CHAPTER

1

Introduction

1.1 Motivation

Although a lot of effort has been placed by agencies across the world to reduce the number and severity of crashes[1] via improvements in highway design, vehicle technology, traffic policy, emergency services, and the like, the effects of highway crashes on road transport networks are still a major source of morbidity (Lord and Washington, 2018). Fig. 1.1 illustrates the historical statistics in roadway fatalities in the United States between 1913 and 2018 (similar trends have been observed among most industrialized countries). This figure shows that the trend in roadway fatalities has been slightly going down since early 1970s, with sharp decreases during economic recessions (further discussed later). This figure also demonstrates that when the values are analyzed by taking into account the vehicle miles traveled (a measure of exposure), the rate has been going significantly down since the beginning of official crash data collected by the federal government. Even though the crash rate shows a great reduction, the raw numbers, as a public health measure, are still the most important factor that guides the allocation of resources. For example, although the crash rate is generally going down, the number of injured people arriving at various emergency rooms located within a jurisdiction, or the patient

[1] In this textbook, we use the term "crash" to reflect outcome of a collision between a vehicle and a fixed object (i.e., an event where only one vehicle is involved), one or more vehicles, or one or more vulnerable road users (i.e., pedestrians, cyclists, etc.). Although some people do not like to label a crash an "accident" because the word accident could absolve the driver of any responsibility, the word accident could still be employed as that word refers to the probabilistic nature of the event. If accidents were coming from a deterministic system, we should therefore be able to "predict" with certainty when one or more crashes would occur in the future. Obviously, in the context of this textbook, this is not possible.

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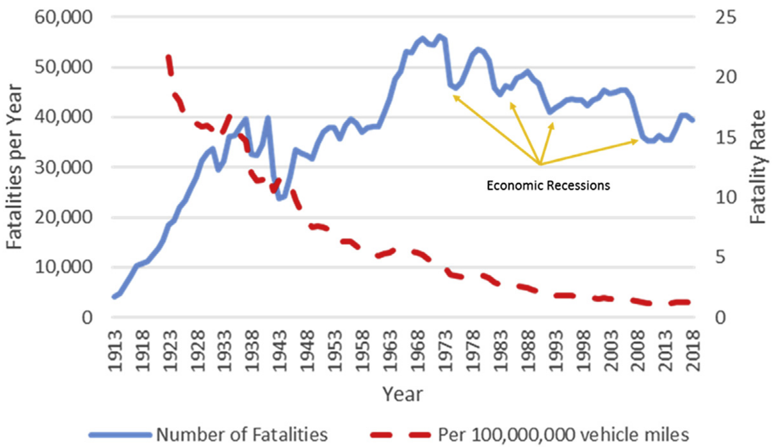

FIGURE 1.1 Number of fatalities and fatalities per 100 million vehicle miles in the United States between 2013 and 1018 (NSC, 2018).

arrival rate, is the primary metric that the hospital management uses to allocate medical services. The same information is also needed, for example, for managing first responders, such as emergency medical services, firefighters, and national, regional, and local police forces. Hence, the desired attention usually focuses on crash or injury counts for many safety interventions, although exposure in terms of vehicular traffic and/or segment length may still need to be incorporated into some of the methods utilized for assessing safety.

According to the World Health Organization (WHO), between 2000 and 2016, roadway-related crashes increased from about 1.15 million to 1.35 million deaths globally (WHO, 2018). On an annual basis, about 80 million nonfatal injuries warranting medical care occur on highway networks (Word Bank, 2014). Road traffic injuries are ranked eighth as the leading cause of death (2.5%) among people of all ages, right in front of diarrheal diseases and tuberculosis (WHO, 2018). Vulnerable road users (i.e., pedestrians and cyclists) represent 26% of road injury deaths, while drivers and passengers of motorized two-wheel and three-wheel vehicles account for another 28% worldwide (WHO, 2018). Unfortunately, while a large proportion of high-income countries have observed either a reduction or no change in traffic-related deaths between 2013 and 2016, a significant number of middle- and low-income countries have observed an increase in traffic-related deaths (WHO, 2018), in large part attributed to the rapid motorization observed in developing countries (World Bank, 2014).

The economic burden of crashes significantly impacts the global economy. In the United States, for instance, highway crashes are estimated to have caused more than US$871 billion in economic loss and societal harm in 2010 (Blincoe et al., 2015). In Europe, it is estimated that crashes have cost more than US$325 billion (€280 billion) in economic harm in 2015 (this value is considered underestimated) (Wijnen et al., 2017), while in Australia the economic burden was estimated to be US$ 23.9 billion (AU$33.2) in 2016 (Litchfield, 2017). Globally, it is estimated that 3% of gross domestic product (GDP) is lost to highway crashes (all severities) and can be as high as 5% for middle- and low-income countries (WHO, 2015). In short, in addition to the pain and suffering that crashes have caused to the victims of such events, highway crashes can significantly impede a country's economic growth or viability across the globe.

As described in Fig. 1.1, the relationship that economic activity is strongly linked to the number of fatalities observed on highways has now been well established (Wijnen and Rietveld, 2015; Elvik et al., 2015; Wegman et al., 2017; Noland and Zhou, 2017; Shimu, 2019). In times of economic growth, the number of crashes increases, while during economic hardship (i.e., recession), the number of crashes decreases. Fig. 1.2 illustrates such a relationship in detail, during the "Great Recession" of 2007–09 in the United States (the right-hand side of Fig. 1.1). The influencing factors include unemployment level, especially among young people, mode shift for people who are unemployed and lower exposure by high-risk drivers (e.g., drivers below 25 years old) during recession periods (Blower et al., 2019). The relationship between economic activity and crash risk is very important to be understood before analytical tools are used for analyzing highway crash data. This is to avoid the potential confounding effects when treatments are implemented and evaluated for reducing the number and severity of crashes.

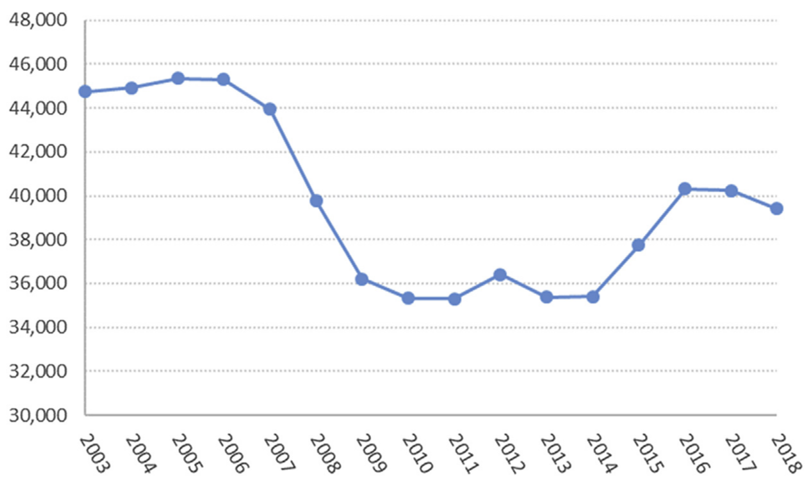

FIGURE 1.2 Fatalities trend during the great recession of 2007–09 in the United States (NCS, 2018).

Given the magnitude of the problem associated with highway crashes, numerous public transportation agencies across the world, from national to local agencies, have placed a lot of effort (i.e., labor, promotion, etc.) and allocated a large amount of funds for reducing the number and severity of crashes, especially over the last 25 years. For example, in the United States, the National Highway Transportation Safety Agency (NHTSA) has devoted US$908 million for highway-safety initiatives related to vehicle safety, driver safety, and traffic enforcement in 2016 (NHTSA, 2016). In 2019, the Federal Highway Administration (FHWA) allocated US$2.60 billion solely for safety projects, which include research, dissemination, engineering, and construction projects among others (FHWA, 2019). Similar financial investments have been placed by various transportation agencies in Europe, Middle East, Asia, South Asia, and Oceania. The strong commitment to reducing the negative effects of highway crashes by decision-makers can be seen in the Vision Zero[2] movement that was first introduced by the Swedish Government in 1997. This movement consists in finding new and innovative approaches and ways of thinking (i.e., shifting the responsibility from road users to highway designers and engineers for reducing crashes) for significantly reducing, if not eliminating, fatal and nonfatal injuries on highways, especially on urban highways (Kristianssen et al., 2018). Vision Zero has been assertively implemented in various communities across the globe.

To respond to the increasing investment in safety-related projects and help with the aim of reducing, if not eliminating (as per Vision Zero) highway crashes, research into methods and tools for analyzing crash data has exponentially grown during the same time period. The testament of such increase has recently been documented in two scientometric overview publications that visually mapped the knowledge in the field of highway safety (i.e., key areas of research) and the impact of the research that has been published in the leading journal *Accident Analysis and Prevention* (Zou and Vu, 2019; Zou et al., 2020). These authors identified "crash-frequency modeling analysis" to be the core research topic in road safety studies, hence showing the relevance of the material covered in this textbook.

Although design and application manuals, such as the Highway Safety Manual (HSM) (AASHTO, 2010) or the Road Safety Manual (RSM) (PIARC, 2019), specialized textbooks, such as the one by Hauer (1997) on before-after studies or Tarko (2020) on surrogate measures of safety, and review papers (see Lord and Mannering, 2010; Savolainen et al., 2011; Mannering and Bhat, 2014), already exist, there is not a single source available that covers the fundamental (and up-to-date) principles related to the analysis of safety data. As discussed by Zou and Vu (2019), the field

[2] https://visionzeronetwork.org/.

of highway safety covers very wide areas of research and applications (i.e., psychology, human factors, policy, medicine, law enforcement, epidemiology). Manuals and textbooks have already been published on these topics (see Dewar and Olson, 2007; Shinar, 2007; Smiley, 2015). This textbook complements these published manuals and focuses on the actual analysis of highway safety data.

The primary purpose of this textbook is to provide information for practitioners, engineers, scientists, students, and researchers who are interested in analyzing safety data to make engineering- or policy-based decisions. This book provides the latest tools and methods documented in the literature for analyzing crash data, some of which have in fact been developed or introduced by the authors. The textbook covers all aspects of the decision-making process, from collecting and assembling data to making decisions based on the results of the analyses. Several examples and case studies are provided to help understand models and methods commonly used for analyzing crash data. Where warranted, helpful hints and suggestions are provided by the authors in the text to support the analysis and interpretation of crash data.

The textbook's readership is suitable for highway safety engineers, transportation safety analysts, highway designers, scientists, students, and researchers who work in highway safety. It is expected that the readers have a basic knowledge of statistical principles or an introductory undergraduate-level course in statistics. This textbook specifically complements the HSM published by AAHSTO and the RSM by the World Road Association. The publication of these manuals has increased the demand for training engineers and scientists about understanding the concepts and methods outlined in the HSM and the RSM.

1.2 Important features of this textbook

This textbook is needed for the following reasons:

(1) There are no manuals nor textbooks that summarize all the techniques and statistical methods that can be utilized for analyzing crash data into a single document (although the words "crash data" are frequently used in this textbook, many methods and techniques can be used for analyzing all types of safety data, such as surrogate measures of safety (i.e., traffic conflicts), speed-related incidents, citations, driver errors or distractions, and the like). The few manuals that cover highway safety concepts usually provide basic information, such as regression equations, figures, charts, or tables that may not always be suitable for the safety analyses. For example, transferring models from one jurisdiction to another may

not be feasible for methodological reasons. Furthermore, no manuals specifically explain how to develop crash-frequency models, crash-severity models, or data mining techniques from the data collection procedures to the assessment of the models using data collected in their own jurisdictions.

(2) There are no textbooks that cover all aspects of safety data analyses and can be used in a teaching or classroom environment, such as data collection, statistical analyses, before-after studies, and real-time crash risk analysis among others. This textbook can be used as a core textbook for a senior undergraduate or graduate course in highway safety. Different chapters could also be used for senior-level undergraduate courses that cover some elements of highway safety, highway design, crash data analyses, or statistical analyses.

(3) Crash data are characterized by unique attributes not observed in other fields. These attributes include the low sample mean and small sample size problem, missing values, endogeneity, and serial correlation among others (Lord and Mannering, 2010; Savolainen et al., 2011). These attributes can significantly affect the results of the analysis and are, to this day, often not considered in analyses conducted by transportation safety analysts. Not taking into account, these attributes can lead to misallocation of funds and, more importantly, could potentially increase in the number and severity caused by motor vehicle crashes. The textbook addresses the nuances and complexity related to the analysis of crash and other types of safety data as well as the pitfalls and limitations associated with the methods used to analyze such data.

1.3 Organization of textbook

The textbook is divided into three general areas. The first area includes chapters that describe fundamental and theoretical principles associated with safety data analyses. This area covers the nature of crash data from the human and statistical/mathematical perspectives, as well as key crash-frequency and crash-severity models that have been developed in the highway safety literature. The second area groups chapters that describe how the models described in the first area are applied for analyzing safety data. The chapters include methods for exploring safety data, conducting cross-sectional and before-after studies, identifying hazardous sites or sites with promise as well as tools for incorporating spatial correlation, and identifying crash risk on a near real-time basis. The third area assembles alternative safety analysis tools. The methods include how to use surrogate measures of safety and data mining techniques for extracting relevant information from datasets, including those categorized as big data (e.g., naturalistic data).

1.3.1 Part I: theory and background

Chapter 2—Fundamentals and Data Collection describes the fundamental concepts related to the crash process and crash data analysis as well as the data collection procedures needed for conducting these analyses. The chapter covers the crash process from the perspectives of drivers, roadways and vehicles, and theoretical and mathematical principles. It provides important information about sources of data and data collection procedures, as well as how to assemble crash and other related data. The chapter also describes a four-step modeling procedure for developing models and analyzing crash data and the methods for assessing the performance of these models.

Chapter 3—Crash-Frequency Modeling describes the basic nomenclature of the models that have been proposed for analyzing highway safety data and their applications. The chapter describes the most important crash-frequency models that have been proposed for analyzing crash count data, along with the important or relevant information about their characteristics. The models are grouped by their intended use and for handling specific characteristics associated with safety data. The chapter ends with a discussion about the modeling process related crash-frequency models.

Chapter 4—Crash-Severity Modeling introduces the methodologies and techniques that have been applied to model crash severity in safety studies. The discussion includes the different forms, constructs, and assumptions that crash severity models have been developed as a function of the prevailing issues related to crash data. The theoretical framework and practical techniques for identifying, estimating, evaluating, and interpreting factors contributing to crash injury severities are also explored.

1.3.2 Part II: highway safety analyses

Chapter 5—Exploratory Analyses of Safety Data describes techniques and methods for exploring safety data. They are divided into two general themes: (1) quantitative techniques that involve the calculation of summary statistics and (2) graphical techniques that employ figures or plots to summarize the data. The exploratory analyses of data help frame the selection of more advanced methodologies such as those associated with cross-sectional analyses, before-after studies, identification of hazardous sites, spatial correlation and capacity, and mobility.

Chapter 6—Cross-Sectional and Panel Studies in Safety describes different types of data and analysis methods, as well as how models described in the previous part can be used to this effort. The discussion includes data and modeling issues and presents some techniques to overcome them. The chapter describes the characteristics of different functional forms, selection of variables, and modeling framework. Techniques for determining the required sample size, identification of outliers, and transferability of models to other geographical areas are also presented. Lastly, a brief outline of other study designs that are not commonly used in highway safety is presented.

Chapter 7—Before-After Studies in Safety covers basic and advanced study techniques for analyzing before and after data. The chapter describes the two critical issues that can negatively influence this type of study and the basic methods for conducting a before-after study with and without control groups. Then, the empirical Bayes and full Bayes methods in the context of before-after studies are presented. The last sections of the chapter document more recent methods, such as the naïve adjustment method, the before-after study using survival analysis, and the propensity score method. The chapter ends with a discussion about the sample size needed for conducting before-after studies.

Chapter 8—Identification of Hazardous Sites first discusses various hazardous site selection methods that rely on observed crashes, predicted crashes, or expected crashes. The discussion includes each method's strengths and weaknesses. Then, the chapter presents geospatial hotspot methods that consider the effects of unmeasured confounding variables by accounting for spatial autocorrelation between the crash events over a geographical space. This chapter also documents the list of the high crash concentration location procedures because the hazardous site selection methods may not efficiently identify the point locations where a deficiency exists. The proactive approach methods are then presented due to their nature of identifying sites before a crash could occur. Lastly, the screening evaluation methods are discussed in detail.

Chapter 9—Models for Spatial Data is dedicated to analyzing and modeling crash data within a spatial context. The chapter begins with an overview of the characteristics of spatial data and commonly used data models. Then, spatial indicators, such as Getis G and Moran's I, are introduced to help determine the distribution of crash locations as clustering, dispersed, or random. Next, the chapter describes techniques for analyzing crash point data that are presented to facilitate the discovery of the underlying process that generates these points. Finally, spatial regression methods are introduced to explicitly consider the spatial dependency of crashes and spatial heterogeneity in the relationship between crashes and their contributing factors.

Chapter 10—Capacity, Mobility, and Safety offers a perceptive account of one of the fastest-developing fields in highway safety analysis, involving traffic flow theory, driver behavior models, and statistical methods. The chapter first describes a theoretical car-following model to demonstrate the safety aspects of a classic driver behavior model, the modeling of relationships between crashes and traffic volume, and how to map crash typologies to a variety of traffic regimes characterized by traffic variables. The use of Bayesian theory to predict crash probability given a real-time traffic input and real-time crash prediction models (RTCPM) are also described. The chapter ends with a description about the motivation and methodology for developing RTCPM from simulated traffic data when actual traffic data are not available.

1.3.3 Part III: alternative safety analyses

Chapter 11—Surrogate Safety Measures focuses on defining, analyzing, comparing, and applying state-of-the-art surrogate safety measures. Following a brief history of traffic conflicts, the chapter explains the basic characteristics of traffic conflicts technique and the practice of observing and collecting traffic conflicts in the field. The chapter also covers both the pragmatic approach and the theoretical development of surrogate safety measures.

Chapter 12—Data Mining and Machine Learning Techniques introduces data mining and machine learning methodologies and techniques that have been applied to highway safety studies, including association rules, clustering analysis, decision tree models, Bayesian networks, neural networks, and support vector machines. The theoretical frameworks are illustrated through exemplary cases published in safety literature and are supplemented with implementation information in the statistical software package R. The chapter ends with a description of a means of specifying the effect of an independent variable on the output, which can assist in deciding on the appropriate safety solutions.

1.3.4 Appendices

Appendix A describes the basic characteristics of the Negative Binomial model, the most popular model in crash data analysis (Lord and Mannering, 2010), with and without spatial interactions and the steps to estimate the model's parameters using the maximum likelihood estimation and Bayesian methods. Appendix B provides a historical description, a detailed and up-to-date list of crash-frequency and crash-severity models that were previously published in peer-reviewed publications (Lord and Mannering, 2010; Savolainen et al., 2011; Mannering and Bhat, 2014). Appendix C presents useful codes for developing many models described in the textbook in SAS, WinBUGS, and R software languages. Appendix D lists the available datasets for each chapter of this textbook. Finally, datasets used for the examples described in various chapters are made available on the personal website of the lead author (https://ceprofs.civil.tamu.edu/dlord/Highway_Safety_Analytics_and_Modeling.htm).

1.3.5 Future challenges and opportunities

The methods and analysis tools documented in this textbook are the accumulation of more than 40 years of research and applications in highway safety. Many of these methods and tools have been introduced in this area when new methods were developed in other fields, such as in statistics, econometric, medicine, epidemiology, and social sciences or when methodological limitations had been identified based on the unique characteristics associated with highway safety data (see Chapters 3 and 4). Despite the foreseeable changes and uncertainties, the techniques and methods introduced in this textbook should not be outdated and will continue to be used as powerful tools for analyzing highway safety data. However, with the significant advancement in transportation technologies and computing power, existing methods may need to be adapted and new ones to be developed to properly measure the safety performance associated with these technologies over the next few decades.

Although the full development of connected and autonomous vehicles is several years, if not decades, away, the impacts of their deployment in mixed traffic conditions (a mixture of human-driven and automated vehicles) are not well understood. Automated vehicles have the potential to significantly reduce vehicle fatalities, but their safety benefits have so far mainly been based on simulation analyses and surrogate measures of safety (Morando et al., 2018; Mousavi et al., 2019; Papadoulis et al., 2019; Sohrabi et al., 2020). On the other hand, crashes involving autonomous vehicles have been reported with limited open road tests, some involving fatalities. Hence, observational tools targeted for small samples would provide a more accurate and reliable picture than simulations and surrogate events.

In the new era of Big Data, a large amount of new and emerging data are becoming more and more available (i.e., smart cities, disruptive technologies, naturalistic data, video processing, etc.). In Chapter 12—*Data Mining and Machine Learning Techniques*, data mining and machine learning techniques for analyzing safety data, such as those collected from naturalistic studies or from connected vehicles (e.g., basic safety messages) are discussed. With the rich data, extracting useful and meaningful information becomes essential. Many competing techniques are capable of handling conventional safety data issues, their strengths and limitations vary, so do the model performance and results. Examples include random forests versus gradient boosted trees, and convolutional neural networks versus recurrent neural networks. Understanding the fundamentals of these techniques that are developed from some of the methodological and modeling principles introduced in the textbook will help the reader to select the most appropriate method when confronted by different data issues and challenges.

Despite the superior performance in handling high-dimensional data, machine learning methods have long been criticized for operating like a black box, with no statistical inferences and model goodness-of-fit or no explicit relationships between outcomes and input variables. Hence, there is a trend to use machine learning techniques as a screening tool for a large quantity of factors, or a clustering tool for grouping data into more homogeneous dataset, and then to apply conventional statistical models. Promising results have been reported in this combination of methods. On the other hand, with the increased use of naturalistic data in safety, new tools have been and are being developed to handle datasets that include video data, social media data, and vehicle performance data that record vehicle location, position, and kinematics every second or fraction of a second. Applying artificial intelligence methods, such as those currently being used by YouTube,[3] for example, should be examined. As the authors, we hope this textbook will serve as a springboard for the reader to continue advancing the safety research frontier through better analytical methods.

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