collected from each instrumented vehicle while being driven. Time series data were collected at 100 HZ frequency (i.e., every 0.01 second), and includes vehicle sensor data such as speed and acceleration (x and y axis, fast), yaw rates, brake and acceleration pedal, wheel steering, distance to lead vehicle, turn signal, wiper setting, headlight setting, ABS activation, electronic stability, traction control, airbag deployment, cabin audio, epoch state head position, cabin audio, elevation, heading GPS, lane marking distance and type, lane position offset, lateral position (latitude and longitude), roll rate, seatbelt use, etc.
- *Video data* include the data collected from the cameras installed in the participant's vehicle. These cameras captured the forward-view and rear-view (dashcam) conditions. In addition, cameras captured images of the driver's face. This information provides the most direct evidence of driving behavior, gaze direction, and the state of the driver in terms of fatigue or inattention. A 30-second sample of the crash and near-crash videos are available at the Insight website. Figure 2 shows an example of video data available at the Insight website together with the sample time series data.

Figure 1. Crash video and time series data.

- *Driver survey and questionnaire* data includes answers to questionnaires, vision test results, and the results of brief physical tests for SHRP2 participants. This data can be used to quantify various participant demographic, physical, knowledge, and psychological characteristics that may be related to driving safety. This data does not contain a participant name or any identifying information and can be used in analyses, both on its own and in combination with the driving data, vehicle data, and additional crash data.

- *Event data* include the crash, near-crash, and baseline event data. This data also includes follow-up investigations for selected crashes as well as driver interview responses as relayed to one of the SHRP2 researchers. Where available, the associated police report that documents the crash may also be available. The inclusion of baseline events provides a sample of normal driving events that did not result in a crash or near-crash.

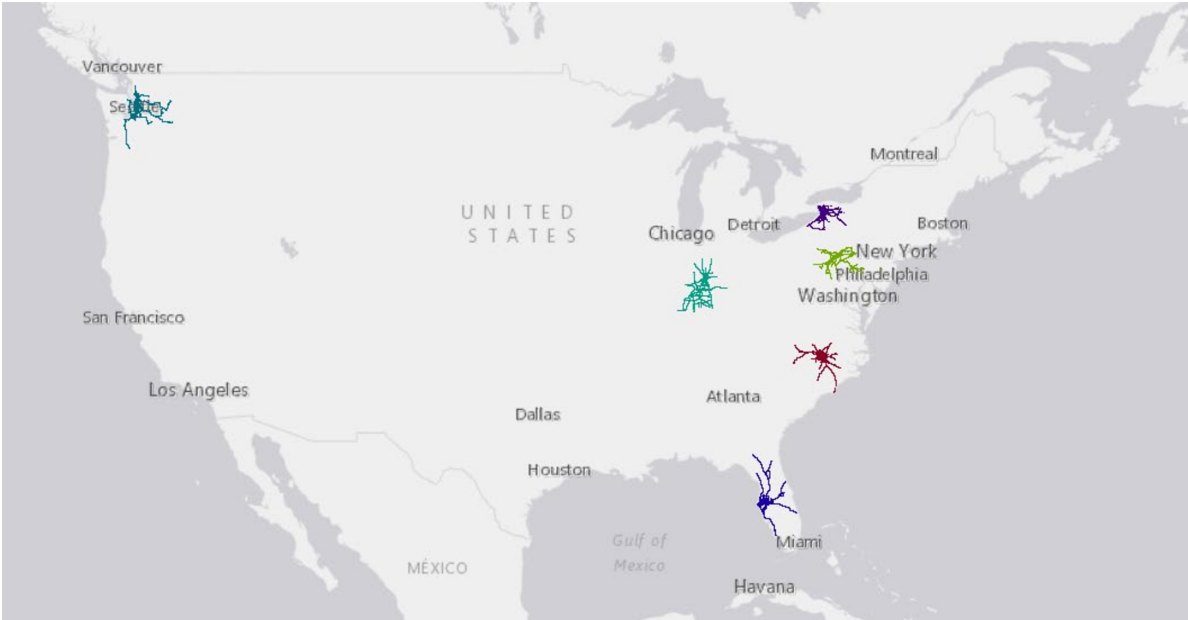
Roadway Information Database

RID indicates the roadway characteristics of the roadway miles traveled by the participants. The RID dataset includes information collected from three sources: Mobile Van Data, State Department of Transportation (DOT) road characteristic information, and Highway Performance Monitoring System information. Future versions will include linear referenced data obtained from the ARNOLD network. The data are available in shapefile and excel formats. Figure 2 shows the areas covered by this data source. RID data is available for six states: FL, IN, NY, NC, PA and WA. In addition to the roadway data, state DOTs also provided the traffic volume, historical crash data, and traffic law information including their enactment years. The coverage of this data varies by jurisdiction. Crash and annual average daily traffic (AADT) data of the study states were available from 2006 to 2013.

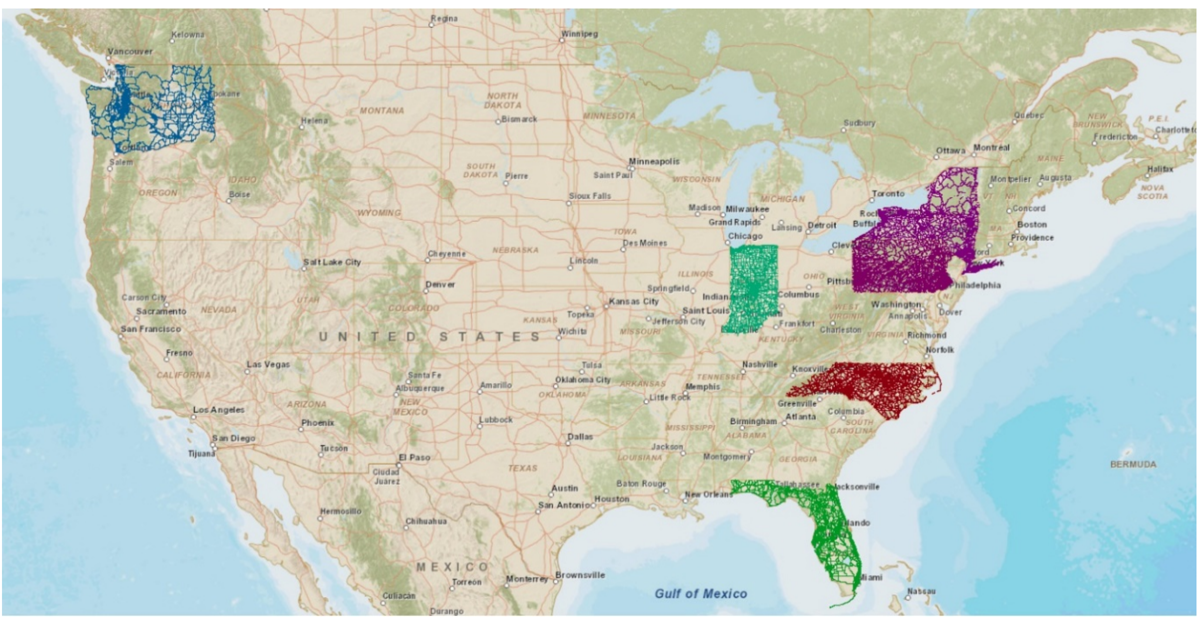
Uses of SHRP2 Data

Early studies used the SHRP2 data for analysis and hypothesis testing of safety and operational performance. Over time, it became apparent that most of the NDS participants were "normal" drivers. This means that very few were actually involved in crashes. Consequently, in more recent years researchers generally used the NDS data to assess the "normal" driving behaviors for deriving parameter estimates to be used for traffic simulation and similar efforts. In addition to these two main uses, the SHRP2 data has also been used for developing or evaluating automated driver assistance systems (ADAS) in automated vehicles.

The initial SHRP2 safety program included four pilot analysis projects (the “S08 projects” referring to the program designation). Following the closure of the SHRP2 program, AASHTO’s IAP provided funding in cooperation with FHWA to states to sponsor research using SHRP2 data. These projects were awarded competitively in tiered phases, advancing to the next phase only if the previous phase(s) showed promising results. In addition to the projects, FHWA sponsored several workshops and webinars between 2014 and 2016. The purpose of these efforts was to discuss results and implementation opportunities. Some of these projects continue today in Phase 3 research efforts.



a) Mobile Van



b) State DOTs

Figure 2. Areas covered in RID database, per data source

In 2019, FHWA initiated a series of projects with the purpose of providing the state DOTs with implementable solutions for safety, operations, and planning. This effort has resulted in several new reduced datasets noted in the next section. This initiative also consists of a series of research projects that will be completed by 2022.

The FHWA NDS Pooled Fund Study began in 2017 and has presented webinars reporting on IAP projects as well as general information about the contents of and access to the SHRP2 Safety dataset.

Readily Available Datasets

Due to the high cost associated with the NDS data, some efforts have been made to make the datasets reduced from the SHRP2 studies available to researchers and practitioners. Several of these efforts stand out:

- Dataverse. Users have the opportunity to access and re-use datasets that have been requested by other researchers through the Dataverse platform (available in this link: https://insight.shrp2nds.us/dataverse/index). Currently, the platform has 109 datasets. The users can select the relevant dataset either by the title of the study or by applying various filters (e.g., year, keyword, data type, author name, etc.).
- Naturalistic Engagement in Secondary Tasks Database. Developed by Owens et al. (2015), this project was the first effort to prepare a sample dataset from the NDS database. The dataset was created using the crash and near-crashes, as well as baseline events that involved a secondary task. The researchers coded the videos frame-by-frame to extract the secondary task and hands-on wheel activity of NDS participants. As a result, a total of 1,180 20-second crash, near-crash, and baseline events were reduced and included in the dataset. In addition to event details, the dataset also includes information about each secondary task engagement prior to the crash and near-crash.
- Reduced RID Datasets Report. In this project, funded by the FHWA's Safety Office, the researchers developed a variety of data elements using the RID database:
    - Speed Limit
    - Lanes
    - Divided/Undivided
    - Intersections
    - Intersection Width
    - Intersection Crashes
    - Curves
    - Curve Crashes
    - Mobile HPMS Presence
    - AADT
    - Homogeneous Segments
    - Link Based Crashes
    - Roadway Attributes for All Crashes
    - Link Roadway Attributes
    - Comprehensive LRS (All States Combined)

  In addition, two additional efforts are ongoing. These include:
    - Relating Opposite Direction on Divided Highways
    - ARNOLD as RID LRS Layer

  The AADT dataset combines the AADT for several years to provide the users with an easier-to-use layer that contains a single record per roadway segment and eliminates the need for users to determine an appropriate data source.

The intersection width reduced dataset provides a longitudinal representation of width measured in the direction of travel for both intersections and access points along routes where RID mobile data were collected. Access points represent locations, such as median openings and driveways.

The intersection crash reduced dataset provides users with easy access to the intersection and intersection-related crash information captured from the state DOTs.

The curve crash reduced dataset provides easy access to curve-related crash information captured from state DOTs. The homogenous segments reduced dataset is a set of homogenous roadway segments based on roadway features collected through the mobile effort. These features are the most accurate within the RID. Homogenous segments represent continuous roadway extents and the least common denominator among the roadway features of interest. In other words, a new segment is created when any feature of interest changes. Directions of travel are also combined for undivided centerlines within the RID.

- Dynamic Segmentation Tool. This tool was developed to make it easier for all users not familiar with GIS tools to access RID data. The tool is included in the RID and allows the user to create his or her own reduced data set from the RID. The tool can accommodate up to 10 variables in the RID.

- In unique cases, researchers may request data sets for studies they have reviewed and for which the data has not yet been developed for Dataverse distribution. For this request, VTTI askes the original research team for permission to re-distribute the unique data set. In the event the original researchers agree to this request, the data can be acquired for limited use.

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CHAPTER 2. LITERATURE REVIEW

Literature Review Methodology

The project team conducted a review of the published literature and identified a wide array of studies developed using the SHRP2 NDS data. This body of literature included approximately 125 papers that were published from 2015 to 2019. The related research generally addressed one of the study topics identified in Table 2.

Table 2. Study Topics and Subtopics

Study Topic	Subtopics
Roadway Design Characteristics	• Horizontal and Vertical Curvature • Functional Class/ Road Type • Pavement Performance • Other Roadway Geometry
Intersection, Interchange, and Ramp Design	• Sight Distance • Ramp Design • Turn and Deceleration Lanes • Crosswalk
Roadside Design Characteristics	• Roadway Lighting
Operational Factors	• Speed • Car-following • Lane Change • Traffic Control Device • Level of Service • Vehicle Mix
Work Zones	• Speed choice • Driver Behavior
Environmental Factors	• Rain • Snow • Time of Day
Behavioral & Demographic	• Mobile phone use • Engagement in secondary tasks • Interacting with Passengers • Drowsy Driving • Law Violations • Age • Socioeconomic factors • Eye Glance • Familiarity with Roadway
Medical Conditions	• Depression • Sleep Disorders • Attention Deficit Disorder • Personality Characteristics • Visual Ability measures
Automated Driver Assistance Systems	• Forward Collision Warning • Automated Emergency Brake

These study topics and associated subtopics are described in greater detail in Appendix A.

Trends in Research Topics

Based on the related studies, the SHRP2 studies included the following three study types:

1. Studies utilizing statistical modeling and hypothesis testing,
2. Studies deriving parameter estimates from normal driving, and
3. Studies deriving parameter estimates for ADAS implementation.

Figure 3 depicts the number of studies per study type. As observed, in most recent years, the number of studies on modeling and hypothesis testing has been decreasing, while the number of studies related to the ADAS implementation has been increasing. The number of studies deriving parameter estimates from normal driving is somewhat consistent, although there is a relatively small decline in the number of these studies.

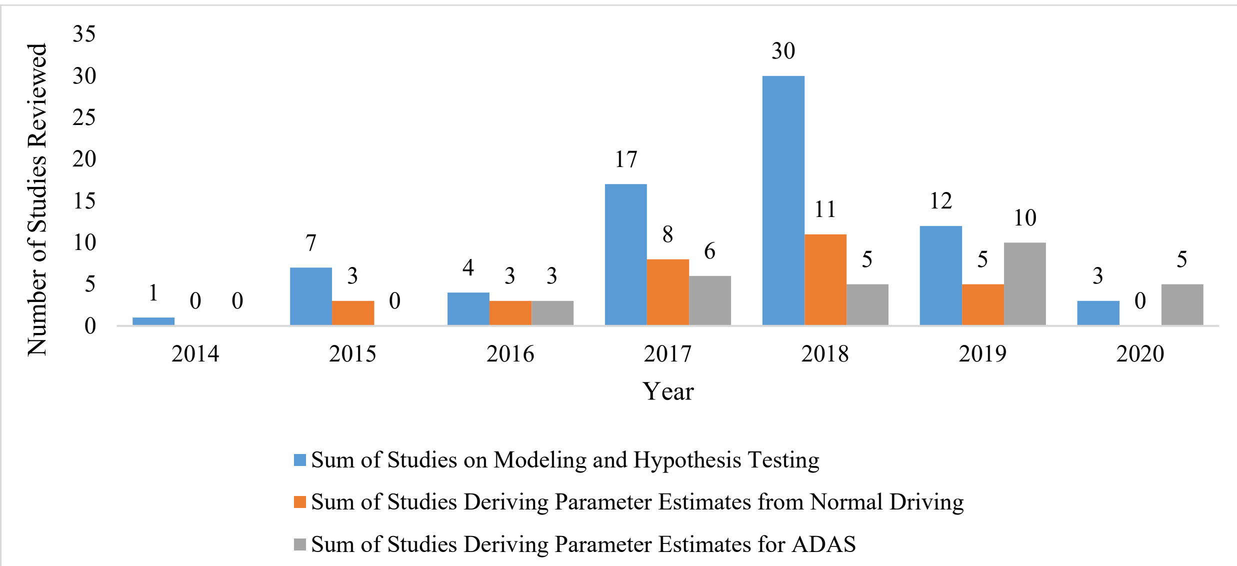


Figure 3. Types and numbers of SHRP2 studies

Table 3 summarizes the identified body of literature, the data used, and the purpose of analysis. Appendix A content expands on these individual studies.

Table 3. Data Use and Type of Analysis Performed

Author (year)	Data Used					Purpose of Analysis		
	Roadway Information Database (RID)	Naturalistic Driving Study				Modeling and Hypothesis Testing	Deriving Parameter Estimates from Normal Driving	Deriving Parameter Estimate for ADAS
		Time Series	Video	Driver Survey	Event			
Aduen et al. (2015)				X	X	X		
Aduen et al. (2018)				X	X	X		
Ahmed et al. (2018)		X		X		X		X
Ali and Ahmed (2019)	X	X	X		X	X		
Antin et al. (2017a)				X	X	X		
Antin et al. (2017b)				X	X	X		
Antin et al. (2017c)			X	X		X		
Arbabzadeh et al. (2019)	X			X			X	
Arvin et al. (2019)		X			X			X
Ashley et al. (2019)	X	X	X		X	X		
Atwood et al. (2018)			X	X	X	X		
Avelar et al. (2018)	X	X		X			X	
Bakhit et al. (2018)			X		X	X		
Bärgman et al. (2015)			X		X	X		
Bärgman et al. (2017)		X						X
Bharadwaj et al. (2019)					X	X		
Brewer and Stibbe (2019)	X	X					X	
Calvo et al. (2020)			X	X	X	X		
Chen and Chen (2019)	X	X		X		X		X
Chen et al. (2020)			X					X
Christ (2020)		X	X		X			X
Dadashova et al. (2018)	X	X		X		X		
Das and Ahmed (2019)		X	X				X	

Author (year)	**Data Used**					**Purpose of Analysis**		
	Roadway Information Database (RID)	**Naturalistic Driving Study**				**Modeling and Hypothesis Testing**	**Deriving Parameter Estimates from Normal Driving**	**Deriving Parameter Estimate for ADAS**
		Time Series	**Video**	**Driver Survey**	**Event**			
Das et al. (2017a)	X	X	X	X	X	X		
Das et al. (2017b)	X	X				X		
Das et al. (2018)		X	X				X	
de Winter et al. (2018)				X		X		
Dhahir and Hassan (2019)	X	X					X	
Dingus et al. (2019)			X			X		
Flannagan et al. (2019)		X		X	X	X		
Fountas et al. (2018)	X	X		X	X	X		
Gao and Davis (2017)		X	X				X	
Gaspar and Carney (2019)		X	X					X
Geng et al. (2016a)	X	X	X				X	X
Geng et al. (2016b)	X	X	X				X	X
Ghasemzadeh and Ahmed (2018)	X	X	X				X	
Ghasemzadeh and Ahmed (2019)	X			X	X			
Hallmark et al. (2015a)	X	X					X	
Hallmark et al. (2015b)	X	X	X	X		X		
Hallmark et al. (2018)	X	X	X	X		X		
Hammit et al. (2019)		X	X				X	
Hammit et al. (2018)		X	X				X	
Hamzeie (2018)	X	X			X		X	
Haslett et al. (2019)	X	X				X		
Haus and Gabler (2018)		X			X	X		X
Hedlund (2014)			X	X		X		
Higgins et al. (2017)	X	X		X		X		
Hoang Ngan Le et al. (2016)			X					X

Author (year)	Data Used					Purpose of Analysis		
	Roadway Information Database (RID)	Naturalistic Driving Study				Modeling and Hypothesis Testing	Deriving Parameter Estimates from Normal Driving	Deriving Parameter Estimate for ADAS
		Time Series	Video	Driver Survey	Event			
Huising et al. (2018)			X	X	X	X		
Hutton et al. (2015)	X	X	X				X	
Ivanco (2017)		X	X					X
James and Hammit (2019)		X		X		X		
Jenkins et al. (2016)		X	X			X		
Kanaan et al. (2019)		X	X					X
Khan and Ahmed (2020)			X					X
Khan et al. (2018)		X	X				X	
Kidd and McCartt (2015)			X		X	X		
Kluger et al. (2016)		X			X	X		
Lanka et al. (2019)		X						X
Lee et al. (2018)		X	X		X	X		
Li et al. (2015)	X	X	X		X	X		
Li et al. (2017)	X	X	X			X		
Lin (2017)		X	X	X		X		
Liu (2017)				X	X	X		
Lindheimer et al. (2018)	X	X			X		X	
Lu et al. (2020)			X	X	X	X		
Markkula et al. (2016)	X	X	X		X	X		
Mastromatto et al. (2017)	X	X		X			X	
Mata-Carballeira et al. (2019)			X					X
Mousa and Ishak (2018)			X	X	X	X		
Mousa et al. (2018)	X		X	X	X	X		
Muhire et al. (2018)	X	X				X		
Muñoz et al. (2015)			X			X		

Author (year)	Data Used					Purpose of Analysis		
	Roadway Information Database (RID)	Naturalistic Driving Study				Modeling and Hypothesis Testing	Deriving Parameter Estimates from Normal Driving	Deriving Parameter Estimate for ADAS
		Time Series	Video	Driver Survey	Event			
Muttart (2015)		X	X	X	X	X		
Muttart et al. (2017)			X		X		X	
Oneyear et al. (2015)	X		X				X	
Oneyear et al. (2016)	X	X		X			X	
Orlovska et al. (2020)			X	X				X
Osman and Rakha (2020)		X		X				X
Osman et al. (2018)		X			X	X		X
Osman et al. (2019a)		X	X	X				X
Osman et al. (2019b)		X			X			X
Owens et al. (2018a)			X	X	X	X		
Owens et al. (2018b)			X	X	X	X		
Papazikou et al. (2017)		X		X	X		X	
Papazikou et al. (2018)		X		X	X		X	X
Penmetsa et al. (2017)				X	X	X		
Perez et al. (2017)		X			X		X	
Pratt et al. (2019)	X	X				X		X
Precht et al. (2017a)	X		X	X	X	X		
Precht et al. (2017b)			X		X	X		
Precht et al. (2017c)			X		X	X		
Precht, L. (2018)			X	X	X	X		
Risteska et al. (2018)	X	X		X		X		
Sarwar et al. (2017)	X	X				X		
Schneidereit et al. (2017)		X	X	X		X		
Seacrist et al. (2016)		X		X	X	X		
Seacrist et al. (2018)		X		X	X	X		

Author (year)	**Data Used**					**Purpose of Analysis**		
	Roadway Information Database (RID)	**Naturalistic Driving Study**				**Modeling and Hypothesis Testing**	**Deriving Parameter Estimates from Normal Driving**	**Deriving Parameter Estimate for ADAS**
		Time Series	**Video**	**Driver Survey**	**Event**			
Simons-Morton et al. (2019)		X		X		X		
Srinivasan et al. (2018)	X	X	X	X		X		
Sun and Wu (2017)	X	X					X	
Taccari et al. (2018)			X		X			X
Taylor et al. (2018)	X	X		X			X	
Teoh and Kidd (2017)					X			X
Thapa et al. (2019)		X	X	X		X		
Wali et al. (2018)		X			X	X		
Wang and Zhou (2018)	X	X		X		X	X	
Wang et al. (2017)	X	X	X		X	X		
Wang et al. (2018)	X	X		X		X	X	
Wood and Zhang (2017)		X	X	X	X		X	
Wotring et al. (2020)			X		X	X		
Wu and Xu (2017)	X	X	X		X	X		
Wu and Xu (2018a)	X	X	X	X		X		
Wu and Xu (2018b)	X	X		X		X		
Wu and Xu (2018c)	X		X	X	X	X		
Wu and Lin (2019)		X	X		X			X
Wu et al. (2017)	X	X			X	X		
Wu et al. (2018a)	X		X	X	X	X		
Wu et al. (2018b)	X	X			X	X		
Yadawadkar et al. (2019)			X	X		X		
Ye et al. (2017a)			X		X		X	
Ye et al. (2017b)		X	X	X				X
Young (2017a)			X		X			X

Author (year)	Data Used					Purpose of Analysis		
	Roadway Information Database (RID)	Naturalistic Driving Study				Modeling and Hypothesis Testing	Deriving Parameter Estimates from Normal Driving	Deriving Parameter Estimate for ADAS
		Time Series	Video	Driver Survey	Event			
Young (2017b)		X	X					X
Zhou and Xu (2018)	X	X				X		

CHAPTER 3. SUBJECT MATTER EXPERT INTERVIEWS

The ultimate goal of this study was to determine how SHRP2-based data-driven research could be used, based on previous and future studies, to better inform the transportation community about driver behavior and performance. To help achieve this objective, it is important to outline a plan for implementation of this information. As shown in Table 4, there are a variety of national guidance documents that could potentially benefit from this expanded knowledge.

Table 4. AASHTO Publication to Consider

Document	Publisher/ Owner	Edition/ Publication Date
AASHTO Documents		
Roadside Design Guide (RDG)	AASHTO	4th Edition, 2011; July 2015 Errata available
Highway Safety Manual (HSM)	AASHTO	1st Edition 2010 with 2014 Supplement; 2nd Edition Expected 2022
A Policy on Geometric Design of Highways and Streets (“Green Book”)	AASHTO	7th Edition, 2018; 8th Edition Planning Stage
Guidelines for Geometric Design of Low-Volume Local Roads	AASHTO	2nd Edition 2019
Guide for the Development of Bicycle Facilities	AASHTO	4th Edition, 2012
Guide for the Planning, Design, and Operation of Pedestrian Facilities	AASHTO	1st Edition, 2004
Roadway Lighting Design Guide	AASHTO	7th Edition, 2018
Manual for Assessing Safety Hardware (MASH)	AASHTO	2nd Edition 2016; PDF available from AASHTO includes June 2020 Errata
Guide for High-Occupancy Vehicle Facilities	AASHTO	3rd Edition, 2004
Other Non-AASHTO Manuals and Reference Documents		
Manual on Uniform Traffic Control Devices	FHWA	2009
Highway Capacity Manual	TRB	6th Edition, 2016
Human Factors Guide	TRB	2nd Edition, 2012 3rd Edition expected 2020
Traffic Engineering Handbook	ITE*	7th Edition, 2016
Freeway Management and Operations Handbook	FHWA	2003 last published by FHWA, 2017 update available on TRB Freeway Operations Committee website

** ITE = Institute of Transportation Engineers*

The research team conducted interviews with 17 subject matter experts to determine their recommendations for future research and potential enhancement of the publications shown in Table 4. These professionals included users and, in many cases, contributors for one or more specific AASHTO or other reference document. A subset of the targeted list of documents shown in Table 4 were directly discussed, based on subject matter expertise, as part of the interview. Interviews were conducted over videoconferencing in July and August of 2020. The interview script is provided in Appendix B.

General Comments about SHRP2 Safety Data

After discussing the contents of and process for updating the subject reference document, the interviews focused on general comments and concerns about using the SHRP2 data. For those interviewees who were unfamiliar with the datasets, the interviewer presented a SHRP2 slide deck developed by FHWA in 2016 as part of the IAP program. This information was presented before discussing the specific strengths and limitations of the data and applicability to the subject document.

Advantages of SHRP2 Safety Data

The experts noted several advantages of using SHRP2 data for research for policy documents and guidelines. This feedback was generally categorized as:

- Geographic diversity,
- RID contents and quality,
- Benefits compared to other methods, and
- Real driving.

These four categories are discussed in the following sections of this report.

Geographic diversity

The fact that SHRP2 had obtained data from multiple sites was viewed as a strength by several people. These multiple sites would allow for examination of regional driving habits in terms of speed choice, following distance, lane change frequency, and headway. This diversity could allow for calibration of safety performance functions in different locations as well as checks of existing crash modification factors for different regions.

The variety of weather conditions present in the dataset was another notable advantage of using these data. This enables research into seasonal weather effects on driving performance as well as identifying unsafe driving behavior in intermittent conditions like rain and snow. Several of the states included in the database have significant winter weather which would allow research into differences in driving patterns in snow and ice compared to warmer weather conditions. If state's maintenance records are available in the RID, the effects of winter maintenance activities could also be examined.

These benefits and advantages are particularly relevant for several of the key AASHTO documents such as the Green Book and the Highway Safety Manual. Several of the above-mentioned topics will be addressed in more detail in the section presenting specific research project ideas.

RID Contents and Quality

The quantity and quality of the data included in the RID was noted by several of the experts. They felt that critical roadway geometric features were included in the RID to enable research to support the Green Book. There was some uncertainty among the interviewees as to how complete the data fields were across the data collection sites and this uncertainty translated into concern about how this may affect research. In general, the experts felt that the RID data was critical to conducting safety analysis by providing context for examining driver behavior. The research team confirmed that the RID data for which the source was mobile data collected by Fugro was consistent (same data types and same data specifications). Any data acquired from states and other local agencies, however, could be inconsistent and vary by agency.

One person experienced with the SHRP2 data noted the quality control process of the RID was very high. Data came from a variety of sources. Although analyses using RID may produce a smaller data set than targeted new data collection, what is in the RID is higher quality than you could get if you wanted to go and collect that yourselves and has already had quality control processes applied.

Benefits compared to other methods

In discussing specific research approaches, several experts compared the use of the SHRP2 dataset to using both traditional data collection methods as well as innovative ones. One advantage is that the study can benefit from a larger sample size of roads and drivers compared to collecting speed with traditional methods such as tubes, cameras, or speed guns. Innovative methods, such as using surveillance cameras to determine car following or speed, often are limited by a small number of sites. SHRP2 forward camera data plus radar allows easy capture of car following behavior.

In the roadside safety arena, the topic of encroachment into the shoulder is an important determinant of safety hardware. Video analytics have been used recently to look at encroachment on a microscopic scale. This approach to determine encroachment from video could be applied to other dashcam type video such as that captured in SHRP2. While much research in this area could be done with surveillance cameras, they are usually in urban areas on freeways. There is a need for encroachment data on lower volume roads. So if you could do machine vision analytics using dashcam video, encroachment rates could be determined.

Real driving

The one advantage mentioned by nearly every interviewee was that SHRP2 represented real driving. Research conducted in a laboratory, simulator, or closed course always suffers from limits to generalizability because drivers are on their best behavior and know they are being observed. With SHRP2, the data user is observing real driving behavior, and this means the analysis can be more confident that the observed driving factors would generalize to real-world situations.

Several people noted that the real value is in the uncoded million hours of uneventful driving. To date much of the SHRP2 research has focused on safety critical events, crashes, and near-crashes. But for many of the policy and guideline documents there is a need for values that represent normal lane-keeping behavior, normal speed maintenance, and normal headways.

Limitations of SHRP2 data

The interviewees discussed a variety of perceived limitations associated with using the SHRP2 datasets. One recurrent theme was the basic difficulty in working with data you did not collect and understanding exactly what each variable represents (issues such as units of measurement, normal range of values, and data capture frequency). One expert involved with the original data collection noted that he has been asked to review papers that used SHRP2 and that purported to analyze variable "X" but given his experience he knew that this variable is not reliable or not actually included in the dataset the way the author states. The likelihood of misinterpreting data that other people collected is high. In other words, despite having data dictionaries, there remains great opportunity for misunderstanding or misinterpretation of the data.

The second common limitation noted was the small sample size for select target features, particularly for crashes. The dataset is often touted as being extremely large and promises to offer insights into crash causality. Several researchers noted, however, that the actual number of crashes and near-crashes is relatively small. When studying specific geometrics or roadway conditions, by the time all the factors are considered, you may only have one to two crashes per condition. While traditional methods would just rely on crash data, having driver behavior can help better understand causality, predecessors to crashes; however, due to the small number of crashes per set of conditions, the SHRP2-based analysis tends to be a case study rather than anything generalizable.

A third recurring comment was that the use of SHRP2 data gets talked about a lot during the proposal and planning stage, but then in the end the research team often takes a different approach. The alternative approach is often selected due to cost and difficulty in using SHRP2 data. There is also a lack of confidence in accuracy of coding of elements. It is also hard to know how much money and time to budget for getting the data.

The interviewer asked about the "shelf life" of the SHRP2 data. The question included (1) the RID data and (2) the NDS data. While some of the interviewees would not venture a guess, most people estimated ten to twenty years for RID data and five to ten years for NDS. The main reason for the data becoming obsolete had to do with vehicle fleet turnover and the rapid introduction of advanced driver assistance systems in new vehicles. Several people noted that since the crash data in RID is essentially from the seven years prior to when NDS data collection began in 2010, that specific crash data is dated and should be used with caution and caveats.

Everyone felt that the RID data has a longer shelf life than NDS because most roadway elements do not change substantially. Traffic volumes may have changed and would not be valuable but geometric design information could still be useful. [Note: As the RID data is linked to the ARNOLD network centerline data in the near future, it will be feasible to update traffic volume information through this resource.]

Several people made the point that even if that particular road has changed over time, the condition it was in 2010-2013 still represents current conditions somewhere in the country on a similar road. For example, how people react to rumble strips probably would not change over time, but vehicle handling characteristics and safety systems will have changed. Despite these concerns, several people addressing different documents commented that data from 2010 is more recent than what is represented in common guidance documents currently. The Green Book and the Roadside Design Guide, in particular, were called out as having some values based on research completed more than 40 years ago.

Individual comments regarding perceived limitations are separated into the following six general areas:

- Shelf life (RID and NDS) – see Table 5,
- Ease of use – see Table 6,
- Cost -- see Table 7,

- Vehicle mix – see Table 8,
- Sample size – see Table 9, and
- Missing or mistaken data elements -- see Table 10.

Table 5. Specific Shelf Life Comments for SHRP2 Data

Shelf Life - RID
The data should be good for another 15-20 years. We are not going to change the environment that much and people do not change.
As long as the crash data are tied accurately to the inventory data, then there is no limit to shelf life. The issue is more of believing that driver behavior has changed dramatically over time that would limit the value. For example, driver behavior can change over time as bikes and peds are more frequent and drivers are more aware. Changes in crosswalk yielding patterns have been seen over time.
Shelf life is only as good as the age of the crash database included with it. This raises the question of how old is the crash data that is in RID, does it really cover the full period that NDS was active?
For studies that are not really using the crash data, there is still a limit to the value of the kinematic data due to changes in land use over time.
Crash data reporting has improved a lot since late 2000's. Model Inventory of Roadway Elements (MIRE) standards are new so shelf life of crash data may be limited.
Changes in speed enforcement policies and technology (dashboard displays of posted speed limit in navigation systems, automated speed enforcement) may have changed driving habits over the past 10 years.
It is hard to think about how you would use the RID without NDS. Some studies use crash data with RID, so that would still be valued because you have detailed roadway data. After 15 years, however, this data may be outdated because vehicles and driver characteristics change in that time.
Vehicle handling characteristics may have changed over time with ABS and electronic stability control.
Roadway lighting technology has changed. Within 10-20 years all lighting will be light-emitting diodes (LEDs). But despite that, the interviewee thinks the data may still be valid. There is no expiration date as long as we are talking about human behavior related to lane keeping, headway, and speed choice.
Shelf Life - NDS
The data could have a long shelf life because it is updating information that is older (some values are from the 1960's). Vehicle mix (e.g. increase in trucks/SUVs in vehicle fleet) may be out of date. Fleet turnover is 20 years, so maybe by 2033 it may not be as useful.
The data should have another five years of usefulness where this interviewee would propose using it. At this time, he would not hesitate to use it.
New data sources like Inrix and Streetlight are actually more comprehensive and cover more geographic area.
The data should be valuable for traffic control device research for a long time. Even with changes to the MUTCD, signs and markings do not change that fast. Until there are major changes to the way we drive with connected and automated vehicles (CAVs), the data could still be useful because those signs are still out there.
Issues related to distracted driving may change over time, so that may affect it. The Safe System approach focuses on looking at driving behavior, complexity, and conflict point movements. The driver workload and behavior will be relevant for a long time, even if the crash data is not.
Driver characteristics may change over time, which may affect crashes and issues such as distribution of age, gender, and experience in the licensed driver population.

Table 6. Specific Ease of Use Limitations

Ease of Use
There can be many challenges when using other's data.
The interviewee was curious where the Dataverse sets came from and if there are available high quality data dictionaries.
A key limitation is knowing what you do and do not have. From proposals the interviewee has seen, it is clear that prospective users do not fully understand what data is available.
It is hard to use this dataset. You really have to know what is in it and what questions to ask to find out what information is available. You may have different interpretation of what a term means than what is shown in their data dictionary.
Working with the data is extremely difficult and there is a need for a lot of filtering and data checks to get to the point of having a data set that can be successfully analyzed. Research knowledge of strengths/weaknesses is key, and you only get that by working with the data.
Having to learn the ins and outs of someone else's data base is harder compared to building your own (even if it involves your own cameras).
The data required a lot of manual verification and quality control effort to evaluate the data received from VTTI. This issue somewhat stems from trying to understand each variable.
For traffic flow estimates, it would be a huge amount of work to estimate volume from the NDS forward view. This is offset by how easy it is to acquire this information from Inrix or to even put out count tubes and for this approach you would be sure of what data you collected.

Table 7. Specific Comments Regarding Cost in Time and Money

Cost in time and money
It is time consuming to search SHRP2 data versus going out and collecting it on your own.
The cost of the data is expensive compared to modern data collection methods (e.g. Inrix, wejo).
The cost of having VTTI extract the data creates some issues.
There are often time delays to projects waiting for data request to be processed by VTTI.
There are time delays due to the inherent recursive nature of the data request process.
The process for how data is transferred is limiting as enclaves restrictions limit its use to those able to travel.
The cost to acquire face video coded (either by VTTI or traveling there to do it yourself) really limits which projects can afford this data. Some researchers may settle on less meaningful measures that can be easily obtained from kinematic data or settle for previously coded datasets that may not include all the relevant trip traces for the research topic.
There seems to be a lack of control over turnaround time to receive data request outputs and this makes project planning difficult and becomes critical path for student theses.
The cost per usable case is really high by the time you sort through all the variables.

Table 8. Perceived Limitations Related to Vehicle Mix

Vehicle Mix
The vehicle mix is limited, yet many of the AASHTO standards use the heavier vehicles as design vehicles for the limiting factor (especially for acceleration, deceleration, braking).
Vehicle mix information would be different for superelevation (roll over propensity) and stopping sight distance would be different for heavy trucks (though the truck driver is sitting higher). Acceleration/deceleration profiles would also differ.
The value will decrease the more ADAS systems become available in standard vehicles. Vehicle fleet has changed so much in the last five years. She thinks that by 2025, the vehicles sampled in SHRP2 will not be relevant as they will not be representative of the fleet.
A limitation is how technology will change. Example fleet changes that influence driver performance include ADAS systems and even global positioning system (GPS) or phone systems that show current posted speed limit and flash if you are exceeding the speed limit.
Certainly, the improved safety of cars limits applicability today. Vehicles are the limiting factor for shelf life. ADAS systems and improved vehicle handling, brakes, etc. will all continue to change.
Autonomous vehicles, ADAS, and people who use those features would affect value.
There may a need to consider a similar data set in the future that may include more ADAS.
Possible limitations that pertain to vehicle fleet mix would require an understanding of changes in the fleet and how that affects crash performance (both vehicle weight and physical features and ADAS). The current NCHRP project should provide an update on the vehicle fleet.
As vehicle fleet with ADAS systems becomes more prevalent, the data set will not be as relevant.

Table 9. Potential Sample Size Limitations

Sample Size
The data has a small number of crashes.
Analysis data sets often result in small sample sizes by the time you narrow down candidate sites and conditions of interest.
For speed studies, it is so much easier to use Inrix or even loops to acquire the data. Even with 3500 drivers, that is a much smaller set of people than you would observe with road tubes.
There really are very few crashes, many of the coded crashes are actually minor or curb strikes.
The dataset does not really include that many crashes. A research would have to use RID+crash data in addition to the crashes that happened when NDS was not in play. The research would also need to trust that the road had not changed between time of crash in the RID database and when NDS data collection occurred.
On the safety side, the data includes limited number of crashes. Ideally, the data could have been used to study many pre-crash situations but that has not worked out. It is not clear what the full safety applications are because of the small sample and generalizability.

Table 10. Limitations about Missing or Mistaken Data Elements

Missing or mistaken data elements
There seems to be missing data on operations such as ramp meter status, variable speed limit status, signal phasing.
The people reducing the data may not have fully understood roadway design subtleties when they were coding (both in RID and NDS). Some of the NDS descriptions are inaccurate (for example, in one case there was a road coded as a two-lane freeway even though this road type does not exist).
For freeways, the data could be used to look at frequency of lane changes, but without minute-to-minute volume or lane occupancy data it is hard to determine what you would get.
How good is the rural road data? Does the RID contain the same information for rural roads as urban or freeways?
Is the data geographically representative? The study sites are very East-coast focused.
The data seems to lack detail on roadside safety hardware elements.
Without eye-tracking info, some human factor researchers do not want to use it.
The data seems to be lacking freeway ramp information in RID.
Some of the sensor data is inconsistent (e.g. speed from GPS versus speed from other equipment).

In addition to these issues raised in the interviews, previous projects have identified similar issues. In addition to echoing many of the points raised in the interviews, Hallmark and McGehee (2014) pointed out that the location data are coded with multiple GPS points linked to a single segment, which is not typical for most researchers examining crash data.

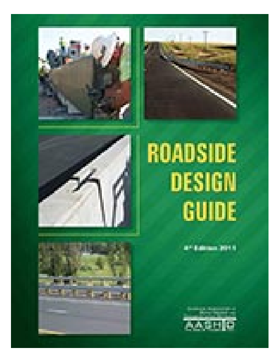
A workshop was held for SHRP2 users in 2016 to resolve issues highlighted that the handling of Personally Identifiable Information (PII) continues to be a significant challenge (Polk, 2016). There is a demand from the research community to access PII which may require additional secure enclaves or secure remote access protocols similar to those used with health care and census data.

The SHRP2 Safety Data Oversight Committee reviewed the ongoing IAP projects through interviews in 2017 (Hutton, 2017). They noted a strong link between success of research and level of engagement with the sponsoring DOT. This group also noted issues with data requests, understanding of the costs and time required, and communications with VTTI.

Comments on Specific Reference Documents

Roadside Design Guide

The AASHTO Roadside Design Guide (RDG) helps practitioners select appropriate locations and types of roadside safety devices. The current edition is from 2011 with a 2015 Errata published. A new version is currently under development within the AASHTO volunteer Technical Committee on Roadside Safety with contractor support from Leidos. This new version will include a significant reorganization. Research results are incorporated into revisions through the committee members, but there is a risk that some research could be overlooked because each chapter is



handled by a different group of volunteers. The values in the document are determined by research results and current practice. This document is meant to be a guide, not a prescriptive document. States use this guide to develop their own specifications and standards. Future editions will have a renewed focus on how to keep vehicles on the roadway using traffic control devices, rumble strips, and pavement treatments.

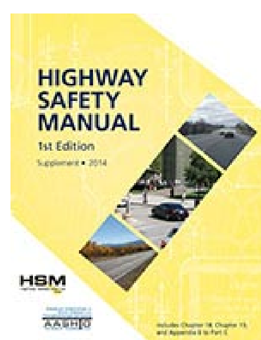
A key feature of the RDG is the Road Safety Analysis Program (RSAP) software tool that is distributed with the RDG document. The software gets very specific and lets you enter roadway information and roadside hazards. RSAP will conduct a comparative benefit-cost analysis based on estimated roadside encroachments. For example, a user enters baseline conditions with no or existing treatment versus a proposed treatment. The benefit is assessed by crash severity (e.g hit the tree versus hit the barrier if you install it). Costs are calculated based on the economic value of crashes. These calculations are fundamentally based on the rate of encroachment toward the hazard whether that is a ditch or a fixed object. For this reason, having encroachment data from normal driving in SHRP2 could be useful for future editions. Some concern about the potentially small number of encroachments and their idiosyncratic nature was expressed. The experts thought the crash data in SHRP2 would likely be less valuable because there are likely few crashes that involved a barrier or other hazard that is addressed in the RDG. If any event data recorder information is available from such crashes, it could be used to judge impact speed which could be helpful in crash severity modeling.

Researchers in this area would like to understand if and how behavior of drivers change if hardware is placed closer to the road or farther away. They would like to be able to make the connection between actual driving behavior (speed, lane placement, type of recovery action) if there was a barrier there.

Another area that the experts thought may benefit from SHRP2 is information obtained from video analytics applied to the forward video captures. If machine vision techniques could be applied, information on clear zones may be obtained and linked to speed, lane-keeping, and encroachment. There is a tradeoff between roadway departures and pedestrian facilities on suburban arterials. Trees on the curb line make things more pedestrian friendly, but they're obstacles to hit in a roadway departure crash. Another data need that may be served by video analytics is the in-service length of barrier (i.e. how far before the fixed object the barrier extends). A third area utilizing machine vision would be to search for minor roadway departure events and study their recovery. Site conditions such as sideslope, pavement edge treatment, and ability to traverse the shoulder could be examined for their role in recovery.

Highway Safety Manual

In 2010, AASHTO published the first edition of the Highway Safety Manual (HSM). The purpose of this document is to provide a data-driven resource that can be used to predict the estimated safety performance of a facility based on road characteristics and vehicle exposure. The 2010 release included fundamental safety information, a review of crash types and crash severity, and predictive methods for rural multi-lane roadways, rural two-lane roadways, and urban and suburban arterials. A supplement released in 2014 provided additional techniques for estimating crashes freeways and interchanges.



Several themes emerged when discussing how SHRP2 data could support research for the HSM. The first is the idea of using SHRP2 data to provide converging evidence or support for selecting one countermeasure over another when crash modification factors (CMFs) are available for both. CMFs are aggregates across multiple sites involving many average values and only use crashes as the outcome variable. The S-01 study on left turn lane offset is an example of this (Hutton, et al. 2015). CMFs for offset turn lane exist but are not terribly strong, but the SHRP2 analysis demonstrated that drivers made better gap decisions with offsets. Decision-makers can then look at the CMF for offset in addition to this research and select an offset countermeasure with more confidence. Similarly, driver behavior can be considered an alternative measure of safety or surrogate for safety. Currently, NCHRP 17-86 is considering alternative measures of safety. By examining NDS normal driving data to find behavior that corresponds to areas where crashes have occurred, successful driving tactics may shed light on additional measures of safety. Having driver behavior can help to identify causality, and this may then help reveal the predecessors to crashes.

The second general area is the idea of using SHRP2 to provide a mechanistic explanation of counterintuitive results or conflicting results (or CMFs). In the same vein, SHRP2 data could be used to verify CMFs that have low star ratings or contradictory findings in the Clearinghouse (i.e. countermeasures that may have two different CMFs one positive and one negative). In the CMF world, there may be a way to confirm low quality CMFs for commonly used treatments. NDS could be used to give extra evidence to these treatments based on driver behavior. One example is lane width where some studies show that wider lanes result in fewer crashes and the interpretation is that this behavior is because drivers are successfully executing appropriate lane keeping behavior. Other studies of lane width have shown that wider lanes result in a higher crash rate and this is interpreted to be caused by higher speeds. Examining SHRP2 data could determine which is the more prevalent behavior.

Another challenge in safety assessment is the underlying method of analysis. Ideally, safety assessment should be based on before-after studies; however, often the actual date of implementation or available before data is not always available and there may not be any unbiased comparison sites to include in the analysis. When this occurs, the analyst must often use cross-sectional studies. This type of study is generally a regression equation that is based on a specific data set and so applies to the unique characteristics of that data set. Ideally, a cross-sectional analysis should not be used for causal inferences; however, this approach is often the only practical analysis method that can be applied to the available data. SHRP2 data could potentially be used as a means of confirming the reliability of these two analysis methods.

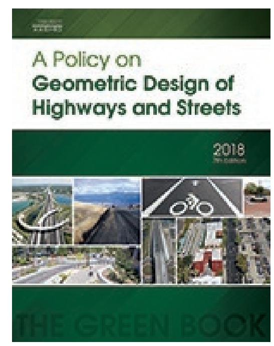
The HSM combines safety performance functions (designed to predict crashes) with adjustment factors that allow unique features to be directly considered. For example, the safety performance function may estimate the predicted number of crashes for roadways with lane widths of 12 feet. If the road under analysis only has 11 feet wide lanes, then a lane width adjustment factor is multiplied to address this difference. More information is needed about how to apply adjustment factors and what is their optimal functional form. SHRP2 data could help isolate the influence of the individual road characteristics that are likely to influence safety performance.

Another area with growing interest is how to develop CMFs from behavioral data without having the benefit of crash data. NCHRP 22-47 (*Incorporating behavioral components in crash* *prediction models)* is now underway and will likely use land use data and driver characteristics. The researchers are also considering using behavioral data from SHRP2, but they are concerned that the database may not contain enough crashes.

Part A of the HSM covers fundamentals of safety analysis and human factors. SHRP2 data could be used in Part A to provide examples of driver behavior patterns. Basic concepts such as the relationship between speed and crash outcomes were researched in the 2000's to support the first edition of the HSM (e.g. Harkey et al., 2008), but the research represented a compromise of several related statistical models. SHRP2 data could be used to test the accuracy of these models' predictions.

The last general area highlighted in the interviews is using SHRP2 data in a Safe Systems approach. For example, by examining many left turns at different intersection types in the general, normal driving data. Understanding driver behavior and interactions with pedestrians and bicyclists could uncover some common site and operational features that result in no crashes or near-misses.

A Policy on Geometric Design of Highways and Streets ("The Green Book")



The Policy on Geometric Design of Highways and Streets (more commonly referred to as the Green Book) provides roadway designers guidance on how to select suitable thresholds for roadways based on expected speed along the corridor, context of the roadway, geographic characteristics, and similar roadway design considerations. Practitioners often use the Green Book in a prescriptive manner. Though this document is not intended to function as a "cookbook", the variety of lookup tables and figures included in the document are often applied to designs in a relatively rigid manner. For example, if a horizontal curve is perceived as safe if the radius is 750 feet or longer, does this mean that a 749 feet radius is not safe? This rigid yes-no application of the document has occurred historically. Currently, the AASHTO committee that oversees development of the Green Book has been trying to develop ways to encourage designers to think about the design principles before simply looking up values in the table.

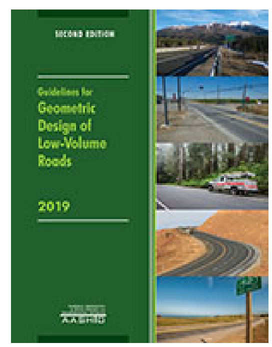
The update to the Green Book, 8th edition, is expected to begin in 2021 with a target completion date of approximately 2023. During the creation of the 7th edition, working groups generated many ideas for more additions and revisions. The 8th Edition will likely include a reformatting. The Green book is developed by a contractor in close cooperation with the AASHTO Committee on Geometric Design and the TRB Committee on the Performance Effects of Geometric Design. Research is incorporated into new editions through the relevant AASHTO sub-committees and state representatives on related NCHRP research project panels. The history of where certain values in the Green Book originated is lost in many cases and revisions have not always been well-documented. Several interviewees commented that when they have tried to track down the source for some tables, like superelevation, they discover the research supporting the values is 40 years old.

One challenge on revising the Green Book is that a change in values could have significant impact on reconstruction projects and liability for existing conditions. The newer Green Book values may dictate a higher value, but the crash data may not always show that there is a problem with the existing conditions. Some states have demonstrated an avoidance to keep changing the numbers in the Green Book to avoid liability for making existing roads sub-standard and adding reconstruction costs needed to upgrade the current project.

Several areas of research applicable to the Green Book include:

- Superelevation values are based on older vehicles and older paving methods, SHRP2 could be used to update this.
- Acceleration profiles for a newer vehicle fleet than what is currently represented in the Green Book could be obtained from SHRP2 normal driving data.
- Driver performance in innovative intersection designs such as diverging-diamond, and reduced conflict U-turns, though concern was expressed as to how many innovative intersections were in place in the U.S. in 2010-2013.
- Guidance on lane width for freeways is weak and based on current maintenance practices that have effectively narrowed these lanes, this guidance could be updated.
- Research on lane width on local streets with parking has produced very mixed results, SHRP2 could examine speed as a function of lane width if the data regarding parking is coded in the RID.
- Definition of trade-offs in allocation cross-sectional width at pedestrian crossings to add a median refuge island.
- Driver behavior on approach to uncontrolled intersections. The current assumption in the Green Book is that when a driver sees a yield sign he or she reduces speed 50 percent, but this is based on research from the 1960's.

Guidelines for Geometric Design of Low-Volume Local Roads



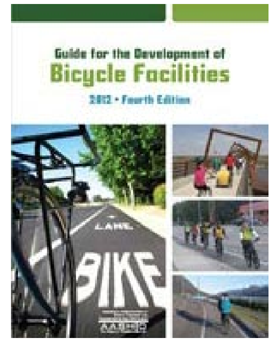
This document contains roadway design guidance for local and rural roads with low traffic volumes. According to the interviewees, the document is not heavily research based, but rather is developed by paring down recommendations from design guidance and research on high volume roads. The document is revised by the AASHTO committee. The document is used by practitioners for responding to complaints, planning improvements, and prioritizing funding.

The TRB committee on low volume roads has an active subcommittee on safety. Topics currently being discussed in this group include driver behavior issues (particularly for unfamiliar drivers), definitions of low-volume roads based on geographic area and jurisdiction, and roadside furniture needs with constrained budgets.

The seasonality of use of many low-volume roads was highlighted due to agricultural and forest management activity. Because low-volume roads are so under-studied, the SHRP2 data may be especially valuable to this area. It is hard to collect enough data on low-volume roads using traditional methods, plus the volume changes so drastically with farming cycles. The SHRP2 data could be used to come up with volume estimates for roads of different types. In addition, forward video may reveal road conditions (mud, snow) that could be used to interpret safety data and understand seasonal weather impacts on roadway surface.

Driver familiarity issues were one area that the interviewees felt would especially be addressable with SHRP2 data. For many low-volume roads, especially in the Midwest, a high proportion of the users of the roads live on that road and the drivers know the location of problems areas. On the other hand, an unfamiliar driver may take curves too fast or fail to slow down for low-water crossings or other roadway hazards. Familiar drivers may not stop at stop signs because there are rarely cars present at these locations. NDS data could examine the driving patterns of people who repeatedly drive the road compared to someone who is driving it infrequently. There is concern as to whether enough locations and trip records would be available and identifiable where an unfamiliar driver entered such a road.

Guide for the Development of Bicycle Facilities



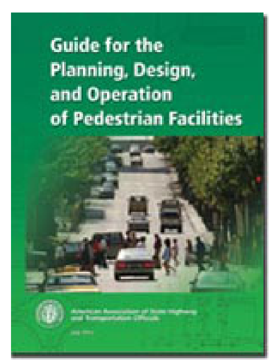
This document assists practitioners in selecting treatments for bicycle facilities given land use, design, and operational features of the area. The guide provides decision-making guidance and discusses trade-offs between use and safety of different treatments. The current edition was published in 2012 and a new version is expected in 2021. The document is created by a contractor working with the AASHTO Active Transportation committee. Recommendations in the guide are based on research and state of the practice. In addition to the AASHTO Bike guide, many practitioners consult FHWA supplemental guides and NACTO guides.

The interviewees identified several areas where more research evidence was desired. They noted that the current standard for data collection regarding driver behavior around bicyclists is to use video recordings. Because of this, the forward-view of the NDS data could potentially be a rich source of vehicle-bicycle interactions. If all instances of drivers interacting with pedestrians and bicyclists are not coded, this would be very labor intensive, but machine vision processing may be applicable. An analysis such as this could provide much-needed exposure data.

A high percentage of bike fatalities occur on two lane rural roads with the presumption that they are due to sight distance problems. SHRP2 data may reveal if a car strikes a bike from behind is it because they are avoiding moving over because of oncoming traffic. Overtaking behavior (cars passing bicyclists) is also of interest, especially as a function of roadway class and volume. Again, these types of analyses would depend on having bicycle presence coded.

The safety effects of bicycle lanes is one topic that could be examined if the RID contains bike lane information. Currently, NCHRP project 17-84 is examining bike lane safety through crash measures. If the SHRP2 database contains bike lane location information and the presence of bicycles, there would be good information about driver behavior and proximity to bike when passing and other conflicts.

Guide for the Planning, Design, and Operation of Pedestrian Facilities

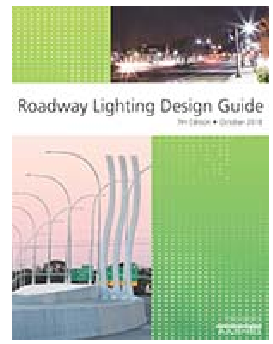


The AASHTO Pedestrian Guide is currently being updated. This guide is reported to be heavily research-based, though the values in some tables from older versions may have been based on best practices or the link to specific research projects has been lost over time. It is updated by contactors examining research and suggesting an outline and topics for the AASHTO committee to consider. Practitioners use the guide during the design process. NACTO and FHWA also has pedestrian facility guides that are used widely.

There is still research needed on driver understanding of crosswalk yielding laws. If the states included in SHRP2 vary in their laws, a study could look at yielding behavior at crosswalk locations after confirming the presence of a pedestrian with the forward video. One interviewee speculated that some drivers may not yield for fear of being rear-ended by a following vehicle. This type of behavior could be determined with video review. The effects of warning signs and yielding behavior is also of interest. In addition, marked and unmarked crosswalks, or crosswalk marking style, could also be examined in this way.

Basic roadway crossing for both pedestrians and bicyclists is of interest, particularly for uncontrolled intersections or suburban signalized intersections without pedestrian signals. Gap acceptance of pedestrians and bicycles may be able to be obtained from SHRP2 forward view cameras if their presence is known. The difference in motorist yielding behavior as well as pedestrian gap acceptance as a function of posted speed limit is also not well understood.

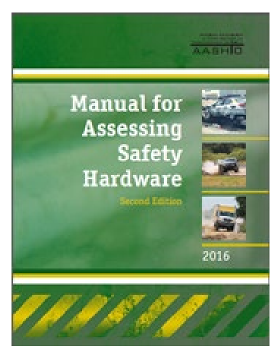
Roadway Lighting Design Guide



The AASHTO Roadway Lighting Design Guide helps practitioners decide whether or not to put in lighting for warrants that are based on AADT, crash history, and proportion of day-to-night crashes. This guidance has not really changed in 20 to 30 years (need safety data for that, this is where SHRP2 data could help). The specific design of lighting is determined by guidance provided in the Recommended Practice for Roadway Lighting published by the Illuminating Engineering Society which is also an approved standard by ANSI. FHWA also publishes a Roadway Lighting guide. Practitioners especially use the IES guide for basic light levels and uniformity requirements. The AASHTO Lighting Guide is a consensus-driven document with AASHTO committee members drawing on their experience as panel members for related NCHRP projects or state DOT research. It was last updated in 2018.

Roadway lighting is changing rapidly toward solid-state LED light sources. Several recent NCHRP projects on this topic will inform the next edition. In addition, one of the AASHTO IAP projects used the SHRP2 data to look at crashes as a function of roadway lighting. Solid-state light sources enable DOTs to lower light levels on demand at certain locations based on functional class, traffic volume, and pedestrian volume. For example, if the road use characteristics change at 1:00 a.m., they could justify that the road now functions as a minor arterial and dim the lights while still being within the warrant (i.e. it would be a major arterial from 6:00 a.m. until 10:00 p.m.), so the facility would meet the warrant for lighting, but would not need lights when it functions as a minor arterial from 10:00 p.m. until 6:00 a.m.

One area that needs more research evidence is urban freeway corridor lighting. Crash statistics really only support lighting at interchanges, but many agencies light long segments. SHRP2 data could be used to look at driver behavior in these lit segments compared to unlit ones. Another area is the effect of a single isolated streetlight at rural intersections which function as a beacon rather than to actually illuminate the roadway. SHRP2 data could look at speed and possibly driver visual search behavior in rural intersection locations varying in their lighting treatments.



Manual for Assessing Safety Hardware

The Manual for Assessing Safety Hardware (MASH) would benefit from defining crash characteristic and in-service performance of roadside devices to identify limitations and gaps in their current suite of MASH testing. Many of the current values in MASH are based on NCHRP 350 which was published in 1993. In 2007-2008 research provided with new vehicle fleet and was then adopted in 2009 for the new MASH.

If crashes exist in the SHRP2 database that involved safety hardware, the data could identify encroachment conditions (departure speed and angles) and encroachment rates in that area if repeated trips on that segment are available. In-service performance evaluations rely on detailed crash reconstruction data and there is a chance that some SHRP2 data could be used for this. Many crash reports just indicate “guardrail present” without any detail on type or installation. If relevant crashes exist, SHRP2 data could be used to validate the models derived from controlled crash tests.

Researchers in this area would like to understand how the devices behave beyond the test conditions used in MASH. The MASH test design characteristics are based on crash frequency distributions but studying specific crash conditions would be helpful to determine needs for additional test conditions. There is concern that the safety hardware data coded in the RID may not be detailed enough concerning post type and spacing as well as maintenance.

Currently, NCHRP project 03-134 is studying workzone encroachments is using SHRP2 NDS videos to obtain patterns and trajectory of encroachment. The goal of this project is to set recommendations for when a barrier is needed in a workzone and if so, how much offset is required.

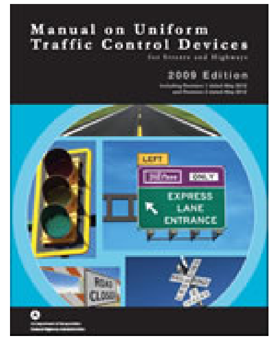
Guide for High-Occupancy Vehicle (HOV) Facilities

This document is used by agencies to design new facilities or adjust operations of existing sites. More recent guidance in the more general topic of managed lanes has generally superseded this document.

The interviewees felt that there may be drivers in the Seattle area who could have driven on HOV lanes in place during the time the NDS was collected. Other cities included in the data collection area did not have HOV lanes in place at that time. One research topic identified was weaving behavior in and out of HOV lanes. The issue of buffer or barrier separation continues to be challenging in modern facilities. The majority of HOV lanes in the Seattle region were concurrent flow at the time with a painted stripe buffer. There were a few barrier-separated reversible flow facilities in operation as well. If enough variety in egress point types existed in the Seattle HOV lanes at the time, a study could examine how buffer type affects weaving behavior. This research could inform geometric design of weave area lengths and lane widths in egress areas for HOV and other types of managed lanes.

Other Key Reference Documents not published by AASHTO

Manual on Uniform Traffic Control Devices



The Manual on Uniform Traffic Control Devices (MUTCD) is published by FHWA. A new edition is expected in 2021. This document is used by practitioners to select and apply traffic control devices across the full range of roadway types. The contents are based on state of the practice, research, and applications of principles present in each section of the document. The National Committee on Uniform Traffic Control Devices is an advisory group of practitioners and researchers who regularly review its contents and suggest revisions and additions to FHWA. The NCUTCD also generates research needs statements.

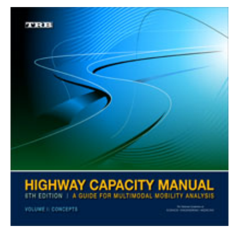
Many of the standards in the MUTCD are based on historical practice and any research-based evidence for their inclusion has been lost to history. The interviewees for this document highlighted several areas where evaluation of driver behavior in response to the presence a particular traffic control device could be accomplished with SHRP2 data. The fact that the RID contains the MUTCD designation for each sign was viewed as a strength of the dataset.

In reviewing research needs statements generated by the technical committees of the NCUTCD several topics could benefit from SHRP2 data analysis:

- Based on various roadway environments, what do operating speeds actually look like to help set posted speed limits? Concern was expressed that once you "slice and dice" the data for all road types the sample size may get too small.
- How do drivers behave around warning signs for rare events (e.g. ice on bridge, deer crossing, falling rocks, school bus stop ahead)? Are there actually any changes in driver behavior that result from passing these signs when the threat is not present?
- For freeway guide signs with multiple lane and option lane ramps, there is a long-standing dispute in the field about the appropriate sign type (arrow per lane, diagrammatic, or text-only). Weaving and lane change behavior in the vicinity of locations where these exist could identify when drivers make unnecessary lane changes or last-minute maneuvers.
- Speed advisory plaques for horizontal curves and ramps. If advisory speed plaques for curve warning signs are coded in the RID, then speed in those curves and trajectory through the curve relative to lane lines could be examined. There was some concern that this analysis would exclude heavy trucks since advisory speeds are often based on those larger vehicles.
- Seasonal weather effects on signal clearance intervals. Should clearance interval settings change due to weather (snow, ice, rain)? SHRP2 data could look at whether drivers make different decisions as to whether or not to run yellow based on weather. Signal phase and timing data would need to be present in the RID for this type of analysis.
- Effect of adding advance street name signs upstream of the intersection and effect on hard braking, lateral acceleration, erratic movements. Could find advanced street name sign locations and query to find all vehicles that turned there and look at trajectories. Effects of letter size (if that is coded in RID) could be evaluated in the same way.

- Driver behavior around highway-rail intersections as a function of traffic control devices and presence of advance warning signs. By viewing face camera records at these locations, one could measure head turn and speed and deceleration just from the normal driving data.
- Wrong way driving continues to be a safety issue. If the 511 data in the RID has any wrong way driving incidents coded one could look at driver response to that. It is likely that there are so few incidents that the research would be more of a case study.
- Symbol versus text signs and the associated driver compliance. The MUTCD allows the option of using either a text-only or a symbol sign for many warning signs (such as right lane ends). If lane changes are lane choices are already coded in the NDS data, this analysis could link those sign codes in the RID to driver lane change position in the NDS data without looking at the video.

Highway Capacity Manual



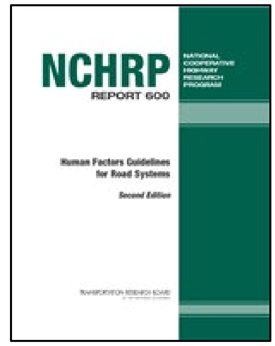
The Highway Capacity Manual (HCM) is used by researchers and practitioners to investigate future year corridor operational conditions for intersections, interchanges, and segments to see if there are any problems anticipated in terms of congestion. This allows practitioners to propose possible roadway treatments that can help the transportation agency avoid congestion or operational constraints in the future. These predictions and models rely heavily on current and historic traffic counts and current field operation conditions. Data on turning movement counts and AADT is needed for HCM methods. The document is published by TRB.

HCM procedures are largely based on macroscopic modeling. This type of individual, microscopic driver/vehicle behavior present in the SHRP2 data may not be that relevant. Aggregated vehicle behavior, like traffic density, is the input for a macroscopic model. This data is gathered through sensors and crowd-sourced data providers like Inrix, Here, and Streetlight.

Despite these reservations about the value of SHRP2 data for modeling, there were a few topics needed for these models that could be obtained from the SHRP2 driver data. Information on typical headway from the radar could be useful as input to models of density. Typical acceleration and deceleration rates drawn from normal driving behavior could be useful to get values for the HCM calculations, but because SHRP2 excluded heavy trucks, there was some concern over the value of only passenger vehicle data.

Another possible application of this dataset is to look at speed fluctuations through weaving sections on freeways and arterials. The HCM's assumptions about lane change frequency could be improved as well. In order to use this for HCM calculations, the current level of service would need to be determined which may be possible from forward video or from 511 information. Information on acceleration and deceleration in weaving sections, as well as at interchanges and intersections, is also desirable and could be derived from SHRP2 data. The lack of heavy truck data was noted as a limitation for these applications.

Human Factors Guide

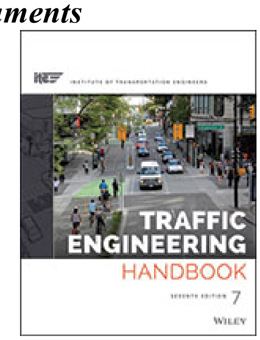


NCHRP Report 600, known as the Human Factors Guide (HFG), provides evidence-based recommendations for practitioners to incorporate human capabilities into a variety of safety, design, and operations applications. The third edition is expected to be released in late 2020 and a fourth edition to add more topics is on the upcoming project list. One of the authors of the document was interviewed for the current project. While no SHRP2 studies are currently referenced in the HFG, future editions could make good use of research using SHRP2 data of normal driving behavior. The interviewee felt that studies to date using SHRP2 data have placed too much evidence on driving segments involving crashes and near-crash events. There are categories of driver error that do not result in a crash (e.g. wrong way driving, red light running, etc.) to see impact of infrastructure on behavior, normal non-crash driving. Some in the human factors community suspect that normal driving is fraught with frequent driver error and we just get lucky that we do not crash. Others think that more attention should be given to normal, event-free driving by studying “healthy” drivers rather than “sick” drivers who crash to use a medical analogy.

Specific topics where more research evidence was desired for inclusion in the HFG are listed here.

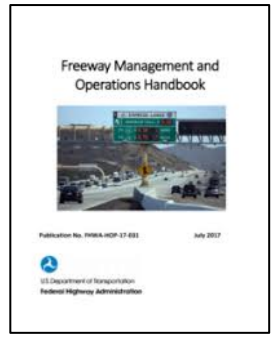
- Speed choice as a function of lane width
- Driver behavior:
  - In transition zones from rural highway to local roads,
  - In work zones and approaches to work zones,
  - At railroad-highway intersections and rail-crossings, and
  - On approaches to complex freeway interchanges.
- Driver behavior around bicyclists.

ITE Traffic Engineering Handbook or ITE Recommended Practice documents



One interviewee also thought there was potential to inform some ITE documents, specifically the Traffic Engineering Handbook or ITE Recommended Practice documents. Driver behavior data on signalized corridors is of particular interest to determine if coordinated signal timing affects driver speed choice as expected and modeled. Another application would be red-light running behavior, this could inform ITE Recommended Practice determining traffic signal change and clearance intervals, but accurate signal phase and timing information in the RID would be necessary.

FHWA Freeway Management and Operations Handbook



This document was identified by two interviewees as another possible beneficiary of research using SHRP2 data. There is a current NCHRP project that is near completion that will create “the Green Book for Operations” as one interviewee described it. Possible applications for research would be driver behavior in recurring and non-recurring congestion locations. In particular, end- of-queue crashes are of interest to determine whether they are happening in recurring congestion or if they are related to special events or other incident management activities. Kinematic data could reveal whether drivers brake hard or try to change lanes when coming upon a queue. Beyond crashes, driver behavior on approach to a queue, whether recurring or not, is of interest to inform Travel Demand Management (TDM) and Transportation Systems Management and Operations (TSMO).

- The respondents felt that urban data would be most relevant though work zones and incidents and other non-recurring events present in rural data would also be of interest. Identification of behavioral trends that are safety-related or linked to crashes in congestion could inform countermeasure selection. Those countermeasures could then be evaluated in a prospective study to look at TSMO intervention (like end of queue warning sign in a known location for recurring intersections, or blind spots on approach to congested intersections).
- The effect of traveler information systems during incidents may be able to be researched with SHRP2 data if 511 information in the RID contains changeable-message sign status. Researchers and practitioners are interested in knowing whether or not people change their route in response to incident and travel time information.
- The effects of Variable Speed Limits and ramp-metering could be evaluated with SHRP2 data. One interviewee knew of specific locations of variable speed limits in the Seattle region, but traditional ways of measuring speed are available and are likely easier and cheaper to obtain from historic traffic management center data.

CHAPTER 4. RESEARCH THEMES AND ROADMAP

Common Themes

After reviewing the literature, interview notes, and previous planning efforts within AASHTO, FHWA, and the TRB SHRP2 program, several common themes have emerged.

- The uneventful, normal driving periods are an untapped source for a distribution of driver behavior variables such as speed, deceleration, acceleration, and lane position that would feed into many guidance and policy documents.
- There are many opportunities to use the SHRP2 Safety dataset for applications outside of safety. The current FHWA pooled fund projects include topics in operations and planning.
- New research to evaluate countermeasures installed after 2013 could be conducted using SHRP2 data as the "Before" condition.
- In some sectors of transportation research and practice, there is still a lack of awareness that this dataset exists.
- Machine vision techniques could be applied to the forward video to support many research topics. The assessment of the quality of the video to apply these techniques may be a research project unto itself.
- Big data techniques of merging multiple datasets can be applied in new ways. For instance, if land use data is not currently in the RID, it could be obtained from related planning documents of the time and be added.
- SHRP2 data use would increase if access was easier and cheaper.
- Newer data collection methods from smartphones and connected cars provide a larger and more easily obtained dataset for positional data than that available as part of the SHRP2 effort.
- The SHRP2 dataset is aging and fleet penetration of new vehicle technology could make parts of the dataset obsolete in the next five to ten years.

Specific Research Project Ideas

Based on common feedback, there appear to be several research project ideas that can be explored. These are generally aligned with the documents described in Chapter 3. The following summary tables (see Table 11 through Table 17) provide a description and potential data needs identified as a result of this effort. This list includes the most common 22 research project ideas suggested by the interviewees and/or project team members.

Chapter 5 includes seven expanded research problem statements. The selection of these prioritized statements was based on research ideas that were most frequently cited, ideas that represented the best opportunity for success, and ideas that could be expected to result in successful and/or impactful research efforts through the expanded use of the SHRP2 data.

Table 11. SHRP2 Data Research Ideas to Benefit the Roadside Design Guide

#	Description	Data Needs
1	Do wide open clear zones lead to higher travel speeds when compared to speeds in areas that have landscape close to the road? This is particularly relevant for urban and suburban areas.	Segment speed data Coding of roadside features and land use. Possibility of machine vision processing to assess clear zone width.
2	Is there a relationship between clear zone width and animal crashes? Do animals linger in those wide bare areas? Do drivers visual search patterns change in those areas? If an animal is visible on the roadside, what do drivers do at different roadway types and traffic conditions?	Possibility of machine vision processing to assess clear zone width and animal presence. Location of animal crossing warning signs.
3	How frequently do drivers leave their lane and when they do, how far into the shoulder do they stray? This research could be conducted in urban areas with existing surveillance cameras but there is a greater need for rural road data. The encroachment rate is the main topic of interest; the other crash and encroachment characteristics are of secondary interest for the RDG.	Machine vision processing of forward view to identify lane departure events Number of trips by that person through that segment Traffic volume data

Table 12. SHRP2 Data Research Ideas to Benefit the Highway Safety Manual

#	Description	Data Needs
4	What effect do rumble strips have on driver lane departure and recovery behavior? There are CMFs for rumble strips, but they have not been separated by installation type (grooved, raised), width, or how far offset from edgeline. FHWA is currently working with a contractor to develop machine vision techniques to estimate rumble strip width. This topic could also support efforts in the RDG to promote countermeasures to keep vehicles on the road.	Detailed information on rumble strip type, possibly obtained from machine vision.
5	Confirmation of SPFs with speed as a variable by using SHRP2 data as the before condition and using some newer data sources like Inrix or Streetlight to assess the after condition.	Good records of countermeasure installations Sufficient number of sites Analysis of normal driving data meeting required conditions
6	Confirmation of CMFs related to Access Management such as number of driveways or presence of signals at intersections. Getting signal installation (whether or not an intersection has a signal or not) is not easy, and not often available. If RID had that, it would be helpful.	Driveway location information Signalization information
7	Does the presence of edgelines have an effect on driver behavior during the day or night or both? Do different widths of edgelines have different effects?	Speed Lane Keeping Edgeline presence (and width if available)
8	What is the effect of design consistency on roadway departure crashes? FHWA Office of Safety is currently sponsoring a project for rural two-lane roads that makes use of the RID superelevation and Lidar data. Similar studies could be done for other roadway classes.	Superelevation Cross-section Speed Lane Keeping
9	Could microscopic predictive crash modeling be developed based on distributions of values of driver behavior of gap acceptance, speed, and turning movements? These data could then be calibrated to crash rates, (especially at intersections). This is predictive modeling based on normal driving behavior. A similar project that is currently underway uses NDS data to obtain typical headway information for microscopic traffic simulation input. Users of these modeling packages often tweak various values of driver behavior in order to get modeled speed based to match observed. This project will define a range of reasonable values of headway beyond which should not be used in order to fit models.	Kinematic data from normal driving behavior, large volume of this type of data so as to develop distributions Roadway geometric information

Table 13. SHRP2 Data Research Ideas to Benefit the Green Book

#	Description	Data Needs
10	How does driver behavior change when approaching uncontrolled intersections? Current values in the Green Book are based on research more than 40 years old. Vehicle handling has changed so much since that time. Would be easy in SHRP2 to pull out approach speeds at uncontrolled and yield-controlled intersections.	Intersection type and location data Speed profiles from normal driving Forward video to determine presence of other vehicles, pedestrians, bicyclists.
11	What effect does enforcement and/or a speed feedback sign have on driver behavior? This research could also look at roadway conditions (traffic, weather) if those data were available.	STEP Enforcement records Location and activation state of dynamic speed feedback signs. This may require forward video review Speed on traces from those locations
12	What are the safety effects of freeway ramp spacing? The current ramp spacing in Ch. 10 of Green Book. Figure 10-68 is drawn from a 1970 ASCE presentation on state of the practice. These require a minimum of one-mile spacing and it has been observed that this design exception influenced some decisions about not allowing a needed, new ramp. The IAP projects on freeway interchanges conducted by VHB was very limited and didn't address this.	Variety of freeway ramp spacings Lane change Speed Traffic Volumes by time of day
13	Are the current values for superelevation in the Green Book still applicable? The superelevation values are based on older vehicles and older paving methods, SHRP2 could be used to update this.	Speed Lane Keeping Superelevation Curve Radius
14	Confirmation of acceleration and deceleration profiles currently in the Green Book. These values are based on very old research. SHRP2 provides a newer vehicle fleet than what is currently represented in the Green Book.	Kinematic data from normal driving Roadway class and cross-section information

Table 14. SHRP2 Data Research Ideas to Benefit Low Volume Roads

#	Description	Data Needs
15	Do local drivers familiar with a particular road drive differently than those driving that road for the first time? Unfamiliar drivers may traverse curves too fast while familiar drivers may ignore stop signs or railroad crossings.	Trip traces tied to individual vehicles and information on repeat trips Speed would be main performance measure
16	What effect do weather and other seasonal variations, such as agricultural activity, have on driver behavior? Safety concerns such as passing of farm equipment and yielding at driveways could be identified.	Weather data Agricultural land use data Forward video to identify farm equipment and trucks present

Table 15. SHRP2 Data Research Ideas to Benefit Bicycle Applications

#	Description	Data Needs
17	What bicycle volume (or pedestrian) justifies the expenditure of money for specific facilities. If you know that a new facility has been put in since 2013, you could collect data now and then go back to SHRP2 video to see behavior and volume before.	Bike volume estimates Identifying facilities installed since 2013 that were included in the SHRP2 driving catchment area and obtaining new "after" data from these sites
18	Driver behavior in presence of bicyclists. Passing and speed as function of road type, cross-section	Presence of bicyclists coded in NDS; possibly through machine vision

Table 16. SHRP2 Data Research Ideas to Benefit Pedestrian Guide Development

#	Description	Data Needs
19	How does Pedestrian Crossing treatment type affect driver yielding behavior? Because pedestrian crossings are relatively rare and random events, it is often difficult to obtain enough data to assess performance of treatments. Sometimes pedestrian crossings are staged to measure driver reaction.	Location of crosswalks and crossing-related traffic control devices Kinematic data Forward video to confirm pedestrian presence or not
20	How does roadway context affect pedestrian activity and subsequent speed limit setting?	Land use data integrated with RID through geo-data Pedestrian activity coded

Table 17. SHRP2 Data Research Ideas to Benefit Roadway Lighting Decisions

#	Description	Data Needs
21	How does normal driving differ between day and night? The basic question of how drivers adjust their speed selection and lane-keeping for nighttime conditions is still not well understood or documented. Reactions to oncoming vehicle headlamp glare could also be assessed in a study like this.	Time of day Normal driving kinematic data Repeated trip traces through same segment day and night Headlight status Presence of oncoming vehicle
22	How does roadway lighting affect driving behavior? A Phase 1 IAP project used SHRP2 data to look at the vehicle trajectory and speed that preceded crashes at night on lighted and unlighted highways. Attempts to review driver face video for glance location were challenging and only a few crashes met the criteria for the study. A more basic question about the effect of roadway lighting, especially on speed selection, still lingers.	Roadway Lighting presence and type Speed Roadway geometric Presence of other vehicles

CHAPTER 5. RESEARCH PROBLEM STATEMENTS AND CONCLUSIONS

Chapter 5 includes seven fully developed individual research problem statements that will be suitable for scoping future research using the SHRP2 data source. These topics are recommended as the first tier in developing an expanded set of research questions that can benefit from the SHRP2 data use. This information is largely based on the research ideas summarized in Chapter 4 as well as additional research ideas suggested by the project panel during the meeting scheduled for October 15. 2020

Chapter 5 then concludes with summary comments and next step recommendations.

Research Problem Statements

In cooperation with the project panel, the research team prioritized the list of potential projects based on importance, feasibility of success, and possibility of results being included in the next revision of the related technical document. Table 18 summarizes the key full Research Problem Statements as developed by the research team for each of these topics.

Table 18. Summary of Developed Research Problem Statements

Problem Statement Number	Document	Question Number*	Research Problem Statement Title
1	AASHTO Green Book	14	Updated Acceleration and Deceleration Rates for Geometric Design
2	AASHTO RDG	3	Encroachment Data for Roadside Design Guide
3	AASHTO HSM	5	Incorporating Motor Vehicle Speed into Safety Performance Functions
4	Lighting	21	Driver Behavior in Daytime and Nighttime Conditions
5	AASHTO Green Book	10	Evaluation of Driver Behavior on Approaches to Uncontrolled and Yield-Controlled Intersections
6	AASHTO Green Book	13	Assessment of Common Superelevation Rates Applied to Modern Motor Vehicles and Road Surfaces
7	AASHTO HSM	6	Influence of Driveway and Intersection Density on Access Management Safety – Development of CMFs
* Questions are included in Chapter 4 tables.			

Problem Statement #1 -- Updated Acceleration and Deceleration Rates for Geometric Design

Background

Acceleration and deceleration rates of vehicles are often critical parameters in determining highway design. Acceleration and deceleration rates often govern the dimensions of design features such as intersections, freeway ramps, climbing or passing lanes, and turnout bays for buses. The various acceleration and deceleration rates incorporated in the Green Book are primarily based on older research and may be outdated. There have been significant changes in the vehicle fleet since the time when the design rates were developed. Vehicle performance capabilities have changed due to new and improved technology and modern tire design. Changes in road wearing surfaces, pavement friction treatments, and potential changes in driver comfort levels could also have impacted acceleration and deceleration rates. As a result, roadways may not be designed as effectively to match current vehicle performance capabilities and driver expectations.

This research will look at the acceleration and deceleration rates used in design criteria and bring them up to date, in order to ensure that roadways are constructed as efficiently as possible. The research findings could be incorporated into the AASHTO *Green Book* and subsequently used in design by roadway engineers.

Literature Search Summary

Several sources of acceleration and deceleration rates are used in design criteria within the Green Book. Green Book Figure 2-33 presents acceleration characteristics of passenger cars for level terrain conditions. These speed versus distance curves are based on research presented in NCHRP Report 270 and published in 1984. NCHRP Report 270, in turn, is based on data in ITE's *Transportation and Traffic Engineering Handbook (1982)*, and this information is based on data collected in conjunction with NCHRP Report 111 in 1971 using a chase-car, equipped with an accelerometer where the researchers endeavored to match the speed change of a sample of other cars in traffic. With the limited available information, Olson et al. developed speed versus distance curves for a hypothetical design-car based to a large extent on dated data, limited research, and a lot of conjecture. The source of Green Book Figure 2-34 (Deceleration Distances for Passenger Vehicles Approaching Intersections) is unclear. Green Book Figures 2-33 and 2-34 can be used in the design of features such as intersections, freeway ramps, and climbing or passing lanes.

The deceleration rate used to calculate stopping sight distance (11.2 ft/s^2) is based upon research documented in NCHRP Report 400. This deceleration rate is based on data collected from 45 drivers and 3,000 braking maneuvers collected under closed-course and open-roadway conditions and represents a comfortable deceleration rate for most drivers.

Design acceleration and deceleration rates directly influence the speed-change length of interchange ramps. Most of the design rates used to develop Green Book Tables 10-4 (Minimum Acceleration Lane Lengths for Entrance Terminals with Flat Grades of Less Than 3 Percent) and 10-6 (Minimum Deceleration Lane Lengths for Exit Terminals with Flat Grades of Less Than 3 Percent) are based on studies published in the 1930s and early 1940s (Wilson, 1940; Loutzenheiser, 1938; Bealey, 1938). While the sources for these acceleration and deceleration rates are from older studies, similar studies have been performed more recently. A comparison of acceleration rates shows maximum rates of the later-model vehicles to be substantially greater than those of vehicles from the 1930s and 1940s and this observation led Hunter and Machemehl (1997) to state, "A comparison of these normal acceleration rates with those from the 1938 study leads to the conclusion that an increase in "comfortable" acceleration rates has occurred." In a more recent study on the design of freeway mainline ramp terminals, Torbic et al. (2012) found that the median acceleration rates for free-flow passenger cars under free-merge conditions are greater than the assumed acceleration rates in the 2004 Green Book and diverging vehicles decelerate at rates lower than those assumed in the 2004 Green Book. Wood and Zhang (2017) recently evaluated perception-reaction times and deceleration rates for determining stopping sight distance using SHRP2 NDS data, and Lindheimer et al. (2018) also used SHRP2 NDS data to explore deceleration rates in urban corridors.

Clearly, there exists some uncertainty about the actual acceleration and deceleration rates that would be best suited for design.

References:

Bealey, J. *Acceleration and Deceleration Characteristics of Private Passenger Vehicles*, Highway Research Board Proceedings, 1938.

Claffey, P.J. *Running Costs of Motor Vehicles as Affected by Road Design and Traffic*, NCHRP Report 111, Highway Research Board, 1971.

Fambro, D.B., K. Fitzpatrick, and R.J. Koppa. *Determination of Stopping Sight Distance*, NCHRP Report 400, Transportation Research Board, 1997.

Hunter, M., and R. Machemehl. *Reevaluation of Ramp Design Speed Criteria: Review of Practice and Data Collection Plan*, Report No. FHWA/TX-98/1732-1, Texas Department of Transportation, 1997.

Lindheimer, T., R. Avelar, M. Dastgiri, M. Brewer, and K. Dixon. *Exploratory Analysis of Deceleration Rates in Urban Corridors Using SHRP2 Data.* Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC., 2018.

Long, G. *Acceleration Characteristics of Starting Vehicles*. TRB 79th Annual Meeting Paper 00-0980, 2000.

Loutzenheiser, D.W. *Speed-Change Rates of Passenger Vehicles*, Highway Research Board, 1938.

Olson, P.L., D.E. Cleveland, P.S. Fancher, L.P. Kostyniuk, and L.W. Schneider. *Parameters Affecting Stopping Sight Distance*, NCHRP Report 270, Transportation Research Board, 1984.

Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, D.W. Harwood, D.K. Gilmore, M.M. Knoshaug, J.J. Ronchetto, M.A. Brewer, K. Fitzpatrick, S.T. Chrysler, and J. Stanley. *Design Guidance for Freeway Mainline Ramp Terminals*, NCHRP Report 730, Transportation Research Board, 2012.

Wilson, E.E. *Deceleration Distances of High-Speed Vehicles*, Highway Research Board Proceedings, 1940.

Wood, J., and S. Zhang. *Evaluating relationships between perception-reaction times, emergency deceleration rates, and crash outcomes using naturalistic driving data* (Report No. MPC 17-338). Washington, DC: Mountain-Plains Consortium University Transportation Center, 2017.

Research Objective
The objective of this research is to determine appropriate acceleration and deceleration rates to be used in design. Acceleration and deceleration rates incorporated in the Green Book should be based on the performance capabilities of a more current vehicle fleet.

Major task or activities that likely have to be performed to successfully conduct this research include:

- Completion of a comprehensive literature review. This effort should include a review of the sources of acceleration and deceleration rate design values, research on vehicle fleet composition, performance of the vehicle, advanced technologies and their presence in the vehicle, percentage of vehicles with the advanced technologies (i.e., anti-lock brakes and other performance/safety innovations related to braking and accelerating), tire / pavement friction based on current tires in production and typical pavement surface parameters.
- Assessment of current acceleration and deceleration rates used for design.
- Assessment of vehicle fleet and design parameters for determining design acceleration and deceleration rates.
- Identification of potential sources of speed, distance, and acceleration data (e.g., SHRP2 naturalistic driving study data, crowd-sourced data from mobile apps, connected vehicle data from automobile manufacturers or data re-sellers) that could be used to develop acceleration and deceleration rates and profiles for the current fleet of vehicles.
- Development of a work plan to update acceleration and deceleration rates to be used in design based on the current fleet of vehicles.
- Composition of recommended text and updated acceleration and deceleration rates/profiles for the next edition of the AASHTO Green Book.

Urgency and Potential Benefits
The design of roadways to effectively match current vehicle performance capabilities and driver expectations may improve the performance of the roadways and reduce construction costs. For example, it may be possible to design shorter interchange ramps. Sight distance requirements would potentially decrease.

Implementation Considerations and Supporters
AASHTO could incorporate the results of this research into future editions of the Green Book, and as appropriate State DOTs could incorporate the research results into their respective design manuals.

The AASHTO Committee that might be interested in the research results and could help support implementation:

- Committee on Design

Recommended Research Funding and Research Period

Research Funding: $750,000
Research Period: 24 months

Problem Statement #2 -- Encroachment Data for Roadside Design Guide

Background

Roadway departure (RwD) crashes represent critical safety concerns. According to the Fatality Analysis Reporting System (FARS), 51 percent of fatal crashes from 2016 to 2018 were attributed to RwD crashes. RwD crashes may occur as the driver leaves the lane or encroaches on the roadside environment. Roadway encroachment is the travel of a vehicle on roadway areas outside the limits of the designated lane(s) of travel and can be affected by numerous factors, such as speed limit, various roadway (e.g., horizontal and vertical alignment, lane/shoulder width) and roadside characteristics (e.g., side slope, access point density), weather and lighting conditions, and driver behavior (e.g., steering, braking).

Roadside encroachment data are critical for updating various guidelines and publications used in roadside design management practices including:

- American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH),
- AASHTO Roadside Design Guide (RDG),
- The Manual of Uniform Traffic Control Devices (MUTCD), and
- The TRB Human Factors Guide.

These guidelines have been using the encroachment data collected from two classic studies: 1) Hutchinson and Kennedy (1962); and 2) Cooper (1980). However, these studies are very old and do not represent a wide range of modern roadway and roadside characteristics. There is also limited knowledge as to how the roadway design elements may impact the encroachment conditions. Currently, two NCHRP projects are underway for developing an encroachment database. However, these studies are using crash data and can be expected to underestimate the actual number of encroachments. Most encroachments do not result in a crash as drivers are able to correct their vehicle’s path and redirect the vehicle to the travel lane. Moreover, police-reported crashes have other limitations in that the data does not provide enough information about the driver's behavior, speed choice, and vehicle trajectory prior to the crash. This project will use the SHRP 2 Naturalistic Driving Study (NDS) data to develop the encroachment data to be used for updating the publications listed noted above.

Literature Search Summary

In the existing NDS literature, a few studies have attempted to evaluate lane departure by analyzing the time series (i.e., vehicle kinematics) and video data. Most of these studies have tried to evaluate the impacts of horizontal curvature and adverse weather conditions on drivers’ lane-keeping behavior.

Hallmark et al. (2015) evaluated driving behavior in terms of speed and encroachment on rural two-lane curves based on various factors. Right side encroachments increase as drivers spend less time glancing at the forward roadway. Right side lane departures are (6.8 times) more likely within the boundaries (inside) of a horizontal curve and when advisory signs may be present. Left side encroachments are four times more likely when drivers are male. For drivers inside of a curve, the left side encroachment is 0.1 times less likely than drivers outside.

In 2015, Oneyear explored how drivers interacted with the roadway environment on a horizontal curve (both inside and outside the curve) by developing a model which helped to identify zones where drivers were more likely to make lane departures. Drivers who glanced down from the roadway showed a shift away from the centerline of the lane towards the inside of the curve. While traversing on an inside lane, the driver who looked down at a point within the curve shifted away from the center by about 0.30 meters to the right. After passing the center of the curve, drivers on the inside of a curve tended to move further to the right, while drivers traversing outside of a curve were at the furthest from the centerline at the center of the curve. The researcher observed that wider paved shoulders were correlated with a shift towards the outside of the lane outside of a curve.

Several studies have demonstrated that extracting lane position data is possible from the SHRP2 database. Das et al. (2018) investigated driver lane-keeping behavior in clear and foggy weather conditions by developing a lane-keeping model using ordered logistic regression. Ghasemzadeh and Ahmed (2018) modeled lane-keeping behavior under heavy rain conditions using logistic regression. Heavy rain conditions decrease lane-keeping ability significantly, and drivers showed 3.8 times higher standard deviation of lane position under these conditions.

References:

Das, S., A. Ghasemzadeh, and M. Ahmed. *A comprehensive analysis of driver lane-keeping performance in fog weather conditions using the SHRP 2 naturalistic driving study data*. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC., 2018.

Ghasemzadeh, A., and M. Ahmed. *Utilizing naturalistic driving data for in-depth analysis of driver lane-keeping behavior in rain: Non-parametric MARS and parametric logistic regression modeling approaches.* Transportation Research Part C: Emerging Technologies, Vol. 90, 2018, pp. 379-392.

Hallmark, S. L., S. Tyner, N. Oneyear, C. Carney, and D. McGehee. *Evaluation of driving behavior on rural two-lane curves using the SHRP 2 naturalistic driving study data.* Journal of safety research, Vol. 54, 2015.

Oneyear, N. *Development of rural curve driving models using lateral placement and prediction of lane departures using the SHRP 2 naturalistic driving data*. (Doctoral dissertation), Iowa State University, Ames, IA., 2015.

Research Objective

The objective of this research is to document lane encroachment frequency from the NDS data for future use in development of AASHTO publications such as MASH and the Roadside Design Guide.

Major task or activities that likely need to be performed to successfully conduct this research include:

- Conduct a literature review of existing studies on encroachment data and roadway departure crashes. The review of studies will develop a comprehensive list of data elements that were found to impact vehicle encroachment, roadway departure crash counts, and crash severities.
- Develop a Data Needs and Data Collection Plan. This will include a review of relevant AASHTO publications to identify the data needs for updating these publications.

- Develop a Database and Data Analysis Work Plan. The research team will collect the list of relevant data elements from NDS (e.g., speed time series, vehicle trajectory, driver behavior, etc.) and other supplementary data sources, such as police crash reports, roadway and roadside design, traffic speed and volume, land use, etc. Team members will then develop the data analysis work plan for evaluating the impact of roadway and roadside design elements as well as driver behavior on vehicle encroachment.
- Develop and Submit Interim Report including the findings of Phase I Tasks.
- Conduct the approved Work Plan.
- Develop and Submit the Final Deliverables reporting the findings of the research conducted in the project. The final deliverable will also include the guidelines about how the findings of this research will be used for updating the AASHTO guidelines.

Urgency and Potential Benefits
This research will have benefits for updating the AASHTO publications as well as related software tools that use encroachment frequency as a parameter to determine roadside design features. The results of this research will provide safety and traffic engineers with better data for improving roadside design and for reducing the RwD crashes that account for 51 percent of total fatalities.

Implementation Considerations and Supporters
The authors of new editions of MASH, the AAHSTO Roadside Design Guide, and related software products and tools will facilitate this research. The findings of this project will be implemented by the state DOTs concerned with roadside safety.

Recommended Research Funding and Research Period
<u>Research Funding</u>: $600,000
<u>Research Period</u>: 30 months

Problem Statement #3 -- Incorporating Motor Vehicle Speed into Safety Performance Functions

Background

Safety performance functions (SPFs) are statistical equations used to predict the number of crashes for a specific type of roadway facility. The development of SPFs are currently based on crash data, vehicle exposure information, and roadway inventory characteristics. The Highway Safety Manual (HSM) incorporates SPFs into crash prediction procedures that agencies can use and calibrate to predict the safety performance of roadways and intersections within their jurisdiction. One of the limitations of the first edition of the HSM and SPFs in general is that they do not consider motor vehicle speed. Speed is generally understood to be an important factor in roadway safety performance. The severity of a crash is particularly sensitive to motor vehicle speeds, and the probability of a crash is likely affected by speed, although this relationship is not well understood. Despite the importance of speed on safety, SPFs generally do not incorporate speed as a predictor. Currently, there is research being conducted to explore this issue and develop a predictive methodology for rural two-lane, two-way highways that incorporates speed measures (or surrogates for speed measures) for potential use in the HSM (see NCHRP Project 17-92). The data selected for that research is based on crowd source speed data. Research is needed to confirm and validate SPFs that incorporate speed as a predictor variable to better understand the relationship between speed, crash frequency, and crash severity and/or develop SPFs that incorporate speed for additional facility types.

Literature Search Summary

Das et al. (2020) examined prevailing operating speeds on a large scale to determine how traffic speeds and different speed measures interact with roadway characteristics and weather condition to influence the likelihood of crashes. Das et al. used three datasets from Washington and Ohio in this study: 1) Highway Safety Information System, 2) the National Performance Management Research Dataset, and 3) National Oceanic and Atmospheric Administration weather data. The research results show that certain speed measures were found to be beneficial in quantifying safety risk. Annual-level crash prediction models show that increased variability in hourly operating speed within a day and an increase in monthly operating speeds within a year are both associated with a higher number of crashes.

Wali et al. (2018) developed several SPFs for two-way, two-lane roads using data from Tennessee. The best-fit model included annual average daily traffic (AADT), segment length, shoulder width, lane width, speed limit, and the presence of passing lanes.

Dixon et al. (2016) developed SPFs for signalized intersections in Oregon. Three SPFs were developed: 1) an SPF for total crashes, which relies on both major and minor AADTs to predict the expected number of crashes; 2) an SPF for KAB crashes, whose predictions derive from both AADTs as well as from the speed limit on the major road; and (3) a severity model to predict the proportion of KAB crashes to be used in combination with the SPF for total crashes. The analyses determined that the speed limit variable significantly improved the quality of the SPFs and severity model, and as expected, suggests increasing severity with speed differentials.

Torbic et al. (2020) develop new intersection crash predictive models for consideration in the second edition of the HSM. SPFs were developed for seven general intersection configurations and traffic control types including intersections on high-speed urban and suburban arterials (i.e., roadways with speed limits greater than or equal to 50 mph). Comparisons of the new crash prediction models for intersections on high-speed urban and suburban arterials to corresponding models in HSM Chapter 12 indicate slightly higher predicted crash frequencies at intersections on higher speed roadways than on lower speed roadways for the same traffic conditions. This seems reasonable as higher speeds will require quicker reaction times to avoid potential conflicts. Torbic et al. also stated that it is not surprising that more multiple-vehicle FI crashes are predicted on high-speed urban and suburban arterials compared to the predictions for lower speed urban and suburban arterials, given the correlation between vehicle speed and crash severity.

References:

Das, S., S.R. Geedipally, and K. Fitzpatrick. *Inclusion of Speed and Weather Measures in Safety Performance Functions for Rural Roads*, International Association of Traffic and Safety Sciences Research, 2020.

Dixon, K.K., R. Avelar, and C. Monsere. *Oregon Signalized Intersection Safety Performance Functions and the Effect of Speed*, TRB 95th Annual Meeting Compendium of Papers, Transportation Research Board, 2016.

Torbic, D.J., D.J. Cook, K.M. Bauer, J.R. Grotheer, D.W. Harwood, I.B. Potts, R.J. Porter, J.P. Gooch, K. Kersavage, J. Medina, and J. Taylor. *Intersection Crash Prediction Methods for the Highway Safety Manual*, Final Report for NCHRP Project 17-68, Transportation Research Board, 2020.

Wali, B., A.J. Khattak, J. Waters, D. Chimba, and X. Li. *Development of Safety Performance Functions: Incorporating Unobserved Heterogeneity and Functional Form Analysis*, TRR 2672, Transportation Research Board, 2018.

Research Objective

This objective of this research is to confirm and validate SPFs that incorporate speed as a predictor variable to better understand the relationship between speed, crash frequency, and crash severity and/or develop new SPFs that incorporate speed for other facility types which do not have SPFs that address speed.

Major task or activities that likely need to be performed to successfully conduct this research include:

- Completion of a comprehensive literature review. This review should include a review of the previous research that developed SPFs that incorporated and/or included speed measures such as NCHRP Project 17-92.
- Identify potential sources of data that could be used to develop SPFs that incorporate speed or speed measures (e.g., SHRP2 naturalistic driving study data, Inrix, Streetlight, etc.).
- Assess the need to confirm the validity and/or validate existing SPFs that incorporate speed measures compared to developing SPFs that incorporate speed for other facility types which do not have SPFs that address speed.
- Develop a work plan to validate existing SPFs that incorporate speed or develop new SPFs that incorporate speed for additional facility types.
- Propose recommended text for a future edition of the AASHTO HSM.

Urgency and Potential Benefits
One of the notable limitations of the first edition of the HSM is that none of the SPFs in the predictive methods incorporate speed. This is simply due to the current state of knowledge regarding the relationship between relationship between speed, crash frequency, and crash severity. By validating existing SPFs that address speed or by developing new SPFs that incorporate speed for a range of facility types, this research could improve the credibility of future editions of the HSM.

Implementation Considerations and Supporters
AASHTO could incorporate the results of this research into future editions of the HSM, and State and local highway agencies could incorporate the research results into their practices to improve the safety performance of roadways within their jurisdiction.

AASHTO Committee that might be interested in the research results and could help support implementation:

- Committee on Safety

Recommended Research Funding and Research Period
<u>Research Funding</u>: $750,000
<u>Research Period</u>: 30 months

Problem Statement #4 -- Driver Behavior in Daytime and Nighttime Conditions

Background

The basic question of how drivers adjust their speed selection and lane-keeping for nighttime conditions is still not well understood or documented. Naturalistic driving data from SHRP2 provides an opportunity to identify basic differences in driving behavior and specifically speed selection and lane keeping.

Crash risk is higher at nighttime compared to other times of day and injury severity is also higher for crashes that occur at night. While drowsiness and impaired driving certainly contribute to this, the limited visibility imposed by nighttime conditions limits drivers' ability to react properly to changes in alignment and roadway hazards. In addition, pedestrian fatalities are most frequent in dark conditions. Bicyclists, as well, are at highest risk between 6:00 and 9:00 PM regardless of season of the year, placing them in dark or twilight conditions.

Transportation agencies may be able to improve nighttime safety through interventions such as roadway lighting, improved retroreflectivity of signs and pavement markings, and geometric design consistency. Understanding driver speed selection and lane-keeping will identify typical driver errors that can lead to nighttime crashes. Using this understanding, appropriate countermeasures can be selected which specifically target these driver errors.

The AASHTO Roadway Lighting Design Guide helps practitioners decide whether or not to install lighting based on factors such as traffic volume, crash history, and proportion of day-to-night crashes. Though this guidance document was most recently published in 2018, the substantive guidance included in the document has not really changed in 20 to 30 years, yet roadway lighting is changing rapidly toward solid-state LED light sources. This research is aligned with the goals of the AASHTO Safety committee. The majority of state Strategic Highway Safety Plans contain some goals related to improving nighttime safety.

Literature Search Summary

Past research into nighttime driving has focused on crash statistical analysis, a routine reporting element for NHTSA and other agencies. Stamatiadis et al. (2018) examined nighttime fatal crashes in the United States and found a relationship between curve radius and crash frequency. In addition, Stamatiadis et al. (2018) demonstrated that design consistency across successive curves resulted in fewer crashes. Chen and Fanny (2019) Showed that left turn crashes at night were particularly problematic, likely due to the difficulty drivers have in estimating the speed of oncoming vehicles in dark conditions. Roadway departure crashes are also more frequent at night. McLaughlin et al. (2009) reviewed crashes in the 100-car naturalistic study and found roadway departure and 2.5 times more likely in nighttime compared to daytime conditions.

Another lighting-related topic in the literature has looked at roadway lighting for segments, intersections, and interchanges. Recent advances in LED lighting systems have prompted some newer studies examining changes in safety due to this new technology. Several of these recent studies have used SHRP2 naturalistic driving data to look at driving behavior in lit and unlit roadway areas (Li, et al. 2015; Li, et al. 2017). The results of these projects may enable transportation agencies to lower light levels on demand at certain locations based on functional class, traffic volume, and pedestrian volume. For example, if the road use characteristics change at 1:00 AM, they could justify that now that road is functioning as a minor arterial and you could dim the lights and still be within the warrant (i.e. it is a major arterial 6:00 AM-10:00 PM so meets warrant for lighting, but from 10:00 PM – 6:00 AM volume drops so now it is a minor arterial and does not need lights).

SHRP2 data have also been used to look at driver response to glare from oncoming headlights (Bullough, 2018). These studies demonstrate the value of SHRP2 data but were limited in their sample size. In addition, only a small subset of roadway types or geographic regions were used in these studies. A larger study such as the one proposed here could extend these methods to a better understanding of nighttime driving at non-freeway settings.

References:

Bullough, J. D. *Influence of Oncoming Light Exposure on Safety Outcomes in a Naturalistic Driving Study* (No. 2018-01-1039). SAE Technical Paper, 2018.

Chen, H., and K. Fanny. *Understanding the contributing factors to nighttime crashes at freeway mainline segments.* Journal of Transportation Technologies, Vol. 9(4), 2019, 450-461.

Li, Y., R. Gibbons, A. Medina, R. Bhagavathula, J. Milton, and I. van Schalkwyk, *Correlation between Roadway Lighting and Driver Behavior at Freeway Interchanges Based on Naturalistic Driving Data*. Paper presented at 96th Annual Transportation Research Board Meeting (No. 17-03849), 2017.

Li, Y., R. Gibbons, and A. Medina. *Integrating Adaptive Lighting Database with SHRP 2 Naturalistic Driving Study Data.* Transportation Research Record: Journal of the Transportation Research Board, Vol. 2526(1), 2015, pp. 1-9.

McLaughlin, S. B., J.M. Hankey, S.G. Klauer, and T.A. Dingus. *Contributing factors to run-off-road crashes and near-crashes.* NHTSA Report 811079, US Department of Transportation, 2009.

Stamatiadis, N., B. Psarianos, K. Apostoleris, and P. Taliouras. *The need for nighttime design consistency evaluation: an exploratory study*. Advances in Transportation Studies, Vol. 46, 2018.

Research Objective

The objective of this research is to document driver speed choice and lane keeping in day and night conditions. The outcomes could be used to justify roadway lighting installation and operation that encourages safe driving behavior. The results could also be used by roadway designers to examine design consistency factors in horizontal curves and intersection design.

The research will examine all roadway types, segments, and intersections. SHRP2 Roadway Information Database (RID) data of roadway lighting and geometric design features will be used to identify a set of locations to examine. The kinematic data acquired from the vehicle concerning speed and acceleration will be one dependent variable. Data from the lane tracking system will be used to measure lane position. It is not anticipated that viewing driver face video will be required for this research.

The results of the research should illustrate patterns of driving performance by day and night. These speed values can then be used for sight distance calculations based on time of day if desired. The results should also be presented to allow comparison of driving on lit and unlit roadway sections.

Urgency and Potential Benefits
Crashes are overrepresented at night considering the lower traffic volume, this is a problem nationwide. Safety behavioral issues such as drowsiness and impairment certainly affect these crashes, but it is unknown what engineering countermeasures could also be applied. This research will expose any unknown trends in speed and lane keeping at day and night that may otherwise be overlooked through traditional data collection methods such as daytime observation and spot speed measurements. The changes in lighting and roadway design that could result from this research should improve nighttime safety.

Implementation Considerations and Supporters
The department responsible for identifying needs, constructing, and maintain streetlights may differ by agency. The design division of a state DOT, for example, could implement any changes to design consistency for horizontal curves that may recommended by the research. For roadway lighting, the traffic engineering or other appropriate department, may change their state's illumination manual, specifications, and standards for intersection and segment lighting. Enforcement practices for speeding may also change as a result of this research.

Recommended Research Funding and Research Period
Studies using the SHRP2 Data can be resource intensive because of the size of the dataset and fees associated with providing the data. The time required will include an initial search of the RID for appropriate locations, an initial data request to assess feasibility and identify key variables, and a second data request for a larger sample based on the initial analysis.

Recommended Research Funding and Research Period

Research Funding: $700,000
Research Period: 30 months

Others Supporting the Problem Statement
The National Committee on Uniform Traffic Control Devices Pedestrian Task Force has also been discussing the need for research concerning modern headlights, glare, and pedestrian detection. Egan Foster (efoster@dublin.oh.us), chair.

Problem Statement #5 -- Evaluation of Driver Behavior on Approaches to Uncontrolled and Yield-Controlled Intersections

Background

Each intersection has the potential for several different types of vehicle conflicts. The possibility of these conflicts actually occurring can be reduced through the proper design of intersections, such as the provision of sufficient sight distances and appropriate traffic controls. Determining design values for appropriate sight distances near intersections requires different assumptions related to approach speeds, perception-reaction time, and braking.

At intersections with no control, intersection sight distance values are based on the assumption that approaching vehicles typically slow to approximately 50 percent of their midblock running speed. Similarly, at yield-controlled intersections, intersection sight distance values are based on the assumption that minor-road vehicles that do not stop are assumed to decelerate to 60 percent of the minor-road midblock running speed. These assumptions are based on field observations collected in the 1990s (Harwood et al., 1996).

Driver behaviors may have changed over the past 25 years especially with improvements in vehicle technologies and braking systems. Thus, these assumptions for uncontrolled and yield controlled intersections may no longer be valid. Therefore, research is necessary to determine if driver behavior has changed over the years when approaching uncontrolled and yield-controlled intersections.

Literature Search Summary

Harwood et al. (1996) conducted research to evaluate driver needs for sight distance on approaches to at-grade intersections and to recommend appropriate revisions to current geometric design policies for intersection sight distance. Field studies were conducted at 25 intersections to observe driver behaviors. Harwood et al. found that drivers on approaches to uncontrolled intersections on urban and suburban residential streets typically slow to about 50 percent of their midblock running speed, even if no potential conflicting vehicles are present on an intersection approach. Similar driver behavior was observed on yield-controlled approaches, expect drivers typically slowed to 60 percent of the midblock running speeds.

References:

Harwood, D.W., J.M. Mason, R.E. Brydia, M.T. Pietrucha, and G.L. Gittings, *Intersection Sight Distance*, NCHRP Report 383, Transportation Research Board, 1996.

Research Objective

The objective of this research is to determine if driver behavior has changed over the past 25 years. In particular, this effort would determine how drivers react when approaching uncontrolled and yield-controlled intersections and to assess whether changes to intersection sight distance values are recommended.

Major tasks or activities that likely need to be performed to successfully conduct this research include:

- Complete a comprehensive literature review. This review should include a review of the AASHTOs current policy on intersection sight distance for uncontrolled and yield-controlled intersections and studies related to driver behaviors on approaches to uncontrolled and yield-controlled intersections.

- Identify potential sources of data that could be used to assess driver behaviors on approaches to uncontrolled and yield-controlled intersections (e.g., SHRP2 naturalistic driving study data).
- Develop a work plan to evaluate driver behaviors on approaches to uncontrolled and yield-controlled intersections.
- As appropriate, propose recommendations to intersection sight distance guidance for uncontrolled and yield-controlled intersections for a future edition of the AASHTO Green Book

Urgency and Potential Benefits
The design of uncontrolled and yield-controlled intersections to more effectively match current driver behaviors and expectations can be expected to improve the operational and safety performance of these intersection types. For example, intersection sight distance requirements may potentially be updated to more effectively match current driver behaviors.

Implementation Considerations and Supporters
AASHTO could incorporate the results of this research into future editions of the Green Book, and as appropriate State DOTs could incorporate the research results into their respective design manuals.

The AASHTO Committee that might be interested in the research results and could help support implementation:

- Committee on Design

Recommended Research Funding and Research Period

Research Funding: $600,000
Research Period: 24 months

Problem Statement #6 -- Assessment of Common Superelevation Rates Applied to Modern Motor Vehicles and Road Surfaces

Background

The application of superelevation for roadway cross-sections at horizontal curve locations is based on a variety of factors. Fundamentally, the procedure utilizes basic vehicle physics and the factors required to counteract centripetal acceleration so that the vehicle can safely stay on the roadway as it transitions at horizontal curve locations. For practical applications, however, several factors have been adjusted to help overcome implementation challenges. For example, a maximum superelevation rate value has historically been established that may be higher at coastal regions with level terrain (where the cross slope enhances road drainage) and flatter at higher elevation regions (where the presence of ice or snow may contribute to the vehicle sliding sideways). Other factors that are considered when establishing superelevation rates include the degree of curvature (or radius), design speed, and pavement friction. The transition to and from the horizontal curvature is also dictated by the rate of change and number of travel lanes. The basic superelevation rates and transition methods remain largely unchanged since their widespread publication in the AASHO document titled *A Policy on Geometric Design of Rural Highways* (1954).

Literature Search Summary

As noted above, the current superelevation rates have been in widespread use for approximately 65 years. These rates were presented in the 1954 edition of *A Policy on Geometric Design of Rural Highways*; however, their use actually preceded this date. During this long period of time, these rates have remained largely unchanged (AASHTO, 2018). Updated values have been generated when speed limits (and therefore design speeds) increased, but the fundamental concepts and values surrounding the superelevation rates are consistent with those from earlier years. During this time, however, vehicle fleets have substantially evolved, and pavement design and surface friction has been enhanced. Other notable changes have also occurred to the road environment. Many agencies have become less dependent on design speed and the application of advisory signs at horizontal curve locations has become common. At the same time, the design of vehicles, vehicle tires, and the road surface friction continue to evolve.

References:

American Association of State Highway Officials (AASHO). *A Policy on Geometric Design of Rural Highways.* Washington, DC, 1954, 655 pp.

American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets. 7th edition.* Washington, DC, 2018, 1047 pp.

Research Objective

There is a need to provide a fresh review of superelevation rates and their suitability for today's roadway environment and vehicle fleet. Major tasks or activities that likely need to be performed to successfully conduct this research include:

- Complete a comprehensive literature review. This review should include a review of the AASHTOs current policy on superelevation rates and friction factor requirements. The review should also explore suitability of the current selection criteria (i.e. design speed, maximum superelevation, etc.).

- Identify potential sources of data that could be used to assess vehicle response at various horizontal curve locations (e.g., SHRP2 naturalistic driving study data). Where possible, the data should also capture vertical grade and curvature and their compatibility with the horizontal alignment. Due to the nature of the SHRP2 data, detailed vehicle assessment could focus on passenger cars; however, RID would provide data that could also be used for an assessment of the broader vehicle fleet including heavy vehicles (a common design vehicle).
- Develop a work plan to evaluate superelevation at various contextual applications (such as high-speed rural roads contrasted to lower speed arterial transitions).
- As appropriate, propose recommendations for enhanced superelevation applications for a future edition of the AASHTO Green Book

Urgency and Potential Benefits

The effective design of superelevation can help to reduce roadway departure crashes and improve vehicle operations on well-designed roadway corridors. The current superelevation rates have been in widespread use for over 65 years, and the presence of roadway departure crashes at horizontal curve locations is no longer a surprise, yet this issue could potentially be resolved by updating superelevation applications. For this reason, there is a potential for a significant safety enhancement if these rates are determined to be deficient.

Implementation Considerations and Supporters

AASHTO could incorporate the results of this research into future editions of the Green Book, and as appropriate State DOTs could incorporate the research results into their respective design manuals.

The AASHTO Committee that might be interested in the research results and could help support implementation:

- Committee on Design

Recommended Research Funding and Research Period

Research Funding: $600,000
Research Period: 24 months

Problem Statement #7 -- Influence of Driveway and Intersection Density on Access Management Safety – Development of CMFs

Background

The density of driveways along a corridor can be expected to influence corridor progression, congestion, and safety performance (often manifesting itself in the form of multi-vehicle crashes). The frequency of public driveways and intersections, therefore, should have a direct influence on roadway safety. Current safety analysis methods evaluate roadway segments and intersections individually and then the resulting savings in crashes are added together to estimate the safety performance of the overall corridor. Because the intersection actually is an access point and the length of the segment represents a measure of intersection density, it is likely that the current safety estimation procedures may not fully capture the actual corridor safety performance. There is a need to assess the influence of the intersection and intermediate driveways on the corridor safety performance.

Literature Search Summary

In 2010, AASHTO published the *Highway Safety Manual* (HSM). This document represents a substantial shift in how agencies can assess the predicted safety for various roadway facility types. As part of this effort, the HSM included predictive methods for urban and suburban arterials. The models included in these chapters use a set of base conditions that can then be adjusted for site-specific features. Corridor safety assessment can be determined by adding the expected number of crashes for the segments and intersections included in the study region. For this analysis, the HSM includes the following driveway types:

- Major and minor commercial driveways,
- Major and minor industrial / institutional driveways,
- Major and minor residential driveways, and
- Other driveways.

A major driveway in this context is further defined as a site with 50 or more parking spaces. This segmented analysis is intuitive; however, there is a need to assess if the results from this composite analysis are consistent with those observed for an overall corridor that incorporates the segments as well as the bounding intersections.

References:

American Association of State Highway and Transportation Officials (AASHTO). *Highway Safety Manual.* Washington, DC, 2010.

Research Objective

The objective of this research is to assess the influence of access density (intersection and driveways) on the overall corridor safety performance. Major tasks or activities that likely need to be performed to successfully conduct this research include:

- Complete a comprehensive literature review. This review should include a review of the HSM treatment of access management applications. The review should also explore if the additive segment and intersection approach currently used in the HSM suitability predicts safety performance of access management treatments with a specific focus on access density.

- Identify potential sources of data that could be used to assess corridor conditions and crash characteristics as they pertain to access management (e.g., SHRP2 RID data will be a valuable resource for this activity).
- Develop a work plan to evaluate access management density and safety prediction accuracy for varying roadway corridor configurations.
- As appropriate, propose recommendations for enhanced access management safety prediction for the AASHTO HSM and the TRB Access Management Manual.

Urgency and Potential Benefits

The effective design of access along a corridor can substantially influence corridor operations and safety performance. For many years, emphasis has focused on enhanced corridor progression, yet angle crashes are very common crash types at intersections and driveways and these specific crash types tend to be more severe. The development of data-driven safety assessment methods in recent years has helped transportation professionals better understand the impact that their decisions can have on the segment and intersection performance. It is important to verify that the methods in use do not discount corridor performance expectations simply due to the additive nature of the assessment that begins and ends at bounding intersections. For this reason, there is a growing need to confirm that analytical techniques in use in the HSM adequately capture the true safety impacts of access management and access density along the entire corridor. If these methods underestimate the crash condition, this research will help to better inform transportation professionals how to overcome this limitation and ultimately this knowledge can be used to further reduce fatal crashes.

Implementation Considerations and Supporters

AASHTO could incorporate the results of this research into future editions of the HSM, the Green Book, and as appropriate State DOTs could incorporate the research results into their respective design manuals.

The AASHTO Committee on Design and Safety might be interested in the research results and could help support implementation:

- Committee on Design
- Committee on Safety

Recommended Research Funding and Research Period

Research Funding: $600,000
Research Period: 24 months

Summary Comments and Next Steps

This section reviews the potential data advantages and limitations identified as part of this study, indicates the target reference documents considered for this analysis, briefly reviews the research themes and roadmap, and concludes with a recommendation for next steps.

Data Advantages and Limitations

This report summarized the various types of projects that researchers have conducted using the SHRP2 naturalistic data. This rich source of data provides robust data analysis options for illusive transportation issues that have historically posed challenges to evaluate. Specific advantages cited in the literature or noted by subject matter experts interviewed for this project include the geographic diversity of the data, the content and quality of the companion RID database, the benefits of the data compared to that acquired using other methods, and the real driving information instead of simulated data or test track data.

Of course, the literature and subject matter expert interviewees also noted some limitations of the data that researchers should consider when applying this information to their studies. These potential limitations included potential shelf-life limitations, challenges using the extensive data, data cost, lack of vehicle mix (passenger cars were the focus), small sample size of drivers (in many cases offset by large sample size of number of trips), and missing or mistaken data elements in the data set.

With these advantages and limitations, the overall recommendations of this research effort suggest that the strengths of the data substantially outweigh the limitations, and this data can be effectively used for many future and impactful research efforts.

Potential Reference Documents to Benefit

The roadmap for identifying research ideas that will utilize the SHRP2 data primarily focused on AASHTO documents that are utilized on a national level. In particular, the research effort evaluated candidate research ideas that could enhance the following documents:

- Roadside Design Guide,
- Highway Safety Manual,
- Green Book,
- Guidelines for Geometric Design of Low-Volume Local Roads,
- Guide for Development of Bicycle Facilities,
- Guide for the Planning, Design, and Operation of Pedestrian Facilities,
- Roadway Lighting Design Guide,
- Manual for Assessing Safety Hardware, and
- Guide for High-Occupancy Vehicle (HOV) Facilities.

The report also identified additional documents published by others; however, the AASHTO publications were the ultimate focus of the recommendations.

Research Themes and Roadmap

Chapter 4 of the report summarized several recurring research themes identified as a result of the literature review, panel feedback, and subject matter expert interviews. Ultimately these themes were synthesized into 22 research ideas that would utilize the SHRP2 data and provide findings suitable for one of the identified reference documents. These research ideas are included in Table 11 through Table 17. Next, the research team prioritized these research ideas and created seven fully developed research problem statements (previously included in this chapter). The priority process for determining these seven research problem statements was based on ideas that had the greatest opportunity for a successful research project, were timely so that they could be considered for near-term publication updates, and that focused on a gap that could be directly addressed through the use of the SHRP2 data.

Next Steps

This report includes seven fully developed research problem statements as well as several additional research ideas. These ideas have been developed so that the transportation community can freely distribute them and gain support. These research problem statements can also be shared with AASHTO and TRB committees to aid with identifying potential funding.

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REFERENCES

AASHTO. Guide for the Development of Bicycle Facilities. 4th ed. Washington, DC., 2012.

AASHTO. Guide for High-Occupancy Vehicle (HOV) Facilities. 3rd ed. Washington, D.C., 2004.

AASHTO. Guidelines for Geometric Design of Low-Volume Local Roads. 2nd ed. Washington, DC., 2019.

AASHTO. Highway Safety Manual. 1st ed. Washington, DC., 2010.

AASHTO. Manual for Assessing Safety Hardware, 2nd edition. Washington, DC. 2016.

AASHTO. A Policy on Geometric Design of Highways and Streets. 7th ed. Washington, DC., 2018.

AASHTO. Roadside Design Guide. 4th ed. Washington, DC., 2011.

AASHTO. Roadway Lighting Design Guide. 7th ed. Washington, DC., 2018.

Aduen, P. A., Kofler, M. J., Cox, D. J., Sarver, D. E., & Lunsford, E. (2015). Motor vehicle driving in high incidence psychiatric disability: Comparison of drivers with ADHD, depression, and no known psychopathology. *Journal of Psychiatric Research*, 64, 59-66. doi:10.1016/j.jpsychires.2015.03.009

Aduen, P. A., Kofler, M. J., Sarver, D. E., Wells, E. L., Soto, E. F., & Co1, D. J. (2018). ADHD, depression, and motor vehicle crashes: A prospective cohort study of continuously-monitored, real-world driving. *Journal of Psychiatric Research*. doi:10.1016/j.jpsychires.2018.02.026

Ahmed, M., Ghasemzadeh, A., Hammit, B., Khan, N., Das, A., Ali, E., & Eldeeb, H. (2018). Driver performance and behavior in adverse weather conditions: An investigation using the SHRP2 Naturalistic Driving Study--Phase 2 (WY-19/05F). Cheyenne, WY: Wyoming Department of Transportation.

Antin, J., Guo, F., Fang, Y., Dingus, T. A., Perez, M. A., & Hankey, & J. M. (2017a). A validation of the low mileage bias using naturalistic driving study data. Journal of Safety Research, 63, pp. 115-120.

Antin, J. F., Guo, F., Fang, Y., Dingus, T., Hankey, J. M., & Perez, M. A. (2017b). The influence of functional health on seniors' driving risk. Journal of Transport & Health, 6, 237-244. doi:10.1016/j.jth.2017.07.003

Antin, J. F., Wotring, B., Perez, M., & Glaser, D. (2017c). Investigating lane change behaviors and difficulties for senior drivers using the SHRP2 naturalistic database (17-UM-055). Blacksburg, VA: National Surface Transportation Safety Center for Excellence.

Arbabzadeh, N., Jafari, M., Jalayer, M., Jiang, S., & Kharbeche, M. (2019). A hybrid approach for identifying factors affecting driver reaction time using naturalistic driving data. Transportation Research Part C: Emerging Technologies, 100(March), 107-124. doi:10.1016/j.trc.2019.01.016

Arvin, R., Kamrani, M. and Khattak, A.J., 2019. The role of pre-crash driving instability in contributing to crash intensity using naturalistic driving data. Accident Analysis & Prevention, 132, p.105226.

Ashley, G., Osman, O.A., Ishak, S. and Codjoe, J., 2019. Investigating effect of driver-, vehicle-, and road-related factors on location-specific crashes with naturalistic driving data. Transportation research record, 2673(6), pp.46-56.

Atwood, J., Guo, F., Fitch, G., & Dingus, T. (2018). The driver-level crash risk associated with daily cellphone use and cellphone use while driving. Accident Analysis and Prevention, 119, 149-154. doi:10.1016/j.aap.2018.07.007

Avelar, R.E., Dadashova, B., Higgins, L. and Gillette, G., 2018. Using SHRP2-Nds Data to Investigate Freeway Operations, Human Factors, and Safety (No. ATLAS-2018-23). ATLAS Center (Mich.).

Bakhit, P., Guo, B., & Ishak, S. (2018, January). Crash and Near-Crash Risk Assessment of Distracted Driving and Engagement in Secondary Tasks: A Naturalistic Driving Study Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Bärgman, J., Lisovskaja, V., Victor, T., Flannagan, C., & Dozza, M. (2015). How does glance behavior influence crash and injury risk? A 'what-if'counterfactual simulation using crashes and near-crashes from SHRP2. Transportation Research Part F: Traffic Psychology and Behaviour, 35, 152-169.

Bärgman, J., Boda, C.-N., & Dozza, M. (2017). Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems. Accident Analysis & Prevention, 102, 165-180. doi:10.1016/j.aap.2017.03.003

Bharadwaj, N., Edara, P. and Sun, C., 2019. Risk factors in work zone safety events: a naturalistic driving study analysis. Transportation research record, 2673(1), pp.379-387.

Brewer, M.A. and Stibbe, J., 2019. Investigation of design speed characteristics on freeway ramps using shrp2 naturalistic driving data. Transportation research record, 2673(3), pp.247-258.

Calvo, J.A., Baldwin, C. and Philips, B., 2020. Effect of age and secondary task engagement on motor vehicle crashes in a naturalistic setting. Journal of Safety Research.

Chen, K.T. and Chen, H.Y.W., 2019. Driving style clustering using naturalistic driving data. Transportation research record, 2673(6), pp.176-188.

Chen, J.C., Lian, Z.Y., Huang, C.L. and Chuang, C.H., 2020, February. Automatic Recognition of Driving Events Based on Dashcam Videos. In Proceedings of the 2020 3rd International Conference on Image and Graphics Processing (pp. 22-25).

Christ, D., 2020. Simulating the relative influence of tire, vehicle and driver factors on forward collision accident rates. Journal of Safety Research, vol. 73, pp. 253-262

Dadashova, B., Di1on, K., & Avelar, R. (2018, January). E1ploring the Effects of Important Predictors of Ramp Speeding Behavior Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Das, A. and Ahmed, M.M., 2019. Exploring the effect of fog on lane-changing characteristics utilizing the SHRP2 naturalistic driving study data. Journal of Transportation Safety & Security, pp.1-26.

Das, A., Ahmed, M.M. & Ghasemzadeh, A., 2019. Using trajectory-level SHRP2 naturalistic driving data for investigating driver lane-keeping ability in fog: an association rules mining approach. Accident Analysis & Prevention, 129, pp.250-262.

Das, S., Brimley, B., Lindheimer, T., & Pant, A. (2017a). Safety impacts of reduced visibility in inclement weather (ATLAS-2017-19). Ann Arbor, MI: ATLAS Center. Retrieved from:

Das, S., Minjares-Kyle, L., & Avelar, R. (2017b). Improper passing-related crashes on rural roadways: Using association rules negative binomial miner. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Das, A., Ghasemzadeh, A., & Ahmed, M. (2018, January). A comprehensive analysis of driver lane-keeping performance in fog weather conditions using the SHRP2 naturalistic driving study data. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

de Winter, J. C. F., Dreger, F. A., Huang, W., Miller, A., Soccolich, S., Machiani, S. G., & Engström, J. (2018). The relationship between the Driver Behavior Questionnaire, Sensation Seeking Scale, and recorded crashes: A brief comment on Martinussen et al. (2017) and new data from SHRP2. Accident Analysis and Prevention, 118, 54-56. doi:10.1016/j.jsr.2014.05.002

Dhahir, B., & Hassan, Y. (2019). Using horizontal curve speed reduction e1tracted from the naturalistic driving study to predict curve collision frequency. Accident Analysis and Prevention, 123, 190-199. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0001457518310479

Dingus, T.A., Owens, J.M., Guo, F., Fang, Y., Perez, M., McClafferty, J., Buchanan-King, M. and Fitch, G.M., 2019. The prevalence of and crash risk associated with primarily cognitive secondary tasks. Safety Science, 119, pp.98-105.

FHWA. Manual on Uniform Traffic Control Devices. Washington, D.C., 2009 with 2020 updates.

Flannagan, C., Bärgman, J. and Bálint, A., 2019. Replacement of distractions with other distractions: a propensity-based approach to estimating realistic crash odds ratios for driver engagement in secondary tasks. Transportation research part F: traffic psychology and behaviour, 63, pp.186-192.

Fountas, G., Anastasopoulos, P., & Abdel-Aty, M. (2018, January). Analysis of Accident Injury Severities Using a Time-Variant Correlated Random Parameters Ordered Probit Approach Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Gao, J., & Davis, G. A. (2017). Using naturalistic driving study data to investigate the impact of driver distraction on driver's brake reaction time in freeway rear-end events in car-following situation. Journal of Safety Research, 63, 195-204.

Gaspar, J. and Carney, C., 2019. The effect of partial automation on driver attention: a naturalistic driving study. Human factors, 61(8), pp.1261-1276.

Geng, X., Liang, H., Xu, H., & Yu, B. (2016a). Influences of leading-vehicle types and environmental conditions on car-following behavior. IFAC-PapersOnLine, 49(15), 151-156.

Geng, X., Liang, H., Xu, H., Yu, B., & Zhu, M. (2016b). Human-driver speed profile modeling for autonomous vehicle's velocity strategy on curvy paths 2016 IEEE Intelligent Vehicles Symposium (IV) (pp. 755-760). Piscataway, NJ: IEEE.

Ghasemzadeh, A., & Ahmed, M. M. (2018). Utilizing naturalistic driving data for in-depth analysis of driver lane-keeping behavior in rain: Non-parametric MARS and parametric logistic regression modeling approaches. Transportation Research Part C: Emerging Technologies, 90, 379-392. doi:10.1016/j.trc.2018.03.018

Ghasemzadeh, A. and Ahmed, M.M., 2019. E1ploring factors contributing to injury severity at work zones considering adverse weather conditions. IATSS research, 43(3), pp.131-138.

Hallmark, S. and McGehee, D. Challenges and Opportunities for State DOTs to use the SHRP2 Naturalistic Driving Study Data (2014). Presentation to AASHTO SHRP2 Safety Task Force.http://shrp2.transportation.org/Documents/Challenges_Opportunies_SHRP2_March_13_2014.pdf

Hallmark, S., Oneyear, N., Wang, B., Tyner, S., Carney, C., & McGehee, D. (2015a). Identifying curve reaction point using NDS data Proceedings of the 2015 IEEE 18th International Conference on Intelligent Transportation Systems (pp. 2237-2242). Piscataway, NJ: IEEE.

Hallmark, S. L., Tyner, S., Oneyear, N., Carney, C., & McGehee, D. (2015b). Evaluation of driving behavior on rural 2-lane curves using the SHRP2 naturalistic driving study data. Journal of safety research, 54, 17. e11-27.

Hallmark, S., Goswamy, A., Smadi, O., & Chrysler, S. (2018, February). Speed prediction in work zones using the SHRP2 Naturalistic Driving Study data. In J. P. Hall (Ed.), Transportation Research Circular E-C229: 10th SHRP2 Safety Data Symposium: From Analysis to Results (pp. 30-34).

Hammit, B.E., James, R., Ahmed, M. and Young, R., 2019. Toward the development of weather-dependent microsimulation models. Transportation research record, 2673(7), pp.143-156.

Hammit, B. E., Ghasemzadeh, A., Jame, R. M., & Ahmed, M. M. (2018). Evaluation of weather-related freeway car-following behavior using the SHRP2 naturalistic driving study database. Transportation Research Part F: Traffic Psychology and Behaviour. doi:10.106/j.trf2018.08.023

Hamzeie, R. (2018). Investigation of drivers speed selection behavior: A naturalistic driving approach (Doctoral dissertation), Iowa State University, Ames, Iowa. Retrieved from https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=7596&conte1t=etd

Harkey, D. L., Srinivasan, R., Baek, J., Persaud, B., Lyon, C., Council, F. M., & Bonneson, J. (2008). Crash reduction factors for traffic engineering and ITS improvements (NCHRP Project 17-25 Final Report). Washington, DC: Transportation Research Board.

Haslett, K.E., Dave, E.V. and Mo, W., 2019. Realistic Traffic Condition Informed Life Cycle Assessment: Interstate 495 Maintenance and Rehabilitation Case Study. Sustainability, 11(12), p.3245.

Haus, S., & Gabler, H. (2018, January). Characteristics of Vehicle–Bicycle Crashes and Near-crashes Using Naturalistic Driving Data. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Hedlund, J. (2014). Continuous observations of seat belt use using naturalistic driving data. Paper presented at the 142nd APHA Annual Meeting and E1position (November 15-November 19, 2014), New Orleans, LA.

Higgins, L., Avelar, R., & Chrysler, S. (2017). Effects of Distraction Type, Driver Age, and Roadway Environment on Reaction Times–An Analysis Using SHRP-2 NDS Data.

Hoang Ngan Le, T., Zheng, Y., Zhu, C., Luu, K., & Savvides, M. (2016). Multiple scale faster-RCNN approach to driver's cell-phone usage and hands on steering wheel detection Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition Workshops (pp. 46-53). Piscataway, NJ: IEEE.

Huisingh, C., Owsley, C., Levitan, E. B., Irvin, M. R., MacLennan, P., & McGwin, G. (2018, May 17). Distracted driving and risk of crash or near-crash involvement among older drivers using naturalistic driving data with case-crossover study design. The Journals of Gerontology: Series A. doi:10.1093/gerona/gly119

Hutton, J. M., Bauer, K. M., Fees, C. A., & Smiley, A. (2015). Analysis of naturalistic driving study data: Offset left-turn lanes (S2-S08B-RW-1). Washington, DC: Transportation Research Board. Retrieved from: http://www.trb.org/Main/Blurbs/171264.asp1

Hutton, P. (2017). Safety Implementation Assistance Program Update. http://shrp2.transportation.org/Documents/SHRP2_SDOC_November_2017_v2.pdf

Ivanco, A. (2017). Fleet analysis of headway distance for autonomous driving. Journal of Safety Research, 63, 145-148.

James, R.M. and Hammit, B.E., 2019. Identifying contributory factors to heterogeneity in driving behavior: clustering and classification approach. Transportation research record, 2673(10), pp.343-353.

Jenkins, S., Codjoe, J., Alecsandru, C., & Ishak, S. (2016). E1ploration of SHRP2 NDS: Development of a distracted driving prediction model. Paper presented at the Transportation Research Board 95th Annual Meeting, Washington, DC.

Kanaan, D., Ayas, S., Donmez, B., Risteska, M. and Chakraborty, J., 2019. Using Naturalistic Vehicle-Based Data to Predict Distraction and Environmental Demand. International Journal of Mobile Human Computer Interaction (IJMHCI), 11(3), pp.59-70.

Khan, M.N. and Ahmed, M.M., 2020. Trajectory-level fog detection based on in-vehicle video camera with TensorFlow deep learning utilizing SHRP2 naturalistic driving data. Accident Analysis & Prevention, 142, p.105521.

Khan, M.N., Ghasemzadeh, A. and Ahmed, M.M., 2018. Investigating the impact of fog on freeway speed selection using the SHRP2 naturalistic driving study data. Transportation research record, 2672(16), pp.93-104.

Kidd, D. G., & McCartt, A. T. (2015). The relevance of crash type and severity when estimating crash risk using the SHRP2 naturalistic driving data. Arlington, VA: Insurance Institute for Highway Safety. Retrieved from:

Kluger, R., Smith, B. L., Park, H., & Dailey, D. J. (2016). Identification of safety-critical events using kinematic vehicle data and the discrete fourier transform. Accident Analysis & Prevention, 96, 162-168. doi:10.1016/j.aap.2016.08.006

Lanka, V.R.R., Heydinger, G. and Guenther, D., 2019. Driver's Response Prediction Using Naturalistic Data Set. SAE International Journal of Advances and Current Practices in Mobility, 1(2019-01-0128), pp.524-530.

Lee, J.Y., Lee, J.D., Bärgman, J., Lee, J. and Reimer, B., 2018. How safe is tuning a radio?: using the radio tuning task as a benchmark for distracted driving. Accident Analysis & Prevention, 110, pp.29-37.

Li, Y., Gibbons, R., & Medina, A. (2015). Integrating Adaptive Lighting Database with SHRP2 Naturalistic Driving Study data. Transportation Research Record: Journal of the Transportation Research Board, 2526, 1-9. doi:10.3141/2526-01

Li, Y., Gibbons, R., & Flintsch, A. M. (2017, January). Using naturalistic driving data for assessing safety impact of roadway improvements. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Lin, K. C. (2017). An analysis of naturalistic driver data in evaluating vehicle longitudinal control systems. (Master's thesis), The Ohio State University, Columbus. Retrieved from https://etd.ohiolink.edu/!etd.send_file?accession=osu1494264277572481&disposition=inline

Liu, S. (2017). The Impact of Sleep Disorders on Driving Safety – Findings from the SHRP2 Naturalistic Driving Study. (Master's thesis), Virginia Tech, Blacksburg, VA.

Lindheimer, T., Avelar, R., Dastgiri, M., Brewer, M., & Di1on, K. (2018, January). E1ploratory Analysis of Deceleration Rates in Urban Corridors Using SHRP2 Data Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Lu, D., Guo, F. and Li, F., 2020. Evaluating the causal effects of cellphone distraction on crash risk using propensity score methods. Accident Analysis & Prevention, 143, p.105579.

Markkula, G., Engström, J., Lodin, J., Bärgman, J., & Victor, T. (2016). A farewell to brake reaction times? Kinematics-dependent brake response in naturalistic rear-end emergencies. Accident Analysis & Prevention, 95, 209-226.

Mastromatto, T., Vardaki, S., Staplin, L., & Sifrit, K. (2017, January). When no difference makes a difference: Older drivers, medical conditions, and freeway ramp negotiation. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Mata-Carballeira, Ó., Gutiérrez-Zaballa, J., del Campo, I. and Martínez, V., 2019. An FPGA-Based Neuro-Fuzzy Sensor for Personalized Driving Assistance. Sensors, 19(18), p.4011.

Mousa, S., & Ishak, S. (2018, January). A Comprehensive Market Basket Analysis for E1tracting Association Rules from the SHRP2 NDS Data: Naturalistic Driving Study. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Mousa, S., Bakhit, P., & Ishak, S. (2018, January). Advanced Machine Learning Tools for Identifying the Factors Contributing to Crash and Near-Crash Events: Naturalistic Driving Study Data Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Muhire, M., Lautala, P., Nelson, D., & Dean, A. (2018, January). Assessment of Driver Compliance at Highway–Rail Grade Crossings Based on Naturalistic Driving Study Data Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Muñoz, M., Lee, J., Reimer, B., Mehler, B., & Victor, T. (2015). Analysis of drivers' head and eye movement correspondence: Predicting drivers' glance location using head rotation data. Paper presented at the 8th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Salt Lake City, UT.

Muttart, J. (2015). Influence of age, secondary tasks and other factors on drivers' swerving responses before crash or near-crash events (2015-01-1417). Warrendale, PA: SAE. Retrieved from: https://saemobilus.sae.org/content/2015-01-1417

Muttart, J., Dinakar, S., Suway, J., Kuzel, M., Maloney, T., Biever, W., & Harms, T. J. (2017). Comparing a timed e1posure methodology to the nighttime recognition responses from SHRP-2 naturalistic drivers (SAE Technical Paper 2017-01-1366). Warrensburg, PA: SAE International.

Neudorff, L.G., Randall, J., Reiss, R.A. and Gordon, R.L., 2003. Freeway management and operations handbook (No. FHWA-OP-04-003).

Oneyear, N. (2015). Development of rural curve driving models using lateral placement and prediction of lane departures using the SHRP2 naturalistic driving data. (Doctoral dissertation), Iowa State University, Ames, IA.

Oneyear, N., Hallmark, S., & Wang, B. (2016). Analyzing stopping behavior at rural intersections using SHRP2 naturalistic driving data. Paper presented at the 17th International Conference Road Safety On Five Continents (RS5C 2016), Rio de Janeiro, Brazil.

Orlovska, J., Novakazi, F., Lars-Ola, B., Karlsson, M., Wickman, C. and Söderberg, R., 2020. Effects of the driving conte1t on the usage of Automated Driver Assistance Systems - Naturalistic Driving Study for ADAS evaluation. Transportation research interdisciplinary perspectives, p.100093.

Osman, O.A. and Rakha, H., 2020. Application of Deep Learning for Characterization of Drivers’ Engagement in Secondary Tasks in In-Vehicle Systems. Transportation Research Record, p.0361198120926507.

Osman, O., Hajij, M., Karbalaieali, S., & Ishak, S. (2018, January). Crash and Near-Crash Prediction from Vehicle Kinematics Data: A SHRP2 Naturalistic Driving Study. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Osman, O., Hajij, M., Karbalaieali, S., & Ishak, S. (2019a). A hierarchical machine learning classification approach for secondary task identification from observed driver behavior data. Accident Analysis and Prevention, 123, 274-281.

Osman, O.A., Hajij, M., Bakhit, P.R. & Ishak, S. (2019b). Prediction of Near-Crashes from Observed Vehicle Kinematics using Machine Learning. Transportation Research Record, 2673(12), pp.463-473.

Owens, J., Dingus, T., Guo, F., Fang, Y., Perez, M., McClafferty, J., & Tefft, B. (2018, January). Estimating the prevalence and crash risk of drowsy driving using data from a large-scale naturalistic driving study. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Owens, J., Tefft, B., Guo, F., Fang, Y., Perez, M., McClafferty, J., & Dingus, T. (2018, January). Crash risk of cell phone use while driving: case-crossover study of SHRP2 Naturalistic Driving Data. 97th Annual Meeting of the Transportation Research Board.

Papazikou, A.-E., Quddus, M., & Thomas, P. (2017, January). Detecting deviation from normal driving using SHRP2 NDS data. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Papazikou, A.-E., Quddus, M., & Thomas, P. (2018, January). What Came Before the Crash? An Investigation Through SHRP2 NDS Data. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC. Parvinashtiani, N., & Smadi, O. (2018, January). Comparing Objective and Subjective Roadway Data Collection Methods Using the U.S. Road Assessment Program Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Penmetsa, P., Pulugurtha, S., & Mane, A. (2017, January). Risk perceptions of drivers: Does it change with crash history or prior convictions? Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Perez, M., Sudweeks, J., Sears, E., Antin, J., Lee, S., Hankey, J. M., & Dingus, T. A. (2017, June). Performance of basic kinematic thresholds in the identification of crash and near-crash events within naturalistic driving data. Accident Analysis & Prevention, 103, 10-19. doi:10.1016/j.aap.2017.03.005

Polk, C. (2016) Issues Resolution Workshop Meeting Summary. http://shrp2.transportation.org/Documents/IRW_Meeting_Summary_FINAL.pdf

Pratt, M.P., Geedipally, S.R., Dadashova, B., Wu, L. and Shirazi, M., 2019. Familiar versus unfamiliar drivers on curves: naturalistic data study. Transportation research record, 2673(6), pp.225-235.

Precht, L., Keinath, A., & Krems, J. F. (2017a). Identifying effects of driving and secondary task demands, passenger presence, and driver characteristics on driving errors and traffic violations – Using naturalistic driving data segments preceding both safety critical events and matched baselines. Transportation Research Part F: Traffic Psychology and Behaviour, 51, 103-144. doi:10.1016/j.trf.2017.09.003

Precht, L., Keinath, A., & Krems, J. F. (2017b). Effects of driving anger on driver behavior--Results from naturalistic driving data. Transportation Research Part F: Traffic Psychology and Behaviour, 45, 75-92. doi:10.1016/j.trf.2016.10.019

Precht, L., Keinath, A., & Krems, J. F. (2017c). Identifying the main factors contributing to driving errors and traffic violations – Results from naturalistic driving data.

Transportation Research Part F: Traffic Psychology and Behaviour, 49, 49-92. doi:10.1016/j.trf.2017.06.002

Precht, L. (2018). Identifying the effects of cognitive distraction on driving performance – Analysis of naturalistic driving data (Doctoral dissertation), Technischen Universität Chemnitz, Chemnitz, Germany.

Risteska, M., Donmez, B., Chen, H.-Y. W., & Modi, M. (2018). Prevalence of Engagement in Single Versus Multiple Types of Secondary Tasks: Results from the Naturalistic Engagement in Secondary Task Data Set. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Sarwar, M. T., Fountas, G., Bentley, C., Anastasopoulos, P. C., Blatt, A., Pierowicz, J., Limoges, R. (2017). Preliminary investigation of the effectiveness of high visibility crosswalks on pedestrian safety using crash surrogates. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Schneidereit, T., Petzoldt, T., Keinath, A., & Krems, J. F. (2017). Using SHRP2 naturalistic driving data to assess drivers' speed choice while being engaged in different secondary tasks. Journal of Safety Research, 62, 33-42. doi:10.1016/j.jsr.2017.04.004

Seacrist, T., Belwadi, A., Prabahar, A., Chamberlain, S., Megariotis, J., & Loeb, H. (2016). Comparison of crash rates and rear-end striking crashes among novice teens and e1perienced adults using the SHRP2 Naturalistic Driving Study. Traffic Injury Prevention, 17(sup1), 48-52. doi:10.1080/15389588.2016.1188384

Seacrist, T., Douglas, E. C., Huang, E., Megariotis, J., Prabahar, A., Kashem, A. & Loeb, H. (2018). Analysis of near-crashes among teen, young adult, and e1perienced adult drivers using the SHRP2 naturalistic driving study. Traffic Injury Prevention, 19(Sup 1), S89-S96. doi:10.1080/15389588.2017.1415433

Simons-Morton, B.G., Gershon, P., Gensler, G., Klauer, S., Ehsani, J., Zhu, C., O'Brien, F., Gore-Langton, R. and Dingus, T., 2019. Kinematic risky driving behavior among younger and older drivers: Differences over time by age group and se1. Traffic injury prevention, 20(7), pp.708-712.

Srinivasan, R., Carter, D., Lan, B., & Signor, K. (2018). Investigation of driver performance in different horizontal and vertical curve combinations using SHRP2 naturalistic driving data. Advances in Transportation Studies, Special Issue, Vol. 1, 121-136.

Sun, Y., & Wu, J. (2017). Data processing framework for driving cycle development with Naturalistic Driving Study data. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Taccari, L., Sambo, F., Bravi, L., Salti, S., Sarti, L., Simoncini, M., & Lori, A. (2018, November). Classification of crash and near-crash events from dashcam videos and telematics. 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA. doi:10.1109/ITSC.2018.8569952

Taylor, J., Medina, J., & Porter, R. J. (2018, February). Driver behavior near urban interchanges with closely spaced ramps. In J. P. Hall (Ed.), Transportation Research Circular E-C229: 10th SHRP2 Safety Data Symposium: From Analysis to Results (pp. 67-71). Washington, DC: Transportation Research Board.

Teoh, E. R., & Kidd, D. G. (2017). Rage against the machine? Google's self-driving cars versus human drivers. Journal of Safety Research, 63, 57-60. doi:10.1016/j.jsr.2017.08.008

Thapa, R., Hallmark, S., Smadi, O. and Goswamy, A., 2019. Assessing driving behavior upstream of work zones by detecting response points in speed profile: A naturalistic driving study. Traffic injury prevention, 20(8), pp.854-859.

TRB. Highway Capacity Manual. 6th ed. Washington D.C., 2016

TRB. Human Factors Guide. 2nd ed. Washington D.C., 2012

Wali, B., Khattak, A., & Karnowski, T. (2018). How Driving Volatility in Time to Collision Relates to Crash Severity in a Naturalistic Driving Environment Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Wang, J., & Zhou, H. (2018). Using naturalistic driving study data to evaluate the effects of intersection balance on driver behavior at partial cloverleaf interchange terminals. Transportation Research Record. doi:10.1177/0361198118774670

Wang, B., Hallmark, S., Savolainen, P. T., & Dong, J. (2017). Crashes and near-crashes on horizontal curves along rural two-lane highways: Analysis of naturalistic driving data. Journal of Safety Research, 63, 163-169. doi:10.1016/j.jsr.2017.10.001

Wang, B., Hallmark, S., Savolainen, P., & Dong, J. (2018). E1amining vehicle operating speeds on rural two-lane curves using naturalistic driving data. Accident Analysis and Prevention. doi:10.1016/j.aap.2018.03.017

Wolshon B, Pande A. Traffic engineering handbook. John Wiley & Sons; 2016 Jan 26.

Wood, J., & Zhang, S. (2017). Evaluating relationships between perception-reaction times, emergency deceleration rates, and crash outcomes using naturalistic driving data (Report No. MPC 17-338). Washington, DC: Mountain-Plains Consortium University Transportation Center.

Wotring, B., Dingus, T., Atwood, J., Guo, F., McClafferty, J. and Buchanan-King, M., 2020. The prevalence of cognitive disengagement in automobile crashes. Applied Cognitive Psychology, 34(2), pp.543-550.

Wu, J., & Xu, H. (2017). Driver behavior analysis for right-turn drivers at signalized intersections using SHRP2 naturalistic driving study data. Journal of Safety Research, 63, 177-185.

Wu, J., & Xu, H. (2018a). Effect of speed variance on crash frequency on freeways using the SHRP2 safety database. In J. P. Hall (Ed.), Transportation Research Circular E-C229: 10th SHRP2 Safety Data Symposium: From Analysis to Results (pp. 27-29). Washington, DC: Transportation Research Board. Retrieved from http://onlinepubs.trb.org/onlinepubs/circulars/ec229.pdf

Wu, J., & Xu, H. (2018b). The influence of road familiarity on distracted driving activities and driving operation using naturalistic driving study data. Transportation Research Part F: Traffic Psychology and Behaviour, 52, 75-85.

Wu, J., & Xu, H. (2018c). Driver behavior analysis on rural 2-lane, 2-way highways using SHRP2 NDS data. Traffic Injury Prevention, 19(8), 838-843. doi:10.1080/15389588.2018.1524142

Wu, K.F. and Lin, Y.J., 2019. E1ploring the effects of critical driving situations on driver perception time (PT) using SHRP2 naturalistic driving study data. Accident Analysis & Prevention, 128, pp.94-102.

Wu, J., Xu, H., Sun, Y., & Geng, 1. (2017, January). Effect of road characteristics and driving cycles on accident risk on full-access-control highways. Paper presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Wu, J., Xu, H., Zheng, Y., Liu, W., Sun, Y., Yue, R., & Song, 1. (2018). Driver behavior fault analysis on ramp-related crashes/near-crashes using SHRP2 Naturalistic Driving Study data. 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA. doi:10.1109/ITSC.2018.8569985

Wu, L., Dadashova, B., Geedipally, S., Pratt, M., & Shirazi, M. (2018, January). Assessing Curve Severity and Crash Rates at Horizontal Curves on Rural Two-Lane Highways Using SHRP2 Safety Data. Paper presented at the 97th Annual Meeting of the Transportation Research Board, Washington, DC.

Yadawadkar, S., Mayer, B., Lokegaonkar, S., Islam, M. R., Ramakrishnan, N., Song, M., & Mollenhauer, M. (2019). Identifying distracted and drowsy drivers using naturalistic driving data.

Ye, M., Osman, O., & Ishak, S. (2017a). Accounting for driver distraction and socioeconomic characteristics in a crash risk inde1. Transportation Research Record: Journal of the Transportation Research Board, 2659, 204-211. doi:10.3141/2659-22

Ye, M., Osman, O. A., Ishak, S., & Hashemi, B. (2017b). Detection of driver engagement in secondary tasks from observed naturalistic driving behavior. Accident Analysis and Prevention, 106, 385-391.

Young, R. (2017a). Removing biases from crash odds ratio estimates of secondary tasks: A new analysis of the SHRP2 Naturalistic Driving Study data (SAE Technical Paper 2017-01-1380). Warrensburg, PA: SAE International. Retrieved from:

Young, R. (2017b). Are rear-end crashes caused mainly by an interaction between glance duration and closure rate? Paper presented at the 9th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Manchester, VT.

Zhou, H., & Xu, D. (2018, February). Impact of deceleration lane length on vehicles' speed and deceleration rates based on NDS data. In J. P. Hall (Ed.), Transportation Research Circular E-C229: 10th SHRP2 Safety Data Symposium: From Analysis to Results (pp. 76-79). Washington, DC: Transportation Research Board.

APPENDIX A. LITERATURE REVIEW RESULTS

Roadway Design Characteristics

Horizontal and Vertical Curvature

Geng et al. (2016b) evaluated 600 driving trips to assess human driving strategies at curvilinear locations such as navigating sharp horizonal curves or turning at intersections. They assessed this for varying environmental, traffic, and trajectory conditions with the use of neural network-based models so that this information can then be used to estimate velocity for autonomous vehicles. One of the input parameters (prediction step) should be selected carefully for the proposed model to be used in practical applications. For a particular driving scenario, the model generates human-like velocities, but long-term prediction may not be smooth and accurate enough.

Wang et al. (2018) examined the vehicle operating speeds on rural two-lane curves. His research team developed regression models to find the factors which affected mean speeds on curves. Results showed that there was a log-linear relationship between curve radius and vehicle speed. When the curve radius was less than 900-1000 ft, the vehicle speeds reduced significantly. There was a speed reduction with statistical significance observed with the presence of curve advisory speed limit signs. The presence of lead vehicles also reduced vehicle speeds. Curve arrow signs also reduced vehicle speeds. In addition to this, the driver's age and gender were also found to have an effect on vehicle speeds.

Hallmark et al. (2015b) evaluated driving behavior in terms of speed and encroachment on rural two-lane roads at horizontal curves based on various factors. They observed that right side encroachments increase as drivers spend less time glancing at the forward roadway. Right side lane departures are (6.8 times) more likely inside of a curve and when any type of advisory signs are present. Left side encroachments are four times more likely when drivers are male. For drivers inside of a curve, the left side encroachment is 0.1 times less likely than drivers on the outside of the curve. Probability of going above five mph was higher when drivers had higher average speeds, were younger, and when the edge markings were unclear. This probability was less when the driver is following; there is low visibility, and shoulders were paved. Probability of going above ten mph was higher when drivers had a higher average speed, and it was lower when the average glance was longer and paved shoulders were present.

Hamzeie (2018) assessed the speed selection behavior of drivers under different settings of contiguous road segments with constant speed limits, transition areas where speed limits changed, and horizontal curves with advisory speed limits. The crash risk was also examined. In areas of constant speed limits, higher speed limits resulted in higher speeds. However, the increase in speeds is less pronounced at higher speed limits. In transition areas where speed limits change, the travel speeds changes vary gradually. In the case of curves, the drivers tend to reduce their speeds. These reductions are higher if advisory speed limit signs are present, and much of the speed reduction occurs between the advisory speed limit sign and the point of curvature.

Dhahir and Hassan (2019) evaluated the safety performance of horizontal curves by developing models to predict the expected curve collision frequency using individual driver trips on 49 horizontal curves. Posted speed limit, curve radius, curve length, and deflection angle were significant variables affecting speed reduction on horizontal curves. Speed reduction parameters were the most significant in predicting collision frequency when contrasted to all geometric curve characteristics (note that these are not necessarily independent relationships). Thus, they determined that the safety performance on horizontal curves is mostly influenced by curve speed reduction.

Wang et al. (2017) assessed the crashes and near-crashes on horizontal curves on rural two-lane highways based on driver behavior, roadway characteristics, and vehicle dynamics using a logistic regression model. Speeding on curves was determined to be one of the major contributing factors for near-crash or crash events. High risks were associated with the wet, icy, and snowy pavement surface. It was also found that the likelihood of a crash was three times higher when the driver was visually distracted. Crash risks increased exponentially as the radius of the horizontal curve decreased.

Wu et al. (2018) assessed the crash rates and curve severity at horizontal curves on rural two-lane highways using operational characteristics from the NDS database and historical crash data from RID. The curve severity of each curve was calculated by four methods, which was then compared to severity obtained based on crash rates. For higher curve severity categories, curve severity was positively associated with crash rates.

Oneyear et al. (2015) explored how drivers interacted with the roadway environment on a horizontal curve (both inside and outside the curve) by developing a conceptual model (Generalized Least Squares for lane position) which helped to identify zones where drivers were more likely to make lane departures. Drivers who glanced down from the roadway showed a shift away from the centerline of the lane towards the inside of the curve. While traversing on an inside lane, the driver who looked down at a point within the curve shifted away from the center by about 0.30 meters to the right. After passing the center of the curve, drivers on the inside of a curve tended to move further to the right, while drivers traversing the outside lanes of a curve were at the furthest from the centerline at the center of the curve. Large paved shoulders were correlated with a shift towards the outside of the lane outside of a curve. Also, lower visibility caused the drivers to maintain centerline movement when outside of a curve.

Hallmark et al. (2015a) used NDS data was to determine the point where drivers begin reacting to the presence of a curve. Depending on the radius of the curve, drivers react 164 to 180 meters before or upstream of the point of curvature. Drivers react sooner for curves with larger radii compared to sharper curves.

Pratt et al. (2019) studied the differences between the speed choice of familiar and unfamiliar drivers as they traverse curves. The results of the analysis confirm earlier findings that familiar drivers choose higher speeds through curves. The successful use of the SHRP2 database for this analysis of route familiarity shows that the database can facilitate similar efforts for a wider range of driver behavior and human factors issues.

Functional Classification / Road Type

Wu et al. (2017) studied the influence of traffic factors and roadway characteristics on crash risk on full access control highways using a negative binomial crash prediction model. For an urban area, the roadway characteristics of the number of through lanes in one direction and speed limits significantly influenced crash risk while the type of functional system, curve level and grade level did not have much effect on crash risk. In traffic factors, high average speeds and high variance in vehicle speeds significantly increased the crash risk.

Pavement Performance

Haslett et al. (2019) developed a life cycle assessment methodology to evaluate the pavement performance. They evaluated pavement performance with realistic traffic conditions and varying material characteristics that were quantified in terms of life cycle cost, global warming potential, and cumulative energy demand for both agencies and users. The inclusion of realistic traffic conditions into the use phase of the life cycle assessment resulted in a 6.4 percent increase in the cumulative energy demand and the global warming potential when compared to baseline conditions simulated for a week-long operation duration. Results from this study show that optimization of the various factors may lead to a 2.7 percent decrease in operational cost and a 47.6 percent decrease in construction and maintenance costs.

Intersection and Ramp Designs

Precht et al. (2017a) identified several factors that caused aberrant driving behavior and crash risk. Factors that were having an influence over violations were driving through intersections, weather, individual differences in driving behavior, and the severity of any safety-critical event. A large number of unusual driving behaviors had a higher crash risk when compared to single errors or violations. Several factors causing aberrant driving behaviors as observed in previous studies were not identified for this research. For example, driving in high-density traffic, in the dark, or in the rain were not related to the number of driving errors.

Mousa et al. (2018) used advanced machine learning models – Bagging Average Neural Network, Deep Neural Network, Gradient Boosting and eXtreme Gradient Boosting (XGB) to determine the likelihood of crash and near-crash events based on various factors such as driver behavior and facility type. The XGB model was the most accurate, with an accuracy of around 85 percent. According to the XGB model, driver behavior, intersection influence, and secondary tasks were the most influential factors for crash or near-crash events with their contribution around 52 percent, 19 percent, and five percent, respectively.

Sight Distance

Wood & Zhang (2017) evaluated the differences in perception-reaction time and emergency deceleration rates between crashes and near-crash events. Drivers involved in crash events took longer to react and decelerated slower than drivers in equivalent near-crashes event. This study confirms that human error is the largest contributing factor to crash occurrence. This report identifies different ways to estimate stopping sight distance. Based on their findings, the values of variables for determining stopping sight distance can use the following: perception reaction time values for 90 percent that of the drivers' deceleration rates where the majority of drivers can maintain control of the vehicle, deceleration rates where 90 percent of the drivers will brake at least that hard. The values can be recommended to AASHTO for further consideration.

Ramp Design

Taylor et al. (2018) examined driver behavior as a function of ramp spacing and presence of auxiliary lane in terms of lane change location, lane change duration, and speed differential (between entering and exiting speeds) on closely spaced ramps on freeway interchanges. Vehicles merging into through lanes before traveling 40 to 50 percent of the distance between physical ramp gores had to wait longer to merge when auxiliary lanes were present. Lane change durations were not very significantly affected by ramp spacing and the presence of auxiliary lane. Speed differential did not vary much with ramp spacing or auxiliary lane presence.

Dadashova et al. (2018) used neural network analysis to identify the most influential of three predictors of the driving state during freeway merging and diverging activities. The results suggest that traffic conditions and geographic location mainly influence the driver's speed choice behavior. Variation in speed was found to be the most important, and it has an increasing impact on speed choice, although as drivers shift from State I to State III, the magnitude of this effect reduces. The effects of driver characteristics were not found to be as important; however, driver's age, Risk Perception Scores, and sleeping habits were observed to contribute the most.

Brewer and Stibbe (2019) explored the feasibility of using data from the NDS dataset to identify relationships between ramp design speed characteristics and drivers' choices of operating speeds on those ramps. This paper summarizes the activities and findings of the current research project, including basic models for estimating vehicle speeds on freeway ramps based on the NDS data. These models may be used in conjunction with other ongoing related research efforts to suggest material for potential updates to existing ramp design guidance.

Wu et al. (2018) evaluated the role of driver behavior fault in crash/near-crash events on freeway ramps using SHRP2 NDS data. Results showed that driver behavior fault is a significant factor when it came to crashes/near-crashes on freeway ramps. The most common type of driver behavior fault was driver distraction. Gender and level of service were highly associated with driver behavior faults. Female drivers were more likely to exhibit unsafe driving behavior and the level of service had an impact when there was traffic congestion.

Wang & Zhou (2018) evaluated the effect on intersection balance on driver speeds, acceleration/deceleration rates, and risk perception. Results indicated that there was a statistically significant difference in vehicle speeds and acceleration/deceleration rates at interchange terminals for different intersection balances. A balanced intersection was found to result in smoother speeds and acceleration/deceleration rates, which in turn reflected lesser crash/near-crash risks. The driver's risk perception did not have a major influence on driver's speeds and acceleration/deceleration rates.

Turn/Deceleration Lane

Hutton et al. (2015) evaluated the gap acceptance behavior of drivers at left-turn lanes with different offsets – negative, positive, or zero using logistic regression. The study found that the critical gap was longer if left turn offsets were negative when compared with positive or zero offsets. The critical gap was also longer when sight distance was blocked by a left-turning vehicle, and sight distance was more likely to be obstructed when there was a negative offset. Thus, drivers are less likely to accept a gap in this case. The findings of this study can be used to develop guidelines for the design of offset left-turn lanes.

Lindheimer et al. (2018) explored the deceleration rates in urban corridors for baseline conditions, near-crash events, and as the number of through lanes vary. Deceleration rates during baseline conditions and near-crash events were significant, while deceleration rates as the number of through lanes vary were not statistically significant. Predicted deceleration rate increased for both baseline conditions and near-crash events. As the number of lanes increased for near-crash events, the range of predicted values for deceleration rates increased. Under baseline conditions or when there was no interference from other vehicles, the deceleration rate was lower than 11.2 ft/s2. However, the deceleration rates increased when there was interaction with other vehicles such as pulling into a driving lane from an intersection or turning into a driveway.

Wu (2017) analyzed the driver's behavior while making right turns at signalized intersections. The study listed the factors affecting the right turn movement and also discussed the benefits of different right turn movements. Wu found that crash severity is high when speed and deceleration increase before crashes. Most of the drivers do not stop at the stop bar at right turn on red scenarios. This study shows that there is a need to improve countermeasures to reduce right-turn crashes. Although this study was limited as geometric designs were not studied.

Wu and Xu (2018b) focused on right-turn drivers at signalized intersections by analyzing influencing factors on the speed control. Right-turn drivers pose a potential risk on pedestrians who tend to have a high acceleration rate and low observation frequency.

Crosswalk

Sarwar et al. (2017) evaluate the effectiveness of high visibility crosswalks in improving the safety of pedestrians using the driver behavior data of participants from SHRP2 NDS data at three uncontrolled locations in Eric County. Driver behavior was evaluated based on acceleration, speed, throttle pedal actuation, and brake application, and mixed logit and linear regression models were estimated. Results showed that high visibility crosswalks were most likely to decrease the speed and throttle pedal actuation and, at the same time, increased the likelihood of application of brakes. There was also a statistically significant reduction in acceleration rates due to the placement of the high visibility crosswalks, thus likely improving pedestrian safety at these locations.

Haus and Gabler (2018) investigated the characteristics of bicycle crash and near-crash events. Most of the events occurred when bicyclists traveled straight across the path of the vehicle or when the vehicle turned left across the bicyclist’s path. In 49 percent of the cases, the bicycle was visible for more than one second; thus, the study suggested that Automatic Emergency Braking systems have the potential to decrease crash risks.

Roadside Lighting Design Characteristics

The adaptive lighting database (ALD) contains detailed lighting measurements for more than 2,000 miles of major roads. Li et al. (2015) integrated ALD and NDS databases to study the safety impacts of lighting using Geographic Information System tools. The result was an extensive database with detailed roadway lighting measurements for seven states. An example of a safety analysis that researchers can now perform is how lighting characteristics of glare, uniformity, illuminance, affect nighttime safety and speeding behavior as well as the crash or near crash sequence of events for a variety of roadway and traffic conditions.

Li et al. (2017) examined the association between roadway lighting and driver behavior. There were statistically significant correlations between lighting variables and some key driver behavior variables of speed, lateral and longitudinal acceleration, and lane offset. Head movements and time to collision had no significant association with lighting. Horizontal illuminance impacted driver behavior more significantly than uniformity of lighting. Effects are more prominent on entrance ramps and after ramps than for exit ramps. An increase in right lane illuminance and uniform lighting was related to low speeds and gradual lane changes. However, the overall increase in illuminance and uniformity was correlated to more lane changes. The effect of lighting extended beyond 400 ft. from painted gore noses at ramps.

Muttart et al. (2017) compared the nighttime object recognition responses from the NDS database to a timed exposure experiment conducted outdoor on a closed road as well as an indoor study by using an automatic shutter system, which limited the time of exposure to a quarter of a second. The results of the study indicated that the responses with limited time exposure experiments showed a significant positive correlation with the naturalistic nighttime object recognition responses. Drivers in the experiment were equally likely to fail or recognize a particular object as in the SHRP-2 data when the distance from the impact is 60 m or 200 feet. The time exposure study results can be used as a surrogate for driver's expectancy with reasonable accuracy.

Operational Factors

Operational studies assessed the speed choice, lane changing, and car-following behavior of drivers using the NDS data. Some studies also assessed the traffic control devices. A majority of the studies assessed the speed choice behavior at two-lane horizontal curves (refer to the section on horizontal curves). The results of these studies could potentially be used for microsimulation purposes.

Speed Choice

Khan et al. (2018) studied the speed reduction behavior of drivers under foggy conditions when compared to clear weather conditions. Results indicated that for near fog conditions, the speed reduction was around ten- percent, and for distant fog conditions, the speed reduction was around three-percent. Also, the odds of reducing speeds were 1.31 and 1.28 times more likely in case of near fog and distant fog conditions, respectively. The results might change if a more diverse range of age is taken as the sample taken in this study was mostly young drivers.

Wali et al. (2018) examined the relationship between driving volatility prior to crash involvement and crash severity. A total of 16 volatility indices were created, which were used to evaluate different crash-related information such as crash severity, pre-crash maneuvers, and secondary tasks. Greater driving volatility, both in longitudinal as well as lateral direction, increases the probability of police reportable or severe crashes. The effect of longitudinal deceleration was more pronounced compared to longitudinal acceleration.

Wu and Xu (2018a) address two questions: the influence of speed variance on the crash frequency and how to describe it. The findings suggest that a potential crash modification factor can be speed variance. It has a strong relationship with crash frequency.

Chen and Chen (2019) explored the possibility of identifying deriving styles directly from driving parameters. Three clusters of driving styles were identified, for which the influential differentiating factors are speed maintained, lateral acceleration maneuver, braking, and longitudinal acceleration. The results showed that all four attributes examined had an impact on how the trips were clustered, thus suggesting that the clusters capture individual differences in driving styles to some extent.

Perez et al. (2017) identified the kinematic thresholds, which can be used to detect the onset of a crash or near-crash event. The identified kinematic thresholds included: longitudinal deceleration $\leq$ -0.75g, longitudinal acceleration $\geq$0.58 g, Advanced Braking System activation > 0.74 s, Electronic Stability Control activation < 1.45 s, traction control activation < 1.20 s, lateral jerk $\geq$ |4.5 g/s|, decelerations on freeways $\geq$ 0.3g when the vehicle speed is $\geq$ 33mph, ±40°/s > Yaw rate oscillations > ±8°/s within 0.75 s and 90°/s2 > Swerve maneuvers > 15°/s2 within two seconds.

Car Following

Geng et al. (2016a) investigated the influence of leading vehicle type and different environmental conditions on car-following behavior under congested as well as uncongested traffic conditions. The following distance is approximately 11percent longer when following a light truck than a passenger car. Following a light truck under bad weather at night time increases time headway, and this time headway is higher in congested conditions than in uncongested conditions. The distance for the following car increases with an increase in speed for congested flows and decreases with an increase in speed for uncongested conditions. Bad weather has a greater influence on the following behavior under congested conditions.

Hammit et al. (2018) evaluated the differences in car-following behaviors under different adverse weather conditions of rain, fog, snow by calibrating the Gipps car-following model. Freeway capacity is predicted to reduce by eight percent for medium rain, 14-percent for a heavy rain, ten percent for medium-heavy snow, and 24 percent for heavy snow. Network speeds are predicted to reduce by six percent for medium rain, seven percent for heavy rain, 14 percent for medium-heavy snow, and 15 percent for heavy snow.

James et al. (2019) evaluated methods to obtain representative car-following model parameters to describe a population of drivers or specific driving condition. The research findings show that the method that captured the average behavior while preserving correlations between the calibrated model parameters performed the best across all four models; this illustrates the importance of accounting for the underlying relationships between model parameters, as observed elsewhere. However, methods that adequately captured the average behavior while relaxing the assumption of underlying parameter correlations performed better than all other methods. In other words, although the more computationally burdensome methods produce optimal results, simply taking the mean or median of the distribution of individual parameter values offers a practical approach for generating a representative parameter set. For all models, these methods demonstrated significantly better performance than the default parameter sets.

Hammit et al. (2019) used NDS data to calibrate the Wiedemann 1999 car-following model for a subset of NDS trips, cluster trips with similar weather conditions, and identify an optimal parameter set to represent that condition. The researchers then applied the optimal model parameters in a realistic microsimulation network to assess the predicted traffic flow in each weather condition. Findings support the hypothesis that the calibration of driving models for use in microsimulation results in more realistic estimations of traffic flow.

Lane Change

Ahmed et al. (2018) assessed the differences in driving behavior and performance of drivers during adverse conditions. This study uses disaggregate trajectory-level data through the SHRP2 database. The driver behavior is carefully studied, and the researchers analyzed the relationship between key parameters such as speed selection, lane-keeping behavior, and weather conditions. Both parametric methods, such as logistic regression and non-parametric methods as well as classification and regression trees, were used in this study. Speed reduction is the most in snowy weather conditions as opposed to other adverse conditions. Through the study, it was found that NDS data can be efficiently used to find the driver behavior during inclement weather conditions. The variables such as vehicle speed, acceleration, and deceleration rate and yaw rate can be used to analyze the safety measures during adverse weather conditions. The report extensively discusses the various methods that can be utilized for this kind of study, such as behavioral models, weather-related microsimulation software. Lane-keeping behavior can be managed by having weather-based Variable Speed Limit systems, which can track the influence of reduced visibility and enforce the speeds.

Das et al. (2018) investigated the driver lane-keeping behavior in clear and foggy weather conditions by developing a lane-keeping model using ordered logistic regression. The affected visibility due to foggy weather decreases lane-keeping ability significantly, and drivers showed 1.37 times higher standard deviation of lane position when visibility is less.

Ghasemzadeh and Ahmed (2018) modeled lane-keeping behavior under heavy rain conditions using logistic regression. Heavy rain conditions decrease lane-keeping ability significantly, and drivers showed 3.8 times higher standard deviation of lane position under these conditions. Drivers show a better lane-keeping ability on roadways with higher posted speed limits.

Das and Ahmed (2019) examined the lane changing behavior as the function of driver type and adverse weather conditions. Using the K-means cluster analysis technique, drivers were classified into two categories: conservative and aggressive. It was found that in heavy fog the mean lane-changing durations were significantly higher than clear weather under mixed-flow conditions. Moreover, the cluster analysis results revealed that conservative drivers had longer lane-changing durations in heavy fog conditions compared to clear weather.

Jenkins et al. (2016) developed a prediction model for driver distraction based on a variety of performance measures using multiple logistic regression. Three models were developed, but none of the models were a good fit and therefore had very little predictive power. Although a change in lateral acceleration was identified to be an indicator of drivers engaged in texting or dialing, more research is needed overall.

Traffic Control Device

Lin et al. (2017) examined the compliance of drivers to pedestrian safety-related features under different traffic conditions, driver demographics, risk, and distraction behavior. The features considered were "Stop Here on Red," "No Turn on Red," "Turning Vehicles Yield to Pedestrians," and "Right on Red Arrow after Stop." The study found that driver compliance was improved when there were pedestrians on all four features. A lower compliance behavior was observed in older, younger, female, and risky drivers.

Muhire et al. (2018) examined the compliance of drivers at highway-railroad grade crossings under different traffic volumes, speed limits, traffic control devices, and number of trains per day using 5,000 individual crossings from the NDS dataset. A "compliance score" was developed in this study based on visual scanning and speed adjustment. The differences in behavior with the presence of different traffic control devices were very significant. Those highway-railroad crossings having active warning devices had lower compliance scores compared to those with passive warning devices. There was some potential trending among numerical parameters; however, more data needs to be analyzed to arrive at results with statistical significance.

Oneyear et al. (2016) developed a driver braking behavior model for rural controlled intersections based on driver's age, type, and direction of turning movements using a Linear mixed-effects model. Results of the analysis in this study indicated that the presence of devices to alert drivers such as flashing beacons caused the drivers to start braking early. Younger drivers braked almost 40 meters after older drivers (aged more than 25 years). In addition to this, drivers turning from major roadway to minor roadway started braking much earlier than those who turned from minor roadway to major roadway.

Work Zones

Speed Choice

Hallmark et al. (2018) used NDS data to predict speeds in work zones based on different distractions, driver characteristics, and work zone configurations. For drivers engaged in distractions, the predicted speed was 3.88 mph higher than when there was no distraction. Female drivers were 1.99 mph slower than male drivers, and drivers with more miles traveled faster. Speeds are slower by an average of 17.90 mph during nighttime. Speeds are slower by about 6.2 mph when channelizers are present. Variable message signs caused a speed reduction of 2 mph on average. For head to head work zone configuration, the speeds were 10.2 mph slower.

Risk Assessment and Driving Behavior

The work zone study by Bharadwaj et al. (2019) had three key objectives: (1) identify factors associated with risk of an individual driver being involved in a safety critical event in a work zone; (2) develop a logistic regression model to predict this risk; and (3) quantify risk for different factors using matched case-control design and odds ratio. The results indicate that performing a non-driving related secondary task for more than six seconds increases the risk by 5.46 times. Driver inattention was found to be the most critical behavioral factor contributing to risk with an odds ratio of 29.06. In addition, traffic conditions corresponding to a level of service D exhibited the highest level of risk in work zones.

Ghasemzadeh and Ahmed (2019) developed an Ordered Probit Model to identify factors affecting the severity of work zone crashes in different spatial, temporal, and environmental conditions in Washington state using five-year of work zone-related crashes (2009–2013).The findings of this study showed that weather and lighting conditions are among the most important factors influencing the severity of crashes at work zones. Lack of daylight was found to be a influential factor in increasing the severity of work zone crashes, specifically, during dusk and dawn. It was also found that although drivers have less severe work zone-related crashes in adverse weather conditions, the interactions between adverse weather conditions and other contributing factors might increase the severity of work zone crashes.

Thapa et al. (2019) assessed driving behavior when presented with different work zone features such as signs. The authors evaluated the driving behavior upstream of a work zone since this is the point where drivers need to slow or react to upcoming conflicts such as lane closures, congested traffic, or presence of workers and equipment. Results indicated the first work zone sign a driver encountered in the immediate area upstream of the work zone was not significantly likely to elicit a driver response. The model found lane ends, speed limit, and active changeable message signs as statistically significant. Since more than one sign can be legible to the driver at the same time, the effect of overlapping signs was evaluated, but was not found to have significant effect on the driver response. In general, drivers were more likely to show a response to the signs the closer they got to the start of the work zone. Static work zone speed limit and dynamic speed feedback signs were both found to be more likely to elicit a response as compared to normal speed limit signs (non-work zone related). Drivers who were traveling over the posted speed limit were more likely to show response at any given work zone signs with the exception of the first sign. In addition, driver distraction, and driver information like age, gender, experience and other environmental factors were not found to be significant in the model.

Environmental

Ali and Ahmed (2019) used NDS data to detect near-crashes on freeways by comparing environmental conditions and vehicle kinematics signatures of near-crash events to normal driving. They used Binary Logistic Regression model as a parametric detection model, while Decision Tree, K-Nearest Neighbors , and Deep Learning Artificial Neural Network were used as non-parametric detection models. The results showed that the logistic regression model provided a good fit of the input data and can detect near-crashes with outstanding discrimination.

Das and Ahmed (2019) examined the lane changing behavior as the function of driver type and adverse weather conditions. Using K-means cluster analysis technique, drivers were classified into two categories: conservative and aggressive. It was found that in heavy fog the mean lane-changing durations were significantly higher than clear weather under mixed-flow conditions. Moreover, the cluster analysis results revealed that conservative drivers had longer lane-changing durations in heavy fog conditions compared to clear weather. The results of this study could be used in microsimulation model calibration and validation related to lane change in reduced visibility due to fog and various traffic conditions.

Das et al. (2017a) examined the safety effects of inclement weather driving by using a parametric model to quantify visibility issues, non-parametric analysis to identify key associated factors for inclement weather crashes, and topic model development using inclement weather-related crash narratives. Crashes in inclement weather are reduced due to higher friction, and older drivers are less involved in inclement weather-related crashes. Higher speed leads to fatal, and injury crashes in low visibility. Certain roadway characteristics- two-way undivided arterial roadways with posted speed 41–50 mph during inclement weather are riskier for old drivers. Rural roadways with no lighting at dark are riskier again in inclement weather. Interstate two-lane roadways with barriers are always prone to crashes. This study also indicated that five areas require attention to reduce crashes: friction, friction and lighting, intersection, signalization of intersection, and undivided roadways.

Das et al. (2017b) study investigated improper passing related crashes using association rules negative binomial miner to identify the pattern of co-occurrence of variables to generate two-itemset and three-itemset rules. Improper passing crashes on divided roadways are associated with higher AADT, wider roadways, and higher speed for two itemset rules, while, undivided roadways have lower AADT, narrower roadways, low to medium percentage of trucks, and fatal crashes. For two itemset rules, fatal injuries are dominant on undivided roadways. Inclement weather contributes significantly to improper crashes on divided roadways, and the average percentage of trucks contributes significantly to improper crashes on undivided roadways for three itemset rules.

Fountas et al. (2018) explored various time-variant and time-invariant factors affecting injury severities. Two sets of time variant (ice thickness or water depth and sub-surface temperature) and three sets of time invariant (roadway geometrics, vehicle characteristics, driver characteristics, and collision characteristics) factors play a significant role in injury severity. Three driver characteristics (alcohol/drug consumption, use of restraining systems, and gender) and one vehicle characteristic (whether the vehicle was towed) had mixed and statistically significant effects on injury severity.

Ahmed et al. (2018) assessed the differences in driving behavior and performance of drivers during adverse conditions. This study uses disaggregate trajectory-level data through the SHRP2 database. The driver behavior is carefully studied, and the relation between key parameters such as speed selection, lane-keeping behavior, and weather conditions was analyzed. Both parametric methods, such as logistic regression and non-parametric methods such as classification and regression trees, were used in this study. Speed reduction is the most in snowy weather conditions as opposed to other adverse conditions. Through the study, it was found out that NDS data can be efficiently used to find the driver behavior during inclement weather conditions. The variables such as vehicle speed, acceleration, and deceleration rate and yaw rate can be used to analyze the safety measures during adverse weather conditions. The report extensively discusses the various methods that can be utilized for this kind of study, such as behavioral models, weather-related microsimulation software. Lane-keeping behavior can be managed by having weather-based Variable Speed Limits systems, which can track the influence of reduced visibility and enforce the speeds.

Khan et al. (2018) studied the speed reduction behavior of drivers under foggy conditions when compared to clear weather conditions. Results indicated that for near foggy conditions, the speed reduction was around ten percent, and for distant fog conditions, the speed reduction was around three percent. Also, the odds of reducing speeds were 1.31 and 1.28 times more likely in case of near fog and distant fog conditions, respectively. The results might change if a more diverse range of age is taken as the sample taken in this study was mostly young drivers.

Das et al. (2018) investigated the driver lane-keeping behavior in clear and foggy weather conditions by developing a lane-keeping model using ordered logistic regression. The affected visibility due to foggy weather decreases lane-keeping ability significantly, and drivers showed 1.37 times higher standard deviation of lane position when visibility is less.

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Behavioral / Demographic

Mobile Phone Use and Engagement in Secondary Tasks

Owens et al. (2018b) investigated the relationship between cell phone use and crash risk using a case-crossover study such that the driver's cell phone use six seconds prior to the crash as compared to the same driver's cell phone use in four or fewer situations three months prior to the crash. Odds ratios of crash risk were estimated using conditional logistic regression. Results showed that the visual-manual tasks overall and texting in particular significantly increased the crash risk associated with cell phone use while tasks such as cell phone conversation without visual-manual interaction were not associated with crash involvement during cell phone use.

Atwood et al. (2018) examined the overall prevalence of cellphone use, including the rates of calls and texts both per day and hourly while driving, and assessed whether or not the individual crash risk was correlated with cellphone use. The study used data from the SHRP2 NDS dataset. Participants experienced 243 crashes in 216,231 hours of driving. It was found that those who texted more often per day or per hour of driving had higher crash rates after adjusting for age and gender effects. These were crash rate increases 0.58 percent for every additional text per day and all 8.3 percent for every text per hour of driving; overall crash rate increases 0.41 percent for every additional text per day and 6.46 percent for every text per hour of driving.

Distraction is typically caused by engagement in secondary tasks and activities such as manipulating objects and passenger interaction, among many others. Bakhit et al. (2018) provided an in-depth analysis of the increased crash/near-crash risk associated with different secondary tasks using the SHRP2 NDS dataset. The results indicate that reaching for objects, manipulating objects, reading, and cell phone texting are the highest crash risk factors among various secondary tasks. Recognizing the effect of different secondary tasks on traffic safety in a real-world environment helps legislators enact laws that reduce crashes resulting from distracted driving, as well as enabling government officials to make informed decisions about the allocation of available resources to reduce roadway crashes and improve traffic safety.

Kidd and McCartt (2015) examined how relevant crash type and crash severity are when estimating crash risk. Crash risks were estimated for five secondary behaviors relative to when there were no secondary behaviors across different severities. Results suggested that crash type and severity should be considered when estimating crash risk. This was supported by the fact that the secondary behavior of cellphone conversation was not correlated to a significant change in the odds of a crash (odds ratio = 1.21, 95 percent confidence interval (0.89, 1.65)) or to the change in odds of a low-risk tire strike (odds ratio = 0.57, 95 percent confidence interval (0.32,1.02)). The cellphone conversation, however, was correlated to higher odds of a minor crash (odds ratio=2.00, 95 percent confidence interval (1.31, 3.06)) or any other crash but not to low-risk tire strikes.

Schneidereit et al. (2017) analyzed the speed choice or speed adjustment behavior of drivers when engaged in different secondary tasks had been examined. Free-flow speed on interstates/highways was analyzed before, during, and after the secondary tasks of texting, eating, smoking, and adjusting of the radio. The study results indicated that there was some adjustment in speed while texting, but the effect was minimal. For other secondary tasks, the driver’s speed adjustment behavior was not affected significantly.

Gao and Davis (2017) evaluated the impact of driver distraction on the driver’s brake reaction time in a freeway car-following situation. This study concluded that distraction duration and secondary task type were significantly related to the driver’s brake reaction time.

Wotring et al. (2019) analyzed crashes identified in a large-scale naturalistic driving database to assess the prevalence of cognitive disengagement (i.e., purely cognitive distraction and mind wandering/microsleep) or episodes wherein the driver did not look away from the roadway during secondary task completion or wherein another clearly observable contributing crash factor was not present, and the driver's reaction to the crash showed symptoms of cognitive disengagement. The study found that less than one percent (95 percent confidence interval [0.45, 1.66]) of higher severity crashes had a potential contributing crash factor of mind wandering/microsleep; approximately 1.5 percent (95 percent confidence ratio[0.83, 2.32]) had a potential contributing factor of purely cognitive distraction. The results suggest a relatively low prevalence of cognitive disengagement among automotive crashes compared with visual/manual secondary tasks.

Dingus et al.(2019) conducted risk estimations of primarily cognitive secondary tasks by analyzing data from a sample of 3,454 drivers whose driving was monitored using in-vehicle cameras and other sophisticated data collection equipment. The results indicate that, collectively, primarily cognitive secondary tasks are not associated with an increased odds ratio relative to all driving but are associated with a significantly increased odds ratio relative to model driving (i.e., drivers are apparently alert, attentive, and sober). Primarily cognitive secondary tasks were observed in 20 percent of select driving references; interacting with a passenger composed the majority of the primarily cognitive secondary tasks in which drivers engaged. Talking/listening on a hands-free cell phone did not have an increased odds ratio.

Lu et al. (2019) evaluated the causal effects of cellphone distraction on traffic crashes using propensity score weighting approaches. The study reveals several highly imbalanced potential confounding factors among cellphone use groups, e.g., income, age, and time of day, which could lead to biased risk estimation. All three propensity score approaches improve the balance of the baseline characteristics. The propensity score adjusted odds ratios differ from unweighted odds ratios substantially, ranging from −44.25 to 54.88 percent. Specifically, the adjusted odds ratios for young drivers are higher than unweighted odds ratios and these for middle-age drivers are lower. Among different cellphone related distractions, the odds ratios associated with visual-manual tasks (odds ratio range: 3.47–6.63) are uniformly higher than overall cellphone distraction and cellphone talking (odds ratio range: 0.63–4.15). Cellphone talking increases the risk for young drivers but has no significant impact on middle-age drivers.

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Flannangan et al. (2019) developed two cell-phone propensity models, one with age and one without, to develop weights for events without cell phone use. Using these weights, they estimated the probability of engagement in a variety of tasks in place of cell-phone use. They also estimated weighted odds ratios for cell-phone use (all uses) and cellphone talking only. Weighted odds ratios are lower than unweighted odds ratios and much lower than odds ratios compared to ideal driving. This is consistent with the idea that in practice, even if cellphone bans are effective at reducing cell-phone use, they may not greatly reduce risk because drivers may replace cell-phone use with other distracting activities in the same situations in which they normally use cell phones while driving. We also discuss the influence of young drivers on our results. Younger drivers in the dataset are more likely to use cell phones and thus are influential in the propensity model results.

Hoang Ngan Le et al. (2016) presented a deep learning approach to automatically detect whether a driver is using a cell phone and his/her hands are on the steering wheel. This study used MS-RCNN (Multiple Scale RCNN) approaches, which outperformed F-RCNN (Fast Region-based Convolutional Neural Networks) and State-of-the-art methods in terms of accuracy and is less time-consuming.

Osman et al. (2019a) explored the effect of a particular secondary task on corresponding driving behavior using a bi-level hierarchical classification methodology. The first level was the driver's engagement in secondary tasks, while the second level consisted of distinct secondary tasks. Nine driving behavior parameters were considered. The decision tree method predicts the driver's engagement in secondary tasks with 99.3 percent accuracy while the random forests method predicts it with 81.7 percent accuracy. This model can be used to characterize the driver's engagement in secondary tasks as well as to warn/alert drivers to pay attention to the task of driving when engaged in any secondary task.

Ye et al. (2017b) developed Artificial Neural Network models to detect secondary tasks based on driving behavior attributes using the SHRP2 NDS database. The developed models detected the secondary tasks of calling, texting, and passenger interaction with an accuracy of 96.3, 95.6, and 95.2 percent, respectively.

Interacting with Passengers
Precht et al. (2017c) identified the important factors that contributed to driving errors and traffic violations. Additionally, factors that determined the driver's willingness to perform common secondary tasks while driving was also identified. According to the results of this study, the main factors responsible for violations committed by drivers were anger, passenger presence, and persistent individual differences. The driver's tendency to engage in risky driving behaviors overall was a factor that influenced the driver's willingness to engage in secondary tasks.

Drowsy Driving
Owens et al. (2018a) examined the risk and prevalence of crash rates associated with drowsy driving using large-scale NDS data. A driver was categorized as drowsy if his/her eyelids were 80 percent closed for more than 12 percent of the time during a one to the three-minute time span. This method is known as the percentage of eye closure. Results indicated that drowsiness was present in 9 percent of crashes and 5 percent of baseline events. Drowsy driving was significantly correlated with an increase in crash risk, with odds ratios ranging between 1.6 to 3.8. Thus, these results pave the way to investigate the effects of fatigue and drowsiness on crash risk.

Yadawadkar et al. (2019) identified the state of drivers in terms of drowsy, distracted or attentive using three methods, including a statistical feature extraction method, deep learning-based long short-term memory, and video classification using convolutional neural networks. Among the methods used, the statistical feature extraction method showed very good results, having an F1 score of 94 percent when data was balanced using the Synthetic Minority Over-sampling Technique compared to the deep learning methods used for this comparison.

Law Violations
Hedlund (2014) examined the use of seat belts for 313,171 trips and provided findings based on the proportion of trip and age group. The seat belt use during 100 percent of the trip was 50.7 percent, for 80-99 percent the use was 39.5 percent, for 60-80 percent the use was 3.6 percent, for 40-60 percent the use was 1.1 percent, for 20-40 percent the use was 0.6 percent, and for

under 20 percent of the trip it was 4.5 percent. Also, the percentage of drivers who always wear seat belts by age group were: 42.6 percent (16-24 mph), 49.0 percent (35-44 mph), 57.8 percent (55-64 mph) and 47.7 percent (75-84 mph).

Ashley et al. (2019) performed a crash-only analysis to identify driver, vehicle, and roadway-related factors that affect the driving risk at different location types using a machine learning tools. The study then analyzed the most important factors obtained from the machine learning analysis to identify how they affect crash risk. The results, in order of importance of variables, were driver behavior, locality, lane occupied, alignment, and through travel lanes. Also, drivers who violated traffic signals were four times more likely to be involved in a crash than drivers who did not. Those who violated stop signs were two time more likely to be involved in crashes than those who did not. Drivers performing visual-manual tasks at uncontrolled intersections were 2.7 times more likely to be involved in crashes than those who did not engage in these tasks. At non-intersections, drivers who performed visual-manual tasks were 3.4 times more likely to be involved in crashes than drivers who did not. These findings add to the evidence that the establishment of safety awareness programs geared toward intersection safety is imperative.

Age

Low-mileage bias is a term coined based on the hypothesis that senior drivers drive less, leading to far less exposure and experience on the road. This could lead to increased crash rates. Antin et al. (2017a) used SHRP2 data to validate the low-mileage bias in senior drivers' crash rates. Preliminary analysis shows that senior drivers have low mileage, and the within-group variation is significantly higher than other age groups. The two basic questions addressed in this study assessed (1) are drivers with fewer miles per year associated with increased crash rate and (2) how prevalent is low-mileage bias in the senior age group.

With the decline in functional health with age, senior drivers can sometimes not be fit to drive. A series of measured health assessments should be conducted to determine the relationship between senior drivers’ health and crash risk. Antin et al. (2017b) used the negative binomial regression models to develop the driver-level crash rate for NDS. Interestingly, it was found that twenty-two health metrics were significantly associated with crash risk, which involves 16 visual metrics, two physical metrics, and one psychological model. Color vision is one of the visual metrics that have the strongest relationship with the crash rate.

Antin et al. (2017c) examined lane-change behavior and glance locations for three age groups, younger (18–29), middle-aged (30–49), and older drivers (70–94), using data from the SHRP2 NDS data. For both uninterrupted and interrupted lane changes, results showed that many drivers, regardless of age, failed to make appropriate glancing patterns prior to initiating the lane change maneuver. When conflict did occur in relation to the lane-change maneuver, it was most frequently associated with either a lead vehicle or a lead vehicle incurring into the destination lane. Results for interrupted lane changes showed that when conflict did occur with relation to the lane-change maneuver, it was most frequently associated with two sources of conflict: lead vehicle in or incurring into the destination lane or a trailing vehicle in or incurring into the destination lane.

Seacrist et al. (2016) compared the crash rates and rear-end striking crashes among teens (novice, 16-19 years) and adult (experienced, 35-54 years) drivers using NDS data. There were significantly more crashes and rear-end striking crashes among teens when compared to adults. Crash rates for teens were 30 crashes per million miles driven, while crash rates for adults were

5.3 crashes per million miles traveled. The crash ratio of teens versus adults was 5.7 and the rear-end striking crashes ratio for teens vs. adults was 7.5. Both rear-end crash severity and rear-end impact velocity was higher in the case of teen crashes when compared to adults.

Seacrist et al. (2018) examined the near-crash rates and critical event rates among three age groups of people, namely, teens (16-19 years), young adults (20-24 years), and adults (35-54 years). The near-crash rates among teens were high, around 81.6 near-crashes per million miles, compared to 56.6 near-crashes per million miles traveled for young adults, and 37.3 near-crashes per million miles traveled for adults. The near-crash events involving rear-end, road departure, sideswipe, and animal involved significantly more teens. In addition to this, teens also showed a greater critical event rate of 102.2 critical events per million miles while young adults and adults showed a critical event rate of 72.4 and 40.0 critical events per million miles traveled, respectively.

De Winter et al. (2018) assessed the correlation of Driver Behavior Questionnaire and Sensation Seeking Scale with the recorded crashes and measures of driving histories. Observations made from this study were: Older drivers report fewer violations, female drivers report more errors (slips and lapses) but fewer violations compared to male drivers. The study concluded that Driver Behavior Questionnaire violations and Sensation Seeking Scale have a small correlation with crash involvement and small to moderate correlation with near-crash events and driving style. On the other hand, Driver Behavior Questionnaire errors are weak in predicting crashes or driving style.

Huising et al. (2018) examined the correlation between secondary task involvement. Risk of a crash and near-crash events among older drivers above the age of 70 years has been examined using conditional logistic regression to generate odds ratios over 95 percent confidence interval. For a crash when there was no secondary task involved, the researchers used an odds ratio (0.94 over 95 percent confidence interval 0.68-1.29, and for a near-crash, it was 1.08 over CI 0.79-1.50. The crash risk with cell phone use was 3.79 times higher than with no cell phone use. Glances in the interior of the vehicle had an increased risk of near-crash involvement with an odds ratio of 2.5 over 95 percent (confidence interval of 1.24-5.26). Distractions external to the vehicle had a decreased risk of crash involvement with an odds ratio of 0.53 over 95 percent (confidence interval of 0.30-0.94).

Mastromatto et al. (2017) examined whether reducing the demand on negotiating ramps would benefit older drivers with medical conditions. Two sets of ramps, one having more favorable geometric features than the other, were considered. Reducing the demand on negotiating ramp caused the older drivers with medical conditions to increase the gap with the lead vehicles. Also, there was no significant effect of ramp design on driver performance.

Penmetsa et al. (2017) examined the changes in risk perception of drivers of different age groups before and after their involvement in a crash or at fault situation in a crash. Results indicated that a change in risk perception became significant after the participants were involved in two or more crashes. Drivers in the age group 16-19 years, found at fault in a crash, showed lower risk perception behavior compared to drivers in the same age group not found at fault in a crash. However, drivers in this age group showed significantly increased risk perception after being involved in a crash. Drivers in the age group 45-54 years showed higher risk perception when found at fault in a crash while showed lower risk perception behavior when involved in a crash.

Wu and Xu (2018c) examined driver behavior on rural two-lane two-way roads with crash risk and analyzed the influence of different factors on driver behavior fault in a crash or near-crash event. According to the results, young drivers in the age group 16-19 years had a higher probability of being involved in driver behavior fault. The presence of intersection and curves also increase the chances of a driver's behavior fault. Drivers with no hands-on wheels were likely to show driver behavior fault.

Avelar et al. (2018) used NDS data to explore the car-following behavior of drivers belonging to different age groups. Researchers calibrated a dynamic mixed-effects model to estimate the reaction time of drivers and found that the reaction time increases with age (from 1.1 seconds for drivers younger than 20 years, up to 2.2 seconds for drivers older than 69 years). Compared to other age groups, younger drivers were found to be over-sensitive to relative speed, and the following gap as the magnitude of their speed adjustment due to these factors was found largest.

Higgins et al. (2017) investigated the driver reaction times across different driver distraction type, driver's age, and roadway environment. For drivers engaged in any type of distraction, the median reaction time was 40.5 percent longer. Median reaction times for young drivers was found to be 0.733 times the median reaction time for older drivers. In the case of urban environments, the median reaction time was 1.377 times larger than in highway or residential areas.

Simons Moron et al. (2019) examined the incidence rates of elevated gravitational force events (kinematic risky driving) among 16- to 17-year-old drivers compared to those of 18- to 20-year-old, 21- to 25-year-old, and 35- to 55-year-old drivers over a 12-month period. The kinematic risky driving incidence rates for 16- to 17-year-old drivers were higher than the rates for older drivers at each three-month period. Analyses of individual differences for the 12-month period indicated that incidence rates for the 16- to 17-year-old group were 1.84 times higher than the rates for 18- to 20-year-old drivers, 2.86 higher than those for 21- to 25-year-old drivers, and 4.92 times higher than those for 35- to 55-year-old drivers. The incident rate for 16- to 17-year-old males was 1.9 times higher than that for same-aged females in the first three months and 2.3 times higher over 12 months. Over the study period, kinematic risky driving rates of 16- to 17-year-old participants declined 24.5 percent among females and 18.0 percent among males.

Calvo et al. (2019 tried to study interaction between age and secondary task engagement and how that impacts crash likelihood and maneuver safety. It was found that the distribution of crashes per one million km driven during the NDS was similar to previous research, but with fewer crashes from older drivers. Additionally, it was found that older and middle-aged drivers engaged in distracted driving more frequently than was expected, and that crashes were significantly more likely if drivers of those age groups were engaged in secondary tasks. However, secondary task engagement did not predict judgment of safe/unsafe vehicle maneuvers.

Socioeconomic Factors

Ye et al. (2017a) proposed a Crash Risk Index to evaluate the crash risk based on socioeconomic factors of drivers, their tendency to be involved in a secondary task, and specific category inside a socio-economic factor using logistic regression analysis. The proposed index was illustrated with an example, including calculation and interpretation. It gave an indication of crash risk associated with the socioeconomic characteristics of drivers along with the possibility of engaging in secondary tasks. This crash risk index measure can be used by DOTs for making policies and safety programs as well as by auto insurance companies to determine the crash risk associated with their clients.

James and Hammit (2019) hypothesizes that there also exist clusters of drivers whose behavior is sufficiently similar to be considered a homogeneous group. To test this hypothesis, this study applied a 664-trip sample of trajectory-level data from the SHRP2 NDS dataset to calibrate the Gipps, Intelligent Driver Model, and Wiedemann 99 CFMs. This research provided evidence of the existence of homogeneous groups of driving behavior using the expectation maximization clustering algorithm. Four classification algorithms were then applied to classify the trip's cluster ID according to driver demographics. Driver age, income, and marital status were most commonly identified as important classification attributes, while gender, work status, and living status appear less significant. The classification algorithms, which sought to classify a trip's behavioral cluster ID by the driver-specific attributes, achieved the highest accuracy rate when predicting the desired velocity car-following parameter clusters.

Eye Glance Behavior

Bärgman et al. (2015) presented a novel method for estimating crash and injury risk from off-road glance behavior for crashes and near-crashes alike. A 'what-if ' (counterfactual) simulation was applied to 37 lead-vehicle crashes and 186 lead-vehicle near-crashes from lead-vehicle scenarios identified in the SHRP2 NDS dataset. Alternative applications of the method and its metrics are also discussed. This method can also be used to evaluate the safety impact of secondary tasks (such as tuning the radio). The method presented in this paper can guide the design of safer driver–vehicle interfaces by showing the best tradeoff between the percent of glances that are on-road, the distribution of off-road glances, and the total task time for different tasks.

The study by Lee et al. (2018) aimed at applying counterfactual simulation to apply the glance patterns from tuning radio onto lead-vehicle events in NDS data to determine rear-end crash risk associated with it. This study showed that there were some near crashes that could have been avoided to transform into crashes if there were no off-road glances. Also, the radio tuning glance patterns produced 2.85 to 5 times more crashes than the normal driving situation.

Markkula et al. (2016) analyzed the naturalistic driver braking behavior by fitting a simple piecewise linear model to the events with or without visual distraction so that details how braking was initiated and controlled can be examined. Brake onset always occurred within 0.5 seconds of a reaction by the physical driver to the collision threat. Brake onset timing could not be described in terms of a single value or distribution or brake reaction time unlike previous studies. Responses are fast when drivers looked on the road late as compared to when the glances were long. The deceleration behavior could be best explained as a linear ramp-up followed by a constant maximum deceleration. The rate of ramp-up increased with the urgency of the situation, while maximum deceleration did not vary with kinematics in case of crashes. However, it was kinematics dependent in near-crash situations.

Precht, L. (2018) analyzed the effects of different cognitive distractions such as secondary tasks (talking on the phone, singing), driver emotions (happiness, anger), and combination of secondary tasks and emotions (arguing with someone) on the driving performance. It was found that there was no relation between cognitive distracting secondary tasks, driver emotion, or a combination of both with driver's performance. However, the activities which required the driver's gaze to move away from the forward roadway had high chances of resulting in poor driving performance or crashes.

Lee et al. (2019) used counterfactual simulation to take the glance patterns for manual radio tuning tasks from an on-road experiment and applied these patterns to lead-vehicle events observed in NDS. The radio tuning task increases crash risk from 9.7 to 11.3 percent in crash imminent situations and from 0.2 to 0.3 percent in everyday driving situations, compared to baseline driving. If the events that were avoidable with the eyes on the forward roadway are removed, the crash risk increased from 0.9 to 2.4 percent (2.9 times) in crash imminent situations and from 0.03 to 0.15 percent (five times) in everyday driving situations.

Kanaan et al. (2019) utilized vehicle-based measures from a naturalistic driving dataset to detect distraction as indicated by long off-path glances (≥ 2 s) and whether the driver was engaged in a secondary (non-driving) task or not, as well as to estimate motor control difficulty associated with the driving environment (i.e. curvature and poor surface conditions). Advanced driver assistance systems can exploit such driver behavior models to better support the driver and improve safety. Given the temporal nature of vehicle-based measures, Hidden Markov Models were utilized; GPS speed and steering wheel position were used to classify the existence of off-path glances (yes vs. no) and secondary task engagement (yes vs. no); lateral (x-axis) and longitudinal (y-axis) acceleration were used to classify motor control difficulty (lower vs. higher). Best classification accuracies were achieved for identifying cases of long off-path glances and secondary task engagement with both accuracies of 77 percent.

Familiarity with Roadway

Wu & Xu (2018a) analyzed the effect of road familiarity on the driver distraction or involvement in secondary tasks and also its effect on driving operations. Results showed that the likelihood of drivers being distracted was higher on familiar roads compared to unfamiliar roads. Most of the secondary tasks considered for this study occurred on familiar roads with the most common being focusing on objects. The average time for drivers eating or drinking while driving was more on familiar roads; around 8.67 seconds. The secondary task of checking cellphones was high on both familiar and unfamiliar roads. In addition to this, drivers were more likely to be speeding and choose a shorter distance in case of familiar roads.

Pratt et al. (2019) studied the differences between the speed choice of familiar and unfamiliar drivers as they traverse curves. The results of the analysis confirm earlier findings that familiar drivers choose higher speeds through curves. The successful use of the SHRP2 database for this analysis of route familiarity shows that the database can facilitate similar efforts for a wider range of driver behavior and human factors issues.

Medical Conditions

Aduen et al. (2018) examined the association among attention deficit hyperactivity disorder, depression, and adverse driving outcomes by eliminating the self-referral bias and lack of psychiatric comparison groups. In this study, SHRP2 data was segregated into groups based on the psychiatric diagnosis. The study is one of the pioneers in comparing high incidence psychopathology with risk factors associated with violation and collision rates. Attention deficit disorder and depression were found to be associated with multiple violations and high risk relative to the healthy drivers. One of the key reasons for the increased risk could be because of the shared symptoms between the disorder and depression – inattentive symptoms. Another observation from the study shows that drivers with depression who were involved in the collision were significantly injured at a higher rate than healthy control drivers (this study included all the participants involved in the NDS).

Aduen et al. evaluated the crash risk in relation with the attention deficit disorder and depression, and these researchers challenged the overestimation and underestimation of previous studies. With an extensive sample size of 3,226 drivers, this study reports several interesting results. It found that with an increase in symptom severity score, there was a five percent increase in crash risk. The study also found 0.65 annual crashes and 1.08 near-crashes per driver with the disorder compared to healthy drivers. Another observation in the study was that drivers with depression are less prone to crashes than driver with severe attention deficit disorder symptoms.

Liu et al. (2017) analyzed the correlation between seven types of sleep disorders (narcolepsy, sleep apnea, insomnia, shift work sleep disorder, restless legs syndrome, periodic limb movement disorder, and migraine) and driving risk using NDS data. Driving risks vary with drivers having different sleep disorders. Drivers having narcolepsy had a high likelihood of crash risk with an adjusted odds ratio of 10.24 (95 percent confidence interval: 0.86-122.24) but with low significance ($p < 0.1$). Female drivers with sleep apnea had an adjusted odds ratio of 1.36 and $p < 0.05$ for crash/near-crash events. Insomniac drivers had a significantly high likelihood of crashes (odds ratio of 1.49, 95 percent confidence interval: 1.07-2.06). For drivers with the swift work sleep disorder, the Poisson log-linear regression model predicted the crash risk to be 7.5 times higher than for those without the disorder. Restless legs syndrome impacted female drivers specifically both in terms of increased crash risks (odds ratio of 2.26, 95 percent confidence interval: 1.20-4.26) and performing unsafe maneuvers (adjusted odds ratio of 3.38, $p < 0.05$). For drivers with periodic limb movement disorder, the associated risk had an adjusted odds ratio of 1.43 with a significance of $p < 0.05$. There were no increased risks observed due to the driving behavior of drivers having migraines as opposed to previous studies.

Precht et al. (2017b) investigated the effects of anger on driving behavior. Ten-minute segments of trips were analyzed in this study where drivers exhibited driving errors, traffic violations, and aggressive expressions, which was compared to the baseline or uneventful data where drivers did not exhibit any such behavior. Results indicated that the driving error frequency was affected neither by anger nor anger in combination with a conversation. However, anger was associated with aggressive expressions and unsafe driving behavior towards other road users. The violation frequency was associated with anger triggered due to other road users or due to threats, provocations, and frustrations. Arguments of drivers with passengers or anyone on the phone were not associated with any type of abnormal driving behavior. Driving violations depended on the anger intensity as well; severe anger was more correlated with driving violations compared to slight or marked anger.

Automated Driver Assistance Systems

Several studies, particularly in recent years, have used the NDS data for developing and assessing the safety and operational impacts of automated driver assistance systems. In a study by Bärgman et al. (2017), the authors demonstrate the importance of the choice of driver model when counterfactual simulations are used to evaluate two systems: (1) forward collision warning, and (2) autonomous emergency braking. Secondly, the paper demonstrates how counterfactual simulations can be used to perform sensitivity analyses on parameter settings, both for driver behavior and automated driver assistance system algorithms. The results for forward collision warning show a large difference in the percent of avoided crashes between conceptually different models of driver behavior, while differences were small for conceptually similar models. As expected, the choice of the model of driver behavior did not have much of an effect on the autonomous emergency braking.

Osman et al. (2018) developed a crash or near-crash event prediction model using vehicle kinematics data from the NDS database. Data was prepared using two approaches: Euclidean point and Similarity matrix. The analysis was done using several algorithms such as K Nearest Neighbor, and Random Forests. Both models had a very good accuracy of around 90 percent at one-second prediction horizon and four-second turbulence horizon. These high accuracy models can be used as crash avoidance systems in Autonomous vehicles.

Ivanco (2017) investigated and quantified the relationship between time headway and vehicle speed in an attempt to quantify naturalistic driving so that it can be adopted for autonomous driving. Median headway distance increases with increasing speed. Time headway decreases as the host vehicle velocity increases and stabilizes at around 2 seconds. Larger time headways are observed during driving speeds around 50 km/hr (city speeds) as there is a variety of driving situations in this case. While in the case of high speeds (around 100 km/hr), time headway less than 2 seconds can be explained by the fact that there are not many changes in driving situations.

Kluger et al. (2016) developed an algorithm to detect safety-critical events using a discrete Fourier Transform in combination with K-means clustering to detect patterns in vehicles' longitudinal accelerations time series data. The algorithm detected approximately 78 percent of crashes and near-crash events with one false positive every 2.7 hours using only longitudinal accelerations time series data. Some of the applications of this algorithm include: Identifying SCEs in connected vehicle environments, allowing insurance companies to evaluate risks better, allowing transportation agencies to provide better emergency response.

Wu and Lin (2019) analyzed the effects of critical driving situations on a driver's perception time during real-world driving. It was found that critical driving situations, the driving environment, and driver behavior are all among the influential factors affecting PT. The longest PTs are during critical driving situations where the vehicle ahead is stop-and-go, which can be as long as 2.84 seconds while controlling for the effects of driving environment and driver behavior factors, compared to other types of driving situations such as a vehicle ahead decelerating or lane changing

Arvin et al. (2019) studied the role of pre-crash driving instability, or driving volatility, in crash intensity (measured on a four-point scale from a tire-strike to an injury crash) by analyzing microscopic vehicle kinematic data. Modeling results of the fixed and random parameter probit models revealed that volatility is one of the leading factors increasing the probability of a severe crash. Additionally, the speed prior to a crash is highly correlated with intensity outcomes, as expected. Interestingly, distracted and aggressive driving are highly correlated with driving volatility and have substantial indirect effects on crash intensity. With volatile driving serving as a leading indicator of crash intensity, given the crashes analyzed in this study, early warnings and alerts for the subject vehicle driver and proximate vehicles can be helpful when volatile behavior is observed.

Lanka et al. (2019) explored machine learning models for predicting and classifying driver's response. For classifying driver's response, longitudinal acceleration vs lateral acceleration plot was divided into nine different classes and selected machine learning modes were trained for predicting the class of driver's response. Performances of models for classification were tabulated and it is observed that Extremely Randomized Trees based model had better prediction accuracies in comparison with other models when fit using SHRP2 NDS data. The input features were reduced using dimension reduction techniques to reduce the computation time by over 70 percent.

Orlovska et al. (2019) investigates the effect of driving context to the use of automated driver assistance systems. The analysis of the NDS data helped to register how drivers use these systems in different driving conditions and indicated several issues associated with their usage. To be able to clarify the outcomes of quantitative sensor-based data analysis, an explanatory sequential mixed-method design was implemented. The method facilitated the subsequent design of qualitative in-depth interviews with the drivers. The findings warrant consideration of the driving context as a key factor enabling the effective development of automated driver assistance system functions.

Christ (2019) simulated the relative influence of tire, vehicle and driver factors on forward collision accident rates This study shows that these vehicle systems have a large impact on safety and can change the amount of influence attributed to other parameters such as tire grip levels. As the use of automated vehicle systems expands, so will the influence of tire grip performance levels on collision risks.

Khan and Ahmed (2019) developed an affordable in-vehicle snow detection system which can provide trajectory-level weather information in real time. To train the snow detection models, two texture-based image features including gray level co-occurrence matrix and local binary pattern, and three classification algorithms: support vector machine, k-nearest neighbor, and random forest were used. The analysis was done on an image dataset consisting of three weather conditions: clear, light snow, and heavy snow. While the highest overall prediction accuracy of the models based on the gray level co0occurrence matrix features was found to be around 86 percent, the models considering the local binary pattern based features provided a much higher prediction accuracy of 96 percent.

Chen et al. (2019) computed the feature values of the dashcam videos using the optical flow method. They also propose a seven-region segmentation method to separate regions of different nature in a video frame and used the random forest classifier to classify the output feature vectors into five driving event categories. According to the experimental results, the recognition accuracy was up to 88 percent, and the average accuracy was 83.6 percent.

Osman and Rakha (2019) investigated the possibility of detecting the engagement in secondary tasks using deep learning tools. The results show excellent performance for the developed models, with a slight improvement for the LSTMN model, with overall classification accuracies ranging between 95 and 96 percent. Specifically, the models are able to identify the different types of secondary tasks with high accuracies of 100 percent for calling, 96–97 percent for texting, 90–91 percent for conversation, and 95–96 percent for the normal driving. Based on this performance, the developed models improve on the results of a previous model developed by the author to classify the same three secondary tasks, which had an accuracy of 82 percent.

Other

Papazikou et al. (2017) determined the thresholds of indicators when normal driving behavior or uneventful driving deviates from crashing or near-crash situations. Four indicators of deviation from normal driving behavior were identified, namely, Time to collision, Acceleration, Deceleration and Lateral Acceleration. Functional equations were developed for each of the thresholds (as a function of speed) to determine the threshold value for an indicator. The results of this study can be used to detect deviation from normal driving behavior on its very early onset.

Papazikou et al. (2018) analyzed the whole crash sequence from a normal driving situation until a crash or near-crash event occurred to identify reliable factors for detecting deviations from normal driving behavior using an empirical approach and a multilevel mixed-effects modeling technique. Reliable indicators of early deviations from normal driving behavior were identified, which included longitudinal and lateral acceleration, yaw rate and time to collision. The time to collision values are influenced based on vehicle type, speed of the vehicle, longitudinal acceleration, and time within the crash sequence. The change in the time to collision values can be used as an indicator of deviation in automated driver assistance systems so that it can be prevented.

Using a combination of state-of-the-art approaches in computer vision and machine learning, Taccari et al. (2018) developed a methodology to identify and distinguish crash, near crash, and safe events from dashcam videos. The results of this study showed that the method used in this study was able to distinguish between dangerous and safe events with 87 percent accuracy. For classifying events into the crash, near crash, and safe events, the method used classified the events with 85 percent accuracy.

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APPENDIX B. INTERVIEW SCRIPT

Because of your expertise related to <name of document>l we would like to ask your opinion about how the research used to support the document could potentially benefit from the SHRP2 NDS and RID data.

1. What has your involvement been with the development of this document?

2. If they have been involved or have knowledge of the process:
   a. How is research tracked and evaluated for potential inclusion in the document?

   b. What is the revision process (contract, committee)?

   c. What is the revision timetable, when will next edition be?

3. What is the basis for any values included in the document?

4. Are the values used in the document regularly reviewed? By whom? Is there any sort of formal documentation as to source information and when values are changed?

5. How do you use this document in your own research?

6. How do practitioners in agencies and consultant firms use this document?

Run through slide show explaining SHRP2 RID and NDS data

7. What are the topics in your document that you wish you had more solid research evidence for?

   a. Do you think SHRP2 data could help that?

8. Are there any specific chapters or sections of the document where you think research using SHRP2 data would be particularly helpful?

9. What do you think should be the shelf life of this data set? At what point is it not useful? RID and NDS separately.

    a. RID

    b. NDS

10. What are the advantages of using SHRP2 data to inform future editions of this document?

11. What are limitations of using SHRP2 data to inform future editions of this document?

12. Are there other documents in your area of expertise that could benefit from research using the SHRP2 data?