DISSERTATION

RELIABILITY-BASED SAFETY EVALUATION OF TRAFFIC ON RURAL HIGHWAY

Submitted by

Feng Chen

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2011

Doctoral Committee:

Advisor: Suren Chen

John W. van de Lindt
Bogusz J. Bienkiewicz
Hiroshi Sakurai

ABSTRACT

RELIABILITY-BASED SAFETY EVALUATION OF TRAFFIC ON RURAL HIGHWAY

In the United States as well as other developed countries, road accidents are causing more injuries and casualties than any other natural or man-made hazard. Some vehicles, such as trucks, emergency vehicles and SUVs, often experience increasing risks of single-vehicle accidents under hazardous driving conditions, such as inclement weather and/or complicated topographical conditions. The objective of this research is to establish a reliability-based framework to evaluate the traffic safety through taking account of more realistic adverse driving conditions, such as wind gust, snow-covered or icy road surface, and/or curves. After some background information is introduced in Chapter 1, Chapter 2 covers the development of a mobile mapping technology aiming at collecting site-specific as well as vehicle-specific wind velocity data for traffic safety evaluations. In Chapter 3, an advanced simulation-based single-vehicle accident assessment model considering the coupling effects between vehicles and hazardous driving conditions is developed. In Chapter 4, ten-year accident data

involving trucks on rural highway from the Highway Safety Information System (HSIS) is studied to investigate the injury severity of truck drivers by using mixed logit models. Based on the advanced transient dynamic vehicle simulation model, the general framework of a reliability-based assessment model for vehicle safety under adverse driving conditions is finally developed in Chapter 5. In Chapter 6, a case study of I-70 in Colorado to evaluate the traffic safety of large trucks is conducted. Finally, conclusions are summarized in Chapter 7.

DEDICATION

To those I love

ACKNOWLEDGEMENT

I gratefully acknowledge my advisor Dr. Suren Chen, for sharing valuable knowledge, research experience, guidance, encouragement and support through the almost four years of my study at Colorado State University. His mentorship was paramount in providing a well rounded experience consistent with my long-term career goals. My appreciation is beyond words.

I am very pleased to have Dr. John W. van de Lindt, Dr. Bogusz J Bienkiewicz and Dr. Hiroshi Sakurai on my dissertation committee. I enjoyed learning a variety of topics from the courses I took from them in the past years. I would like to thank them for their guidance on my dissertation research. My appreciation also goes to all the teachers of the classes I have taken at Colorado State University, which helped me gain a good amount of useful knowledge. I would also like to thank my fellow graduate students at Colorado State University for their support, encouragement and friendship during my studies. Gratitude is also extended to Professor Xinyang Jin at China Academy of Building Research for his encouragement and support. The financial support I received from the CSU startup fund, CDOT research grant, MPC research grant and NIOSH MAP ERC research grant, which has made my dissertation study possible, is also much appreciated.

Last but not the least, the constant support from my parents and my wife is deeply appreciated. It was from them that I gained so much motivation and ability to face the challenges. The dissertation could not have been completed without their encouragement, love and devotion.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background

In the United States as well as other developed countries, road accidents are causing more injuries and casualties than any other natural or man-made hazard. Each year, adverse weather alone is associated with more than 1.5 million vehicular crashes, which result in 800,000 injuries and 7,000 fatalities nationwide (The National Academies, 2006). The hazardous driving environments may include inclement weather (e.g. strong crosswind gusts, snow, rain, or ice) and/or complicated terrain (e.g. steep slopes or sharp curves) (USDOT 2005). Some vehicles, such as trucks, emergency vehicles and SUVs, often experience increasing risks of single-vehicle accidents under hazardous driving conditions, such as inclement weather and/or complicated topographical conditions. In addition, compared to passenger vehicles which are much more flexible on adjusting the travel plans, trucks often have to be operated in adverse or even hazardous driving conditions, such as inclement weather and/or complex terrain (USDOT, 2005; NIOSH, 2007).

Although the absolute number of single-vehicle (SV) accidents is often lower than that of multiple-vehicle (MV) accidents, SV accidents usually result in more serious injury (The National Academies, 2006). For example, SV accidents were responsible for 57.8% of all crash fatalities in 2005 (USDOT, 2005). And truck drivers experience significantly higher risk of suffering serious injury and fatality than passenger vehicle drivers (USDOT 2005). In the United States, commercial truck drivers face huge risk of injury and death from crashes –

as much as 7 times more likely to die and 2.5 times more likely to suffer an injury than the average worker (NIOSH 2007). In addition to direct safety threats, frequent single-vehicle accidents will also cause serious congestions, affecting the functionality of the whole highway network in normal situations, as well as under emergency.

As a result of this unique coupling, observations solely from historical crash data in one place can hardly be translated into accurate risk prediction in different places or under driving environments which were not covered by the actual crash data. Therefore, in addition to analyzing actual historical crash data gathered after the crashes, a reasonable reliability-based traffic safety evaluation system on rural highway under adverse driving conditions becomes crucial, which can reasonably predict the potential risk of crashes under comprehensive scenarios including those which may not be covered by historical crash data.

1.2 Literature Review and Scope of the Dissertation

1.2.1 Field wind data collection

Vehicle accidents by strong crosswind gust have been frequently reported around the country (Brassfield and Allison, 2001; U.S. Department of Transportation, 2003; Willett, 2005). Over the past decade, a number of researchers have been working on safety assessment under crosswind for high-sided commercial trucks (Baker, 1991; Baker, 1994; Chen and Cai, 2004; Sigbjornsson and Snabjornsson 1998; Snaebjornsson et al., 2007) and fire trucks (Pinelli et al., 2004). Recently, Chen et al. (2009) studied the single-vehicle crash risk assessment under adverse environmental conditions, including crosswind, inclement weather, complex terrain, and adverse driving manners. Most of the existing studies were primarily analytical works with limited experimental studies. It is well known that the wind velocity at the typical height of vehicles varies significantly from one highway to another, due to the differences in roadside environments and surrounding terrain. Even for different segments on the same highway, the actual wind environments at the same time can be considerably different due to topographic effects, for example, highway turns, nearby mountains and trees. Therefore, wind velocity data along any particular highway is desired for realistic traffic safety assessments of various vehicles passing through every day. In addition to general site-specific wind velocity data which can be applied to vehicles with common and streamlined shapes on the same highway, vehicle-specific wind velocity data is often required in order to conduct a reasonable assessment of high-sided vehicles with unique shapes.

In principle, site-specific wind velocity data can be obtained from weather stations located close to the highway. However, wind data from locations between two weather stations is usually not available. With the typically scattered distribution of weather stations in proximity to the highway, only generic and scattered wind data at several fixed points along a highway are available. Thus obtaining accurate and continuous wind data along roads is challenging with the existing technology, especially as appropriate accuracy is essential for a reliable safety assessment of various vehicles moving along a specific highway. To collect relevant wind velocity data, an effective way is to conduct field testing using the actual vehicle as a full-size moving "sensor".

A limited number of studies on field wind data collection at the typical height of vehicles have been reported in literature. Pinelli et al. (2004) measured static wind pressure on a fire truck parked on a road. Schmidlin (1998) investigated in full scale the impacts from strong wind, caused by a tornado. Snaebjornsson et al. (2007) conducted wind velocity measurement using an anemometer attached to a minivan.

1.2.2 Simulation model of truck safety

In automobile engineering, significant efforts have been put forth on simulating vehicle dynamics and accidents with engineering simulation models, from the simple rigid body model, the bicycle model to the complicated spring-mass multiple-degree-of-freedom model (Thomas 1992). Despite extensive works in these fields (e.g. Winkler and Ervin 1999; Gaspar et al. 2004, 2005; Sampson 2000), research on vehicle accident risks, which considers the coupling between the vehicle dynamic model, inclement weather and topographical condition, is still very limited. Baker (1986, 1987, 1991, 1994) was the first researcher who tried to investigate the high-sided vehicle accident risks under strong crosswind. In his studies, vehicle accident risks were assessed through solving several static equilibrium equations with some predefined accident criteria. Based on Baker's work, several reliability-based accident assessments were recently conducted (Sigbjornsson and Snaebjornsson 1998; Sigbjornsson et al. 2007). Chen and Cai (2004) improved the accident risk assessment by introducing a general dynamic interaction model, based on which the vehicle accident assessment was conducted by considering excitations from the supporting structure (e.g. bridge). Guo and Xu (2006) introduced an integrated vehicle safety assessment model on bridges. In the model, the dynamic bridge-vehicle-wind interaction analysis as well as the safety assessment was carried out at the same time based on the same accident criteria by Baker (1991). In most existing studies, however, only situations that vehicles are driven on straight routes with only crosswind excitation were considered.

1.2.3 Injury severity of truck-involved accidents

It is known that SV and MV accidents have different mechanisms of occurrence (Chen and Chen, 2010; Baker, 1991), critical risk factors (Savolainen and Mannering, 2007) and accordingly different injury mitigation strategies (NIOSH, 2007). Therefore, to investigate injury severity and associated risk factors in both SV and MV accidents of trucks is crucial to implementing more effective injury prevention strategy for truck drivers in their daily work. Moreover, the findings from such an investigation will provide scientific basis to improve the current highway design and traffic management policy, and propose next-generation safety initiatives in order to reduce the injury severity, live and financial losses of truck-involved accidents. There exists, however, a gap between the current injury studies of truck drivers and reality. Of the limited studies that have investigated injury severity of truck-involved accidents, both SV and MV accidents were usually analyzed as a whole, in which some important phenomena and critical risk factors unique to SV or MV accidents involving trucks cannot be identified. For thousands of truck drivers working around the country every day, the lack of such a vital piece of knowledge may hinder efforts concerning injury prevention and traffic management on national highways.

Existing studies on truck-involved accidents typically follow two categories of topics: accident frequencies (or rates), and injury severity as well as their respective risk factor analyses. Different from a number of studies on accident frequencies (or rates), there are only limited studies specifically focusing on injury severity of truck drivers or occupancies in truck-involved accidents. Golob et al. (1987) and Alassar (1988) investigated the influence of some risk factors such as collision type, the number of involved vehicles and road class on injury severity of truck drivers using log-linear models. Chirachavala et al. (1984) studied the factors that increase accident severity for different truck types based on discrete multivariate analysis. Duncan (1998) studied the injury severity of passenger occupancy caused by truck-passenger-car rear-end collisions using ordered logit models. They found collisions under some conditions, such as with passenger cars or on undivided rural roads, usually result in a higher level of injury severity. Chang and Mannering (1999) analyzed the accident severity of occupancy in truck-involved and non-truck-involved accidents using nested logit models. The characteristics of truck-involved and non-truck-involved accidents were compared and some risk factors were found unique to truck-involved accidents. Khorashadi et al. (2005) compared the difference of driver-injury severities from truck-involved accidents in rural and urban roads using multinomial logit models. The study identified 13 and 17 risk factors which significantly influence the driver-injury severity only in rural and only in urban areas, respectively. In addition to injury severity, there are also some studies focusing on the fatality of occupants related to trucks (Shibata and Fukuda, 1994; Lyman and Braver 2003). Most of the existing studies with a focus on severity of truck-involved accidents, as summarized above, covered all types of accidents as a whole without separating MV and SV accidents.

In recent years, there are a few studies which have started investigating injury severity from SV and MV accidents separately. For example, Kockelman and Kweon (2002) used ordered probability models to investigate injury severity in two-vehicle crashes and single-vehicle crashes datasets separately. They found that there is large difference of injury severity behavior for SV and MV accidents involving different vehicle types such as pickups and sport utility vehicles. In the work conducted by Ulfarsson and Mannering (2004), single-vehicle and two-vehicle accidents were studied using separate models because it was found a single model cannot accurately tell the different characteristics of these accidents. Savolainen and Mannering (2007) estimated the probabilistic models of motorcyclists' injury severity by separating SV and MV crashes using multinomial and nested logit models. Different risk factors on the injury severity of motorcyclists in SV ad MV crashes were found. In realizing the considerably different causality mechanisms of SV and MV accidents, some other studies investigated SV accidents only (e.g. Shankar and Mannering, 1996; Islam and Mannering, 2006). So far, however, no study has been reported on investigating the injury severity of truck drivers in SV and MV crashes separately.

Over the past ten years, various disaggregate models have been widely used to compare different datasets due to the unique advantages as compared to the previous methods. These advantages include being able to test a broad range of variables that influence injury severity and capture comprehensive disaggregate information about how the injury severity is influenced by these variables (Chang and Mannering, 1999). Some studies applied ordered logit (Duncan, 1998) or ordered probit models (Abdel-Aty, 2003) to investigate various risk factors associated with injury severity. Multinomial logit models (Ulfarsson and Mannering, 2004) and nested logit models (Chang and Mannering, 1999) have also been frequently used in order to obtain more detailed information about the influence of various risk factors on different injury severity levels.

Although multinomial logit models have been widely applied in injury severity studies during the past years, people find some limitations of this model such as (Jones and Hensher, 2007): (1) questionable assumptions associated with the IID (independently and identically distributed errors) condition and the IIA (independence of irrelevant alternatives) assumption condition; and (2) observed and unobserved heterogeneity in parameter effects are not considered. Most of the approaches used in the existing studies on truck driver injury severity were based on the assumption that the effects of all variables are fixed across observations. Mixed logit models, which can address these limitations and consider the random effects of variables, have recently been adopted in the studies on accident injury (e.g. Milton et al., 2008; Kim et al., 2010; Malyshkina and Mannering, 2010; Moore et al., 2010). For example, Moore et al. (2010) applied mixed logit model to compare the statistical difference of bicyclist injury severity from motor vehicle crashes at intersection and non-intersection locations. It was found that some risk factors need to be modeled as random parameters.

1.2.4 Reliability-based model of truck safety

There has been limited progress on investigating single-vehicle accident risk considering adverse driving environments in past decades. Baker (1987, 1991, 1994) started series of studies on dynamic stability of high-sided vehicles under crosswind with the simplified rigid-body vehicle model. Chen and Cai (2004) and Guo and Xu (2006) improved the accident risk assessment by introducing fully-coupled dynamic interaction models of vehicles, bridge and wind, respectively. To consider uncertainties associated with some variables of the rigid-body model, reliability-based accident risk studies were also conducted (Sigbjornsson and Snaebjornsson 1998; Snaebjornsson et al. 2007). As a result of adopting the simplified rigid-body model, the limit state functions in these studies were able to be easily expressed as explicit ones in terms of random variables. All these existing studies, however, only considered vehicles on straight routes under excitations from only wind and/or the bridge. As a result, these models can do not serve as a general methodology which can accurately replicate various driving environments as well as associated uncertainties in nature.

It is all known that wind exists in nature all the time from breeze to strong wind. For any vehicle, the specific driving condition primarily consists of natural wind, the local topographic condition of the highway stretch that the vehicle is driven on, and the particular road surface condition (Chen et al. 2010). All these driving conditions work integrally to affect the safety of any vehicle on highways. To provide a general safety assessment tool, Chen and Chen (2010) recently developed an advanced deterministic dynamic simulation model which can consider more realistic driving environments. Single-vehicle accident performance can be simulated under different combinations of crosswind conditions, road surface conditions (e.g. wet, icy or snow-covered) and specific topographical conditions (e.g.

curve, superelevation and grade) by using the advanced transient dynamic equations, improved accident criteria and critical variables (Chen and Chen 2010).

1.3 Summary of Dissertation

This dissertation seeks to propose a reasonable reliability-based framework evaluating traffic on rural highway. More specifically, the objectives of this dissertation include:

(1) A mobile mapping technology aiming at collecting site-specific as well as vehicle-specific wind velocity data for traffic safety evaluations is developed. Wind-tunnel investigations employing the scaled models of the truck used in the field test as well as a common streamlined sedan car are conducted to evaluate the accuracy and the feasibility of the developed technology;

(2) An advanced simulation-based single-vehicle accident assessment model is developed considering the coupling effects between vehicles and hazardous driving conditions, including wind gust, snow-covered or icy road surface and/or curves;

(3) Ten-year accident data involving trucks on rural highway from the Highway Safety Information System (HSIS) is studied to investigate the difference in driver-injury severity between SV and MV accidents by using mixed logit models;

(4) The framework of a reliability-based assessment model for vehicle safety under adverse driving conditions is developed.

(5) By integrating both historical data analysis and simulations, a case study is established to evaluate the traffic safety of large trucks on mountainous interstate highways.

The contents of this dissertation are based on five relevant papers which have already been published or accepted by three refereed journals. The dissertation is therefore divided into seven chapters and each chapter corresponds to a journal paper except for Chapter 1 and 7. Chapter 1 herein is to introduce the state-of-the-art in the related field and also the objective and scope of this study.

In Chapter 2, a mobile wind velocity mapping technique is developed to collect site-specific as well as vehicle-specific wind velocity data in both time and spatial domains. A test vehicle equipped with a 3-D sonic anemometer and a geospatial video mapping system is employed. The developed mobile testing technique can be used to: 1) generate site-specific wind velocity data along any particular highway for vehicles with common and streamlined shapes; and 2) directly measure vehicle-specific wind velocity for those vehicles with unique and high-sided shapes. A field test was conducted on the interstate I-70 corridor in Colorado to prove the idea and demonstrate the technology. In order to evaluate the feasibility and the accuracy of the introduced technology, a wind tunnel investigation was conducted and the scaled model of the test vehicle used in the field test, as well as a common streamlined sedan car, was employed in the laboratory testing.

In Chapter 3, a general vehicle safety behavior simulation model is introduced to consider the coupling effects with more realistic hazardous environments, including combinations of both inclement weather and complicated topographical conditions. Improved transient dynamic equations, accident criteria and new critical variables will also be incorporated into the model. Compared to existing simulation models, the new model has following improvements: 1) adopting series of dynamic equations to simulate the transient process of accidents; 2) for the first time, combining crosswind, different road surfaces, curving and excitations from supporting structures in one single model which can be used to consider more realistic scenarios; 3) introducing a new and important variable “critical sustained time (CST)” of each specific combination of adverse environmental and driving conditions in addition to the “critical driving speed (CDS)” which has been adopted in existing studies. Such a new variable will be helpful on characterizing the accident risks more realistically; and 4) as a holistic deterministic model, the present study can be used directly to provide useful information for traffic and emergency management as well as accident preventions. Comprehensive parametric studies and site-specific analyses are conducted based on the model.

Chapter 4 is to model the injury severity from SV and MV accidents involving trucks on rural highways separately, their respective critical risk factors such as driver, vehicle, temporal, roadway, environmental and accident characteristics are evaluated. It is found that there exists substantial difference between the impacts from a variety of variables on the driver-injury severity in MV and SV accidents. By conducting the injury severity study for MV and SV accidents involving trucks separately, some new or more comprehensive observations, which have not been covered in the existing studies can be made. Estimation findings indicate that the snow road surface and light traffic indicators will be better modeled as random parameters in SV and MV models respectively. As a result, the complex interactions of various variables and the nature of truck-driver injury are able to be disclosed in a better way.

By using the mixed logit models, the complex interactions between roadway characteristics, driver characteristics, accident characteristics, temporal characteristics and environmental characteristics in both SV and MV accidents will be untangled.

Chapter 5 is to develop the framework of a reliability-based assessment model for vehicle safety under adverse driving conditions is developed. Such a framework is built based on the advanced transient dynamic vehicle simulation models which can consider the coupling effects between vehicles and adverse driving conditions, such as wind gust, snow-covered or icy road surface and/or curves. The single-vehicle safety index is introduced to provide rational assessment of accident risks by considering uncertainties of critical variables. In order to consider the complicated implicit limit state functions, the response surface method (RMS) is adopted to provide an efficient estimation of accident risks. Finally, a parametric study is conducted to demonstrate the methodology and the impacts of different critical variables on accident risks of a typical truck under several representative hazardous scenarios are investigated.

Chapter 6 is about the evaluating the safety performance of large trucks on mountainous highways. The I-70 corridor in Colorado is chosen to demonstrate the methodology because of its typical mountainous terrain and adverse weather conditions. Firstly, the ten-year historical accident records are analyzed to identify the accident-vulnerable-locations (AVLs) and site-specific critical adverse driving conditions. Secondly, simulation-based single-vehicle assessment is performed for different driving conditions at those AVLs along the whole corridor. It is found that this approach can provide insightful observations of the highway safety performance, which is especially important for mountainous highways.

Finally, Chapter 7 concludes the whole dissertation and some discussions about future studies will also be reported.

1.4 References

Abdel-Aty, M. (2003). “Analysis of driver injury severity levels at multiple locations using ordered logit models.” J. Safety Res. 34 (5), 597–603.

Alassar, L. (1988). “Analysis of heavy large-truck accident severity.” J. Adv. Transport. 22 (1), 77–91.

Baker, C. J. (1987). “Measures to control vehicle movement at exposed sites during windy periods.” Journal of Wind Engineering and Industrial Aerodynamics, 25(2), 151-161.

Baker, C.J. (1991). “Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system.” J. of Fluids and Structures 5, 221–241.

Baker, C.J. (1994). “Quantification of accident risk for road vehicles in cross winds.” Journal of Wind Engineering and Industrial Aerodynamics, v 52, 1-3, 93-107.

Brassfield, M., Allison, W. (2001). “Skyway sees wind-blown crash, fatal leap.” St. Petersburg Times, http://www.sptimes.com/News/032101/TampaBay/Skyway_sees_wind_blow.shtml

Chang, L.-Y., Mannering, F. (1999). “Analysis of injury severity and vehicle occupancy in truck- and non-truck-involved accidents.” Accident Anal. Prevent. 31 (5), 579–592.

Chen, S. R. and Cai, C. S. (2004). “Accident assessment of vehicles on long-span bridges in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 92(12), 991-1024.

Chen, S. R., Cai, C. S., Wolshon, B. (2009). “From normal operation to evacuation: single-vehicle safety under adverse weather, topographic and operational conditions.” Natural Hazards Review, ASCE, 10, 2, 68-76.

Chen, S. R. and Chen, F. (2010). “Simulation-based assessment of vehicle safety behavior under hazardous driving conditions.” J. of Transportation Engineering, ASCE. 136(4), 304-315.

Chirachavala, T., Cleveland, D., Kostyniuk, L.P. (1984). “Severity of large-truck and combination-vehicle accidents in over-the-road service: a discrete multivariate analysis.” Transport. Res. Rec. 975, 23–36.

Duncan, C., Khattak, A., Council, F. (1998). “Applying the ordered logit model to injury severity in truck-passenger car rear-end collisions.” Transport. Res. Rec. 1635, 63–71.

Golob T., W. Recker, J. Leonard. (1987). “An analysis of the severity and incident duration of truck-involved freeway accidents.” Accident Anal. Prevent. 19(5), 375-396.

Guo, W. H. and Xu, Y. L. (2006). “Safety analysis of moving road vehicles on a long bridge under crosswind”, Journal of Engineering Mechanics, 132 (4), 438-446.

Islam, S., Mannering, F. (2006), “Driver aging and its effect on male and female single-vehicle accident injuries: some additional evidence.” Journal J. Safety Res. 37 (3), 267 – 276.

Jones, S., Hensher, D. (2007). “Evaluating the behavioural performance of alternative logit models: an application to corporate takeovers research.” Journal of Business Finance & Accounting 34, 1193–1220.

Khorashadi, A., Niemeier, D., Shankar, V., Mannering, F. (2005). "Differences in rural and urban driver-injury severities in accidents involving large trucks: an exploratory analysis." Accident Anal. Prevent. 37 (5), 910–921.

Kim, J.-K., Ulfarsson, G., Shankar, V., Mannering F. (2010). "A note on modeling pedestrian injury severity in motor vehicle crashes with the mixed logit model." Accident Anal. Prevent. 42(6), 1751-1758.

Kockelman, K., Kweon, Y. (2002). "Driver injury severity: an application of ordered probit models." Accident Anal. Prev. 34 (3), 313-321.

Lyman, S., Braver, E.R. (2003). "Occupant deaths in large truck crashes in the United States: 25 years of experience." Accident Anal. Prevent. 35(5), 731-739.

Malyshkina, N., Mannering, F. (2010). "Empirical assessment of the impact of highway design exceptions on the frequency and severity of vehicle accidents." Accident Anal. Prevent. 42(1), 131-139.

Milton, J., Shankar, V., Mannering, F. (2008). "Highway accident severities and the mixed logit model: An exploratory empirical analysis." Accident Anal. Prevent. 40(1), 260-266.

Moore, D.N., Schneider, W., Savolainen, P.T., Farzaneh, M. (2010). "Mixed logit analysis of bicyclist injury severity resulting from motor vehicle crashes at intersection and non-intersection locations." Accident Anal. Prevent. (2010), doi:10.1016/j.aap.2010.09.015

National Institute for Occupational Safety and Health (NIOSH). (2007). "Truck driver occupational safety and health, 2003 conference report and selective literature review." Centers for Disease Control and Prevention, Department of Health and Human Services.

Pinelli, J.P., Subranmanian, C., Plamondon, M. (2004). "Wind effects on emergency vehicles." Journal of Wind Engineering and Industrial Aerodynamics, 92, 7-8, 663-685.

Savolainen, P., Mannering, F. (2007). "Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes." Accident Anal. Prevent. 39, 955–963.

Shankar, V.N., Mannering, F.L. (1996). "An exploratory multinomial logit analysis of single-vehicle motorcycle accident severity." J. Safety Res. 27 (3), 183–194.

Shibata, A., Fukuda, K. (1994). "Risk factors of fatality in motor vehicle traffic accidents." Accident Anal. Prevent. 26 (3), 391–397.

Sigbjornsson, R., and Snaebjornsson, J. T. (1998). "Probabilistic assessment of wind related accidents of road vehicles: A reliability approach." Journal of Wind Engineering and Industrial Aerodynamics, 74-76, 1079-1090.

Snaebjornsson, J. T., Baker, C. J., and Sigbjornsson, R. (2007). "Probabilistic assessment of road vehicle safety in windy environments." Journal of Wind Engineering and Industrial Aerodynamics, 95, 1445-1462.

The National Academies. (2006). “Where the weather meets the road – a research agenda for improving road weather system.” Report in Brief, The National Academies.

Thomas D. G. (1992). Fundamentals of vehicle dynamics, SAE, Warrendale, PA, USA.

Ulfarsson, G., Mannering, F. (2004). “Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents.” Accident Anal. Prevent. 36 (2), 135–147.

U. S. Department of Transportation (USDOT). (2005). “Report to Congress on the Large Truck Crash Causation Study.” Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Washington, S., Karlaftis, M., Mannering, F. (2003). Statistical and Econometric Methods for Transportation Data Analysis. Chapman and Hall/CRC, Boca Raton, FL.

Willett, A. (2005). “Wind wreak havoc, Gazette.” The (Colorado Springs), November 4, 2005, http://www.findarticles.com/p/articles/mi_qn4191/is_20051104/ai_n15844795

Winkler C. B., and Ervin R. D. (1999). Rollover of heavy commercial vehicles. SAE, Warrendale, PA, USA.

CHAPTER 2: MOBILE MAPPING TECHNOLOGY OF WIND DATA

2.1 Introduction

Each year, adverse weather alone is associated with more than 1.5 million vehicular crashes, which result in 800,000 injuries and 7,000 fatalities nationwide (The National Academies, 2006). Crashes due to adverse natural environments usually cause serious traffic congestion and further deteriorate driving conditions on highways. For example, vehicle accidents by strong crosswind gust have been frequently reported around the country (Brassfield and Allison, 2001; U.S. Department of Transportation, 2003; Willett, 2005). Over the past decade, a number of researchers have been working on safety assessment under crosswind for high-sided commercial trucks (Baker, 1991; Baker, 1994; Chen and Cai, 2004; Sigbjornsson and Snabjornsson 1998; Snaebjornsson et al., 2007) and fire trucks (Pinelli et al., 2004). Recently, Chen et al. (2009) studied the single-vehicle crash risk assessment under adverse environmental conditions, including crosswind, inclement weather, complex terrain, and adverse driving manners. Most of the existing studies were primarily analytical works with limited experimental studies. It is well known that the wind velocity at the typical height of vehicles varies significantly from one highway to another, due to the differences in roadside environments and surrounding terrain. Even for different segments on the same highway, the actual wind environments at the same time can be considerably different due to topographic effects, for example, highway turns, nearby mountains and trees. Therefore, wind velocity data along any particular highway is desired for realistic traffic safety assessments of various vehicles passing through every day. In addition to general site-specific wind velocity data which can be applied to vehicles with common and streamlined shapes on the same highway, vehicle-specific wind velocity data is often required in order to conduct a reasonable assessment of high-sided vehicles with unique shapes.

In principle, site-specific wind velocity data can be obtained from weather stations located close to the highway. However, wind data from locations between two weather stations is usually not available. With the typically scattered distribution of weather stations in proximity to the highway, only generic and scattered wind data at several fixed points along a highway are available. Thus obtaining accurate and continuous wind data along roads is challenging with the existing technology, especially as appropriate accuracy is essential for a reliable safety assessment of various vehicles moving along a specific highway. To collect relevant wind velocity data, an effective way is to conduct field testing using the actual vehicle as a full-size moving “sensor”.

A limited number of studies on field wind data collection at the typical height of vehicles have been reported in literature. Pinelli et al. (2004) measured static wind pressure on a fire truck parked on a road. Schmidlin (1998) investigated in full scale the impacts from strong wind, caused by a tornado. Snaebjornsson et al. (2007) conducted wind velocity measurement using an anemometer attached to a minivan. In the present chapter, a mobile wind velocity mapping technique is developed to collect site-specific as well as vehicle-specific wind velocity data in both time and spatial domains. A test vehicle equipped with a 3-D sonic anemometer and a geospatial video mapping system is employed. The developed mobile testing technique can be used to: 1) generate site-specific wind velocity data along any particular highway for vehicles with common and streamlined shapes; and 2) directly measure vehicle-specific wind velocity for those vehicles with unique and high-sided shapes. A field test was conducted on the interstate I-70 corridor in Colorado to prove the idea and demonstrate the technology. In order to evaluate the feasibility and the accuracy of the introduced technology, a wind tunnel investigation was conducted and the scaled model of the test vehicle used in the field test, as well as a common streamlined sedan car, was employed in the laboratory testing. In the end, some brief discussions about applying the developed technology on developing wind velocity surface for highway safety evaluation and risk management were made.

2.2 Geospatial Wind Mobile Field Testing

2.2.1 The sonic anemometer

To accurately measure time-dependent wind velocity data, including wind speed and direction, an ultrasonic 3-D anemometer manufactured by R. M. Young's Inc. was adopted (Fig. 2.1). The anemometer can measure wind speed from 0 through 40 m/s, with a resolution of 0.01 m/s. Wind direction ranging from 0 through 360 degrees can be covered. The anemometer was calibrated in the wind tunnel by the manufacturer before its use in the field test. Digital output of the measurements is acquired by a laptop computer, via a serial RS-232 connection. The data sampling frequency is 15 Hz. The acquired data includes turbulent wind velocity components in *u (longitudinal)*, *v (lateral)* and *w (vertical)* directions. The anemometer was installed about 0.91 meter above the roof on the front passenger side with the "north direction" (*u* component) aligned with the longitudinal axis of the vehicle. The location of the anemometer on the roof was decided primarily based on the considerations of convenient wiring and operation during the test. During the test, the wind data was recorded on the laptop.

Fig. 2.1 3-D sonic anemometer installed on testing vehicle

2.2.2 Geospatial video mapping system

The geospatial video mapping system consists of two major components: a navigation system and mapping sensors (Fig. 2.2). The navigation system, typically a GPS receiver combined with an inertial navigation system or laser range finder, is capable of continuously determining the position information of the system. Mapping sensors include digital cameras, video cameras, and audio devices. The video mapping system (VMS 300) developed by Red Hen System Inc. (Red Hen System Inc., 2005) is used to collect the geospatial multimedia information on what a driver can actually see in the front (Fig. 2.2). There was one camcorder in the video mapping system and multiple camcorders or cameras can be adopted to gather more comprehensive information of surroundings of the vehicle, if necessary. The GPS coordinates as well as the time stamp are recorded by the digital camcorder continuously on one channel of the audio track of the videotape. By using the accompanying software (VMS MediaMapper) as well as the VMS 300 unit, the captured video can be played back for indexing during the transfer of the GPS data from the videotape to a computer, as well as during the data processing.

During the test, the SONY® digital video camcorder and VMS 300 were mounted behind the wind shield on the front passenger side. The zooming of the camcorder was adjusted to ensure the almost same scenery that the driver sees is captured, such as the view of the highway and roadside features (e.g. speed limit and other road signs, roadside trees and bushes). The GPS receiver antenna was mounted on the top of the driving cab outside of the vehicle in order to receive signals from up to eight satellites, simultaneously. The sampling frequency of the GPS receiver was 1 Hz. The geospatial video information was recorded on a video tape (of the VMS) and was subsequently processed and transferred to the computer. Time stamps were utilized to synchronize the data originating from various measurement equipments.

Fig. 2.2 VMS installed on testing vehicle

2.2.3 Test vehicle and site

The test truck was a GMC SAVANA G3500 16' Truck. The primary parameters of this truck include: 10.9 square meter of floor space, 22.7 cubic meter of loading space, 1225 kg load capacity and the interior dimensions of 4.65m L x 2.33m W x 1.88m H. Fig. 2.3 shows the truck with the anemometer installed above the top outside surface of the truck. The adoption of the high-sided vulnerable truck as the test vehicle serves two purposes: (1) to collect general site-specific crosswind data along the highway which is independent from the test vehicle adopted; and (2) to acquire the vehicle-specific crosswind velocity associated with this particular high-sided truck.

Fig. 2.3 The test truck with equipments

The Interstate I-70 Mountain Corridor, from Denver to Grand Junction, is an important interstate highway in Colorado and it is well known for complicated terrain and severe snowstorms during winter seasons. For Colorado residents, visitors and businesses, I-70 is a gateway to recreation, commerce and everyday necessities. At some locations along the corridor, steep grades and curves, coupled with extreme weather conditions, pose serious safety threats on passing vehicles, especially high-sided trucks. Congestion caused by high volume of traffic and number of accidents has caused significant economic and societal impacts in the past decades. In the present chapter, I-70 is selected to demonstrate the proposed measurement technology for assessment of wind and topographic effects on traffic safety. Two routes were selected during the field test on the interstate I-70 between Exits 252 and 266: one on I-70 W (11.7 kilometers) and another on I-70 E (24.1 kilometers), which are marked on the GIS highway map in Fig. 2.4.

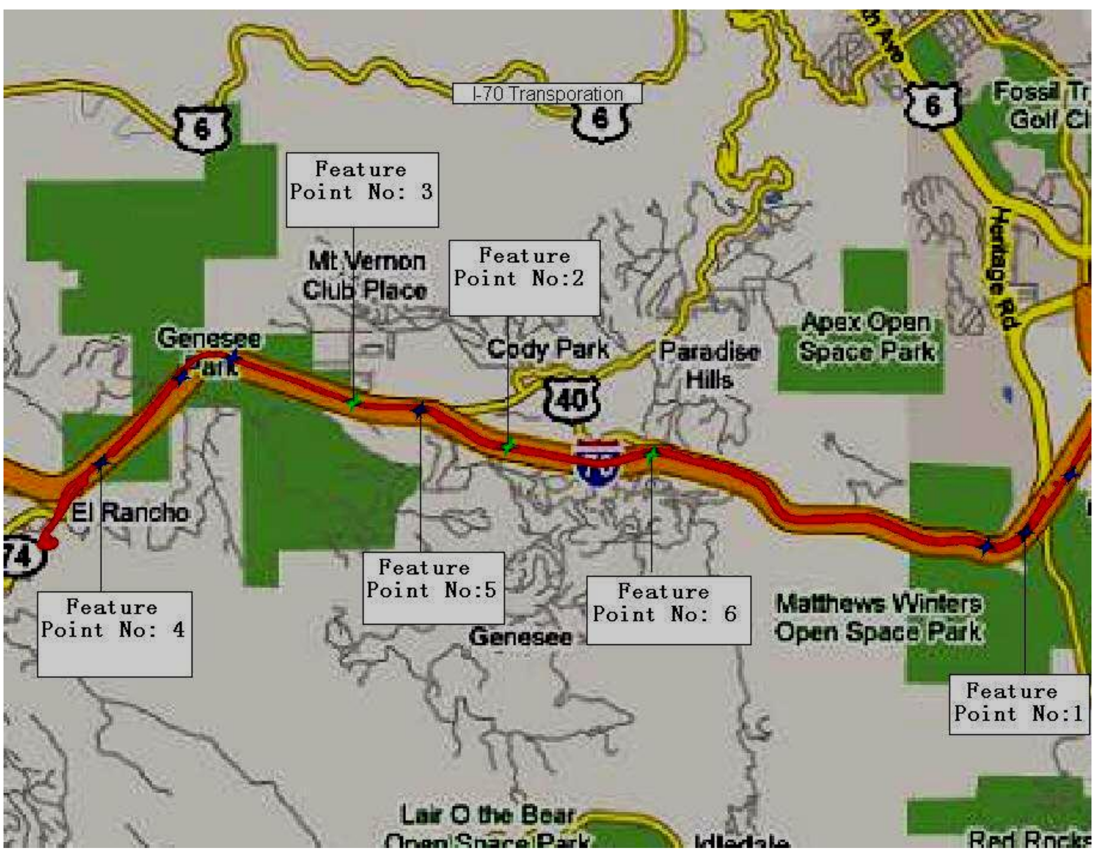


Fig. 2.4 Testing site on I-70 and selected feature points

Table 2.1 GPS data for specified feature points

Feature Point	Longitude decimal	Latitude decimal	Altitude (m)	Instantaneous vehicle driving speed (m/s)	Course (degree)	Description
No.1	-105.20767472	39.69651722	1980.590	19.190	220.600	Turning right
No.2	-105.27344278	39.70567333	2312.070	23.740	280.400	Driving by a large truck
No.3	-105.29392167	39.71006000	2381.040	26.120	286.200	Under a bridge
No.4	-105.32594833	39.70508444	2386.330	19.490	235.900	On ramp
No.5	-105.28405139	39.70888139	2334.380	27.860	97.000	Turning right
No.6	-105.25537472	39.70442472	2209.310	25.860	82.600	Driving by a large truck and curving

2.2.4 Vehicle-specific and site-specific wind velocities

As shown in Fig. 2.5, the fixed Cartesian coordinate system XYZ was used to define the general wind environment on the highway and this reference frame is not specific to the test vehicle. The wind velocity in the fixed coordinate system (on the ground) can be separated into components v, u *and* w, *in the* X, Y and Z directions, respectively. The coordinate system denoted as xyz in Fig. 2.5 is the moving coordinate system attached to the test vehicle, and the wind velocity components in this system are v', u' *and* w', respectively in the x, y and z directions. As discussed earlier, the anemometer installed on the top of the test vehicle is positioned by aligning the "north direction" of the anemometer with the longitudinal axis of the vehicle. The wind velocity measurements of the anemometer can be separated as v_m, u_m and w_m in the "east", "north" and "vertical" directions, respectively.

Most highways have slopes and camber angles, and these angles usually do not have considerable impact on crosswind velocity measurements due to their relative small values. If it is assumed that the X-Y plane is always horizontal and the Z axis is parallel to *z* axis, the *w* components of the wind velocities in both the coordinate systems are approximately the same, namely $w \approx w' = w_m$. The measured wind velocity component along the "north" direction u_m is actually equal to u'+V_D and the measured crosswind component in the "east" direction of the anemometer is v_m= v, where V_D is the vehicle velocity ′. The moving coordinate system xyz is ideal for traffic safety study, as it directly gives *vehicle-specific wind velocity* components (u', v' and w') applying on a moving vehicle which is used to quantify wind loading on the vehicle.

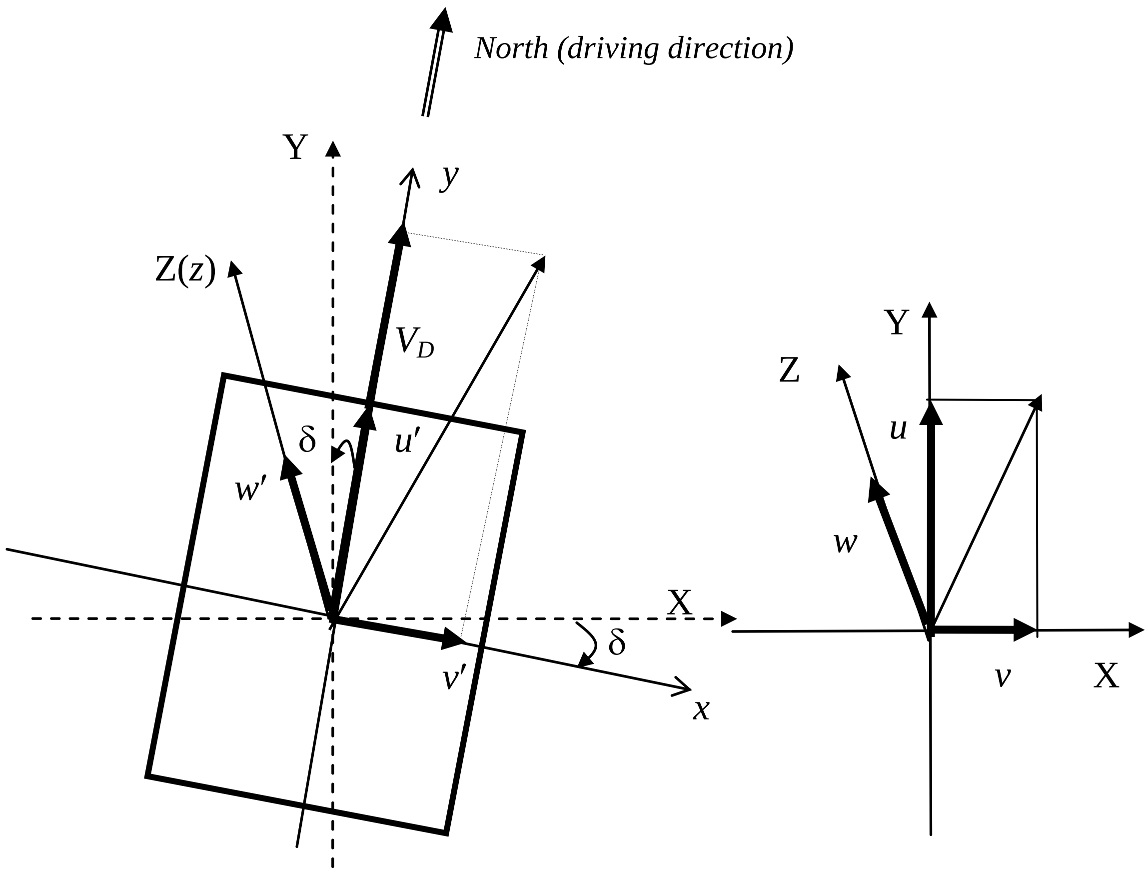
The vehicle-specific wind velocity defined based on the moving coordinate system is dependent not only on the environment of the highway, but also the specific shapes, and the instantaneous driving direction of the test vehicle. In order to provide spatially continuous general wind velocity data which can be used for various vehicles driven through the same highway**,** *site-specific wind velocity* components (u, v, w), which are dependent on the environment of the specific highway but with little or no dependence on the specific test vehicle being used, are often needed,. The wind velocity measurements by the anemometer on the moving coordinate system can be easily converted to the general wind velocity data in the fixed coordinate system through following formulas (Fig. 2.5(b)):

$$u = (u_m - V_D)\cos\delta - v_m \sin\delta \tag{2.1}$$

$$v = (u_m - V_D)\sin\delta + v_m \cos\delta \tag{2.2}$$

$$w = w_m \tag{2.3}$$

where δ is the angle between the driving direction and the absolute Y direction. Both the driving speed V_D and the δ can be obtained from the GPS data provided by the VMS.



(a) Wind speed components in moving coordinate system

(b) Wind speed components in fixed coordinate system

Fig. 2.5 Wind velocity interpretation of the introduced technology

2.2.5 Wind data analysis

The geospatial wind data and multimedia information were collected for the total of 35.4 kilometers, during the field test carried out on I-70. Among all the data, six feature points (FP) along the tested routes were selected as representatives of typical traffic scenarios: a sharp turn, driving on a highway ramp in the presence of relatively strong wind, passing a large truck on a straight road as well as on a curve and under a bridge. The detailed information on these feature points, including their coordinates and features, are presented in Table 2.1. These feature points

(FP) are labeled 1 through 6 on the GIS-based map in Fig. 2.4. With the geospatial information of the points, the geo-referenced data can be easily integrated into a geographic information system (GIS) database using ArcMap or Google Earth®. Since crosswind is of the primary concern for traffic safety studies under windy conditions, only the crosswind speed component in the moving coordinate v' direction is discussed hereafter.

Time histories of the crosswind speed measured at the six feature points are shown in Figs. 2.6-2.7. In Fig. 2.6, the time histories of wind speed measured at FP-1, 2 and 3 are displayed from the top to the bottom of the figure, while the time histories for FP-4, 5 and 6 are shown in Fig. 2.7. For each feature point, corresponding time duration has been identified to describe each event according to the geo-referenced video clips, for example, a curving sequence. Respective time period for each feature point is marked by two vertical black lines as shown in each figure, representing the starting and the finishing time of the event, respectively. Two still pictures are extracted from the video clips, visualizing driving conditions for the starting and the finishing time instant. The GPS coordinates and the time stamps are shown in each picture. As a result, the actual surrounding information and the corresponding spatial position on the highway can be linked with each time history of wind speed measurements.

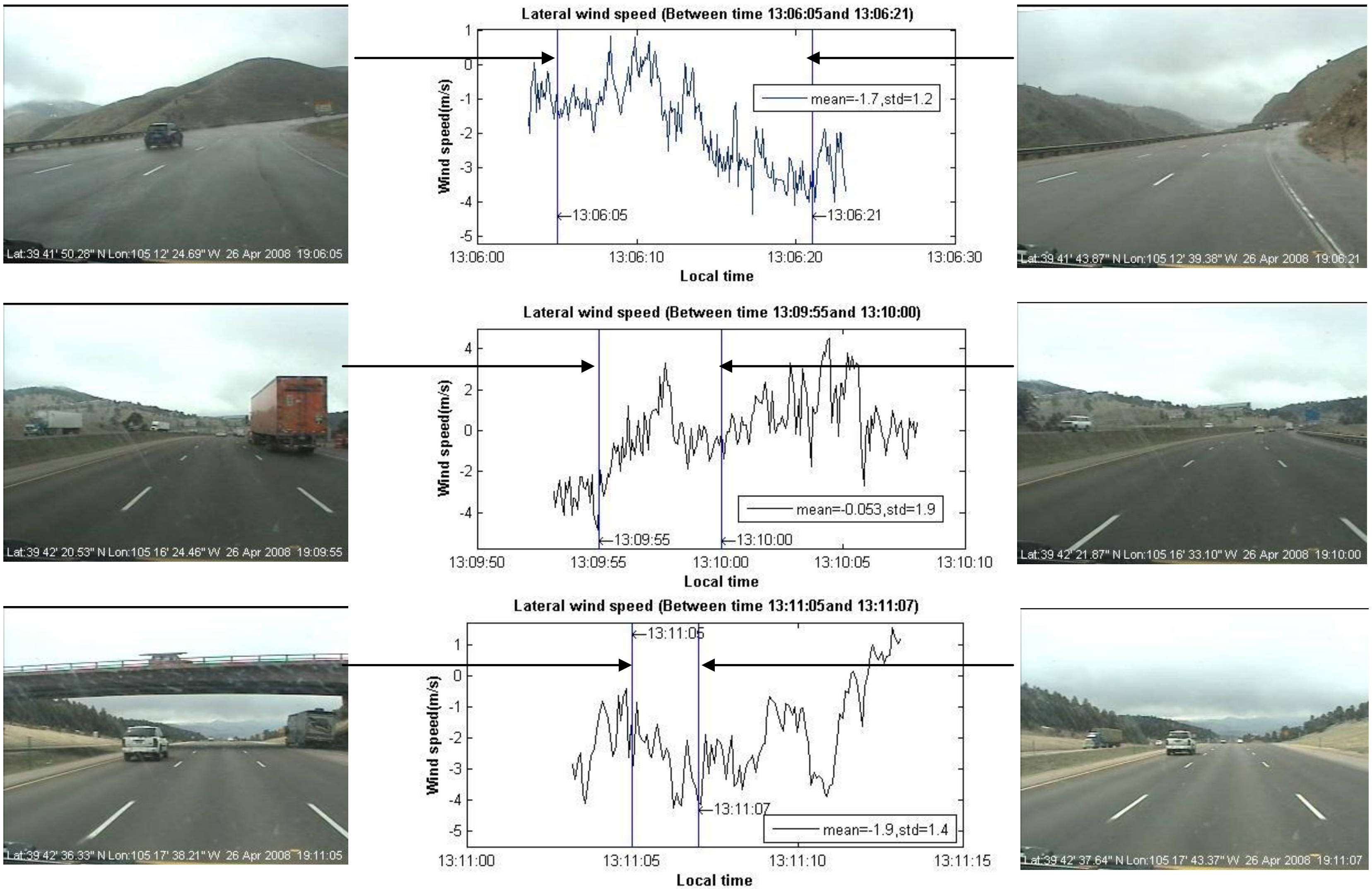


Fig. 2.6 Geospatial crosswind speed time histories for FP-1, 2 & 3

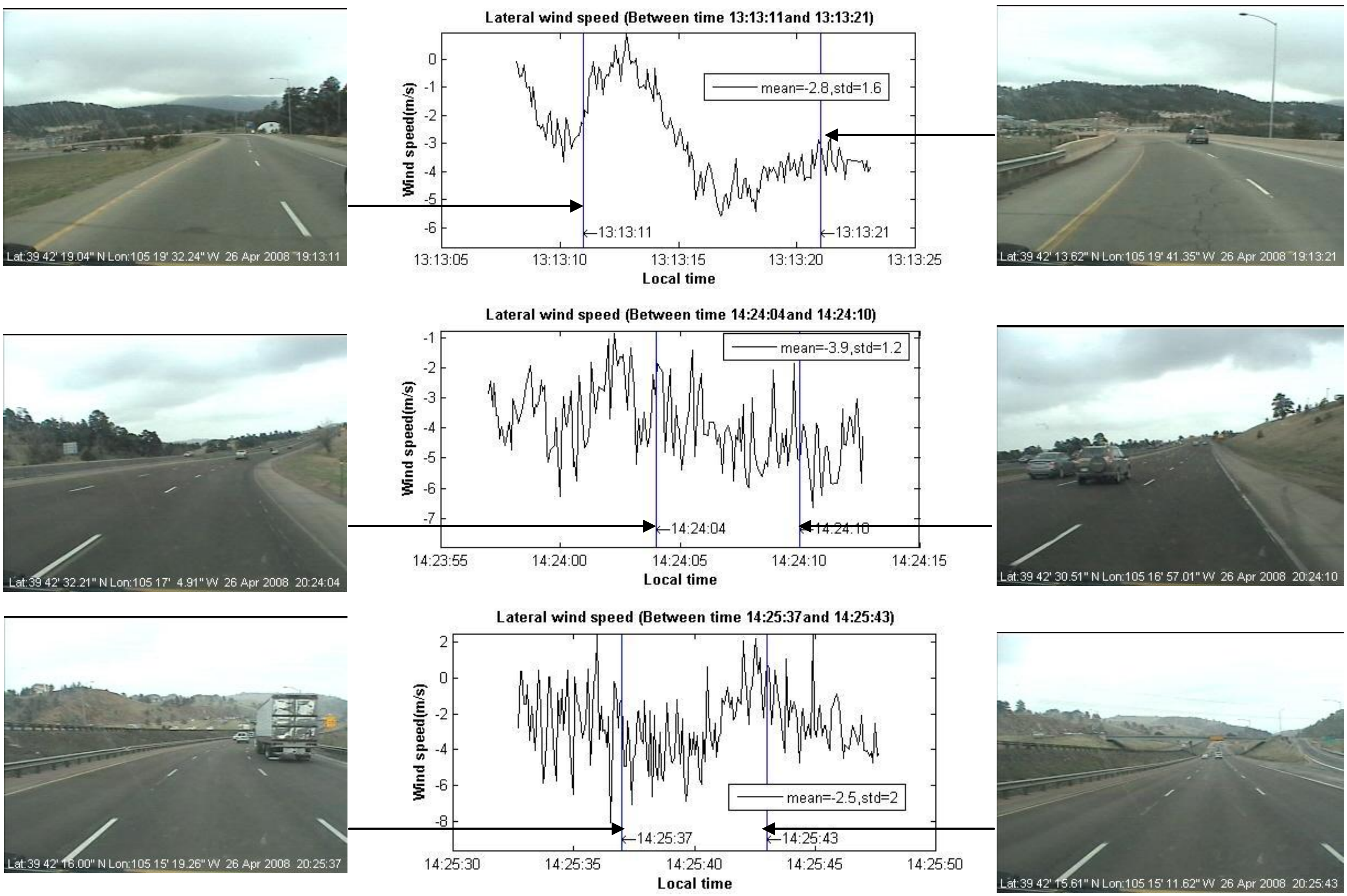


Fig. 2.7 Geospatial crosswind speed time histories for FP-4, 5 & 6

2.3 Wind Tunnel Evaluation of Field Testing Setup

For the mobile testing technique demonstrated on I-70, the anemometer was installed on the outside top surface of the high-sided truck to collect wind velocity data, primarily for the purposes: (1) to collect general site-specific wind velocity data on I-70, and (2) to collect vehicle-specific wind velocity data for the particular test truck. For both the cases, it is important to evaluate the impact of the experimental setting on the accuracy of the measurements. In order to address this issue, a series of wind tunnel experiments were conducted with the scaled vehicle models. These efforts are described next.

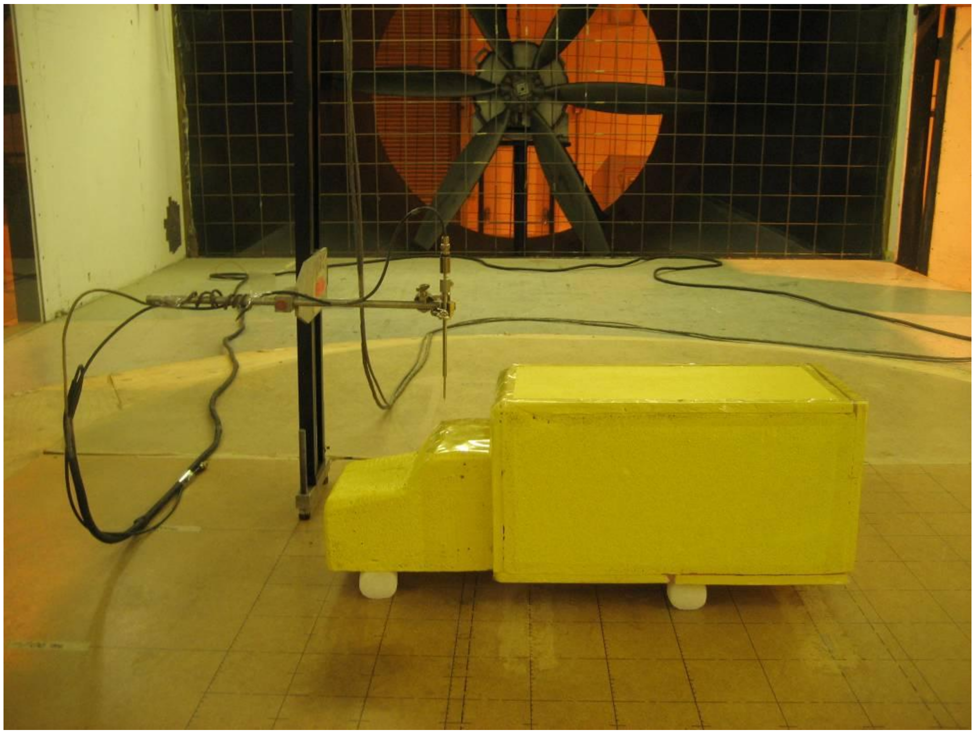
2.3.1 Wind tunnel facility

The wind tunnel study was conducted in the Environmental Wind Tunnel (EWT) at the Wind Engineering and Fluids Laboratory (WEFL), at Colorado State University. EWT is an open-circuit wind tunnel of a test section 3.66 m wide by 18.29 m long, with a flexible ceiling which can be adjusted from 2.13 m to 2.74 m. Fig. 2.7 shows the test section of EWT. The hot-wire anemometry (using hot-film probes) was employed to measure wind velocity at heights varying from 2 cm from the ground (test section floor) with a 1 cm increment, to develop the mean wind velocity and turbulence intensity profiles. The reference wind speed was measured at a height of 60cm in the wind tunnel. A pitot-static probe was used to monitor this speed (Fig. 2.8).

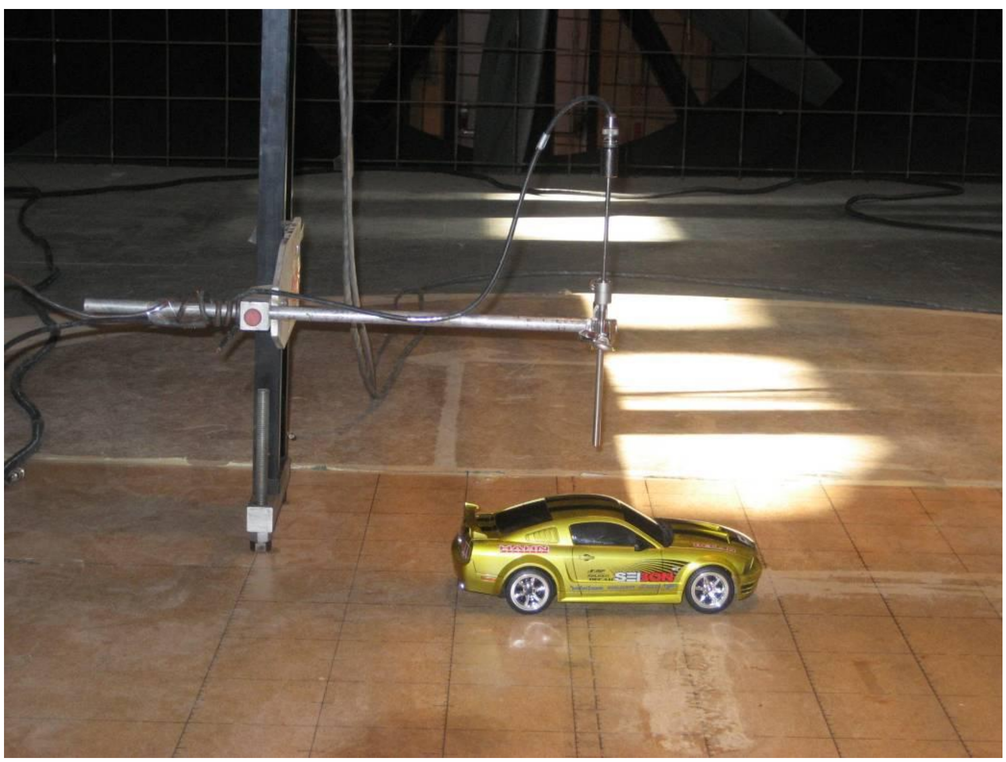
Fig. 2.8 Wind tunnel and the test section

2.3.2 Scaled vehicle models

A 1:10 geometrical scale model of the truck used in the field testing was fabricated of foam and a 1:18 commercially available model of a sedan car was purchased. Both the models are shown in Fig. 2.9 (a-b), respectively. In the field testing, the sonic anemometer was installed above the truck, on the passenger side. In the wind tunnel, the wind speed vertical profile was measured at the corresponding position relative to the truck model (Fig. 2.9 (a)). In order to evaluate the possible impacts of the experimental set-up employed in field testing, two testing configurations were considered during wind tunnel testing: the anemometer near the windward and leeward sides of the truck relative to incoming crosswind, respectively.



(a) 1:10 Penske truck model and hot-wire anemometry



(b) 1:18 Sedan car model and hot-wire anemometry

Fig. 2.9 Scaled vehicle models used in the wind tunnel testing

2.3.3 Wind tunnel results

The benchmark wind speed profile was initially measured at different heights w/o any vehicle model placed inside the wind tunnel. Then the measurements were taken with the truck model positioned in the wind tunnel test section, and the corresponding crosswind speed profiles w/ vehicles were acquired. Similar measurements were acquired for the sedan car model. For each vehicle model, the wind speed profiles were taken from both the windward and leeward sides of the vehicle model relative to incoming crosswind in a perpendicular direction.

2.3.3.1 Both site-specific and vehicle-specific wind velocity data measurements with high-sided test truck

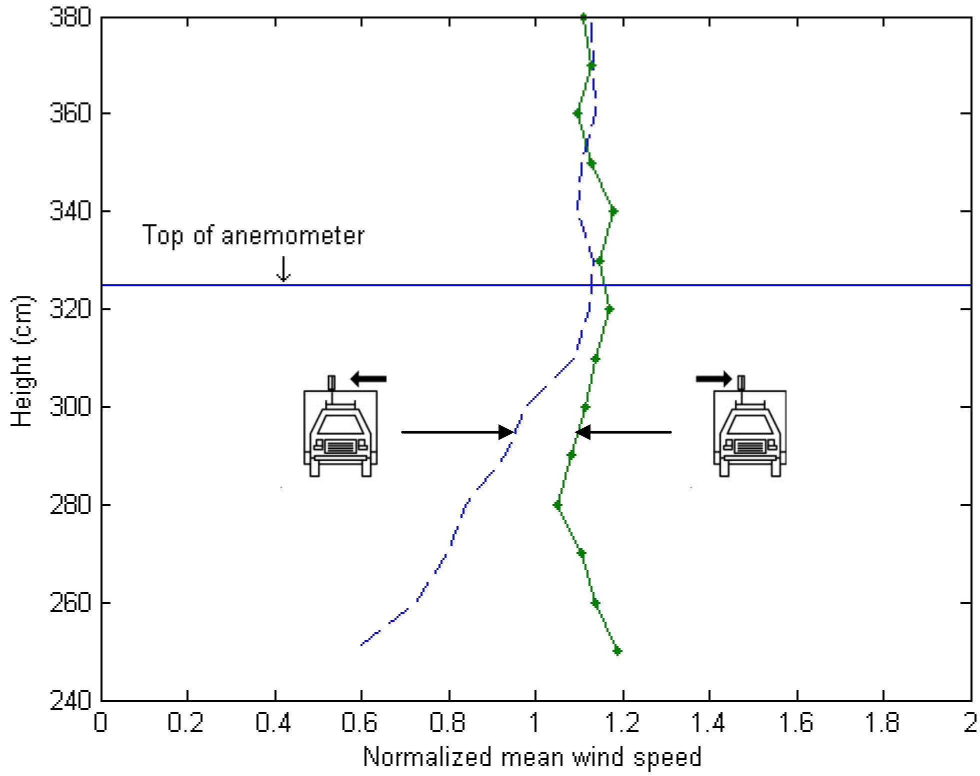
The normalized wind speed profiles are generated by dividing the wind speed value w/ vehicles by the corresponding wind speed value w/o vehicles (benchmark wind speed profile) at each height of measurements. The normalized profiles allowed for an easy assessment of the difference and a correction, if necessary, between the measured wind speed and the site-specific wind speed data. For example, the unit value of the normalized wind speed of the profile means the measured wind speed is the same as the site-specific wind speed data, i.e. with no distortion because of the existence of the test vehicle. The difference between the value and unity is a direct indicator of the correction needed to account for the bias in the wind speed readout, due to close proximity of the wind sensor and the car (cabin) surface.

The normalized mean wind speed profiles are shown in Fig. 2.10 (a) and the normalized standard deviation of wind speed profiles are depicted in Fig. 2.10 (b). These results are presented with two configurations: “with truck – windward side” (anemometer on windward side of vehicle relative to crosswind) and “with truck – leeward side” (anemometer on leeward side of vehicle relative to crosswind), as indicated in Fig. 2.9. The arrows show the directions of the oncoming crosswind. The *y* axis in Fig. 2.9 shows the actual elevation above the ground level. The full-scale vertical position of the anemometer is marked with a horizontal line.

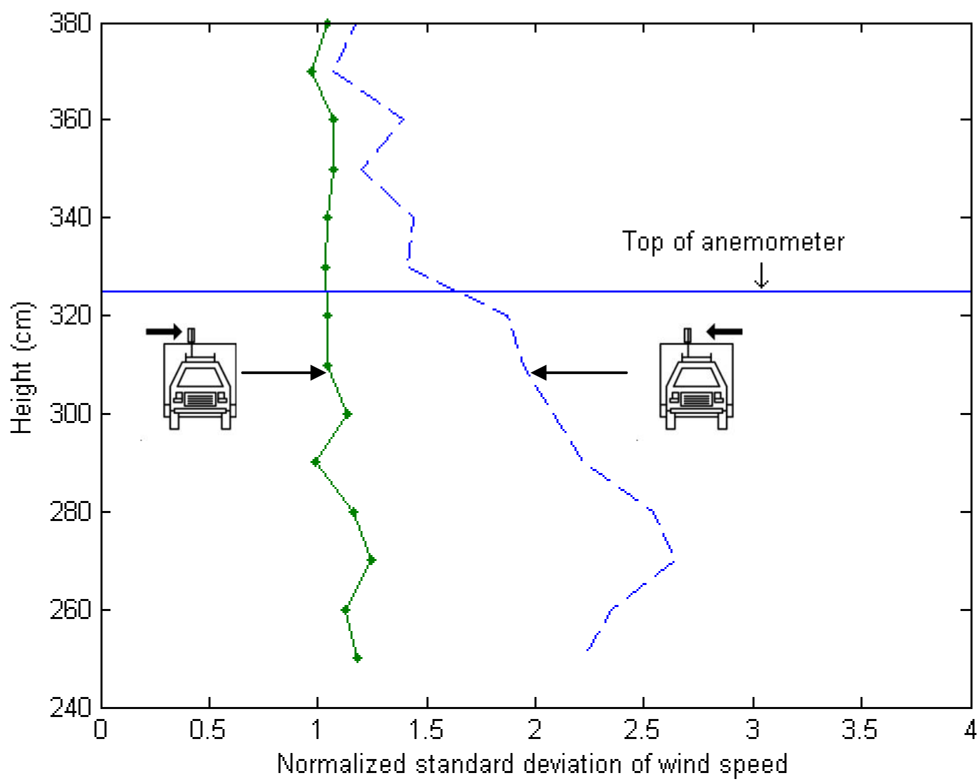
As shown in Fig. 2.10(a), the normalized mean wind speed values at the height of the sonic anemometer, for both the configurations vary between 1.05 to 1.1, suggest offsets of about 5% to 10% from the ideal site-specific wind velocity values w/o vehicles. It is apparent from Fig. 2.10(b) that the normalized standard deviation (STD) of wind speed at the height of the anemometer, for both the configurations, varies considerably: about 1.05 for the windward configuration and about 1.75 for leeward configuration. It is well known that flow past bluff bodies (e.g. high-sided vehicles) is associated with flow separation/reattachment combined with vortex shedding. This leads to higher level of turbulence on the leeward side of the truck than on the windward side. The large discrepancy between the crosswind speed measured at leeward and windward sides is primarily attributed to these phenomena.

In presence of a vehicle, the wind velocity at the typical height of the vehicle may deviate from the benchmark wind velocity (w/o a vehicle), depending on the vehicle shape. Namely, the normalized wind velocity value usually deviates from the unity. The comparison of the normalized wind speeds in Fig. 2.10, at the height of the anemometer and the height of the top surface of the truck (i.e. around 95 inch) suggests that the anemometer measurement represents the vehicle-specific mean wind speed (see Fig. 2.10(a)) pretty well (with an error lower that 10%), for the windward configuration. For the leeward configuration, the anemometer measurement will be 50% higher than the vehicle-specific measurement at the height of the top surface of the truck. Examination of the standard deviation (STD) of wind speed (Fig. 2.10(b)) shows considerably larger discrepancy for the leeward configuration as well.

Crosswind flow can approach the test vehicle from either side. In order to obtain consistent accuracy of measurements under all circumstances for high-sided trucks, the above results suggest the need for installation of two anemometers – one on each side - for the high-sided truck, in the transverse direction. Only the readings from the anemometer located at the windward side would be used in determining the conditions of incoming crosswind. Such a configuration would lead to improved mapping of the wind velocity data.

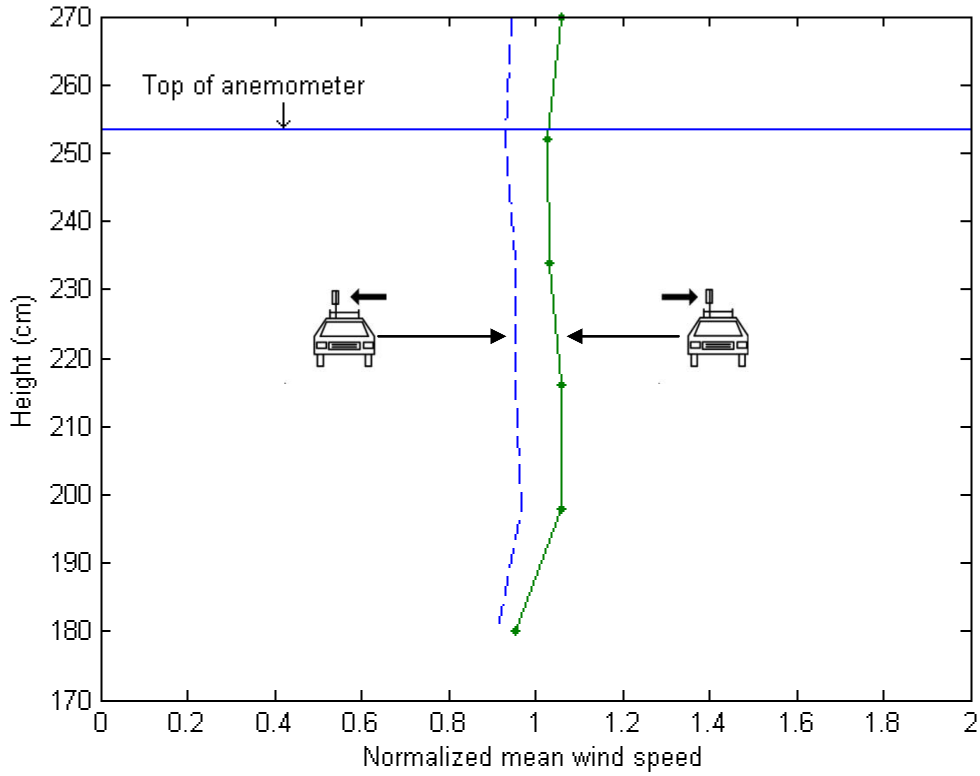


(a) Normalized mean wind speed profile

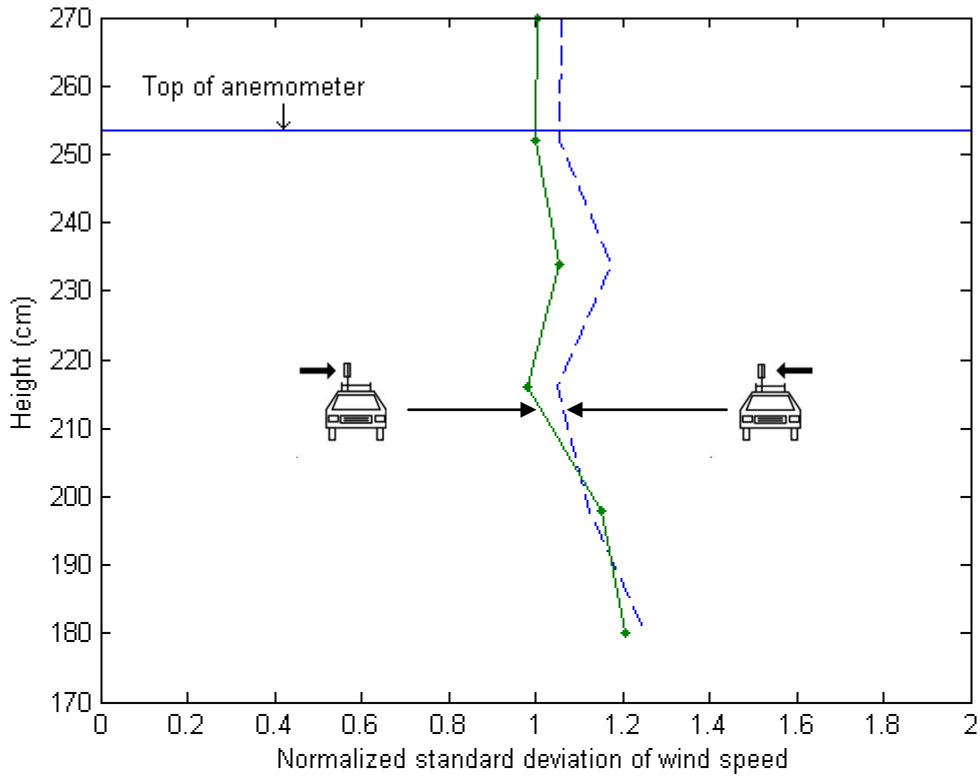


(b) Normalized STD of wind speed profile

Fig. 2.10 Normalized mean and STD of crosswind speed profiles for the truck



(a) Normalized mean wind speed profile



(b) Normalized STD of wind speed profile

Fig. 2.11 Normalized mean and STD of crosswind speed profiles for the sedan

2.3.3.2 Site-specific wind velocity data measurements with a streamlined sedan

In order to evaluate the situation when only site-specific wind velocity data is of concern, the same wind tunnel testing methodology was employed for the 1:18 scale model of a streamlined sedan car and the testing results are presented in Fig. 2.11. It can be seen in Fig. 2.11 (a) that the normalized mean wind speed values at the height of the anemometer are about 1.02 and 0.95, respectively for windward and leeward configurations. A similar comparison of the mean wind speeds at the height of the top surface of the car (vehicle-specific wind data) shows that the difference between the readings taken at both the locations does not exceed 5%.

As illustrated in Fig. 2.11 (b), the normalized STD of wind speed values at the height of the anemometer are around 1.05 and 1.1 for the windward and leeward configurations, respectively. The corresponding values at the height of the top surface of the car (vehicle-specific wind data) are about 1.05 and 1.15 for the windward and leeward configurations, respectively. Compared to the results obtained for the high-sided truck, the cross-wind measurements using anemometers placed on the top of a sedan car can generate more accurate site-specific wind velocity measurements than those obtained using a high-sides truck. Accordingly, no or minimal corrections of the measurements are needed in the former case. The comparison between the measurements with the high-sided truck and the sedan car also confirms that the shape of the test vehicle is one the primary factors responsible for the larger error of measurements observed for leeward location of the anemometer fastened to high-sided trucks.

2.3.4 Discussion

Based on the above observations, if only the general site-specific wind velocity data (both mean and turbulent speed) along a highway is of interest, the developed field set-up leads to acceptable wind velocity mapping for both a streamlined common passenger car and a high-sided vehicle (with dual-anemometer setup) used as a test vehicle. The accuracy can be further improved with about 5% to 10% adjustment in the measurements. The adoption of a streamlined passenger car (equipped with roof mounted anemometers) as a test vehicle is found to give more accurate results for the crosswind speed due to the lower impact on the wind field by the vehicle itself, than a high-sided vehicle.

If the vehicle-specific wind data acting on the high-sided vehicle is needed, the particular high-sided vehicle of interest should be adopted as the test vehicle. In this case, the dual-anemometer setup is suggested in order to ensure accurate measurements of the wind turbulence, with little or no adjustment. The advantage of adopting the high-sided truck as the test vehicle is that both the general site-specific (subject to possible adjustments during the data processing) and vehicle-specific wind data can be acquired at the same time.

The proposed data measurement strategy can acquire the spatially distributed wind velocity data along the highway under one particular wind condition each time when the test vehicle is driven through. With one “line” each time, a comprehensive wind velocity surface can be developed by multiple runs under different representative wind conditions. For example, these representative wind conditions can be “strong wind”, “moderate wind” and “mild wind”, depending on the requirements of the data details.

2.4 Conclusions

The present chapter introduced a mobile testing technology developed to collect crosswind velocity data in both time and spatial domains along any highway, for traffic safety studies. The developed technology can be used for two primary purposes: (1) acquisition of general site-specific wind velocity data along any highway, independent of the choice of the test vehicle; and (2) direct measurement of wind velocity at the roof height of a specific vehicle driven along a highway. A field test was carried out on I-70 corridor to evaluate the performance of the developed technology. Subsequently, wind tunnel investigation was performed, using a scaled model of the test truck, to investigate the effects of proximity of the car cabin surface on the anemometer (crosswind velocity) readouts. A wind tunnel test on a sedan car was also conducted to evaluate other alternatives of the test vehicle.

The following conclusions are drawn from the present chapter:

(1) The developed technology was proven to be feasible to collect wind velocity data in both time and spatial domains. Multiple runs under different wind conditions through the same highway of interests can generate a wind velocity surface;

(2) The wind tunnel testing showed that for high-sided vehicles, the measurements with the introduced technology can give accurate results with no or limited adjustment (about 5% to 10%) when the windward wind velocity is measured. An adjustment exceeding these bounds is needed when the leeward turbulence data is measured. The adoption of the dual-anemometer setup is suggested - one anemometers on the windward and another on the transversely leeward side of the vehicle. Such an arrangement would significantly improve the accuracy of crosswind velocity measurements acquired for high-sided vehicles.

(3) It was found from the wind tunnel testing that for the purpose of general site-specific wind velocity data collection along highways, streamlined common passenger cars (e.g. sedans) will generally give more accurate measurements of both mean wind velocity and wind turbulence than high-sided trucks. However, when high-sided trucks are used in tests, both vehicle-specific and site-specific wind velocity (with some possible adjustments according to wind tunnel testing) can be acquired simultaneously.

2.5 References

Baker, C. J. (1991). "Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system. " Journal of Fluids and Structures, 5, 221-241.

Baker, C.J. (1994). "Quantification of accident risk for road vehicles in cross winds." Journal of Wind Engineering and Industrial Aerodynamics, v 52, 1-3, 93-107.

Brassfield, M., Allison, W. (2001). “Skyway sees wind-blown crash, fatal leap.” St. Petersburg Times, http://www.sptimes.com/News/032101/TampaBay/Skyway_sees_wind_blow.shtml

Chen, S.R., Cai, C.S. (2004). “Accident assessment of vehicles on long-span bridges in windy environments. ” Journal of Wind Engineering and Industrial Aerodynamics, 92, 12, 991-1024.

Chen, S. R., Cai, C. S., Wolshon, B. (2009). “From normal operation to evacuation: single-vehicle safety under adverse weather, topographic and operational conditions.” Natural Hazards Review, ASCE, 10, 2, 68-76.

Huang, M. L. Wu, Long, S. R., Shen, S. S., Qu, W. D., Gloersen, P., Fan, K.L. (1998). “The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis.” Proc. Roy. Soc. Lond., 454A, 903-993.

Pinelli, J.P., Subranmanian, C., Plamondon, M. (2004). “Wind effects on emergency vehicles.” Journal of Wind Engineering and Industrial Aerodynamics, 92, 7-8, 663-685.

Redhen Inc. (2004). VMS 200-Video Mapping System Hardware User’s Guide.

Schmidlin, T.W., King, P.s., Hammer, B.O., Ono, Y. (1998). “Behavior of vehicles during tornado winds.” Journal of Safety Research, 29 (3), 181-186.

Simiu, E., Scanlan, R. H. (1996). Wind Effects on Structures - Fundamentals and Applications to Design, 3rd Edition, Wiley, New York.

Sigbjornsson, R., Snabjornsson, J. T. (1998). “Probabilistic assessment of wind related accidents of road vehicles: A reliability approach.” Journal of Wind Engineering and Industrial Aerodynamics, 74-76, 1097-1090.

The National Academies. (2006). “Where the weather meets the road- a research agenda for improving road weather system.” Report in Brief, The National Academies.

U. S. Department of Transportation (USDOT)-Intelligent Transportation Systems. (2003). “I-90 truck/wind warning system.” Columbia River, http://www.its.dot.gov/resources/IntegrationProject/projects /CVO-141.htm

Willett, A. (2005). “Wind wreak havoc, Gazette.” The (Colorado Springs), November 4, 2005, http://www.findarticles.com/p/articles/mi_qn4191/is_20051104/ai_n15844795

CHAPTER 3: SIMULATION-BASED ASSESSMENT OF VEHICLE SAFETY BEHAVIOR UNDER HAZARDOUS DRIVING CONDITIONS

3.1 Introduction

In the United States as well as other developed countries, road accidents are causing more injuries and casualties than any other natural or man-made hazard. Large commercial trucks, high-sided SUVs and emergency vehicles (e.g. fire trucks and EMS vehicles) are especially vulnerable to single-vehicle crashes (e.g. rollover, sideslip) under hazardous driving environments on rural highways. The hazardous driving environments may include inclement weather (e.g. strong crosswind gusts, snow, rain, or ice) and/or complicated terrain (e.g. steep slopes or sharp curves) (USDOT 2005). In 2005, single-vehicle accidents were responsible for 57.8% of accident fatalities (USDOT 2005). Each year in the United States, adverse weather alone is associated with more than 1.5 million vehicular crashes, which result in 800,000 injuries and 7,000 fatalities (The National Academies 2006). Among various causes of crashes in rural areas, it has been found that the dominant causes are excessive speeds and adverse environments (The Road Information Program 2005). In addition to direct safety threats, frequent single-vehicle accidents will also cause serious congestions, affecting the functionality of the whole highway network in normal situations, as well as under emergency. Therefore, for trucking industries, transportation and emergency management agencies, it is critical to accurately predict the crash risk, and further advise appropriate driving speeds under complicated adverse driving environments.

Different from multi-vehicle crashes, single-vehicle crashes under adverse or hazardous environments were found to be closely related to the coupling between vehicle, infrastructure and environment (Baker 1991; Guo and Xu 2006; Chen and Cai 2004; Chen et al. 2009). As a result of this unique coupling, observations solely from historical crash data in one place can hardly be translated into accurate risk prediction in different places or under driving environments which were not covered by the actual crash data. Therefore, in addition to analyzing actual historical crash data gathered after the crashes, investigations on single-vehicle crashes also require a reasonable simulation model which can be used more than for an after-the-fact reconstruction of the crash (TRB 2007), but more importantly, to reasonably predict the potential risk of crashes under comprehensive scenarios including those which may not be covered by historical crash data.

In automobile engineering, significant efforts have been put forth on simulating vehicle dynamics and accidents with engineering simulation models, from the simple rigid body model, the bicycle model to the complicated spring-mass multiple-degree-of-freedom model (Thomas 1992). Despite extensive works in these fields (e.g. Winkler and Ervin 1999; Gaspar et al. 2004, 2005; Sampson 2000), research on vehicle accident risks, which considers the coupling between the vehicle dynamic model, inclement weather and topographical condition, is still very limited. Baker (1986, 1987, 1991, 1994) was the first researcher who tried to investigate the high-sided vehicle accident risks under strong crosswind. In his studies, vehicle accident risks were assessed through solving several static equilibrium equations with some predefined accident criteria. Based on Baker's work, several reliability-based accident assessments were recently conducted (Sigbjornsson and Snaebjornsson 1998; Sigbjornsson et al. 2007). Chen and Cai (2004) improved the accident risk assessment by introducing a general dynamic interaction model, based on which the vehicle accident assessment was conducted by considering excitations from the supporting structure (e.g. bridge). Guo and Xu (2006) introduced an integrated vehicle safety assessment model on bridges. In the model, the dynamic bridge-vehicle-wind interaction analysis as well as the safety assessment was carried out at the same time based on the same accident criteria by Baker (1991). In most existing studies, however, only situations that vehicles are driven on straight routes with only crosswind excitation were considered. In the present chapter, a general vehicle safety behavior simulation model is introduced to consider the coupling effects with more realistic hazardous environments, including combinations of both inclement weather and complicated topographical conditions. Improved transient dynamic equations, accident criteria and new critical variables will also be incorporated into the model.

3.2 Theoretical Formulation

The general accident simulation model is introduced in this section: after the primary forces acting on a vehicle are introduced, series dynamic models are developed to simulate the dynamic response under different stages of the transient process of accidents.

3.2.1 Primary forces acting on vehicles

3.2.1.1 Tire force

When a vehicle is cornering, the lateral tire forces perpendicular to the direction of the driving velocity applied at the contact patches of the wheels are approximated to be proportional to the tire slip angle. The lateral tire forces of the front and the rear tires are defined in Eqs. (3.1, 3.2) as follows, respectively (Gaspar et al. 2004, 2005):

$$F_{y,f} = \mu c_f \alpha_f \tag{3.1}$$

$$F_{y,r} = \mu c_r \alpha_r \tag{3.2}$$

where c_i *(i= f* or *r)* is the tyre cornering stiffness and α_i *(i= f* or *r)* is the tire side slip angle associated with the front and the rear axles, respectively. μ is the road adhesion coefficient and subscripts *y*, *f* and *r* denote the lateral direction (*y* direction), front and rear wheels, respectively.

The classic equations for the tire slip angles of the front (α_f) and the rear (α_r) wheels can be defined as (Gaspar et al. 2004, 2005):

$$\alpha_f = -\beta + \delta - a_f \cdot \dot{\psi} / V \tag{3.3}$$

$$\alpha_r = -\beta - a_r \cdot \dot{\psi} / V \tag{3.4}$$

where β, δ and $\dot{\psi}$ are the sideslip angle, steer angle and yaw rate, respectively; V is the driving speed of the vehicle and a_f and a_r are the longitudinal distances from the centre of sprung mass to the front and the rear axles, respectively.

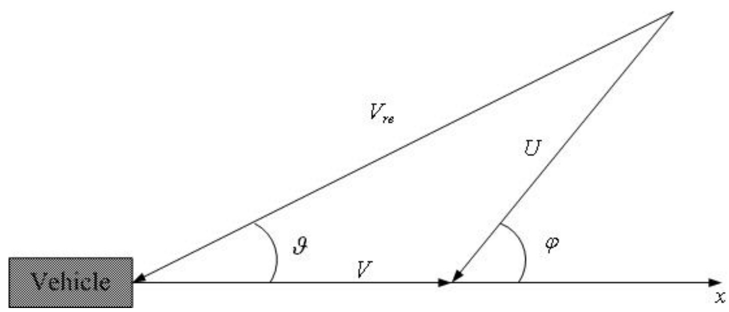


Fig. 3.1 Addition of the velocity vectors

3.2.1.2 Crosswind forces

Crosswind velocity can be obtained from actual measurements or from numerical simulations based on existing wind velocity spectra (Baker 1991; Chen and Cai 2004). Typically, quasi-static assumptions are applied in order to simulate the wind loadings acting on moving vehicles (Baker 1987, 1994; Coleman and Baker 1994). The crosswind-induced quasi-static forces and moment acting on the vehicle body on *x*, *y* and *z* directions are defined as follows (Baker 1994):

$$F_x = 0.5 \rho C_{Fx} A V_{re}^2 \quad \text{drag force} \tag{3.5}$$

$$F_y = 0.5 \rho C_{Fy} A V_{re}^2 \quad \text{lift force} \tag{3.6}$$

$$F_z = 0.5\rho C_{Fz} A V_{re}^{\ 2} \qquad \text{side force} \quad (3.7)$$

$$M_x = 0.5\rho C_{Mx} A V_{re}^{\ 2} h_{re} \qquad \text{rolling moment} \quad (3.8)$$

$$M_y = 0.5\rho C_{My} A V_{re}^{\ 2} h_{re} \qquad \text{yawing moment} \quad (3.9)$$

$$M_z = 0.5\rho C_{Mz} A V_{re}^{\ 2} h_{re} \qquad \text{pitching moment} \quad (3.10)$$

where ρ is the density of air. A is the reference area. h_{re} is the reference arm. $C_{F\,x}, C_{F\,x}$, and $C_{F\,z}$ are wind force coefficients and $C_{M\,x}, C_{M\,y}$, and $C_{M\,z}$ are wind moment coefficients in (about) *x*, *y* and *z* directions, respectively. These wind coefficients, which are typically obtained from wind tunnel testing (Baker 1994), are related to the profile of a specific vehicle and are functions of attack angle ϑ. Due to the lack of wind tunnel testing results of vehicles during the process of accident-related motions, it is assumed in the present chapter that the wind loadings acting on the vehicle remain the same during the process of rollover or sideslip. V_{re} is the wind velocity relative to the vehicle, which is defined as (Fig. 3.1):

$$V_{re} = \sqrt{V^2 + \left(U + u(t)\right)^2 + 2V\ \left(U + u(t)\right) \cdot \cos\ \varphi} \qquad (3.11)$$

where U is the mean wind velocity and *u(t)* is the turbulent component of wind velocity in the alongwind direction. Wind turbulent velocity can be obtained from actual wind measurements or from simulations based on wind velocity spectrums (Chen and Cai 2004). φ is the wind direction (Fig. 3.1).

3.2.1.3 Forces due to topology

In typical highway designs, there will be an appropriate roadway superelevation on any curved path to provide centripetal acceleration which acts toward the center of the curvature (AASHTO 2004). So it is necessary to consider the corresponding superelevation θ in the model in order to replicate the real situation when a vehicle moves through a curved path. In the following numerical results, θ is defined based on typical design values suggested by AASHTO (2004), which are dependent on the road design speed and radius of curvature.

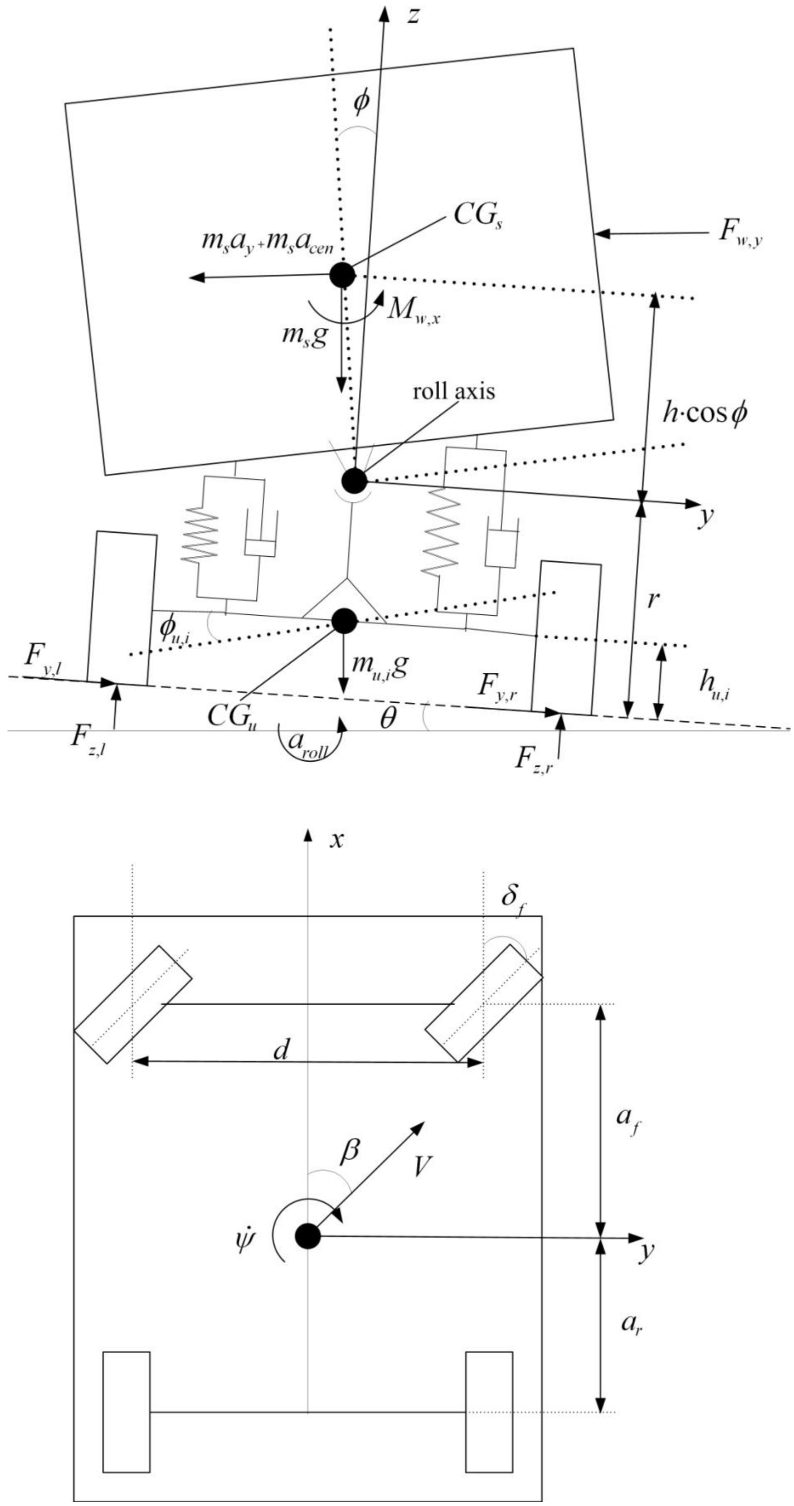


Fig. 3.2 Single-body vehicle model

3.2.2 Basic vehicle dynamic model – wheels are not lifted up nor sideslip

The vehicle model is shown with the coordinate system fixed on the vehicle in Fig. 3.2. In the following model, pitching and bouncing motions are not considered because that they typically have insignificant impacts on the rolling and lateral movements of the vehicle (Sampson 2000). The sprung mass rotates about the roll center which is dependent on the kinematical properties of the suspensions. The unsprung masses can also rotate, combined with the effect of the vertical compliance of the tires. The vehicle motion equations are developed according to the change of the momentum and the sum of external forces based on the model introduced by Sampson (2000). The suspension parameters such as damping coefficients are assumed to be constant.

As a general model which considers wind load, road superelevation, curvature and excitations from supporting structures (e.g. vibration induced by pavement roughness or bridge/vehicle interactions), five force and moment equilibrium equations of vehicle motions of sprung mass and suspensions in *y* and *z* directions are defined in Eqs. (3.12) to (3.16), respectively.

$$m_s h\ddot{\phi} = mV(\dot{\beta}+\dot{\psi}) - F_{y,f} - F_{y,r} + F_{w,y} - mg\theta + ma_y \tag{3.12}$$

$$-I_{x'z'}\ddot{\phi} + I_{z'z'}\ddot{\psi} = F_{y,f}a_f + F_{y,r}a_r + M_z \tag{3.13}$$

$$\begin{aligned} I_{x'x'}\ddot{\phi} - I_{x'z'}\ddot{\psi} &= m_s gh\phi + m_s Vh(\dot{\beta}+\dot{\psi}) + M_x - m_s gh\theta + m_s ga_y + F_{w,y}h_w \\ &\quad -k_f(\phi-\phi_{t,f}) - l_f(\dot{\phi}-\dot{\phi}_{t,f}) + u_f - k_r(\phi-\phi_{t,r}) - l_r(\dot{\phi}-\dot{\phi}_{t,r}) + u_r \end{aligned} \tag{3.14}$$

$$\begin{aligned} rF_{y,f} &= -m_{u,f}V(h_{u,f}-r)(\dot{\beta}+\dot{\psi}) + m_{u,f}g(h_{u,f}-r)\phi_{t,f} + m_{u,f}g(h_{u,f}-r)\theta - a_{roll}I_{x'x'}m_f / m \\ &\quad -m_{u,f}a_y(h_{u,f}-r) + k_{t,f}\phi_{t,f} - k_f(\phi-\phi_{t,f}) - l_f(\dot{\phi}-\dot{\phi}_{t,f}) + u_f \end{aligned} \tag{3.15}$$

$$rF_{y,r} = -m_{u,r}V(h_{u,r} - r)(\dot{\beta} + \dot{\psi}) + m_{u,r}g(h_{u,r} - r)\phi_{t,r} + m_{u,r}g(h_{u,r} - r)\theta - a_{roll}I_{x'x'}m_r / m$$

$$-m_{u,r}a_y(h_{u,r} - r) + k_{t,r}\phi_{t,r} - k_r(\phi - \phi_{t,r}) - l_r(\dot{\phi} - \dot{\phi}_{t,r}) + u_r \tag{3.16}$$

where $F_{w,y}, M_x, M_z$ are lateral wind force, wind induced roll moment and wind-induced yaw moment, respectively. θ is road superelevation. a_y and a_{roll} are accelerations in *y* direction and rolling direction of the supporting infrastructures (e.g. pavement or bridge), respectively. m, m_s, m_u are total mass, sprung mass and unsprung mass, respectively. h is the height of the centre of sprung mass, measured upwards from the roll centre. r and h_u are the heights of rolling center and unsprung mass center, measured upwards from ground, respectively. $F_{y,f}$ and $F_{y,r}$ are lateral forces of front and rear tyres, respectively. $I_{x'x'}$, $I_{x'z'}$, $I_{z'z'}$ are roll moment, yaw-roll product and yaw moment of inertia of sprung mass, respectively. k, k_t, l are suspension roll stiffness, tyre roll stiffness and suspension roll damping rate, respectively. ϕ and ϕ_t are absolute roll angle of sprung mass and unsprung mass, respectively. β and ψ are sideslip angle and heading angle. u is active roll torque. A full list of all variables can be found in the nomenclature.

The above equations can be expressed using a state-space representation, which is suitable for numerical integrations:

$$\dot{x} = Ax + B_0u + B_1\delta + C \tag{3.17}$$

where

$$x = \begin{bmatrix} \beta & \dot{\psi} & \phi & \dot{\phi} & \phi_{t,f} & \phi_{t,r} \end{bmatrix}^T \tag{3.18}$$

$$u = [u_f \quad u_r]^T \tag{3.19}$$

$$B_0 = E^{-1}\begin{bmatrix} 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \end{bmatrix} \tag{3.20}$$

$$B_1 = E^{-1}\left[\mu Y_\delta \quad -\mu N_\delta \quad 0 \quad r\mu Y_{\delta,f} \quad 0 \quad 0\right]^T \tag{3.21}$$

$$A = E^{-1}\begin{bmatrix} \mu Y_\beta & \mu Y_{\dot\psi} + mV & 0 & 0 & 0 & 0 \\ -\mu N_\beta & -\mu N_{\dot\psi} & 0 & 0 & 0 & 0 \\ 0 & m_s Vh & m_s gh - k_f - k_r & -l_f - l_r & k_f & k_r \\ r\mu Y_{\beta,f} & r\mu Y_{\dot\psi,f} - m_{u,f}V(h_{u,f} - r) & -k_f & -l_f & k_f + k_{t,f} + m_{u,f}g(h_{u,f} - r) & 0 \\ r\mu Y_{\beta,r} & r\mu Y_{\dot\psi,r} - m_{u,r}V(h_{u,r} - r) & -k_r & -l_r & 0 & k_f + k_{t,r} + m_{u,r}g(h_{u,r} - r) \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{3.22}$$

$$C = E^{-1}\begin{bmatrix} F_{w,y} - mg\theta + ma_y, M_z, M_x - m_s gh\theta + m_s a_y h + F_{w,y}h_w, m_{u,f}g(h_{u,f} - r)\theta - m_{u,f}a_y(h_{u,f} - r), \\ m_{u,r}g(h_{u,r} - r)\theta - m_{u,r}a_y(h_{u,r} - r), 0 \end{bmatrix}^T \tag{3.23}$$

$$E = \begin{bmatrix} -mV & 0 & 0 & m_s h & 0 & 0 \\ 0 & I_{z'z'} & 0 & -I_{x'z'} & 0 & 0 \\ -m_s Vh & -I_{x'z'} & 0 & I_{x'x'} & -l_f & -l_r \\ m_{u,f}V(h_{u,f} - r) & 0 & 0 & 0 & -l_f & 0 \\ m_{u,r}V(h_{u,r} - r) & 0 & 0 & 0 & 0 & -l_r \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{3.24}$$

N and Y terms in Eqs. (3.21-3.22) are partial derivatives of net tyre yaw moment or lateral force, and the detailed definitions can be found in the nomenclature. Runge-Kutta Method will be used to solve dynamic equations in time domain with a time step of $dt = 0.001$ s.

3.2.3 Criteria of wheel being lifted up or sideslip

Taking the summation of moment about the point on the ground plane at the mid-track position, one can get the weight transfer ratio between the left and right wheels:

$$W_{trans} = ((mV(\dot\beta + \dot\psi) + ma_y + mg(\phi - \theta)) \times h_{cm} + F_{w,y}(h_w + r) + M_x + a_{roll}I_{x'x'}) / d \tag{3.25}$$

3.2.3.1 Wheel being lifted up

When the weight transferred between the left and right wheels is larger than a half of the vehicle weight minus a half of the vertical wind force (lift force), there is no reaction force existing on one side of wheels. In addition, the roll angle between the sprung mass and the suspension system typically can not exceed 6 or 7 degrees due to the mechanical restraints of the suspension movements (Sampson 2000). Thus if either of the following two criteria is satisfied, the wheel is believed to be lifted up:

$$W_{trans} > mg/2 - F_{w,z}/2 \tag{3.26}$$

or

$$\phi^i - \phi^i_{t,f} \geq \phi^{cri} \text{ or } \phi^i - \phi^i_{t,r} \geq \phi^{cri} \tag{3.27}$$

where ϕ^{cri} is the maximum allowable relative rollover angle due to the mechanical restraints (e.g. 7 degrees).

3.2.3.2 Sideslip

The front or the rear wheel will start to sideslip when the actual lateral tyre forces $F_{y,f}$ or $F_{y,r}$ quantified with Eqs. (3.1-3.2) exceeds the corresponding sideslip critical friction forces, respectively:

$$F_{y,f} > F_{la,f}^{\max} = \mu F_{z,f} \tag{3.28}$$

or

$$F_{y,r} > F_{la,r}^{\max} = \mu F_{z,r} \tag{3.29}$$

where $F_{z,f}$ and $F_{z,r}$ are the vertical reaction forces on the front and rear axles, respectively; $F_{la,f}^{\max}$ and $F_{la,r}^{\max}$ are the sideslip critical friction forces of the front and the rear wheels, respectively. μ is the static lateral friction coefficient. The longitudinal rolling resistance of the tires in the driving direction, which is related to vehicle driving speed and tire condition (temperature, inflation pressure and so on), is relatively insignificant to the vehicle stability compared to the side friction force. Therefore, the longitudinal rolling resistance is not considered in this model.

Two sets of criteria as shown in Eqs. (3.26-3.29) will be checked at each time step to identify whether any wheel will be lifted up or will start to sideslip, under either of which, the corresponding new dynamic equations as introduced below will be used to continue the simulation.

3.2.4 Updated vehicle dynamic model – after wheels being lifted up or sideslip

3.2.4.1 After wheels being lifted up

After wheels on one side of the vehicle are lifted up, the suspension system of a vehicle can not generate resistant moment anymore and the roll center moves toward the wheels which are not yet lifted up. Accordingly, in Eqs (3.12-3.16), $I_{x'x'}$, $I_{z'z'}$ and $I_{x'z'}$ will be changed to $I'_{x'x'}$, $I'_{z'z'}$ and $I'_{x'z'}$, which are moments of inertia about the wheels remaining on the ground in three directions, respectively. $k_{t,i}\phi_{t,i}$ in Eqs. (3.12-3.16) will be changed to $k_{t,i}\phi^*_{t,i}$, where $\phi^*_{t,i}$ is the value of $\phi_{t,i}$ when the wheels are just lifted up. In addition, in Eqs (3.12-3.16), all the moment reference arms are changed to the distances to the wheels remaining on the ground from originally to the suspension roll center of the vehicle due to the fact that the vehicle starts to rotate about the contact points of the wheels remaining on the ground once the wheels on one side are lifted up.

3.2.4.2 After starting to sideslip

When a wheel starts to sideslip, the lateral slipping friction forces can be assumed approximately equal to the slideslip critical friction forces $F_{la,f}^{\max}$ and $F_{la,r}^{\max}$ that the road can generate for the left and right wheels, respectively. Before the vehicle hits roadside or another object, $F_{y,f}$ and $F_{y,r}$ in Eqs (3.12, 3.15-3.16) will be changed to $F_{la,f}^{\max}$ and $F_{la,r}^{\max}$, respectively. As a result, the vehicle will laterally slip with the slipping acceleration a_{slip} which can be derived as:

$$a_{slip} = (mV(\dot{\beta}+\dot{\psi}) - F_{f,f}^{\max} - F_{f,r}^{\max} + F_{w,y} - mg\theta + ma_y - m_s h\ddot{\phi}) / m \tag{3.30}$$

3.2.5 Vehicle accident assessment criteria

3.2.5.1 Vehicle rollover

A vehicle ultimately rollovers only when the *y* value of the center of gravity (CG) exceeds the *y*-coordinate of the wheel. Therefore, the corresponding roll angle at the moment when the vehicle ultimately rolls over is set as the criterion to identify the occurrence of rollover accidents:

$$\phi > arc\sin(d / 2\sqrt{d^2/4 + h_{cm}^2}) + \theta \tag{3.31}$$

where d is the track width of the truck. h_{cm} is the height of the mass center of the truck. θ is the r oad superelevation.

3.2.5.2 Sideslip

Once a vehicle starts to sideslip, driver operations such as applying steering or brakes usually have little effect on stopping the motion before the vehicle hits an object (e.g. road side curbs, other vehicles), which may or may not cause tripped rollover. With the purpose of introducing the general model in this chapter, the travel distance after sideslip starts will be the critical variable to be investigated without dealing with different site-specific road conditions (e.g. different distances from the center of the driving lane to the curb). It is noted that any particular tripped rollover scenario can be simulated with the proposed model as long as the specific descriptions of the obstacle (e.g. locations, size and material) are available. Due to the limited scope of the present study, different particular tripped rollover scenarios will not be discussed in this chapter.

3.2.5.3 Critical driving speed (CDS) and critical sustained time (CST)

For any given hazardous condition and any specific vehicle, the occurrence of single-vehicle accidents is significantly related to excessive driving speeds. To maintain an appropriate driving speed in order to balance the safety and efficiency is obviously critical. Therefore, for the proposed deterministic model, the "*critical driving speed (CDS)*" is the highest allowable driving speed without causing any type of accidents under a specific combination of environmental and vehicular conditions. In the future reliability-based model, it will become the highest allowable driving speed which results in the crash risk at the desired level.

In addition to the CDS which has been studied in some existing studies (e.g. Baker 1991; Chen and Cai 2004; Guo and Xu 2006; Sigbjornsson and Snaebjornsson 1998; Sigbjornsson et al. 2007), another critical variable which has been rarely discussed is the "*critical sustained time (CST)*". CST is the minimum time period required to sustain the specific combination of the adverse environments (e.g. wind speed, curvature) and the driving conditions (e.g. specific driving speed). For example, a vehicle may only take 2 seconds to go through a ramp at one specific driving speed. If the CST for this vehicle under the specific combination of the adverse environmental and driving conditions is larger than 2 seconds, the accident may not really happen as the environmental conditions will change right after 2 seconds. One common situation is when the truck suddenly experiences a change of strong wind gust load on the vehicle (i.e. both imposing and removing) due to special topographical conditions, such as getting into a valley from open areas or passing a bridge tower or mountain and getting to open areas.

According to the "Green Book" (AASHTO 2004), the median reaction time of drivers is 0.66 seconds based on the data from 321 drivers (Johansson and Rumar 1971). The design reaction time is 2.5 seconds which exceeds 90th percentile of reaction time for all drivers (AASHTO 2004). In the present study, both "median reaction time" (0.66 s) and "design reaction time" (2.5 s) will be checked. If the CST is larger than the reaction time of the driver, the driver may have sufficient time to take appropriate actions (e.g. reduce speeds) to possibly prevent the occurrence of accidents. Obviously, CDS suggests the appropriate driving speed assuming the driver has sufficient time to react, while CST discloses the information about whether the driver has enough time to react under a particular driving condition.

3.3 Parametric Study

A numerical example will be conducted for demonstration purposes. Although the simulation process as introduced above can be applied to any type of single-body vehicle, a truck model is adopted in the parametric study because of its relatively larger safety risks under hazardous driving conditions. Comparative studies between different types of vehicles are beyond the scope of the present study.

Table 3.1 Parameters of the single-body truck model

Parameters	Value	Parameters	Value
m_s	23000 lb	C_f , C_r	714.6 lb/deg , 2544 lb/deg
$m_{u,f}$, $m_{u,r}$	1202 lb , 4603 lb	k_f , k_r	24119 in.lb/deg , 245826 in.lb/deg
a_f , a_r	14.8 ft , -5.22 ft	l_f , l_r	393 lb/deg , 938 lb/deg
h	2.12 ft	$k_{t,f}$, $k_{t,r}$	318491 in.lb/deg , 274583 in.lb/deg
h_{cm}	3.98 ft	$h_{u,f}$, $h_{u,r}$	1.67 ft , 1.67 ft
$h_w\,(h_{re})$	5.46 ft	I_{xx}	66132 in.lb.sec.sec
r	2.42 ft	I_{xz}	31799 in.lb.sec.sec
d	6 ft	I_{zz}	465180 in.lb.sec.sec
μ	1	A	$107.6\ \text{ft}^2$
u_f , u_r	0 in.lb , 0 in.lb	ϑ	90°

3.3.1 Truck model

A single-body truck model will be used in the numerical studies and the same parameters from Winkler and Erwin (1999) are adopted (Table 3.1). In automobile engineering, the steering angle δ is typically expressed as $\delta = L / R$ (neutral steer), where L is the wheelbase of the vehicle, R is the turning radius of the curved path and the steering angle can be determined for each different R . The corresponding superelevation is considered for different R and typical speed limits according to AASHTO (2004). Although there are some limited studies on quantifying the steering angle due to driver behavior (Baker 1991; Chen and Cai 2004), to the writers' knowledge, there is not yet a well-accepted model which can accurately relate the steering angle and the motion of vehicles from existing literature. Besides, existing studies also showed limited impact of driver behavior of steering on single-vehicle accidents (Chen and Cai 2004). Therefore, in the present study, impacts of driving behavior on steering angles will not be considered. However, it is noted that the present model can easily incorporate the driver behavior model on steering angles when a reliable one becomes available in the future.

3.3.2 Adverse/hazardous driving environments

It is well known the same vehicle experiences different accident risks under different driving environments. For large trucks, some driving environments can be hazardous which often cause rollover or sideslip accidents. These adverse driving environments typically include strong crosswind gust, slippery road surface which is covered by snow or ice, a curved path or with dynamic excitations from the supporting structures (e.g. roughness of pavement and/or bridge structure). These adverse driving environments may work individually or integrally to significantly increase the crash risk of trucks. In the present chapter, three different road surface conditions (dry, snow-covered and icy) and the situation with excitations from supporting structures will be considered along with different wind gust conditions, on both straight and curved paths. In order to capture the most critical scenarios, wind is assumed to be perpendicular to the driving direction of the vehicle all the time, including on both straight and curved path. Given the randomness of actual wind directions in nature, this assumption will lead to slightly more conservative results than the reality, which is usually preferred in engineering fields. However, the present model can easily consider varying wind directions during curving when one specific initial wind direction is given. In following sections, critical sustained time (CST), critical driving speed (CDS) and transient accident-related response in time domain will be investigated for various conditions.

3.3.3 Critical sustained time (CST) of accidents

3.3.3.1 On straight road

When the truck is driven on a straight road with dry road surface, rollover accidents are found to occur first. Fig. 3.3 shows the relationship between critical sustained time (CST) of rollover, the wind speed U and the driving speed V. The lowest V of each curve also suggests the critical driving speed (CDS) under which the accident may happen. There are two horizontal lines shown in the figure which suggest the median (0.66 second) and design reaction time (2.5 seconds), respectively. It can be found from Fig. 3.3 that the CST of rollover decreases when U or V increases. When the wind speed is relatively low (lower than 45 mph), the required CST in order to rollover a truck quickly drops when the vehicle driving speed increases. For instance, when the truck moves in a speed of 70 mph and the wind speed is 35 mph, it requires about 1.7 seconds in order to rollover the truck. Depending on the driving experience and how fast an individual driver senses and reacts to the danger, a rollover accident may or may not actually happen. When the wind speed is more than 50 mph, it only takes around 0.6 seconds to rollover the truck with about 25 mph driving speed and there is no significant difference for the CST of rollover when the wind speed keeps increasing. As compared to the median reaction time (0.66 seconds), 0.6 seconds are usually too short for most drivers to react and a rollover accident is very likely to happen in this scenario. An accurate accident risk assessment based on the CST relies on a reliability-based risk assessment model considering the uncertainties of reaction times among different drivers. It will be the future task for the writers based on the proposed deterministic model. It is also noted that none of the scenarios in Fig. 3.3 can satisfy the design reaction time requirement (2.5 seconds) as specified in AASHTO, which is known to be very conservative.

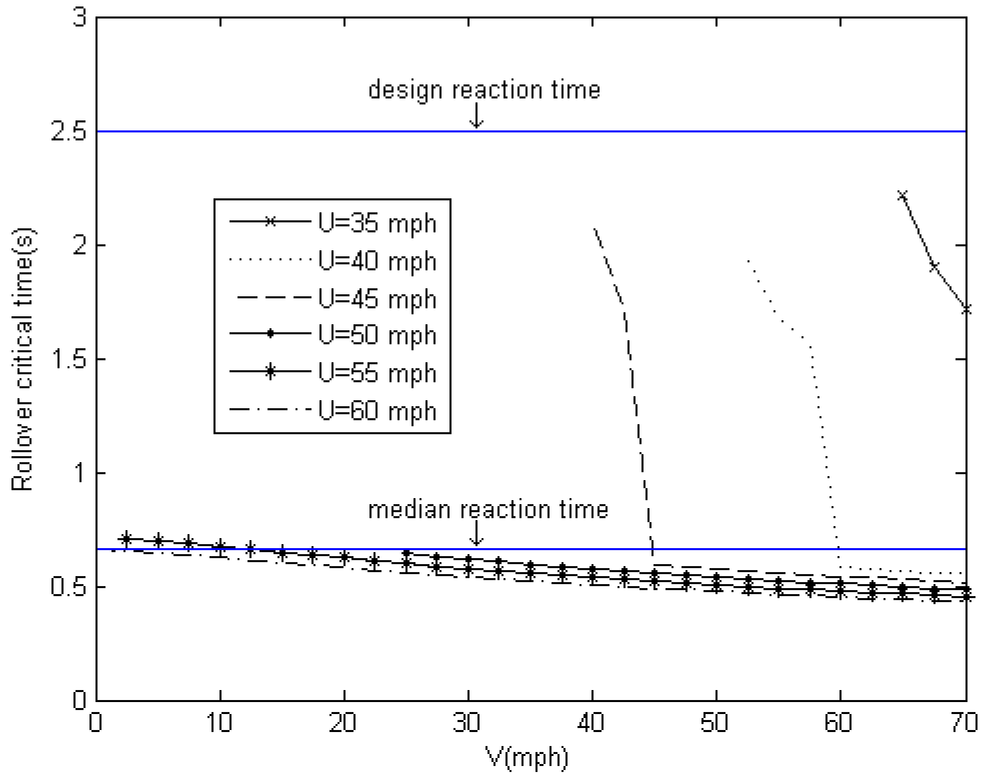


Fig. 3.3 Critical sustained time (CST) of rollover on a straight and dry road

When road surface is covered by snow or ice, sideslip accidents usually happen first. Fig. 3.4 shows the relationship between the critical sustained time (CST) of sideslip and the driving speed V when the truck moves straight on a snow-covered and ice-covered road surface, along with different wind speeds. For any higher driving speeds beyond the *x* coordinate of each curve in Fig. 3.4, rollover accidents will happen first, as marked in the figure with the text “rollover”. Under the same wind condition, driving faster (e. g. higher V) will require a shorter duration of the sustained hazardous condition (i.e. smaller CST) to finally make the accident happen.

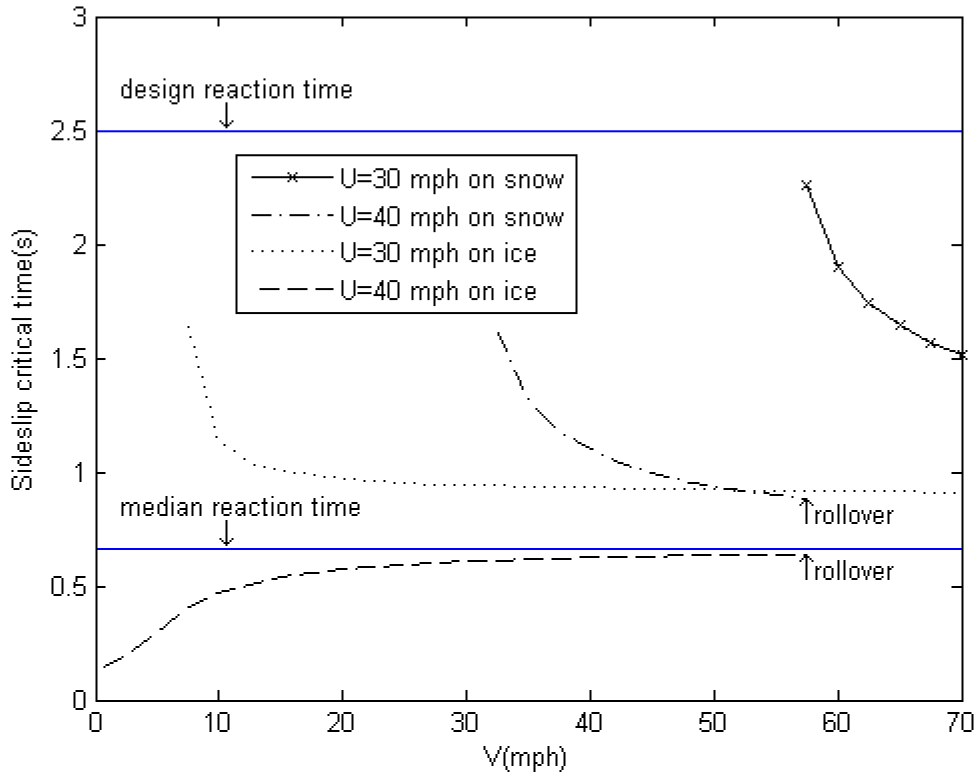


Fig. 3.4 Critical sustained time (CST) of sideslip accident on a straight road

When the truck is on icy road surface, the CST remains relatively constant when the driving speed is above 20 mph (Fig. 3.4). The CST values are all smaller than the median reaction time when the wind speed is more than 40 mph, which suggest sideslip accidents are very difficult to be avoided by majority of drivers. When the truck is on icy road surface with 40 mph wind speed, it is also found that the CST actually slightly increases with the driving speed and this trend continues until the driving speed reaches 30 mph when the CST becomes nearly constant despite further increasing of the driving speed. This is different from the observation under the snow-covered situation, and it is probably related to the unique vehicle movement manner on ice when the lateral friction is very small. As shown in Fig. 3.4, when wind is strong (U=40 mph), the truck will experience rollover accidents first when the driving speed is over 57.5 mph on both snow-covered and icy road surfaces.

3.3.3.2 On curved roads

Fig. 3.5 show the relationship between the CST of rollover and the driving speed V under different radii of curvature R and wind conditions. Two representative curve radii (130 ft and 260 ft) and three wind conditions (U=0, 20 and 40 mph) are studied. It can be found that the respective CST considerably decreases under the same curving situation when the wind speed increases. For example, when the curving radius R is 130 ft (a typical value of many highway ramps), the driving speed of 42.5 mph and higher may cause rollover accidents with the CST about 3 seconds when there is no wind. When the wind speed is 20 mph, the driving speed of 37.5 mph or higher will cause rollover accidents with the CST of about 2 seconds on the same path. When the wind speed is further increased to 40 mph, the truck will rollover with the driving speed of 30 mph and the CST is about 0.6 seconds. In reality, wind gust with 20-40 mph wind speed is pretty common on highways and 0.6 second is typically not enough for more than 50% drivers to react. As we often observe on highways, curving operations of large trucks in windy weather, especially under a sharp curve (e.g. ramp, or in mountain areas), are much more vulnerable than the situation without strong wind. By comparing the differences of results for R=130 ft and R=260 ft under various wind speeds, it is found that the different radii affect the CST significantly when wind is not strong. While wind is strong (e.g. U=40 mph), different radii only affect the CST slightly, which suggests that the dominant impact shifts from the geometric condition (curvature) to environmental condition (wind).

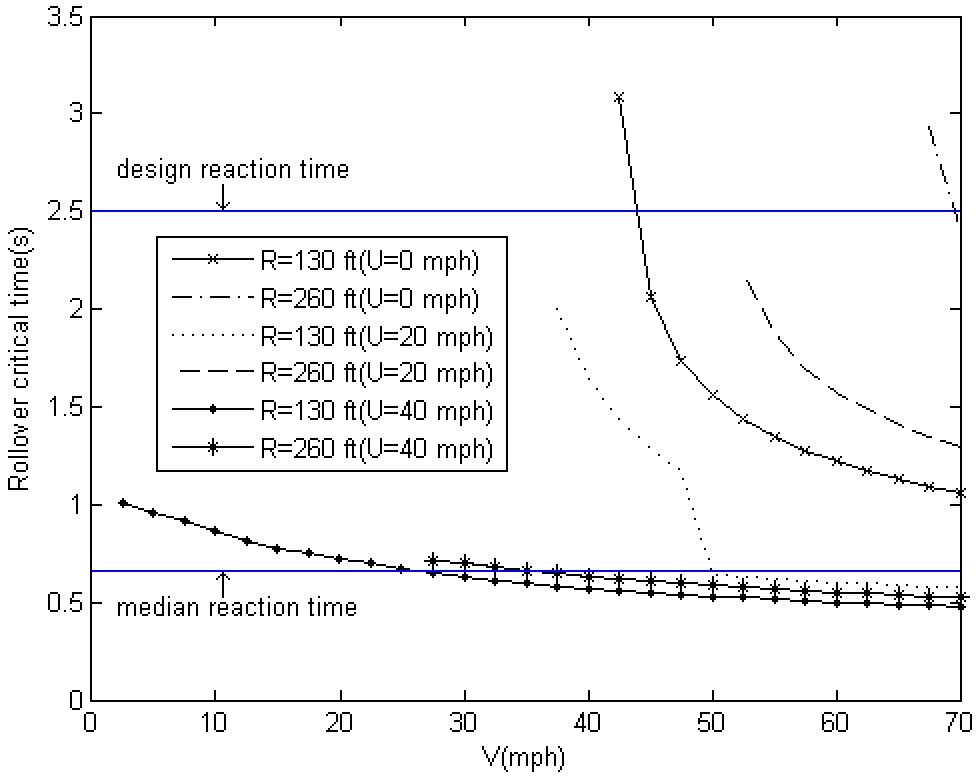


Fig. 3.5 Critical sustained time (CST) of rollover accident on a dry curved road

Fig. 3.6 gives the results of the CST of sideslip under different combinations of driving speeds and curvature radii when the wind speed is 0 or 20 mph while the road surface is covered by snow. It is found that when the radius R is about 130 ft, 60 mph driving speed without existence of wind or 50 mph driving speed with 20 mph wind will all cause the CST to be lower than the median reaction time.

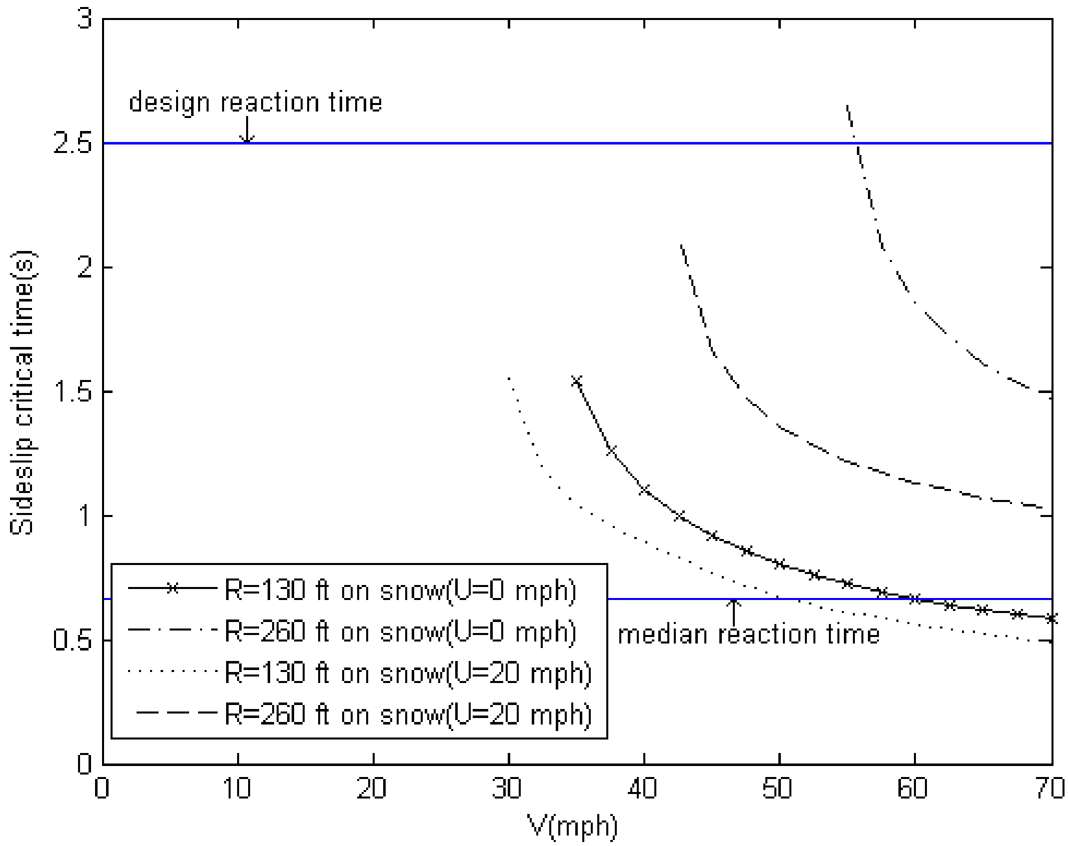


Fig. 3.6 Critical sustained time (CST) of sideslip accident on snow-covered curved roads

Fig. 3.7 shows the CDS under different radii when the road surface is covered by ice. Similar to the results for the snow-covered road on curves and icy surface on a straight road, sideslip accidents will dominate and the truck may experience sideslip accidents when it is driven in a speed of 45 mph on a curve with a radius of 260 ft, or the driving speed of 25 mph on a curve with a radius of 130 feet when there is no wind. When wind speed increases to 20 mph, the CDS will be changed to 17.5 mph on a curve with a radius of 260 ft, or 15 mph on a curve with a radius of 130 feet. For all these cases, the CST is generally between the median and design reaction time.

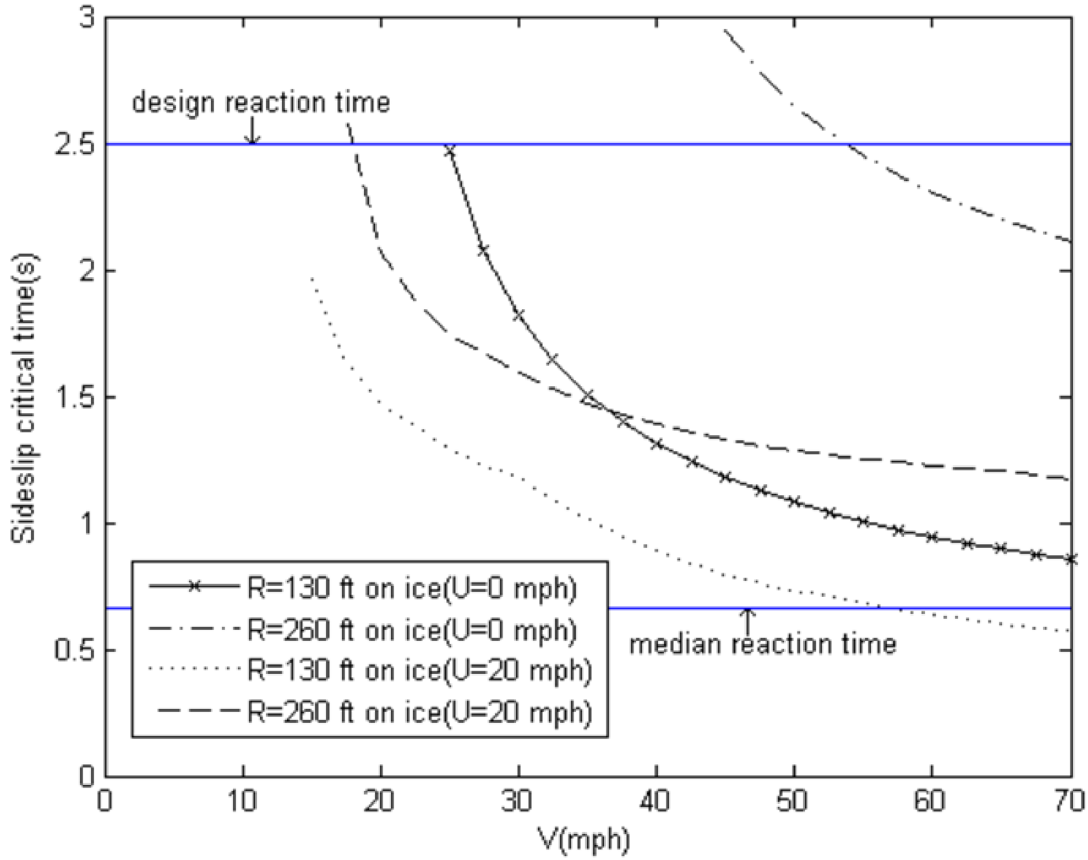


Fig. 3.7 Critical sustained time (CST) of sideslip accident on ice-covered curved roads

3.3.3.3 With excitations from supporting infrastructures

When a vehicle moves on roadways, vehicles will be excited to vibrate in several directions by the surface roughness on the roadway (Xu and Guo 2003; Chen and Cai 2004). When a vehicle moves on a bridge, dynamic interactions between the bridge and the vehicle will cause the vehicle to vibrate more significantly (Chen et. al. 2006). In either case (i.e. on pavement or on bridges), the vehicle will experience additional accelerations as a type of base excitations. In the present vehicle accident assessment model, safety behavior of the truck will be evaluated through a general consideration of excitations from supporting infrastructures by defining accelerations in the lateral direction a_y and that in rolling direction a_{roll} as base excitations. The relationship between rollover critical time and a_y as well as a_{roll} (U=40 mph, V=40 mph) is demonstrated in Fig. 3.8. When $a_{roll} > 0.4$ rad/s^2, rollover accidents will occur even the wind speed and vehicle velocity are both not very high. It is found the rolling acceleration caused by interaction with supporting structures is pretty critical to the truck safety and will increase the chance of having accidents when all other conditions are the same. Since considerable rolling excitations may exist on some bridges, it suggests that vehicles are more vulnerable to rollover accidents on a vibrating bridge, which has also been observed in existing studies (Guo and Xu 2006; Chen and Cai 2004).

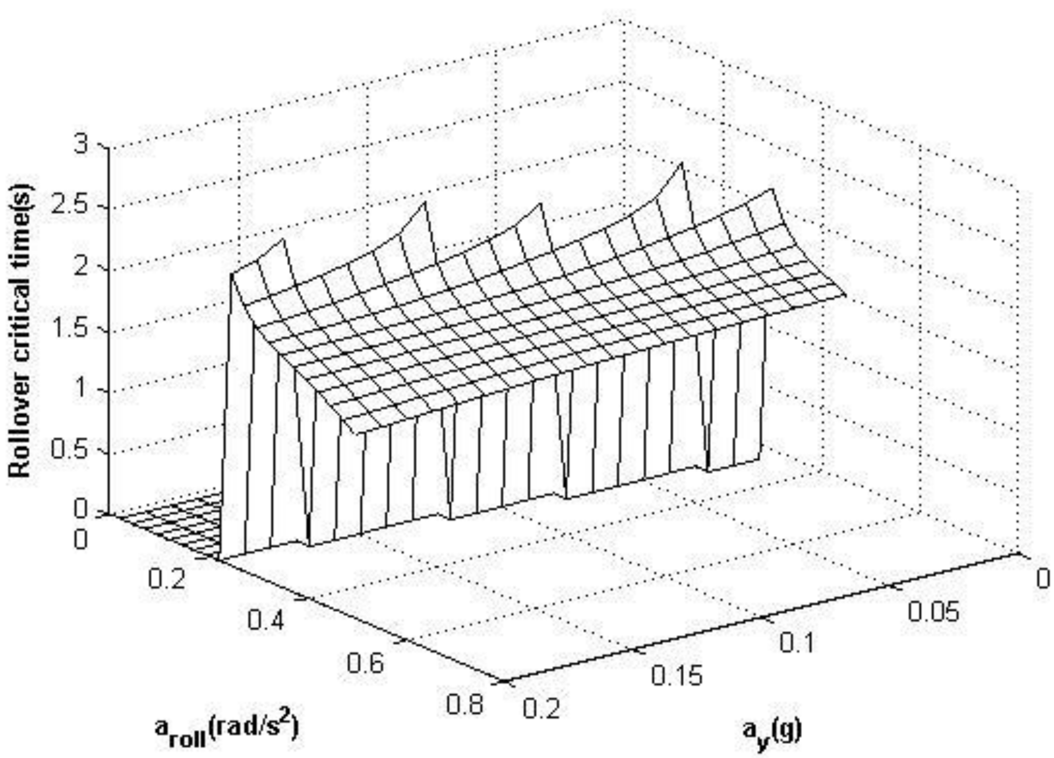


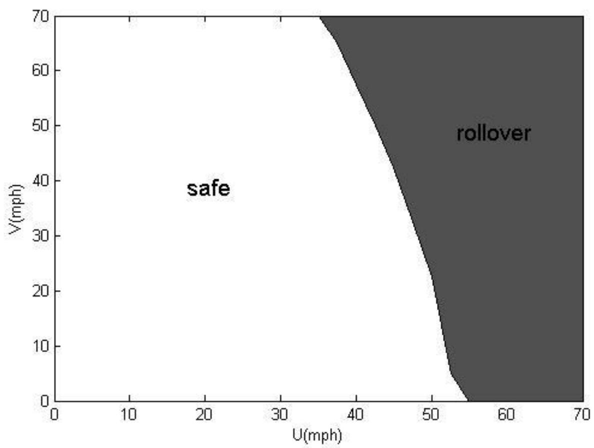
Fig. 3.8 Critical sustained time (CST) of rollover on a supporting structure
(U= 40 mph; V=40 mph; dry surface)

3.3.4 Critical driving speeds (CDS) of accidents

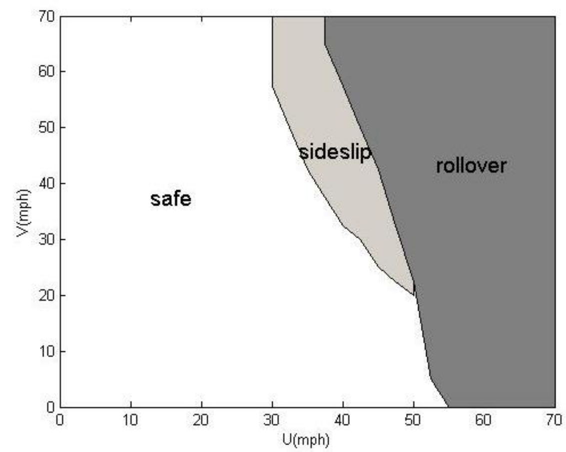
3.3.4.1 On straight roads

Assuming the CST of the specific environmental conditions is satisfied (i.e. the actual time duration of a specific set of conditions is longer than the required CST), Fig. 3.9 shows the critical driving speed (CDS) of the truck under different wind conditions on dry (Fig. 3.9(a)), snow-covered (Fig. 3.9(b)), and icy road surface (Fig. 3.9(c)).

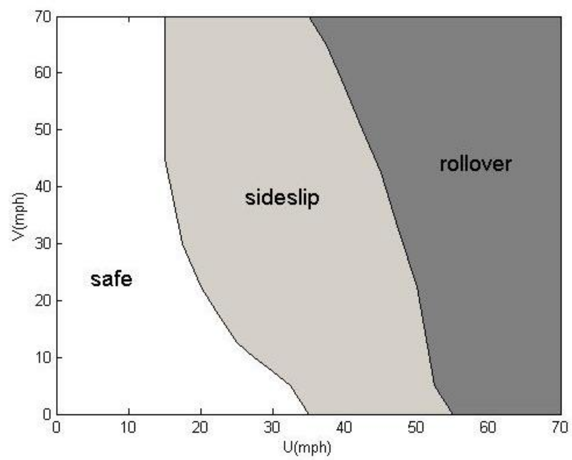
With the increase of the wind speed, the critical driving speed (CDS) generally decreases. It can be found from Fig. 3.9(a) that a sideslip accident will not occur before a rollover accident does first when the truck moves on a dry and straight path. Generally speaking, depending on the driving speed of the truck, it is found that there exist various levels of rollover risk when the wind speed exceeds 35 mph. When the wind speed is more than 55 mph, even the truck in still (V=0 mph) will have the risk of being blown over. Fig. 3.9(b) shows the critical U or V under which at least one type of accidents may happen when the truck is driven on a snow-covered road surface. It is easy to find that when U and V are not high, no rollover or sideslip accidents will happen. If the wind speed is moderate, sideslip accident will likely happen when the vehicle driving speed is more than 20 mph. When the wind speed is more than 50 mph, rollover accidents instead of sideslip will happen first. Fig. 3.9(c) shows the critical U or V when the truck moves on an icy road surface assuming the CST of sideslip is satisfied. By comparing Fig. 3.9(a), Fig. 3.9(b) and Fig. 3.9(c), it is obvious that sideslip accidents will be more prone to occur first than rollover accidents when the road kinetic friction coefficient decreases. Sideslip accidents can happen even when the wind speed is below 20 mph and the vehicle driving speed is 25 mph on icy roads. This observation is consistent with the fact of frequent sideslip accidents observed in cold regions.



(a) Dry road surface



(b) Snow-covered road surface surface



(c) Icy road surface

Fig. 3.9 Critical driving speeds (CDS) on a straight road with various surface conditions

3.3.4.2 On curved roads

Fig. 3.10 gives the results of critical driving speed (CDS) under different wind speeds U and radii R when the road surface is dry. It can be found that with the increase of wind speeds or the decrease of radius, the CDS decreases dramatically. When wind is very weak (U<10 mph), any radius lower than 330 feet will impose considerable safety threats to the truck with a driving speed about 65 mph or higher. A further decrease of the radius to 165 feet and 100 feet leads to a dramatic decrease of the CDS to around 50 mph and 37.5 mph, respectively. With the increase of wind speed, the CDS under the same radius will also significantly decrease compared to the case only with breeze. For example, when the wind speed increases from 10 mph to 40 mph, the CDS for a radius of 360 feet will decrease from 70 mph to 35 mph.

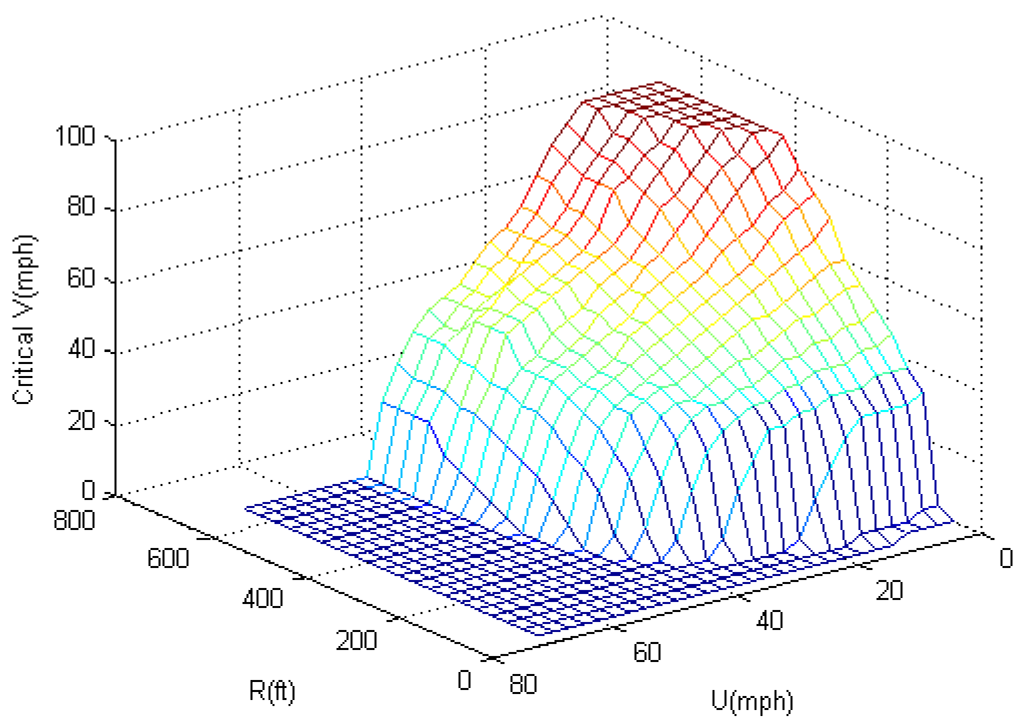
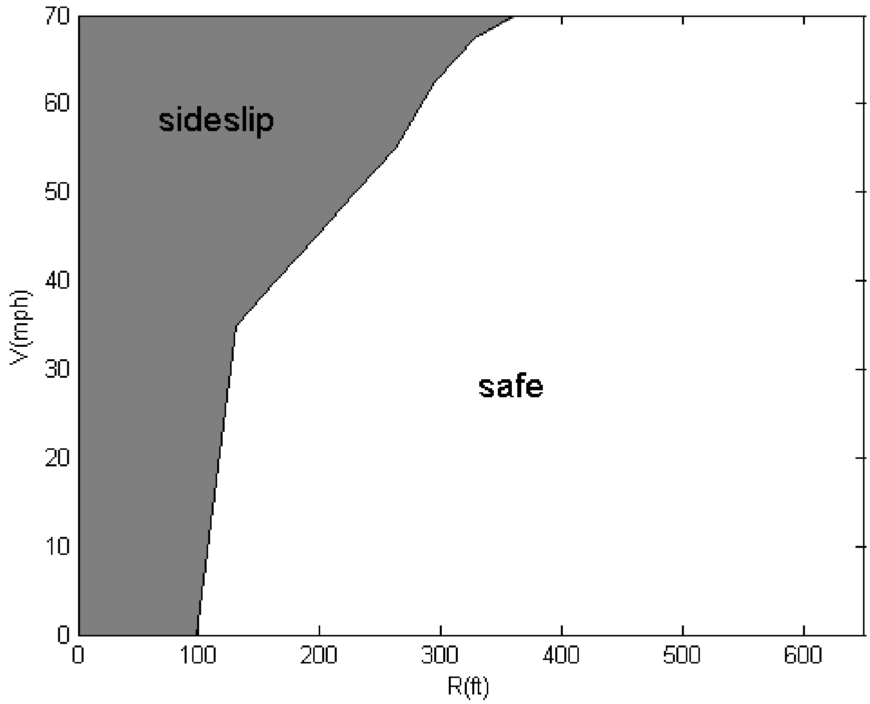


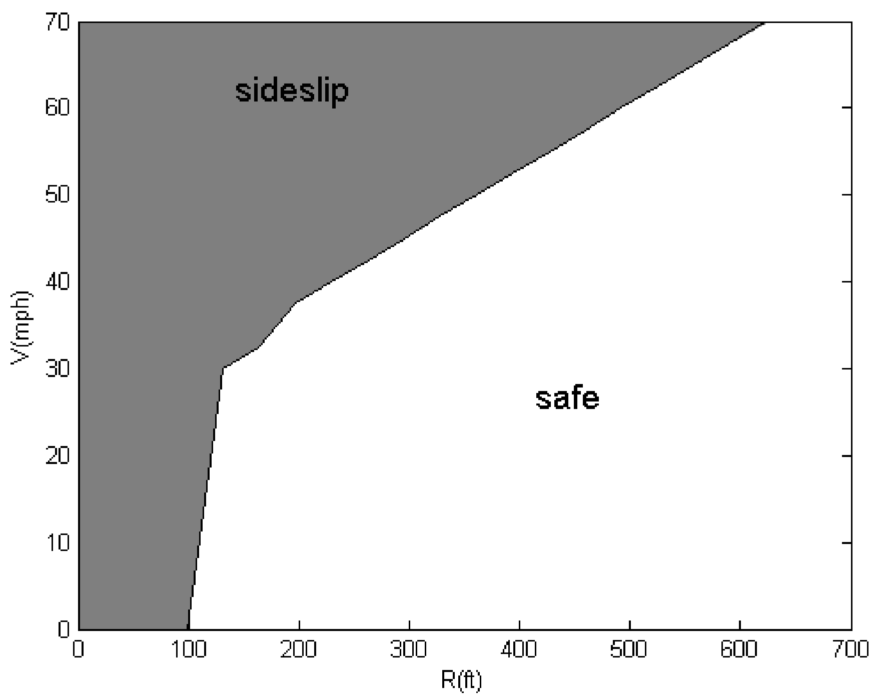
Fig. 3.10 Critical driving speeds (CDS) on dry roads with different radius and wind conditions

Fig. 3.11 gives the CDS results under different curvature radii when the road surface is covered by snow. It can be found that sideslip will be the only accident type which will happen first (if there is an accident). It is found that depending on the driving speeds, the curvature radius of 590 feet and lower along with 20 mph wind speed will possibly cause accidents. With a radius of 130 feet, 30 mph will be the critical driving speed (CDS) for the truck in the present study if there is no wind. Due to the high number of possible combinations of wind, driving speed and curvature radius, a full parametric study of all possible scenarios will not be discussed here. By comparing Fig.3.11(a) with Fig.3.11(b), it can be found that if the driving speed is more than 35 mph and the radius of the curved road is more than 130 ft, the possibility of sideslip increases dramatically when the wind speed changes from 0 mph to 20 mph.

Fig. 3.12 shows the CDS under different radii when the road is covered by ice. Two different wind speeds (0 and 20 mph) are studied. Similar to the results for snow-covered curved roads and icy straight roads, sideslip accidents will dominate and the truck may experience sideslip accidents when it is driven in a speed of 60 mph on the curved road with a radius of 330 feet, or in a driving speed of 25 mph on the curve with a radius of 130 feet when there is no wind. We can find that the truck with the driving speed more than 20 mph is prone to sideslip accidents when the radius is more than 330 ft and the wind speed is 20 mph. Comparing Fig.3.12 (a) and Fig.3.12 (b), people can find that even very moderate wind can affect the stability of the truck significantly on curved roads covered by ice.

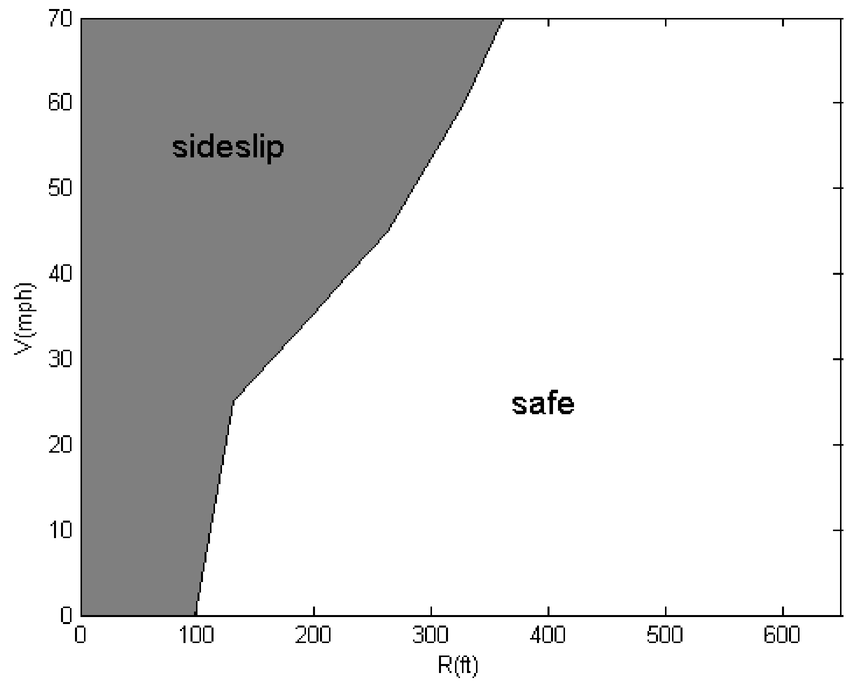


(a) U=0 mph

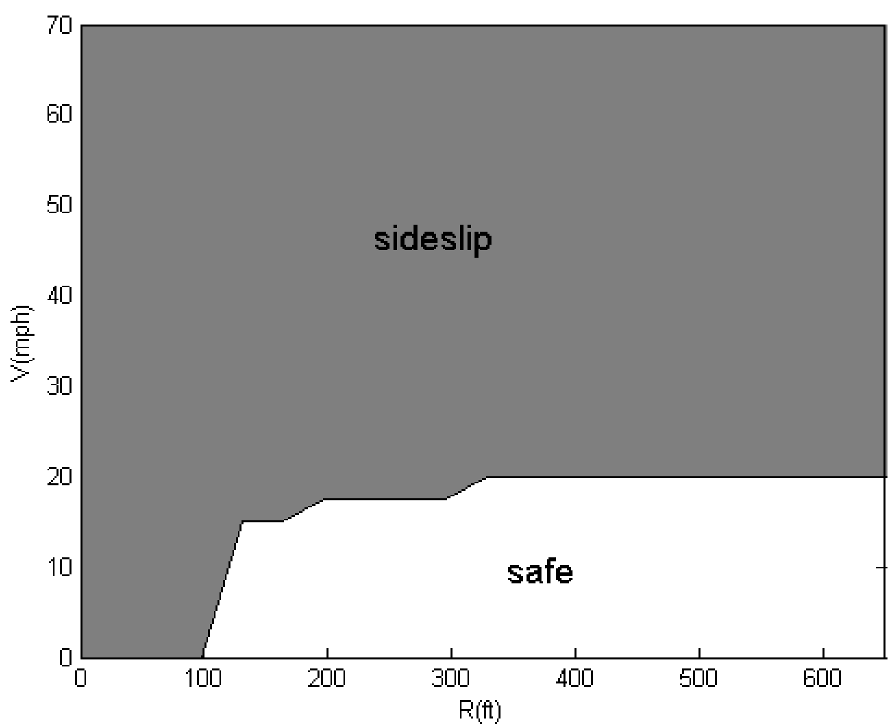


(b) U=20 mph

Fig. 3.11 Critical driving speeds (CDS) on snow-covered roads with various radii



(a) U=0 mph



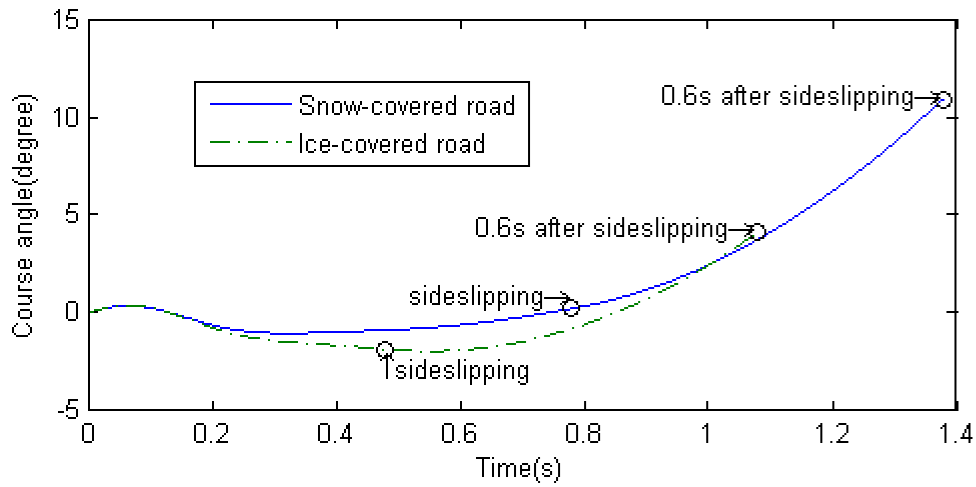
(b) U=20 mph

Fig. 3.12 Critical driving speeds (CDS) on icy roads with various radii

3.3.5 Transient accident-related responses

Fig. 3.13 shows the time-history results of course angle and lateral displacement of the truck on snow-covered and icy road surface respectively when V=32.5 mph and U=47.5 mph. Fig. 3.14 displays the corresponding time history of lateral friction force. It can be found that when wind gust is applied on the truck moving on the snow-covered surface, after a slight lateral displacement about 0.6 feet in Fig. 3.13 (b), the joint effect of wind-induced lateral force and moment will change the vehicle course angle (Fig. 3.13(a)) and bring the driving direction of the truck opposite to the wind direction until the truck moves laterally about 1.8 feet, when the lateral friction force of the rear tire reaches the sideslip critical friction force (Fig. 3.14). So at 0.8 seconds after wind gust is applied on the truck, the truck starts to sideslip after it has traveled laterally about 1.8 feet from its original path. As shown in Fig. 3.13 (a), the course angle is lower than 2 degrees when sideslip just happens. But 0.6 seconds after vehicle starts to sideslip, the course angle is about 11 degrees, which suggests a strong rotational movement of the truck has occurred after the tires start to sideslip.

When the road is covered by ice, as shown in Fig. 3.13(a), the course angle is lower than -2 degree when sideslip happens. But 0.6 second after the truck starts to sideslip, the course angle is about 4 degrees, which means that strong rotational motion of the truck has happened under the strong wind load after the tires start to sideslip. Fig. 3.13(b) suggests that the lateral displacement of the truck on icy roads is pretty straightforward-gradually increasing along the wind direction, which is different from that observed on the snow-covered road. It is found that the lateral friction force of the rear tire increases quickly over time and will exceed the critical friction forces and start to sideslip at about 0.5 seconds (Fig. 3.14). While the same truck is driven in the same speed on a snow-covered road, it requires 0.8 seconds to start sideslip (Fig. 3.13 (a)). As discussed earlier, once sideslip starts, the driver usually can do very little to regain the control of the vehicle.



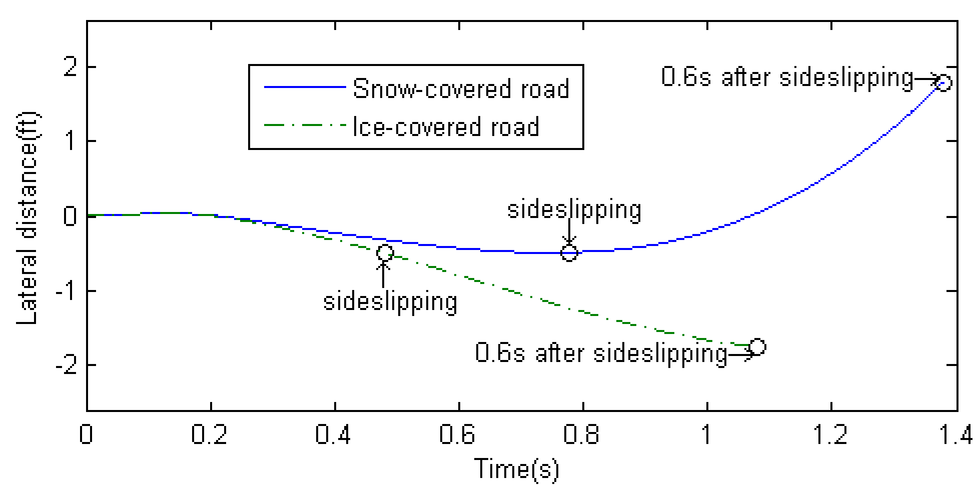


Fig. 3.13 Time histories of vehicle course angle and lateral distance

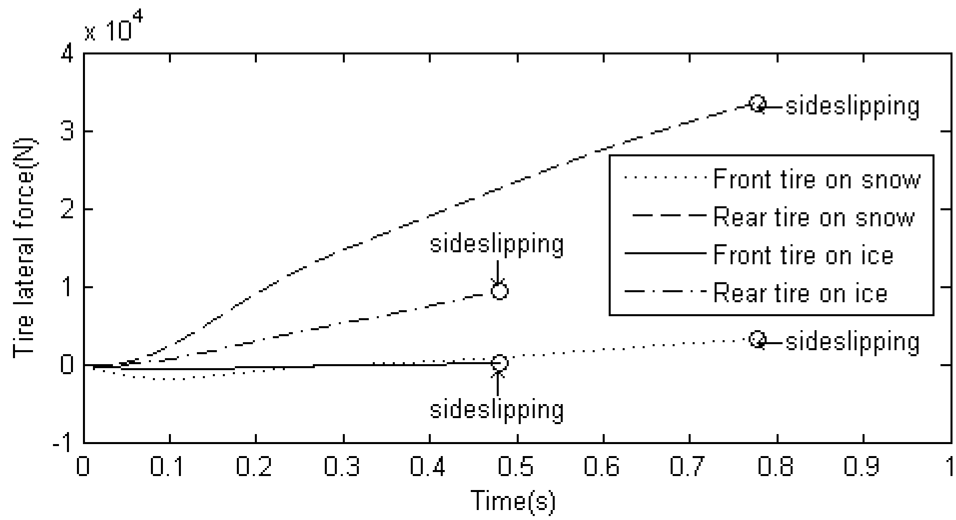


Fig. 3.14 Time history of tire lateral force

3.4 Discussion

Compared to existing simulation models, the new model has following improvements: 1) adopting series of dynamic equations to simulate the transient process of accidents; 2) for the first time, combining crosswind, different road surfaces, curving and excitations from supporting structures in one single model which can be used to consider more realistic scenarios; 3) introducing a new and important variable "critical sustained time (CST)" of each specific combination of adverse environmental and driving conditions in addition to the "critical driving speed (CDS)" which has been adopted in existing studies. Such a new variable will be helpful on characterizing the accident risks more realistically; and 4) as a holistic deterministic model, the present study can be used directly to provide useful information for traffic and emergency management as well as accident preventions. Moreover, the developed model also lays a critical basis for future reliability-based vehicle safety studies under hazardous environments.

Several assumptions have been made in the proposed model due to the lack of more detailed information: 1) driver behavior uncertainties on steering angle is not considered due to the lack of a reliable model. Possible solutions include adopting CST to study driver behavior and consider uncertainties using the reliability theory; and 2) wind loads on a truck during the rollover process are assumed to be constant. A preliminary sensitive study conducted by the writers showed the impact from such an assumption is insignificant. If necessary, this could be further improved by conducting more extensive wind tunnel tests or applying the reliability theory to appropriately simulate the distributions of wind force coefficients during the rollover process. More comprehensive parametric studies and site-specific analyses can easily be conducted based on the model developed in the present chapter, which will be reported by the writers later.

3.5 Conclusion

An integrated vehicle safety behavior simulation model was developed which adopts more realistic dynamic equations and accident criteria to characterize the transient process of accidents. Numerical analyses on one type of typical trucks under several representative scenarios were conducted. Major findings from the numerical studies are summarized as follows:

(1) The new model can be used to predict the safety performance of vulnerable vehicles under various hazardous weather, topographic and road surface conditions by using the variables CST and CDS. The rigorous validation of the new simulation model depends on the availability of comprehensive experimental data, which is beyond the scope of the present study;

(2) For both straight and curved roads, rollover accidents usually happen first when the road surface is dry. When the wind speed is low, the difference of curvature has noteworthy

impacts on CST and CDS. With the increase of the wind speed, wind will gradually replace the curvature to dominate the impacts on CST and CDS;

(3) Sideslip accidents usually happen first on curved roads when the road surface is covered by either snow or ice. Both CST and CDS usually decrease with the increase of the driving speed or the wind speed significantly. When wind is weak, the decrease of the curvature radius will cause the CST and CDS dramatically decrease under the same driving speed. When wind is strong, the CST and CDS will only slightly decrease for smaller curvature radii. It was found that the truck is very vulnerable to accidents on curved roads covered by ice even with the existence of very moderate wind;

(4) On straight roads, the dominant accident type exhibited a relatively complicated pattern when the road surface is covered by snow or ice. When the wind speed is moderate (U is not more than 50 mph), sideslip accidents may happen first on snow-covered roads depending on the specific combination of wind and driving speeds. On icy roads, sideslip accidents usually happen first when the wind speed is not very high (less than 50 mph). When the wind speed exceeds 50 mph, rollover accidents usually will happen first for both snow-covered and icy road surface;

(5) It was found that the road surface condition, wind speed and the curvature all play vital roles on the accident risks integrally. To accurate predict the safety risk under adverse driving conditions requires a detailed simulation with the developed model on a case by case basis;

(6) CST was found to be a critical variable which can be used to conduct more accurate and personalized risk analysis by considering the site-specific environmental conditions as well as reaction time of individual drivers. This will be incorporated into the reliability-based accident model based on the present study in the future.

3.6 References

AASHTO. (2004). A Policy on Geometric Design of Highways and Streets. Washington, D.C.

Baker, C. J. (1986). “Simplified analysis of various types of wind-induced road vehicle accidents.” Journal of Wind Engineering and Industrial Aerodynamics, 22(1), 69-85.

Baker, C. J. (1987). “Measures to control vehicle movement at exposed sites during windy periods.” Journal of Wind Engineering and Industrial Aerodynamics, 25(2), 151-161.

Baker, C. J. (1991). “Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system.” Journal of Fluids and Structures, 5, 221-241.

Baker, C. J. (1994). “Quantification of accident risk for road vehicles in cross winds.” Journal of Wind Engineering and Industrial Aerodynamics, 52(1-3), 93-107.

Cai, C. S., Chen, S. R. (2004). “Framework of vehicle-bridge-wind dynamic analysis,” J. Wind. Eng. Ind. Aerodyn., 92 (7-8), 579-607.

Chen, S. R. and Cai, C. S. (2004). “Accident assessment of vehicles on long-span bridges in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 92(12), 991-1024.

Chen, S. R., Cai, C. S. and Wolshon, B. (2009). “From normal operation to evacuation: single-vehicle safety under adverse weather, topographic and operational conditions”, Natural Hazards Review, ASCE, 10 (2), 68-76.

Coleman, S. A., and Baker, C. J. (1994). “Experimental study of the aerodynamic behavior of high sided lorries in cross winds.” Journal of Wind Engineering and Industrial Aerodynamics, 53(3), 401-429.

Gaspar, P., Szaszi, I., and Bokor, J. (2004). “The design of a combined control structure to prevent the rollover of heavy vehicles.” European Journal of Control, 10(2), 148-162.

Gaspar, P., Szaszi, I., and Bokor, J. (2005). “Reconfigurable control structure to prevent the rollover of heavy vehicles.” Control Engineering Practice, 13(6), 699-711.

Guo, W. H. and Xu, Y. L. (2006). “Safety analysis of moving road vehicles on a long bridge under crosswind”, Journal of Engineering Mechanics, 132 (4), 438-446.

Sampson, D. J. M. (2000). “Active roll control of articulated heavy vehicles.” PhD Thesis, University of Cambridge.

Sigbjornsson, R., and Snaebjornsson, J. T. (1998). “Probabilistic assessment of wind related accidents of road vehicles: A reliability approach.” Journal of Wind Engineering and Industrial Aerodynamics, 74-76, 1079-1090.

Snaebjornsson, J. T., Baker, C. J., and Sigbjornsson, R. (2007). “Probabilistic assessment of road vehicle safety in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 95, 1445-1462.

The National Academies. (2006). "Where the weather meets the road- a research agenda for improving road weather system." Report in Brief, The National Academies.

The Road Information Program (2005). "Growing Traffic in Rural America: Safety, Mobility and Economic Challenges in America's Heartland", http://www.tripnet.org/RuralRoads2005Report.pdf, last accessed May 17, 2008.

Thomas D. G. (1992). Fundamentals of vehicle dynamics, SAE, Warrendale, PA, USA.

Transportation Research Board (TRB) (2007). "The domain of truck and bus safety research", Transportation Research Circular, Number E-C117, May 2007.

USDOT (2005). "Report to Congress on the Large Truck Crash Causation Study", Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Winkler C. B., and Ervin R. D. (1999). Rollover of heavy commercial vehicles. SAE, Warrendale, PA, USA.

Xu, Y. L. and Guo, W. H. (2003). "Dynamic analysis of coupled road vehicle and cable-stayed bridge system under turbulent wind." Engineering Structures, 25, 473-486.

Nomenclature

a	longitudinal distance to axle, measured forwards from centre of sprung mass
a_y	lateral acceleration caused by the movement of bridge
c_1, c_2	tyre cornering stiffness coefficients, in $\frac{F_y}{\alpha} = c_1 \times F_z + c_2 \times F_z^2$
c_α	tyre cornering stiffness, measured at rated vertical tyre load
d	track width
F_y	lateral tyre force
F_z	vertical tyre force
$F_{w,y}$	lateral wind force
$F_{w,z}$	vertical wind force
g	acceleration due to gravity
h	height of centre of sprung mass, measured upwards from roll centre
h_{cm}	height of centre of mass for whole truck, measured upwards from ground
h_s	height of centre of sprung mass, measured upwards from ground
h_u	height of centre of unsprung mass, measured upwards from ground
h_w	height of lateral wind load $F_{w,y}$, measured upwards from roll center
I_{xx}	roll moment of inertia of sprung mass, measured about sprung centre of mass

$I_{x'x'}$ roll moment of inertia of sprung mass, measured about origin of (x0; y0; z0) coordinate system

I_{xz} yaw-roll product of inertia of sprung mass, measured about sprung mass centre

$I_{x'z'}$ yaw-roll product of inertia of sprung mass, measured about origin of (x_0; y_0; z_0) coordinate system

I_{yy} pitch moment of inertia of sprung mass, measured about sprung mass centre

I_{zz} yaw moment of inertia of sprung mass, measured about sprung mass centre

$I_{z'z'}$ yaw moment of inertia of total mass, measured about origin of (x_0; y_0; z_0) coordinate system

k suspension roll stiffness

k_t tyre roll stiffness

L wheelbase

l suspension roll damping rate

M_x wind-induced roll moment

M_z wind-induced yaw moment

m total mass

m_s sprung mass

m_u unsprung mass

N_β $\dfrac{\partial M_z}{\partial \beta} = \sum_j a'_j c_{\alpha,j}$, partial derivative of net tyre yaw moment with respect to sideslip angle

N_δ $\dfrac{\partial M_z}{\partial \delta} = -a'_1 c_{\alpha,1}$, partial derivative of net tyre yaw moment with respect to steer angle

$N_{\dot\psi}$ $\dfrac{\partial M_z}{\partial \dot\psi} = \sum_j \dfrac{a'^2_j c_{\alpha,j}}{U}$, partial derivative of net tyre yaw moment with respect to yaw rate

r height of roll axis, measured upwards from ground

U forward speed

u active roll torque

Y_β $\dfrac{\partial F_y}{\partial \beta} = \sum_j c_{\alpha,j}$

partial derivative of net tyre lateral force with respect to sideslip angle

Y_δ $\dfrac{\partial F_y}{\partial \delta} = -c_{\alpha,1}$

partial derivative of net tyre lateral force with respect to steer angle

$Y_{\dot\psi}$ $\dfrac{\partial F_y}{\partial \dot\psi} = \sum_j \dfrac{a'_j c_{\alpha,j}}{U}$

partial derivative of net tyre lateral force with respect to yaw rate

α tyre slip angle

β	sideslip angle
δ	steer angle
ϕ	absolute roll angle of sprung mass
ϕ_t	absolute roll angle of unsprung mass
ϕ_t^*	roll angle of unsprung mass when one wheel lift up
ϕ_t^{cri}	critical roll angle of unsprung mass
ψ	heading angle
$\dot{\psi}$	yaw rate
θ	road superelevation

Additional subscripts

f	front
j	jth axle, counted from front
r	rear

CHAPTER 4: INJURY SEVERITY OF TRUCK DRIVERS IN SINGLE- AND MULTI-VEHICLE ACCIDENTS ON RURAL HIGHWAYS

4.1 Introduction

Truck drivers experience significantly higher risk of suffering serious injury and fatality than passenger vehicle drivers (USDOT 2005). In the United States, commercial truck drivers face huge risk of injury and death from crashes – as much as 7 times more likely to die and 2.5 times more likely to suffer an injury than the average worker (NIOSH 2007). Given the high number of trucks on highways around the country every day, how to protect truck drivers from serious injury in traffic crashes has become not only an occupational safety issue, but also critical to the overall traffic safety and efficiency of the highway network as a whole in the nation.

Compared to passenger vehicles which are much more flexible on adjusting the travel plans, trucks often have to be operated in adverse or even hazardous driving conditions, such as inclement weather and/or complex terrain (USDOT, 2005; NIOSH, 2007). It is known that in various adverse driving conditions, trucks are often involved in single-vehicle (SV) accidents in addition to multi-vehicle (MV) accidents (Chen and Chen, 2010; Baker, 1991; Chen and Cai, 2004). Although the absolute number of SV accidents is often lower than that of MV accidents, SV accidents usually result in more serious injury (The National Academies, 2006). For example, SV accidents were responsible for 57.8% of all crash fatalities in 2005 (USDOT, 2005).

It is known that SV and MV accidents have different mechanisms of occurrence (Chen and Chen, 2010; Baker, 1991), critical risk factors (Savolainen and Mannering, 2007) and accordingly different injury mitigation strategies (NIOSH, 2007). Therefore, to investigate injury severity and associated risk factors in both SV and MV accidents of trucks is crucial to implementing more effective injury prevention strategy for truck drivers in their daily work. Moreover, the findings from such an investigation will provide scientific basis to improve the current highway design and traffic management policy, and propose next-generation safety initiatives in order to reduce the injury severity, live and financial losses of truck-involved accidents. There exists, however, a gap between the current injury studies of truck drivers and reality. Of the limited studies that have investigated injury severity of truck-involved accidents, both SV and MV accidents were usually analyzed as a whole, in which some important phenomena and critical risk factors unique to SV or MV accidents involving trucks cannot be identified. For thousands of truck drivers working around the country every day, the lack of such a vital piece of knowledge may hinder efforts concerning injury prevention and traffic management on national highways.

This chapter aims at narrowing such an existing gap by looking into injury severity of truck drivers in MV and SV accidents on rural highways separately. In addition, more advanced random effect models, rather than fixed effect models which have been commonly applied in existing injury studies, will be adopted. By using the mixed logit models, the complex interactions between roadway characteristics, driver characteristics, accident characteristics, temporal characteristics and environmental characteristics in both SV and MV accidents will be untangled. More discussions on the methodology of injury studies will be presented in the next section.

Existing studies on truck-involved accidents typically follow two categories of topics: accident frequencies (or rates), and injury severity as well as their respective risk factor analyses. Different from a number of studies on accident frequencies (or rates), there are only limited studies specifically focusing on injury severity of truck drivers or occupancies in truck-involved accidents. Golob et al. (1987) and Alassar (1988) investigated the influence of some risk factors such as collision type, the number of involved vehicles and road class on injury severity of truck drivers using log-linear models. Chirachavala et al. (1984) studied the factors that increase accident severity for different truck types based on discrete multivariate analysis. Duncan (1998) studied the injury severity of passenger occupancy caused by truck-passenger-car rear-end collisions using ordered logit models. They found collisions under some conditions, such as with passenger cars or on undivided rural roads, usually result in a higher level of injury severity. Chang and Mannering (1999) analyzed the accident severity of occupancy in truck-involved and non-truck-involved accidents using nested logit models. The characteristics of truck-involved and non-truck-involved accidents were compared and some risk factors were found unique to truck-involved accidents. Khorashadi et al. (2005) compared the difference of driver-injury severities from truck-involved accidents in rural and urban roads using multinomial logit models. The study identified 13 and 17 risk factors which significantly influence the driver-injury severity only in rural and only in urban areas, respectively. In addition to injury severity, there are also some studies focusing on the fatality of occupants related to trucks (Shibata and Fukuda, 1994; Lyman and Braver 2003). Most of the existing studies with a focus on severity of truck-involved accidents, as summarized above, covered all types of accidents as a whole without separating MV and SV accidents.

In recent years, there are a few studies which have started investigating injury severity from SV and MV accidents separately. For example, Kockelman and Kweon (2002) used ordered probability models to investigate injury severity in two-vehicle crashes and single-vehicle crashes datasets separately. They found that there is large difference of injury severity behavior for SV and MV accidents involving different vehicle types such as pickups and sport utility vehicles. In the work conducted by Ulfarsson and Mannering (2004), single-vehicle and two-vehicle accidents were studied using separate models because it was found a single model cannot accurately tell the different characteristics of these accidents. Savolainen and Mannering (2007) estimated the probabilistic models of motorcyclists' injury severity by separating SV and MV crashes using multinomial and nested logit models. Different risk factors on the injury severity of motorcyclists in SV ad MV crashes were found. In realizing the considerably different causality mechanisms of SV and MV accidents, some other studies investigated SV accidents only (e.g. Shankar and Mannering, 1996; Islam and Mannering, 2006). So far, however, no study has been reported on investigating the injury severity of truck drivers in SV and MV crashes separately.

Over the past ten years, various disaggregate models have been widely used to compare different datasets due to the unique advantages as compared to the previous methods. These advantages include being able to test a broad range of variables that influence injury severity and capture comprehensive disaggregate information about how the injury severity is influenced by these variables (Chang and Mannering, 1999). Some studies applied ordered logit (Duncan, 1998) or ordered probit models (Abdel-Aty, 2003) to investigate various risk factors associated with injury severity. Multinomial logit models (Ulfarsson and Mannering, 2004) and nested logit models (Chang and Mannering, 1999) have also been frequently used in order to obtain more detailed information about the influence of various risk factors on different injury severity levels.

Although multinomial logit models have been widely applied in injury severity studies during the past years, people find some limitations of this model such as (Jones and Hensher, 2007): (1) questionable assumptions associated with the IID (independently and identically distributed errors) condition and the IIA (independence of irrelevant alternatives) assumption condition; and (2) observed and unobserved heterogeneity in parameter effects are not considered. Most of the approaches used in the existing studies on truck driver injury severity were based on the assumption that the effects of all variables are fixed across observations. Mixed logit models, which can address these limitations and consider the random effects of variables, have recently been adopted in the studies on accident injury (e.g. Milton et al., 2008; Kim et al., 2010; Malyshkina and Mannering, 2010; Moore et al., 2010). For example, Moore et al. (2010) applied mixed logit model to compare the statistical difference of bicyclist injury severity from motor vehicle crashes at intersection and non-intersection locations. It was found that some risk factors need to be modeled as random parameters. With the promising potentials on injury studies as discussed above, mixed logit models will be adopted in the present study to investigate the injury severity of truck drivers in both SV and MV accidents.

4.2 Data Description

Highway Safety Information System (HSIS) is a database sponsored by Federal Highway Administration (FHWA) and has detailed traffic accident data from nine states across the United States which contains accident, roadway inventory, and traffic information. HSIS data is known for its comprehensive sets of major risk factors and excellent quality of the data (Noland and Lyoong, 2004). The 10-year (1991-2000) detailed accident data on rural highways in Illinois will be utilized in this study.

According to the “roadway classification” in the collected data, three highway classes were considered as rural highways in the study: unmarked state highways (rural), controlled-access highways (rural), other state-numbered highways (rural). Based on the variables of “vehicle type”, only accident records involving at least one truck were selected into this study. Three different truck types were classified in the Illinois HSIS database: single-unit truck, tractor with semi-trailer, and tractor without semi-trailer. After removing the accident records with insufficient accident information, there were in total 19,741 truck-involved accidents occurring on the rural highways in Illinois during the 10-year period, which include 6,891 SV accidents and

12,850 MV accidents (only count as one MV accident if there was more than one truck involved in an accident, and only the first truck involved will be considered).

The variable "driver extent of injury" defined in the HSIS database of Illinois is an indicator of driver-injury severity, which is defined as numerical scales from 1-5, representing no injury, possible injury, non-incapacitating injury, incapacitating injury and fatal, respectively. Out of a total of 6,891 SV accidents, 5,539 (80.4%) accidents had no injury, 214 (3.1%) accidents had possible injury, 754 (10.9%) accidents had non-incapacitating injury, 341 (5.0%) accidents had incapacitating injury and 43 (0.6%) accidents had fatal injury. Out of a total of 12,850 MV accidents, 11,811(91.9%) accidents had no injury, 314 (2.5%) accidents had possible injury, 451 (3.5%) accidents had non-incapacitating injury, 249 (1.9%) accidents had incapacitating injury and 25 (0.2%) accidents had fatal injury. In the present chapter the injury severity of truck drivers is grouped into three categories to ensure a sufficient number of observations are available in each category (it was otherwise not possible to make all five categories statistically different): (1) no injury (same as original Scale 1), (2) possible injury/non-incapacitating injury (including the original Scales 2 and 3), and (3) incapacitating injury/ fatal (including original Scales 4 and 5).

The data showed that MV accidents have a higher percentage of no injury outcome (91.9% vs 80.4%) and lower percentages for all other injury levels as compared to SV accidents. It is noteworthy that such a finding from truck-involved accidents is opposite to some existing comparisons of SV and MV accidents when all types of vehicles were considered as a whole. For example, by looking into the accidents caused by all types of vehicles, Geedipally and Lord (2010) found that SV accidents have a much larger percentage of non-injury than MV accidents on four-lane highways. The different findings on injury severity of truck-involved accidents as compared to the accidents caused by all types of vehicles, for one more time, underscore the necessity of studies with a focus on the injury severity of truck drivers.

Table 4.1 Driver-injury frequency and percentage distribution for SV model

	No injury		Possible injury/non-incapacitating injury		Incapacitating injury/fatal		Total
Driver characteristics							
Young driver (age<=25)	421	77.8%	100	18.5%	20	3.7%	541
Old driver (age>=50)	1503	81.7%	225	12.2%	112	6.1%	1840
Female driver	183	76.3%	38	15.8%	19	7.9%	240
Driver trapped/extract	3	2.9%	41	40.2%	58	56.9%	102
Driver safety belt not used	48	24.1%	79	39.7%	72	36.2%	199
Driver was asleep/fainted	112	54.1%	62	30.0%	33	15.9%	207
Driver was fatigued	76	65.5%	28	24.1%	12	10.3%	116
Vehicle characteristics							
Single unit truck	710	74.4%	187	19.6%	57	6.0%	954
Truck brakes defect	64	63.4%	28	27.7%	9	8.9%	101
Truck tires defect	70	64.2%	23	21.1%	16	14.7%	109
Truck cargo defect	22	57.9%	11	29.0%	5	13.2%	38
Carrying hazardous material	67	62.6%	17	15.9%	23	21.5%	107
Temporal characteristics							
Rush hour (6:00am-9:59am)	954	75.8%	222	17.7%	82	6.5%	1258
Roadway characteristics							
Light traffic (AADT/number of lanes<=2k)	1518	79.1%	291	15.2%	109	5.7%	1918
Class I designated truck route	3137	80.2%	552	14.1%	221	5.7%	3910
Stop sign/flasher	141	86.5%	17	10.4%	5	3.1%	163
Traffic signal	60	95.2%	2	3.2%	1	1.6%	63
Sharp curve (degree of curve>=5)	64	59.8%	31	29.0%	12	11.2%	107
Steep grade (vertical curve grade>=2.2)	41	66.1%	10	16.1%	11	17.7%	62
Environmental characteristics							
Wet road surface	728	77.0%	171	18.1%	46	4.9%	945
Snow/slush road surface	399	87.5%	45	9.9%	12	2.6%	456
Ice road surface	437	84.9%	61	11.8%	17	3.3%	515
Fog/smoke/haze	128	78.1%	28	17.1%	8	4.9%	164
Severe cross wind	161	62.7%	81	31.5%	15	5.8%	257
Accident characteristics							
Truck ran off the roadway	1800	69.6%	549	21.2%	236	9.1%	2585
Truck overturn	250	57.5%	139	32.0%	46	10.6%	435
Truck jackknife	322	90.2%	34	9.5%	1	0.3%	357
Exceeding speed limit	44	58.7%	23	30.7%	8	10.7%	75
Improper lane usage	322	62.0%	137	26.4%	60	11.6%	519
Hitting animal	1538	96.6%	42	2.6%	13	0.8%	1593
Exceeding safe speed for conditions	207	72.6%	61	21.4%	17	6.0%	285
Failing to reduce speed to avoid crash	101	60.5%	41	24.6%	25	15.0%	167
Truck was passing/overtaking	38	76.0%	5	10.0%	7	14.0%	50
Truck was turning left	102	73.9%	29	21.0%	7	5.1%	138
Truck was skidding/control loss	825	69.2%	262	22.0%	106	8.9%	1193
Truck was merging	11	55.0%	8	40.0%	1	5.0%	20

Table 4.2 Driver-injury frequency and percentage distribution for MV model

	No injury		Possible injury/non-incapacitating injury		Incapacitating injury/fatal		Total
Driver characteristics							
Old driver (age>=50)	3170	91.8%	221	6.4%	61	1.8%	3452
Female driver	386	88.9%	31	7.1%	17	3.9%	434
Driver trapped/extract	4	9.3%	13	30.2%	26	60.5%	43
Driver safety belt not used	96	59.3%	37	22.8%	29	17.9%	162
Driver was asleep/fainted	18	56.3%	8	25.0%	6	18.8%	32
Driver was fatigued	29	82.9%	1	2.9%	5	14.3%	35
Vehicle characteristics							
Single unit truck	2542	89.0%	233	8.2%	81	2.8%	2856
Tractor with semi-trailer	8974	92.8%	505	5.2%	189	2.0%	9668
Truck brakes defect	167	79.2%	32	15.2%	12	5.7%	211
Truck tires defect	98	96.1%	1	1.0%	3	2.9%	102
Carrying hazardous material	115	82.1%	10	7.1%	15	10.7%	140
Roadway characteristics							
Light traffic (AADT/number of lanes<=2k)	3092	89.8%	267	7.8%	86	2.5%	3445
Low truck percentage (percentage [a] <=0.1)	3061	91.8%	199	6.0%	74	2.2%	3334
Class I designated truck route	4379	93.9%	208	4.5%	78	1.7%	4665
Class II designated truck route	6367	90.9%	485	6.9%	156	2.2%	7008
Wide lane(lane width>=13ft)	1669	92.5%	96	5.3%	39	2.2%	1804
Wide median (median width>=60ft)	1833	94.5%	70	3.6%	36	1.9%	1939
Unprotected median	4627	93.7%	220	4.5%	91	1.8%	4938
Painted median	307	88.5%	34	9.8%	6	1.7%	347
Stop sign/flasher	2015	90.1%	169	7.6%	53	2.4%	2237
No passing zone sign	254	85.2%	37	12.4%	7	2.4%	298
Environmental characteristics							
Darkness light condition	1945	90.3%	154	7.2%	56	2.6%	2155
Snow/slush road surface	1045	94.8%	48	4.4%	9	0.8%	1102
Ice road surface	591	94.1%	26	4.1%	11	1.8%	628
Accident characteristics							
Number of vehicles in accident >=3	909	86.2%	111	10.5%	34	3.2%	1054
Truck ran off the roadway	155	78.3%	29	14.7%	14	7.1%	198
Truck overturn	7	35.0%	9	45.0%	4	20.0%	20
Exceeding speed limit	190	89.6%	18	8.5%	4	1.9%	212
Failing to yield right-of-way	776	88.7%	80	9.1%	19	2.2%	875
Driving on wrong side/wrong way	110	77.5%	26	18.3%	6	4.2%	142
Driver influenced by alcohol/drugs	136	85.5%	17	10.7%	6	3.8%	159
Truck was turning left	723	93.5%	41	5.3%	9	1.2%	773
Truck was turning right	414	96.5%	12	2.8%	3	0.7%	429
Truck slowed/stopped in traffic	732	94.3%	39	5.0%	5	0.6%	776
Truck was avoiding vehicle/objects	489	85.9%	62	10.9%	18	3.2%	569
Truck was skidding/control loss	401	82.3%	54	11.1%	32	6.6%	487

[a] truck percentage is equal to commercial volume/AADT

The HSIS data contains very detailed information related to truck-involved accidents, which can be separated into following groups such as roadway characteristics, driver characteristics, vehicle characteristics, temporal characteristics, environmental characteristics and accident characteristics. The specifications of some selected indicators for some groups are given as follows. Driver characteristics: the young driver (≤ 25 years old) and old driver (≥ 50 years old) indicator. Vehicle characteristics: the carrying hazardous material indicator shows if the truck is carrying hazardous material or not. Temporal characteristics: the rush hour indicator refers to the accidents occurring between 6:00 am and 9:59 am. Road characteristic: the light traffic indicator and Class I designated truck route indicator. The light traffic indicator implies that the AADT divided by the number of the lanes is less than or equal to 2,000. Illinois-designated truck routes include Class I designated truck route (approved for all load widths of 8 foot 6 inches or less), Class II designated truck route (approved for all load widths of 8 foot 6 inches or less and a wheel base no greater than 55 feet) and Class III designated truck route (approved for all load widths of 8 foot 0 inches or less and a wheel base no greater than 55 feet). Environmental characteristics: one example is the darkness light indicator, which shows that the light condition was dark when the accident occurred. Accident characteristics: for example, the ran off the roadway indicator suggests that the truck ran off the roadway when the accident happened. These indicators as shown above were selected in the present study based on the hypothesis that they would affect injury severity of truck drivers. The hypothesis of no significant difference from zero for each parameter of severity category will be tested using the likelihood ratio t-test and the parameters not significantly different from zero at the 90% level will be restricted to zero.

Table 4.1 and 4.2 give the number of observations and the percentage distribution across the injury severity of truck drivers for SV and MV accidents involving at least one truck, respectively. As compared to the SV accident datasets (Table 4.1), the MV accident datasets have more indicators with percentages less than 5% for incapacitating injury/fatal (28 indicators (MV) vs 9 indicators (SV)) and possible injury/non-incapacitating injury (24 indicators (MV) vs 4 indicators (SV)). The difference of the aggregated data between the datasets of SV and MV accidents indicates possible difference in terms of driver-injury severity, which will be studied in the following sections comprehensively.

4.3 Statistical Method

In the present study, base multinomial logit models and subsequently, mixed logit models, will be developed (Moore et al., 2010). Mixed logit models allow for the possibility that the influence of variables affecting injury-severity levels may vary across observations. We follow the works by Revelt and Train (1998), McFadden and Train (2000) and Bhat (2001), which have demonstrated the effectiveness of this approach to explore the variations of the effects (across observations) that variables can have on injury-severity levels.

Let $P_n(i)$ be the probability of the accident n causing the injury severity category i (Ulfarsson and Mannering, 2004):

$$P_n(i) = P(\beta_i X_n + \varepsilon_{ni} \geq \beta_{i'} X_n + \varepsilon_{ni'}) \;\; \forall i' \in I, \quad i' \neq i \tag{4.1}$$

where I is a set of all possible discrete outcomes, mutually exclusive severity categories. i and i' are different injury severity categories. β_i and $\beta_{i'}$ are vectors of estimated parameters of severity category i and i', respectively. X_n is the vector of characteristics (e.g. driver, vehicle, roadway and environmental) for the accident observation n that influences the injury severity category i and i'. ε_{ni} and $\varepsilon_{ni'}$ are random components (error terms) that explain the unobserved effects on injury severity of the accident observation n.

If ε_{ni} is assumed to be in a type I extreme-value distribution, a standard multinomial logit model can be expressed as (McFadden, 1981):

$$P_n(i) = \frac{e^{\beta_i X_n}}{\sum_{\forall i' \in I} e^{\beta_{i'} X_n}} \tag{4.2}$$

where the parameter β_i is typically estimated by the maximum likelihood method.

The mixed logit model will be generated from this multinomial logit model if the parameter β_i is allowed to vary across individuals (observations). Then a mixing distribution is introduced to the model formulation (Train, 2003):

$$P_n(i) = \frac{e^{\beta_i X_n}}{\sum_{\forall i' \in I} e^{\beta_{i'} X_n}} f(\beta \mid \varphi) d\beta \tag{4.3}$$

where $f(\beta \mid \varphi)$ is a density function of β with φ which is a vector of parameters of the density function (mean and variance), and all other terms are previously defined (Milton et al., 2008).

We examined four potential distributions for our model parameters: normal, uniform, lognormal and triangle distributions. Simulation-based maximum likelihood methods with Halton draws are adopted, which have been confirmed to be more efficient than purely random draws (Bhat, 2003). In the present study, the final results are based on 200 Halton draws, which have been found capable of producing accurate parameter estimates (Bhat, 2003; Milton et al., 2008; Gkritza and Mannering, 2008).

It is known that the estimated parameters of logit model analysis sometimes are not sufficient to explore how changes in the explanatory variables affect the outcome probabilities because the marginal effect of a variable depends on all of the parameters in the model (Kim et al., 2007). So in addition to the estimated parameters, elasticity is often used to describe the magnitude of the impact of the explanatory variables on the outcome probabilities (Ulfarsson and Mannering, 2004). Because the exogenous variables we explored later are discrete instead of continuous (coded as 0 and 1 indicator values), a direct pseudo-elasticity of the probability $E_{x_{nk}}^{P_n(i)}$ has been introduced to measure the effect in percentage that a 1% change in x_{nk} (the indicator varies from 0 to 1 or from 1 to 0) has on the severity probability $P(i)$. For example, a pseudo-elasticity of 50% for a variable in the fatal severity category means that when the value of the variable in the sub-set of the observations is changed from 0 to 1, the probabilities of fatal severity outcome for these observations in the sub-set increase by 50% on average. This method has been used in previous studies by several researchers such as Ulfarsson and Mannering (2004) and Khorashadi et al. (2005):

$$E_{x_{nk}}^{P_n(i)} = e^{\beta_{ik}} \frac{\sum_{\forall i' \in I} [e^{\beta_{i'} x_n}]_{x_{nk=0}}}{\sum_{\forall i' \in I} [e^{\beta_{i'} x_n}]_{x_{nk=1}}} - 1 \tag{4.4}$$

where $E_{x_{nk}}^{P_n(i)}$ is the direct pseudo-elasticity of the k^{th} variable from the vector x_n for observation n. x_{nk} is the value of the variable k for the outcome n. β_{ik} is the k^{th} component of the vector β_i of severity category i. $[e^{\beta_{i'} x_n}]_{x_{nk=0}}$ is the value of $e^{\beta_{i'} x_n}$ with the x_{nk} in x_n being set to zero and $[e^{\beta_{i'} x_n}]_{x_{nk=1}}$ is the value of $e^{\beta_{i'} x_n}$ with the x_{nk} in x_n being set to one.

4.4 Results

The whole data has been separated into two parts, one is the SV accident dataset and the other is the MV accident dataset. Table 4.3 and 4.4 show the estimated driver-injury severity models of SV and MV accidents, which include the estimated parameters and t-statistic identified for each severity category of mixed logit models. No-injury category is chosen as the base case, so the estimated parameters in the tables show the difference between the results of the target category and the base case (no-injury category). Following each variable name in Table 4.3 and 4.4, the abbreviation of the corresponding severity category to which each parameter belongs is listed in a bracket. They are defined as: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal. The tables suggest that a wide variety of variables are statistically significant on driver injury severity. The ρ^2 of the SV and MV models equal to 0.548 and 0.732 respectively, which indicate that the models fit the data satisfactorily.

We follow the work by Moore et al. (2010): first select all the parameters as random parameters, and then reduce one random parameter at a time until no further reduction of the random variables can be made. It is found that there are two random parameters in the SV model and one random parameter in the MV model. As shown in Table 4.3, the parameter of the snow/slush road surface indicator of possible injury/non-incapacitating injury in the SV model is normally distributed with mean -0.518 and standard deviation 1.41. With snow/slush road surface, 64.3% of the distribution is less than 0 and 35.7% of the distribution is greater than 0. This indicates that 64.3% of the SV accidents that occurred on snow-covered roads result in a decrease in possible injury/non-incapacitating injury accidents, while 35.7% of the accidents result in an increase in possible injury/non-incapacitating injury accidents. Such phenomena can be in part due to the fact that people often drive slower and more carefully on snowy roads than normal road conditions but on the other hand, it becomes truly harder to control the truck on snowy days despite carefulness of driving. The constant term of possible injury/non-incapacitating injury in the SV model is also found to be randomly distributed.

From Table 4.4, the parameter of the light traffic indicator of possible injury/non-incapacitating injury in the MV model is normally distributed with mean 0.15 and standard deviation 1.77. It is then found that 46.6% of the distribution is less than 0 and 53.4% of the distribution is greater than 0. This implies that nearly half of the MV accidents occurred with the light traffic condition result in a decrease in possible injury/non-incapacitating injury accidents while the other half of the accidents result in an increase in possible injury/non-incapacitating injury accidents. This result, which is similar to the finding of Milton et al. (2008) about the influence from average daily traffic (ADT) per lane, reveals the complex interaction among traffic volume, driver behavior and accident-injury severity. Obviously, without adopting the mixed logit models, the complex interaction and random nature of the parameters (e.g. the snow/slush road surface indicator and light traffic indicator) as described above would have been extremely hard, if not impossible at all, to be discovered.

In a logit model, the estimated parameters alone are not sufficient to explore the actual effect of a variable on the probability of an injury severity category. It is thus important to consider the marginal effects given by the pseudo-elasticity instead of the parameter values (Ulfarsson and Mannering, 2004). So the average direct pseudo-elasticity for the SV and MV models are studied and the results are presented in Table 4.5 and 4.6, respectively. The detailed results in Table 4.5 and 6 will be discussed by category in the following section.

Table 4.3 Mixed logit model of driver-injury severity conditioned on SV accident for truck-involved accidents

Variable[a]	Estimated parameter	t-statistic
Constant [II/F]	4.740	4.31
Constant [PI/NII]	2.910	2.22
Std. dev. of distribution of this parameter **(normal distribution)**	0.953	1.81
Driver characteristics		
Young driver (age<=25) [II/F]	-0.313	2.31
Old driver (age>=50) [PI/NII]	-0.116	1.90
Female driver [II/F]	0.320	2.18
Driver trapped/extract [II/F]	2.670	8.64
Driver trapped/extract [PI/NII]	2.230	6.51
Driver safety belt not used [II/F]	1.350	11.85
Driver safety belt not used [PI/NII]	1.100	6.72
Driver was asleep/fainted [II/F]	0.402	3.13
Driver was asleep/fainted [PI/NII]	0.547	3.85
Driver was fatigued [PI/NII]	0.384	2.24
Vehicle characteristics		
Single unit truck [PI/NII]	0.357	4.25
Truck brakes defect [PI/NII]	0.310	1.68
Truck tires defect [II/F]	0.394	2.35
Truck cargo defect [PI/NII]	0.561	1.90
Carrying hazardous material [II/F]	0.638	4.18

Temporal characteristics		
Rush hour (6:00am-9:59am) [PI/NII]	0.132	2.05
Roadway characteristics		
Light traffic (AADT/number of lanes<=2k) [PI/NII]	0.178	2.30
Class I designated truck route [PI/NII]	0.160	2.15
Stop sign/flasher [II/F] [PI/NII]	-0.723	3.11
Traffic signal [PI/NII]	-0.889	2.08
Sharp curve (degree of curve>=5) [II/F]	0.407	2.11
Sharp curve (degree of curve>=5) [PI/NII]	0.552	2.97
Steep grade (vertical curve grade>=2.2) [II/F]	0.904	4.39
Environmental characteristics		
Wet road surface [II/F]	-0.265	2.78
Snow/slush road surface [II/F]	-0.633	3.33
Snow/slush road surface [PI/NII] **(Random Parameter)**	-0.518	4.38
Std. dev. of distribution of this parameter **(normal distribution)**	1.410	2.55
Ice road surface [II/F] [PI/NII]	0.497	3.76
Fog/smoke/haze [PI/NII]	0.312	1.95
Severe cross wind [PI/NII]	0.689	4.83
Accident characteristics		
Truck ran off the roadway [II/F]	0.431	5.93
Truck ran off the roadway [PI/NII]	0.548	6.19
Truck overturn [II/F]	0.640	5.58
Truck overturn [PI/NII]	0.864	5.89
Truck jackknife [II/F]	-1.090	2.14
Exceeding speed limit [II/F] [PI/NII]	0.567	2.56
Improper lane usage [II/F]	0.263	2.87
Improper lane usage [PI/NII]	0.400	4.09
Hitting animal [II/F] [PI/NII]	-0.758	5.33
Exceeding safe speed for conditions [PI/NII]	0.359	3.00
Failing to reduce speed to avoid crash [II/F]	0.462	3.34
Failing to reduce speed to avoid crash [PI/NII]	0.318	2.20
Truck was passing/overtaking [II/F]	0.460	1.95
Truck was turning left [II/F]	-0.501	1.93
Truck was skidding/control loss [II/F] [PI/NII]	0.313	4.32
Truck was merging [PI/NII]	0.695	1.76
Number of observations		
Log likelihood at zero		-7570.5
Log likelihood at convergence		-3418.6
Number of observation used		6891
ρ^2		0.548

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

Table 4.4 Mixed logit model of driver-injury severity conditioned on MV accident for truck-involved accidents

Variable[a]	Estimated parameter	t-statistic
Constant [II/F]	5.380	3.82
Constant [PI/NII]	5.320	5.06
Driver characteristics		
Old driver (age>=50) [PI/NII]	0.103	1.77
Female driver [II/F]	0.404	2.92
Female driver [PI/NII]	0.238	1.81
Driver trapped/extract [II/F]	2.740	9.61
Driver trapped/extract [PI/NII]	2.180	5.14
Driver safety belt not used [II/F]	1.170	9.19
Driver safety belt not used [PI/NII]	1.070	4.42
Driver was asleep/fainted [II/F] [PI/NII]	1.387	4.76
Driver was fatigued [II/F]	1.040	4.00
Vehicle characteristics		
Single unit truck [II/F]	0.499	1.76
Tractor with semi-trailer [PI/NII]	-0.339	2.23
Truck brakes defect [II/F]	0.425	2.56
Truck brakes defect [PI/NII]	0.594	3.23
Truck tires defect [PI/NII]	-1.010	1.74
Carrying hazardous material [II/F]	0.737	4.26
Roadway characteristics		
Light traffic (AADT/number of lanes<=2k) [PI/NII] **(Random Parameter)**	0.150	2.21
Std. dev. of distribution of this parameter **(normal distribution)**	1.770	2.33
Low truck percentage (percentage[b] <=0.1) [PI/NII]	-0.120	1.79
Class I designated truck route [II/F]	-0.932	4.64
Class II designated truck route [II/F]	-0.243	2.32
Wide lane(lane width>=13ft) [PI/NII]	-0.202	2.40
Wide median (median width>=60ft) [PI/NII]	-0.202	2.00
Unprotected median [II/F]	0.395	2.58
Painted median [PI/NII]	0.300	2.10
Stop sign/flasher [PI/NII]	0.144	1.91
No passing zone sign [PI/NII]	0.470	2.91
Environmental characteristics		
Darkness light condition [II/F] [PI/NII]	0.232	2.85
Snow/slush road surface [II/F]	-0.488	2.78
Snow/slush road surface [PI/NII]	-0.198	1.89
Ice road surface [PI/NII]	-0.262	1.84

Accident characteristics		
Number of vehicles in accident >=3 [II/F]	0.216	2.13
Number of vehicles in accident >=3 [PI/NII]	0.433	3.78
Truck ran off the roadway [II/F] [PI/NII]	0.477	2.80
Truck overturn [II/F]	1.690	4.70
Truck overturn [PI/NII]	2.140	3.78
Exceeding speed limit [PI/NII]	0.287	1.71
Failing to yield right-of-way [PI/NII]	0.264	2.59
Driving on wrong side/wrong way [II/F]	0.418	1.90
Driving on wrong side/wrong way [PI/NII]	0.830	3.49
Driver influenced by alcohol/drugs [PI/NII]	0.439	2.19
Truck was turning left [II/F]	-0.336	1.89
Truck was turning right [II/F]	-0.631	2.05
Truck was turning right [PI/NII]	-0.510	2.47
Truck slowed/stopped in traffic [II/F]	-0.529	2.30
Truck was avoiding vehicle/objects [PI/NII]	0.379	3.08
Truck was skidding/control loss [II/F]	0.637	5.62
Truck was skidding/control loss [PI/NII]	0.453	3.31
Number of observations		
Log likelihood at zero		-14117.2
Log likelihood at convergence		-3786.8
Number of observation used		12850
ρ^2		0.732

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

Table 4.5 Average direct pseudo-elasticities of driver-injury severity of SV accidents

Variable	Elasticity (%) [a]		
	NI	PI/NII	II/F
Driver characteristics			
Young driver (age<=25)	7.3	10.9	-21.5
Old driver (age>=50)	4.5	-6.9	5.4
Female driver	-14.6	-1.9	17.6
Driver trapped/extract	-87.7	14.6	78.0
Driver safety belt not used	-61.9	14.6	47.1
Driver was asleep/fainted	-30.4	20.2	4.0
Driver was fatigued	-21.0	16.0	-0.5
Vehicle characteristics			
Single unit truck	-15.8	20.4	-10.8
Truck brakes defect	-13.1	18.5	-12.1
Truck tires defect	-16.7	-4.7	23.6

Truck cargo defect	-32.0	19.2	6.7
Carrying hazardous material	-21.7	-18.3	48.1
Temporal characteristics			
Rush hour (6:00am-9:59am)	-7.5	5.5	0.1
Roadway characteristics			
Light traffic (AADT/number of lanes<=2k)	-7.5	10.5	-6.2
Class I designated truck route	-7.6	8.4	-3.1
Stop sign/flasher	59.2	-22.9	-22.9
Traffic signal	58.6	-34.8	-5.4
Sharp curve (degree of curve>=5)	-30.7	20.3	4.0
Steep grade (vertical curve grade>=2.2)	-38.4	-8.4	52.1
Environmental characteristics			
Wet road surface	9.0	5.9	-16.4
Snow/slush road surface	42.6	-15.1	-26.0
Ice road surface	39.6	-16.9	-16.9
Fog/smoke/haze	-16.6	13.9	-2.1
Severe cross wind	-31.9	35.6	-14.6
Accident characteristics			
Truck ran off the roadway	-30.1	20.8	7.5
Truck overturn	-44.5	31.6	5.2
Truck jackknife	14.2	37.5	-61.6
Exceeding speed limit	-34.1	16.5	16.5
Improper lane usage	-22.2	16.0	1.2
Hitting animal	67.2	-21.3	-21.3
Exceeding safe speed for conditions	-18.3	17.0	-4.6
Failing to reduce speed to avoid crash	-24.5	3.8	19.9
Truck was passing/overtaking	-4.3	-33.5	51.6
Truck was turning left	15.4	11.3	-30.1
Truck was skidding/control loss	-20.7	9.8	9.8
Truck was merging	-29.5	41.4	-25.7

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

Table 4.6 Average direct pseudo-elasticities of driver-injury severity of MV accidents

Variable	Elasticity (%) [a]		
	NI	PI/NII	II/F
Driver characteristics			
Old driver (age>=50)	-1.1	9.7	-7.5
Female driver	-20.2	1.3	19.5
Driver trapped/extract	-88.0	6.5	86.4
Driver safety belt not used	-57.4	24.1	37.1

Driver was asleep/fainted	-66.0	33.6	33.6
Driver was fatigued	-35.0	-49.9	83.8
Vehicle characteristics			
Single unit truck	-16.3	-18.5	37.9
Tractor with semi-trailer	1.6	-27.6	39.8
Truck brakes defect	-30.3	26.3	6.6
Truck tires defect	16.1	-57.7	38.8
Carrying hazardous material	-28.6	-20.7	49.1
Roadway characteristics			
Light traffic (AADT/number of lanes<=2k)	-3.9	11.7	-6.4
Low truck percentage (percentage[b] <=0.1)	8.8	-3.5	-5.2
Class I designated truck route	29.4	49.4	-49.1
Class II designated truck route	5.0	17.6	-17.7
Wide lane(lane width>=13ft)	8.0	-11.7	3.2
Wide median (median width>=60ft)	3.5	-15.5	11.5
Unprotected median	-7.7	-24.1	37.0
Painted median	-4.1	29.4	-22.6
Stop sign/flasher	-6.6	7.9	-0.6
No passing zone sign	-15.7	34.9	-16.0
Environmental characteristics			
Darkness light condition	-14.3	9.2	9.2
Snow/slush road surface	23.8	1.5	-24.0
Ice road surface	16.9	-10.1	-7.2
Accident characteristics			
Number of vehicles in accident >=3	-20.0	23.4	-0.7
Truck ran off the roadway	-28.8	17.3	17.3
Truck overturn	-79.3	76.0	12.2
Exceeding speed limit	-7.0	23.9	-14.9
Failing to yield right-of-way	-8.2	19.5	-9.4
Driving on wrong side/wrong way	-36.7	45.1	-3.9
Driver influenced by alcohol/drugs	-22.1	20.8	3.2
Truck was turning left	16.1	1.4	-17.0
Truck was turning right	40.8	-15.4	-25.1
Truck slowed/stopped in traffic	19.5	12.1	-29.6
Truck was avoiding vehicle/objects	-18.2	19.5	0.5
Truck was skidding/control loss	-32.4	6.3	27.8

[a] Characters in the parentheses indicate variables defined for: [NI] no injury, [PI/NII] possible injury/non-incapacitating injury, [II/F] incapacitating injury/fatal.

[b] truck percentage is equal to commercial volume/AADT

4.4.1 Driver characteristics

The different influence of older drivers in SV and MV accidents is worthy of investigation. When the driver is older (≥ 50 years), depending on getting involved in a SV or MV accident, it has a 5.4% increase or 7.5% decrease in incapacitating injury/fatal probability, respectively. This phenomenon is perhaps because of the combined effects from cautious driving behavior, likely more driving experience, and yet longer reaction time of older drivers. The opposite effects of older drivers on driver-injury severity of the SV and MV accidents show the statistical difference of the two models, and are possibly also the reason why this indicator had not been found to be significant in the past when SV and MV accidents involving trucks were typically analyzed altogether. For older drivers, it is found that the chances of suffering severe injury and fatality increase while involving a SV accident. Accordingly, specific mitigation strategies of severe injury for older drivers may need to be developed in the future by considering the unique characteristics of SV accidents.

In addition to older drivers, young drivers (≤ 25 years) are also specifically studied. It is found that there are respectively 21.5% decreases and 10.9% increases in the probability of incapacitating injury/fatal probability and possible injury/non-incapacitating injury probability, if the driver is young and involves SV accidents. However the young driver indicator is not significant in the MV model at all. Similar to older drivers, the results suggest that more attention probably should be given to the traffic safety of young drivers in SV accidents in the future. Other than older and young drivers, female truck drivers are also found vulnerable to severe injury. Perhaps a combination of physiological and behavioral factors significantly affects the injury severity of truck driver and causes the observed differences between male and female drivers. It is found that the incapacitating injury/fatal probability increases in both the SV and MV models if the driver is female. Being consistent with the observations from other studies (e.g. Chang and

Mannering, 1999), this finding suggests that a higher probability of experiencing severe injury exists for female truck drivers regardless of the type of the accidents involved.

For truck drivers, it is not uncommon to become fatigued or sometimes even fall into sleep when driving (NIOSH, 2007). The probabilities of incapacitating injury/fatal in the SV and MV models both increase if the truck driver was asleep/fainted, but the probability in MV accidents is around 8 times higher than that of the SV accidents (33.6% vs 4%). The influence of a fatigued truck driver in the SV and MV models is totally different. The difference of elasticity is more than 50% for both categories of possible injury/non-incapacitating injury (16% vs -49.9%) and incapacitating injury/fatal (-0.5% vs 83.8%). This interesting observation implies that severe injury will likely happen if a fatigued truck driver is involved in a MV accident. In contrast, less severe injury is likely expected if a fatigued driver experiences a SV accident. The detailed reasons behind the observation are not straightforward and require further studies. Possible explanations may include different crash nature between SV and MV accidents, as well as the fact that a fatigued or asleep truck driver can otherwise do much more to avoid a MV accident than to avoid a SV accident. Based on the results illustrated above, to effectively reduce the probability of severe injury or fatality of truck drivers due to fatigue or falling into sleep, both types of accidents are important, but the focus should be put on preventing the occurrence of MV accidents.

The SV and MV models give similar findings about incapacitating injury/fatal probability if the driver did not use safety belt (47.1% vs 37.1%). These findings confirm again that using safety belts by truck drivers can notably reduce incapacitating injury/fatal probability in both SV and MV accidents. Similar observations have been made by for example, Chang and Mannering (1999) among other researchers.

4.4.2 Vehicle characteristics

Opposite effects on driver-injury severity were found between SV and MV accidents if the truck is single-unit. For example, if a truck is single-unit, the probability of incapacitating injury/fatal increases by 37.9% in a MV accident while decreases by 10.8% in a SV accident as compared to trucks which are not single-unit. Also the tractor with semi-trailer indicator is significant in the MV model by increasing the probability of incapacitating injury/fatal by 39.8%, but not significant in the SV model. So from the perspective of lowering injury severity of the driver, a single-unit truck is better than other non-single-unit trucks in a SV accident, but usually becomes worse than other non-single-unit trucks in a MV accident.

If a truck has a brake or tire defect, there is considerable difference of incapacitating injury/fatal probability between the SV and MV models (-12.1% vs 6.6% for brake defect, 23.6% vs 38.8% for tire defect). Comparatively, tire defect is found to be more critical than brake defect in terms of causing severe injury of truck drivers. This finding may help trucking industry on developing safer maintenance process and highway patrol on conducting improved law enforcement. The probabilities of incapacitating injury/fatal in both SV and MV accidents will increase significantly if the truck is carrying hazardous material (48.1% and 49.1% for the SV and MV accidents respectively). This result highlights the significantly elevated life threats to the drivers of HazMat trucks no matter what kind of accident is involved.

4.4.3 Temporal characteristics

In this study, only one temporal characteristic variable was found to be statistically significant. The rush hour indicator slightly increases the possible injury/non-incapacitating injury probability in the SV model while it has no significant effect in the MV model. Although high traffic volume has a large impact on accident frequency of MV accidents, it seems to be not critical from the perspective of injury severity of truck drivers.

4.4.4 Roadway characteristics

Roadway characteristics affect the driver injury severity in the SV and MV accidents in a rather complex manner. In MV accidents both Class I and II designated truck routes increase the probability of possible injury/non-incapacitating injury (49.4% vs 17.6%), while they decrease the probability of incapacitating injury/fatal (49.1% vs 17.7%) at the same time. Because of the trade-offs, Class I and II designated truck routes may not have considerable impacts on the two injury levels as a whole, but they both significantly decrease the probability of severe injury and fatality, which are usually very critical to policy-making. Comparatively, Class I designated truck routes are more effective than Class II designated truck routes. Since this study is only based on the data in Illinois, it is advisable that transportation agencies may evaluate the effectiveness of the designated truck routes by considering the site-specific accident and injury data. It is believed that studies on optimizing the strategy of designated truck routes may need to be conducted on a case-by-case basis for different highways, especially those historically suffering severe injury of truck drivers.

There are some variables which are found to be significant only for one type of accidents. For example, wide lane, wide median, unprotected median indicators decrease the probability of possible injury/non-incapacitating injury by 11.7%, 15.5%, 24.1% while increase the probability of incapacitating injury/fatal by 3.2%, 11.5% , 37% in the MV model, respectively. All these indicators, however, are found to be not significant in the SV model. Obviously, the impacts from wide lanes, wide medians or unprotected median on the injury severity of truck drivers in MV accidents are complex in nature: these roadway design features help on reducing the probability of moderate injury, but increasing the probability of severe injury and fatality at the same time. This is probably the outcome from the trade-offs between the provided physical protection and the affected driving behavior due to either “safer” or “more dangerous” feeling by the drivers. For example, on one hand, wide lanes and wide medians do provide more physical safety margins for truck drivers. On the other hand, the "safer" feeling may also encourage unsafe driving behavior by the truck drivers. In contrast, an unprotected median may pose higher risks of injury during accidents, but it may also alert truck drivers to drive more cautiously. The results imply the need to evaluate the impacts of some roadway design features on traffic safety more comprehensively by traffic agencies and the research community, from both engineering and psychological perspectives simultaneously.

The low truck percentage indicator decreases the probability of both possible injury/non-incapacitating injury and incapacitating injury/fatal for the MV model, and is found to be not significant for the SV model. Class II designated truck route, painted median and no passing traffic control indicators increase the possible injury/non-incapacitating injury probability by 17.6%, 29.4% and 34.9% respectively in the MV model although they were not found to be significant in the SV model. Different from Class II designated truck route, Class I designated truck route will decrease the probability of incapacitating injury/fatal in both the MV and SV models, but with substantial difference (49.1% (MV) vs 3.1% (SV)). These findings can help transportation agencies to evaluate the related roadway feature designs and further identify those features which are really helpful on effectively reducing traffic injury severity.

Similar to those variables as summarized above which are only significant in the MV model, there are also some variables which are only significant in the SV model. For example, if a highway has sharp curves, the probability of possible injury/non-incapacitating injury or incapacitating injury/fatal increase by 20.3% or 4% in the SV model respectively, but no significant impact was observed in the MV model. The steep grade indicator will increase the probability of incapacitating injury/fatal by more than 50% in the SV model but has no influence in the MV model. These findings underscore the substantial effects of complex terrains on injury severity in SV accidents. It is known that SV accidents are pretty common in areas with complex terrains (e.g. mountainous states). The results suggest that highways should be designed very carefully, given that optimizing the terrain may potentially save many lives and avoid injuries of many truck drivers through these highways each day.

4.4.5 Environmental characteristics

If an accident happens on an icy road, the probabilities of possible injury/non-incapacitating injury and incapacitating injury/fatal in both the SV and MV models are all found to decrease. Besides, the results for both SV and MV accidents are generally similar if the accidents occur on a snow-covered road, except for one situation: the probability of possible injury/non-incapacitating injury in the MV model slightly increases by 1.5% while that in the SV model decrease by 15.1%. Trucks are well known to be vulnerable to both SV and MV accidents on icy and snow-covered roads. The results in the present chapter show that severe injuries of truck drivers are overall less likely to occur in both SV and MV accidents than normal road conditions. But as discussed in the first part of Section 5, it is noted that snow-covered road surface condition has been identified as randomly distributed over observations of SV accidents.

The darkness indicator was found to be significant in the MV model, but no in the SV model. The finding that the probability of severe injury increases in the night condition has also been found by a study on truck-involved accidents as a whole (Chang and Mannering, 1999). But the different impacts on SV and MV accidents, as introduced above, have not been discussed previously. Contrary to the darkness indicator, the wet road surface indicator was found to be significant in the SV model, but no in the MV model. Another interesting finding is that inclement weather like fog or windy weather increases the possible injury/non-incapacitating injury probability in the SV model while these weather conditions were found to be not significant in the MV model. So depending on the specific adverse environmental condition, more effective injury mitigation technology for truck drivers can be developed accordingly with an emphasis on SV accidents based on the findings summarized above.

4.4.6 Accident characteristics

Many variables of accident characteristics were also found to have totally different influence on SV and MV accidents. There are many characteristic indicators which only have significant impacts on the truck-driver injury severity in either MV or SV accidents, but not both. For example, six accident characteristic indicators (e.g. the failing to yield right-of-way indicator) were found to be significant in the MV model but no in the SV model. While other seven accident characteristics indicators (e.g. the improper lane usage indicator) were found to be significant in the SV model but not in the MV model. Details of these variables and all other characteristics are summarized in Table 4.7 and 4.8.

Even for some indicators which were found to be significant in both models, there is still considerable difference. For example, if a truck is overturned, the probability of possible injury/non-incapacitating injury in the MV model increases more significantly than in the SV model (76% vs 31.6%). When a truck loses control, there is also large difference between the increasing of the probability of incapacitating injury/fatal in the SV and MV models (9.8% vs 27.8%). Considerably higher probabilities of experiencing severe injury in MV accidents than SV accidents are possibly related to the difference of the crash nature of SV and MV accidents.

It is known that the influence of alcohol or drugs can increase the probability of severe injury (Khorashadi et al., 2005). In addition to having the same observation, the present study further shows there is different influence of these variables on SV and MV accidents: the driver influenced by alcohol or drugs undergoes increasing probability of both possible injury/non-incapacitating injury and incapacitating injury/fatal in the MV model, while the same indicator is found to be insignificant in the SV model.

It can be found from the above results that there is substantial difference between the impacts from a variety of variables on the driver-injury severity in MV and SV accidents. For clarity purpose, Table 4.7 and 4.8 summarize all the indicators which have different influence in the SV and MV models, including those only significant to one type of accidents, with opposite trends and with the same trend but significantly different elasticity to both types of accidents. By conducting the injury severity study for MV and SV accidents involving trucks separately, some new or more comprehensive observations, which have not been covered in the existing studies, can be made. As a result, the complex interactions of various indicators and the nature of truck-driver injury are able to be disclosed in a better way.

4.5 Model Specification Tests

The likelihood ratio test is also conducted to verify the statistical justification of estimating SV and MV accidents separately in the present study. The method is conducted to check the significance of the combined model for all vehicle accidents (both SV and MV accidents) and two separate models for SV and MV only. The following formula is adopted to apply the likelihood ratio test (Ulfarsson and Mannering, 2004):

$$-2\left[L_N\left(\beta\right)-L_{N_s}\left(\beta^s\right)-L_{N_m}\left(\beta^m\right)\right] \tag{4.5}$$

where $L_{N(\beta)}$ is the log-likelihood at convergence of the all data model, with a parameter β, $L_{N_s}(\beta^s)$ and $L_{N_m}(\beta^m)$ are the log-likelihood at convergence of the model estimated on the SV data subset, and the MV data subset, respectively. The test adopts χ^2 distribution with the degrees of freedom equal to the sum of the number of the estimated parameters in the SV and MV models minus the number of the parameters estimated in all data models.

With P<0.001, the result of the test indicates that significant difference of severity likelihood exists between SV and MV accidents, which justifies the choice of modeling SV and MV accidents separately in the present study. We also conduct the likelihood ratio tests to check whether the random parameter models (mixed logit models) are significantly better than the fixed parameter models (base multinomial models). The likelihood ratio test is (Washington et al., 2003):

$$2\left[L_{MXL}\left(\beta\right)-L_{MNL}\left(\beta\right)\right] \tag{4.6}$$

where $L_{MXL}\left(\beta\right)$ and $L_{MNL}\left(\beta\right)$ are the log-likelihood at convergence of mixed logit model and multinomial logit model of the same dataset (e.g. SV or MV dataset), respectively.

The statistic is in χ^2 distribution with the degrees of freedom equal to the difference of the numbers of the parameters between the two models. For the SV model, the χ^2 value of the test is 7.04 with two degrees of freedom. The corresponding *p*-value is 0.03. The χ^2 value of the test for the MV model is 9.06 with one degree of freedom. The corresponding *p*-value is 0.003. Therefore, it is obvious that there exists significant difference between the random parameter models and the fixed parameter models.

4.6 Discussions and Conclusions

Ten-year detailed HSIS accident data on major interstate highways, US highways and state highways in Illinois were studied. The mixed logit model was adopted to analyze the injury severity of truck drivers on rural highways. The result of the likelihood ratio test indicates that the injury mechanisms of SV and MV accidents involving trucks are clearly distinct. A comprehensive collection of different risk factors including driver characteristics, vehicle characteristics, temporal characteristics, roadway characteristics, environmental characteristics, and accident characteristics were included in the mixed logit models. For the first time, SV and MV accidents involving trucks were studied separately to identify those risk factors which have significant influence on the driver-injury severity.

The detailed findings on risk factors in MV and SV accidents will add to the existing knowledge of injury studies about truck drivers. Based on the improved understanding of the injury severity of truck drivers, it is expected that more rational and effective injury prevention strategies may be developed for truck drivers by trucking industry and related agencies, such as occupational safety and transportation agencies. In the mean time, some findings may be helpful for transportation agencies to evaluate and improve the existing designs of transportation infrastructure and traffic management system. Finally, the present study can also help on developing training and educational courses for truck drivers, state patrols, engineers and general public.

Table 4.7 Summary of indicators by influence types

Indicators only significant to SV model	**Indicators only significant to MV model**
(1)-Young driver (age<=25)	**(2)-**Tractor with semi-trailer
(2)-Truck cargo defect	**(4)-**Low truck percentage (percentage[b] <=0.1)
(3)- Rush hour (6:00am-9:59am)	**(4)-**Class II designated truck route
(4)-Traffic signal	**(4)-**Wide lane(lane width>=13ft)
(4)-Sharp curve (degree of curve>=5)	**(4)-**Wide median (median width>=60ft)
(4)-Steep grade (vertical curve grade>=2.2)	**(4)-**Unprotected median
(5)-wet road surface	**(4)-**Painted median

(5)- Fog/smoke/haze	**(4)-**No passing zone sign
(5)- Severe cross wind	**(5)-** Darkness light condition
(6)-Truck jackknife	**(6)-**Number of vehicles in accident >=3
(6)-Improper lane usage	**(6)-**Failing to yield right-of-way
(6)-Hitting animal	**(6)-**Driving on wrong side/wrong way
(6)-Exceeding safe speed for conditions	**(6)-**Driver influenced by alcohol/drugs
(6)-Failing to reduce speed to avoid crash	**(6)-**Truck was turning right
(6)-Truck was passing/overtaking	**(6)-**Truck slowed/stopped in traffic
(6)-Truck was merging	**(6)-**Truck was avoiding vehicle/objects
Indicators having influence on SV and MV models with the same trend and the difference of elasticity is small (smaller than 10% for both PI/NII and II/F)	**Indicators having influence on SV and MV models with the same trend but the difference of elasticity is large (bigger than 20% for either of PI/NII and II/F)**
(1)-Driver trapped/extract	**(1)-**Driver was asleep/fainted (II/F)
(1)-Driver safety belt not used	**(2)-**Truck tires defect (PI/NII and II/F**)**
(2)-Carrying hazardous material	**(4)-**Class I designated truck route (PI/NII and II/F**)**
(4)-Light traffic (AADT/number of lanes<=2k)	(6)-Truck overturn (II/F)
(5)- Ice road surface	(6)-Truck was skidding/control loss
(6)-Truck ran off the roadway	

The numbers in brackets before indicators are defined as: (1) driver characteristics (2) vehicle characteristics (3) temporal characteristics (4) roadway characteristics (5) environmental characteristics (6) accident characteristics

The major findings in terms of different influence on injury severity in MV and SV accidents are summarized in the following.

(1) Some variables are only significant in the SV accident model or the MV accident model, but not both. According to the results in the present chapter, there are sixteen variables which are only significant in the SV model while not in the MV model. Also there are sixteen variables which were found to be significant in the MV model only.

(2) Even if some variables were found to be significant in both SV and MV models, there is considerable difference of marginal effects on these two models. Some of them can have opposite effects for SV and MV accidents. There are also some variables which have noteworthy

difference of magnitudes even with the same trend. All the variables which have different influence on the injury severity in SV and MV accidents are summarized in Table 4.7 and 4.8.

(3) Estimation findings indicate that snow road surface will be better modeled as random-parameters in the SV model and the same with the light traffic indicators in the MV model.

The ultimate goal of any injury study is to provide scientific basis to potentially reduce injury severity through advancing the state-of-the-art of modeling, manufacturing and policy-making. Therefore, among a large number of risk factors being investigated in the present chapter, it is felt helpful to summarize those critical risk factors which have been rarely reported before, while cause more severe injury or less severe injury in truck-involved accidents. Depending on the impacts, these risk factors should be considered strategically in any future injury mitigation strategy, transportation design and management.

(1) As shown in Table 4.7 and 4.8, there are some risk factors which were found to be significant to the severity of truck-related accidents in the present study, but were rarely reported in the existing studies about truck-involved accidents. These risk factors include old driver, driver trapped/extract, driver was asleep/fainted, driver was fatigued, carrying hazardous material, light traffic, low truck percentage, class I and II designated truck route, wide lane, wide median, no passing zone sign, stop sign/flasher, traffic signal, sharp curve, fog/smoke/haze, severe cross wind, hitting animal, truck overturn, truck jackknife, improper lane usage, driving on wrong side/wrong way, failing to reduce speed to avoid crash, truck was avoiding vehicle/objects, truck was passing/overtaking and truck was skidding/control loss indicators. In fact, some of these variables which are significant to the severity of SV or MV accidents would not have been identified if only the analysis of the data from all the accidents as a whole were conducted.

(2) Among those factors summarized above which were rarely reported before, the injury severity analysis presented in this chapter revealed that several risk factors may lead to more severe injuries (higher probability of incapacitating injury/fatal) of truck drivers. These factors

include old driver (SV accident), driver trapped/extract(both SV and MV accidents), driver was asleep/fainted (both SV and MV accidents), driver was fatigued (MV accidents), carrying hazardous material (both SV and MV accidents), wide lane (MV accidents), wide median (MV accidents), truck overturn(both SV and MV accidents), improper lane usage (SV accidents), failing to reduce speed to avoid crash(SV accidents), truck was avoiding vehicle/objects (MV accidents), truck was passing/overtaking(SV accidents), truck was skidding/control loss indicators (both SV and MV accidents). These risk factors deserve special considerations in future transportation design, management and policy-making.

(3) The injury of truck drivers were found less severe (lower possibility of incapacitating injury/fatal) under following conditions: old driver (MV accidents), light traffic (both SV and MV accidents), low truck percentage (MV accidents), Class I designated truck route (both SV and MV accidents), Class II designated truck route (MV accidents), stop sign/flasher (SV accidents), traffic signal (SV accidents), no passing zone sign (MV accidents), fog/smoke/haze (SV accidents), severe cross wind (SV accidents), hitting animal (SV accidents), truck jackknife (SV accidents), driving on wrong side/wrong way (MV accidents). Some risk factors become helpful on reducing the probability of severe injury through complex interactions between driver behavior and measureable factors such as driving environmental conditions, which can play a significant role in truck driver injury severity.

Similar to most studies, the present study also has some limitations, such as the fact that data reflect information from a single US state, were obtained from a single database, as well as the fact that the truck types investigated are limited by the available types from the database. Future studies with multiple states, data from different databases and more comprehensive truck types may be conducted, which may provide more comprehensive insights.

Table 4.8 Indicators which have opposite influence on SV and MV models

	SV		MV	
Variables	possible injury/non-incapacitating injury	incapacitating injury/fatal	possible injury/non-incapacitating injury	incapacitating injury/fatal
(1)-Old driver (age>=50)	⇩	⬆	⬆	⇩
(1)-Female driver	⇩	⬆	⬆	⬆
(1)-Driver was fatigued	⬆	⇩	⇩	⬆
(2)-Single unit truck	⬆	⇩	⇩	⬆
(2)-Truck brakes defect	⬆	⇩	⬆	⬆
(4)-Stop sign/flasher	⇩	⇩	⬆	⇩
(5)-Snow/slush road surface	⇩	⇩	⬆	⇩
(6)-Exceeding speed limit	⬆	⬆	⬆	⇩

Arrows show increase (up) or decrease (down) in elasticity. The numbers in brackets before indicators are defined in the same way as Table 7.

4.7 References

Abdel-Aty, M. (2003). "Analysis of driver injury severity levels at multiple locations using ordered logit models." J. Safety Res. 34 (5), 597–603.

Alassar, L. (1988). "Analysis of heavy large-truck accident severity." J. Adv. Transport. 22 (1), 77–91.

Baker, C.J. (1991). "Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system." J. of Fluids and Structures 5, 221–241.

Bhat, C. (2001). "Quasi-random maximum simulated likelihood estimation of the mixed multinomial logit model." Transport. Res. Part B 17 (1), 677–693.

Bhat, C. (2003). "Simulation estimation of mixed discrete choice models using randomized and scrambled Halton sequences." Transport. Res. Part B 37 (1), 837–855.

Bierlaire, M. (2003). "BIOGEME: A free package for the estimation of discrete choice models." Proceedings of the 3rd Swiss Transportation Research Conference, Ascona, Switzerland.

Bierlaire, M. (2008). Estimation of discrete choice models with BIOGEME 1.8, biogeme.ep.ch

Chang, L.-Y., Mannering, F. (1999). "Analysis of injury severity and vehicle occupancy in truck- and non-truck-involved accidents." Accident Anal. Prevent. 31 (5), 579–592.

Chen, S. R. and Cai, C. S. (2004). "Accident assessment of vehicles on long-span bridges in windy environments." Journal of Wind Engineering and Industrial Aerodynamics, 92(12), 991-1024.

Chen, S. R. and Chen, F. (2010). "Simulation-based assessment of vehicle safety behavior under hazardous driving conditions." J. of Transportation Engineering, ASCE. 136(4), 304-315.

Chirachavala, T., Cleveland, D., Kostyniuk, L.P. (1984). "Severity of large-truck and combination-vehicle accidents in over-the-road service: a discrete multivariate analysis." Transport. Res. Rec. 975, 23–36.

Duncan, C., Khattak, A., Council, F. (1998). "Applying the ordered logit model to injury severity in truck-passenger car rear-end collisions." Transport. Res. Rec. 1635, 63–71.

Geedipally S.R., Lord D. (2010), "Investigating the effect of modeling single-vehicle and multi-vehicle crashes separately on confidence intervals of Poisson gamma models." Accident Anal. Prevent. 42(4), 1273-1282.

Gkritza, K., Mannering, F.L. (2008). "Mixed logit analysis of safety-belt use in single- and multi-occupant vehicles." Accident Anal. Prevent. (40)2:443-451.

Golob T., W. Recker, J. Leonard. (1987). "An analysis of the severity and incident duration of truck-involved freeway accidents." Accident Anal. Prevent. 19(5), 375-396.

Islam, S., Mannering, F. (2006), "Driver aging and its effect on male and female single-vehicle accident injuries: some additional evidence." Journal J. Safety Res. 37 (3), 267 – 276.

Ivan, J.N., Pasupathy, R.K., Ossenbruggen, P.J. (1999). "Differences in causality factors for single and multi-vehicles crashes on two-lane roads." Accident Anal. Prevent. 31, 695–704.

Jones, S., Hensher, D. (2007). "Evaluating the behavioural performance of alternative logit models: an application to corporate takeovers research." Journal of Business Finance & Accounting 34, 1193–1220.

Khorashadi, A., Niemeier, D., Shankar, V., Mannering, F. (2005). "Differences in rural and urban driver-injury severities in accidents involving large trucks: an exploratory analysis." Accident Anal. Prevent. 37 (5), 910–921.

Kim J.K., Kim S, Ulfarsson G.F., Porrello L.A. (2007). "Bicyclist injury severities in bicycle-motor vehicle accidents." Accident Anal. Prevent. 39(2), 238-251

Kim, J.-K., Ulfarsson, G., Shankar, V., Mannering F. (2010). "A note on modeling pedestrian injury severity in motor vehicle crashes with the mixed logit model." Accident Anal. Prevent. 42(6), 1751-1758.

Kockelman, K., Kweon, Y. (2002). "Driver injury severity: an application of ordered probit models." Accident Anal. Prev. 34 (3), 313-321.

Lyman, S., Braver, E.R. (2003). "Occupant deaths in large truck crashes in the United States: 25 years of experience." Accident Anal. Prevent. 35(5), 731-739.

Malyshkina, N., Mannering, F. (2010). "Empirical assessment of the impact of highway design exceptions on the frequency and severity of vehicle accidents." Accident Anal. Prevent. 42(1), 131-139.

McFadden, D. (1981). In: Manski, C., McFadden, D. (Eds.), Econometric models of probabilistic choice. In Structural Analysis of Discrete Data with Econometric Applications. MIT Press, Cambridge, MA.

McFadden, D., Train, K. (2000). "Mixed MNL models for discrete response." J. Appl. Econom. 15, 447–470.

Milton, J., Shankar, V., Mannering, F. (2008). "Highway accident severities and the mixed logit model: An exploratory empirical analysis." Accident Anal. Prevent. 40(1), 260-266.

Moore, D.N., Schneider, W., Savolainen, P.T., Farzaneh, M. (2010). "Mixed logit analysis of bicyclist injury severity resulting from motor vehicle crashes at intersection and non-intersection locations." Accident Anal. Prevent. (2010), doi:10.1016/j.aap.2010.09.015

National Institute for Occupational Safety and Health (NIOSH). (2007). "Truck driver occupational safety and health, 2003 conference report and selective literature review." Centers for Disease Control and Prevention, Department of Health and Human Services.

Noland R.B., Oh, L. (2004). "The effect of infrastructure and demographic change on traffic-related fatalities and crashes: a case study of Illinois county-level data." Accident Anal. Prevent. 36 (4) , 525-532.

Revelt, D., Train, K. (1998). "Mixed logit with repeated choices: households' choices of appliance efficiency level." Review of Economics and Statistics 80 (4.), 647 – 657.

Savolainen, P., Mannering, F. (2007). "Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes." Accident Anal. Prevent. 39, 955–963.

Shankar, V.N., Mannering, F.L. (1996). "An exploratory multinomial logit analysis of single-vehicle motorcycle accident severity." J. Safety Res. 27 (3), 183–194.

Shao, S.P. (1987). “Estimating passenger-vehicle driver injury severity in car/tractor-trailer collisions.” Accident Anal. Prev. 19 (3), 207–217.

Shibata, A., Fukuda, K. (1994). “Risk factors of fatality in motor vehicle traffic accidents.” Accident Anal. Prevent. 26 (3), 391–397.

The National Academies. (2006). “Where the weather meets the road – a research agenda for improving road weather system.” Report in Brief, The National Academies.

Train, K. (2003). Discrete Choice Methods with Simulation. Cambridge University Press, Cambridge, UK.

Ulfarsson, G., Mannering, F. (2004). “Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents.” Accident Anal. Prevent. 36 (2), 135–147.

U. S. Department of Transportation (USDOT). (2005). “Report to Congress on the Large Truck Crash Causation Study.” Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Wahlberg A.E. (2008). “Meta-analysis of the difference in accident risk between long and short truck configurations.” J. of Risk Research. 11(3), 315-333.

Washington, S., Karlaftis, M., Mannering, F. (2003). Statistical and Econometric Methods for Transportation Data Analysis. Chapman and Hall/CRC, Boca Raton, FL.

CHAPTER 5: RELIABILITY-BASED ASSESSMENT OF VEHICLE SAFETY IN ADVERSE DRIVING CONDITIONS

5.1 Introduction

Different from multi-vehicle crashes, single-vehicle crashes under adverse driving environments were found to be closely related to the coupling between vehicle, infrastructure and driving environments (USDOT 2005; Baker 1991; Guo and Xu 2006). Every year, adverse weather alone is associated with more than 1.5 million vehicular crashes in the United States, which result in 800,000 injuries and 7,000 fatalities (The National Academies 2006). Thus for transportation authorities, trucking industry, public health professionals and general public, to accurately predict and mitigate the single-vehicle accident risk under different driving conditions is crucial.

There has been limited progress on investigating single-vehicle accident risk considering adverse driving environments in past decades. Baker (1987, 1991, 1994) started series of studies on dynamic stability of high-sided vehicles under crosswind with the simplified rigid-body vehicle model. Chen and Cai (2004) and Guo and Xu (2006) improved the accident risk assessment by introducing fully-coupled dynamic interaction models of vehicles, bridge and wind, respectively. To consider uncertainties associated with some variables of the rigid-body model, reliability-based accident risk studies were also conducted (Sigbjornsson and Snaebjornsson 1998; Snaebjornsson et al. 2007). As a result of adopting the simplified rigid-body model, the limit state functions in these studies were able to be easily expressed as explicit ones in terms of random variables. All these existing studies, however, only considered vehicles on straight routes under excitations from only wind and/or the bridge. As a result, these models do not serve as a general methodology which can accurately replicate various driving environments as well as associated uncertainties in nature.

It is all known that wind exists in nature all the time from a breeze to a strong wind. For any vehicle, the specific driving condition primarily consists of natural wind, the local topographic condition of the highway stretch that the vehicle is driven on, and the particular road surface condition (Chen et al. 2010). All these driving conditions work integrally to affect the safety of any vehicle on highways. To provide a general safety assessment tool, Chen and Chen (2010) recently developed an advanced deterministic dynamic simulation model which can consider more realistic driving environments. Single-vehicle accident performance can be simulated under different combinations of crosswind conditions, road surface conditions (e.g. wet, icy or snow-covered) and specific topographical conditions (e.g. curve, superelevation and grade) by using the advanced transient dynamic equations, improved accident criteria and critical variables (Chen and Chen 2010).

In the present chapter, a reliability-based traffic safety prediction model will be developed based on the advanced vehicle dynamic deterministic simulation model developed by the writers (Chen and Chen 2010) to consider necessary uncertainties of critical variables. In order to efficiently cope with implicit limit state functions in the model, the response surface method (RSM) and the first order reliability method (FORM) will be used in the reliability-based analysis.

5.2 Reliability-based Vehicle Safety Assessment Model

In chapter 3, the deterministic model of vehicle accident simulation has been developed. Based on the deterministic vehicle accident simulation model, the reliability-based vehicle safety assessment model present in this chapter is established.

5.2.1 Limit state function

Taking the summation of moment about the point on the ground plane at the mid-track position, the weight transfer ratio W_{trans} between the left and right wheels can be derived as (Sampson 2000):

$$W_{trans} = ((mV(\dot{\beta}+\dot{\psi}) + ma_y + mg(\phi-\theta)) \times h_{cm} + F_{w,y}(h_w + r) + M_x + a_{roll} I_{x'x'}) / d \quad (5.1)$$

where h_{cm} is the height of centre of mass for the whole truck, d is the track width and h_w is the height of lateral wind load $F_{w,y}$ measured upwards from the roll center.

It is known that a vehicle may or may not actually rollover when the wheels are lifted up. The existing studies (Chen and Chen 2010) showed that in most scenarios rollover accidents occur after wheels are lifted up. Only in a few special cases the truck may not actually rollover after wheels are lifted up. In order to capture more general scenarios of rollover, the criterion of wheels being lifted up is selected in the present study to develop the limit state function $g_{\lim}$ for rollover accidents:

$$g_{\lim} = mg/2 - F_{w,z}/2 - W_{trans} \quad (5.2)$$

where W_{trans} is the weight transfer ratio as defined in Eq. (5.1), $F_{w,z}$ is the wind-induced lift force.

For sideslip accidents, the limit state function $g_{\lim}$ is developed based on the criterion that the summation of the actual lateral friction forces of all wheels equals to the maximum allowable lateral friction forces for the particular road surface. Accordingly, the limit state function $g_{\lim}$ for sideslip can be developed in Eq. (5.3):

$$g_{\lim} = F_{la,f}^{\max} + F_{la,r}^{\max} - \left(F_{y,f} + F_{y,r}\right) = \mu_{friction}\left(F_{z,f} + F_{z,r}\right) - \left(F_{y,f} + F_{y,r}\right) \qquad (5.3)$$

where $F_{z,f}$ and $F_{z,r}$ are the vertical forces on the front and rear axles, respectively. $F_{la,f}^{\max}$ and $F_{la,r}^{\max}$ are the maximally allowable lateral friction forces of the front and the rear wheels for a given road surface condition, respectively. $\mu_{friction}$ is the road friction coefficient. The effect of acceleration or deceleration on tire friction force is not considered in the equation.

Due to the fact that $F_{y,f}$, $F_{y,r}$ in Eq. (5.3) as well as W_{trans} in Eq. (5.2) can only be quantified after solving coupled dynamic equations (e.g. Eqs. (3.4-3.8)), the limit state functions as shown in Eqs. (5.2) and (5.3) can not be expressed as explicit functions like the case when the rigid-body vehicle model was used in some existing studies (Sigbjornsson and Snaebjornsson 1998; Snaebjornsson et al. 2007). Under any combination of driving conditions, continuous simulations with the deterministic model will be conducted until whichever of the two accident types occurs first or the simulation results converge (i.e. no accident occurs). The corresponding limit state function for the particular accident type will be used to continue the reliability analysis.

5.2.2 Response surface method

Monte Carlo simulation is an accurate, robust, and easy-to-use method for the reliability analysis of structures with implicit limit state functions (Bucher and Bourgund 1990). The associated enormously large amount of computation time, however, often makes the application of Monte Carlo simulation on some complicated problems, like the vehicle dynamic simulations as introduced above, cost-prohibitive. Response surface method (Bucher and Bourgund 1990, Rajashekhar and Ellingwood 1993) is a popular approach to approximate the originally complex and implicit limit state functions by a simple response surface function. In the present study, Response Surface Method (RSM) is adopted here to predict the reliability index under adverse driving conditions. Given the fact that different advanced reliability analytical approaches have their respective advantages, it is noted that the RSM approach may not necessarily be the only or the best reliability method for this particular problem. An investigation of other advanced approaches and the comparison deserve a separate study in the future.

A second-order polynomial without cross terms will be used in the present study (Bucher and Bourgund 1990):

$$\hat{g}(X) = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{i=1}^{k} a_{ii} X_i^2 \tag{5.4}$$

where $\hat{g}(X)$ is the approximate limit state function of Eq. (5.2) or Eq. (5.3). X_i (i=1,2,…,k) is the i^{th} random variable. k is the total number of random variables. a_0, a_i, a_{ii} are coefficients to be determined by solving a set of simultaneous equations. As a result, the total number of unknown coefficients of Eq. (5.4) is 2k+1.

The random variable X_i in Eq. (5.4) can be defined as (Bucher and Bourgund 1990; Rajashekhar and Ellingwood 1993)

$$X_i = \mu_i \pm h_i \sigma_i \tag{5.5}$$

where h_i is an arbitrary factor. μ_i and σ_i are the mean and the standard deviation of X_i, respectively.

In the present study, the initial value of h_i is assumed to be a typical value of 3.0 for the first iteration and 1 for the subsequent iterations (Rajashekhar and Ellingwood 1993). The initial center point is chosen by setting all the random valuables as their respective mean values. The iterative linear interpolation scheme of RSM suggested by Rajashekhar and Ellingwood (1993) is used in this study.

5.2.3 Safety index of vehicle

After the limit state functions have been approximated using RSM, first order reliability method (FORM) is applied to predict the failure probability and safety index (Haldar and Mahadevan 2000). The typical FORM method has been utilized by many previous studies (Haldar and Mahadevan 2000). The corresponding limit state probability (accident probability) $p_{failure}$ can be estimated by the following equation (Haldar and Mahadevan 2000):

$$p_{failure} = \Phi(-\beta) \tag{5.6}$$

in which $\Phi(\ )$ is the standard normal probability distribution function. β is the reliability index, which will be referred as safety index in the following numerical study.

5.3 Numerical Study

With the reliability-based analytical model illustrated above, a numerical example of assessing truck safety is conducted in the following. Firstly, random variables are selected and defined to capture the associated uncertainties. Secondly, the comparison of the dynamic deterministic model and the rigid-body model is made. Finally, the safety index β of a typical truck under different driving conditions will be studied parametrically.

5.3.1 Basic random variables

Depending on the degree of uncertainty and the relative significance to the accident risk prediction results, all the parameters in the analytical model as introduced in Section 2 can be treated as either random variables or deterministic parameters. Based on the findings from the parametric studies of the deterministic model (Chen and Chen 2010) as well as other existing studies (Snaebjornsson et al. 2007), the random variables selected in this study include wind velocity, wind direction, vehicle speed, frictional coefficients, steering angle, vehicle sprung mass and the height of the center of the sprung mass. Similar to the existing studies on describing the uncertainties of variables (Snaebjornsson et al. 2007), most basic random variables are assumed to have a normal distribution, except that the friction coefficient has the truncated normal distribution. The full list of random variables as well as their distributions is given in Table 5.1. The values for other deterministic parameters of vehicles and environments will be introduced throughout the example and the details can be found in Ref. (Chen and Chen 2010).

Table 5.1 Statistics of the random variables for the simulation

Variable	**Notation**	**Distribution**	**Standard deviation (σ)**	**Source**
Road friction coefficient	$\mu_{friction}$	Truncated normal	0.05	Snaebjornsson et al. (2007)
Vehicle driving velocity (km/h)	V	Normal	0.15 μ_V	Snaebjornsson et al. (2007)
Steer angle ($^\circ$)	δ	Normal	0.2 μ_δ	Assumed
Wind speed (m/s)	U	Normal	2	Snaebjornsson et al. (2007)
Wind direction ($^\circ$)	φ	Normal	7.5	Snaebjornsson et al. (2007)
Vehicle sprung mass (kg)	m_s	Normal	0.1 μ_{m_s}	Assumed
Height of center of sprung mass (m)	h	Normal	0.1 μ_h	Assumed
Bridge accelerations in lateral direction (g)	a_y	Normal	0.2 μ_{a_y}	Assumed
Bridge accelerations in rolling direction (rad/s^2)	a_{roll}	Normal	0.2 $\mu_{a_{roll}}$	Assumed

Note: μ() is the mean value of the random variable.

5.3.2 Model comparison

As discussed earlier, the rigid-body vehicle model has been used in some existing studies (e.g. Baker 1991, 1994; Snaebjornsson et al. 2007). The rigid-body vehicle model is greatly simplified as compared to the dynamic model. As discussed earlier, it can also significantly simplify the related reliability-based analysis, as only explicit limit state functions will be used. A comparison between the deterministic results with both the simplified rigid-body and the dynamic vehicle models is conducted by identifying the critical wind speed under each vehicle driving speed on a straight route (Fig. 5.1). It is found in Fig. 5.1 that considerable difference (about 10% to 25%) exists between the critical wind speed results of using the simplified rigid-body model and those of using the dynamic model. Furthermore, the traditional rigid-body model will give non-conservative results as compared to the coupled dynamic model, with the identified critical wind speed about 3-5 m/s higher. Although a comprehensive comparison has not been made, the results suggest that the rigid-body approximation may cause considerable underestimation of vehicle safety risks in some circumstances. Thus the adoption of the more realistic dynamic vehicle model is deemed necessary when complicated adverse driving conditions are considered

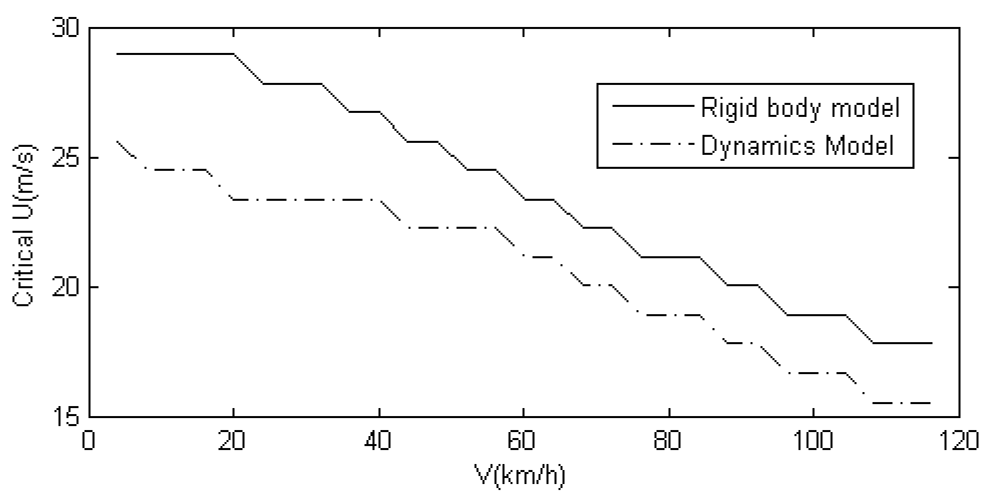


Fig. 5.1 Results comparison of different models on a straight and dry road

5.3.3 Parametric study results

Risk index has been widely used to define safety risk in many fields. In the present study, the safety index β is the most important parameter which describes the safety reserve and obviously, lower safety index suggests higher accident risk. Figs. 5.2 –5.10 give the parametric study results of safety index under various adverse driving conditions. Two general scenarios such as on straight roads and on curves will be considered in the following. The same truck model used in Chen and Chen (2010) will be used here to represent typical trucks on US highways. In order to exclude unnecessary contributions from other variables, each figure shows a three-dimensional relationship between the safety index and two random variables with varying mean values while all other random variables remain the constant mean values. Except for otherwise defined, the default mean values (μ) of random variables $\mu_{friction}$, φ, m_S and h are 1, 90^o, 10433 kg and 1.39 m, respectively.

5.3.3.1 On straight road

With dry road surface conditions as shown in Figs. 5.2-5.4, rollover accidents will occur earlier than sideslip accidents. Fig. 5.2 shows the safety indices under different combinations of the mean values of vehicle driving speed (μ_V) and wind velocity (μ_U). It can be found that the safety index usually decreases with the increase of the mean values of wind velocity or driving speed. But comparatively, the influence of wind velocity on safety index is generally more significant than the driving speed. For any mean value of wind velocity μ_U higher than 25 m/s, the safety indices remain similar despite the change of the mean value of driving speed μ_V. The safety index is around 0 when the μ_U equals to 25m/s and μ_V is about 80 km/h. The corresponding rollover accident probability is about 50% according to Eq. (5.6). When the μ_U is more than 30m/s, the reliability index is typically below -3, which indicates that the rollover accident probability is more than 99.87%. On one hand, the result confirms the fact that high-sided trucks usually experience high rollover accident risk (i.e. lower safety index) under strong crosswind, and its driving speed has little impact on the accident risk under such an extreme situation. As a result, traffic closure to these vulnerable vehicles is probably the only justified way to protect the trucks and drivers. The introduced reliability-based model can help on decision-making by the transportation officials or emergency managers based on the desired safety index (or acceptable accident probability).

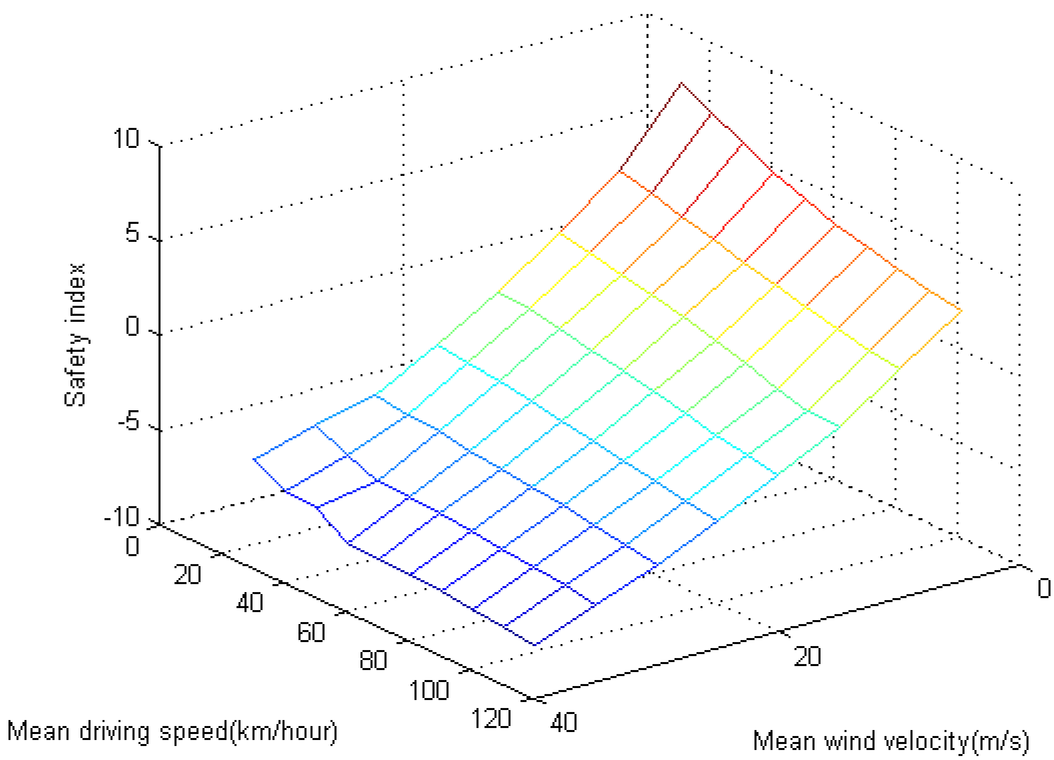


Fig. 5.2 Safety index as a function of the mean values of driving speed and wind velocity (straight route)

In contrast, under relatively low mean value of wind speeds (e.g. μ_U =5-10 m/s), it can be found that the driving speed has much larger impacts on the values of safety index. Since low and moderate crosswind is very common in most areas around the world, a rational selection of driving speed limits for high-sided trucks to maintain an acceptable accident risk level by considering the impacts of environments is very important. Therefore, the reliability-based model as developed can be helpful on deciding these advisory speed limits by considering the specific environments of the particular highway.

Fig. 5.3 exhibits the relationship between wind velocity, wind direction and the safety index. It is found that the safety index becomes the lowest (i.e. highest accident probability) when the mean value of wind direction (μ_φ) is between 60° and 90°. With the increase of the mean value of wind velocity μ_U, the impacts of wind directions on the safety index gradually become more notable. Although the safety index generally decreases with the increase of the wind speed, Fig. 5.3 actually shows a fairly complicated relationship between the mean values of wind velocity and wind direction and the safety index. This is primarily because the wind coefficients identified under different wind speeds and directions do not vary in a linear way (Baker 1987). Therefore, in order to give an accurate assessment of safety risk for a vehicle on a specific highway, a systematic analysis with the reliability-based model on a case by case basis is necessary.

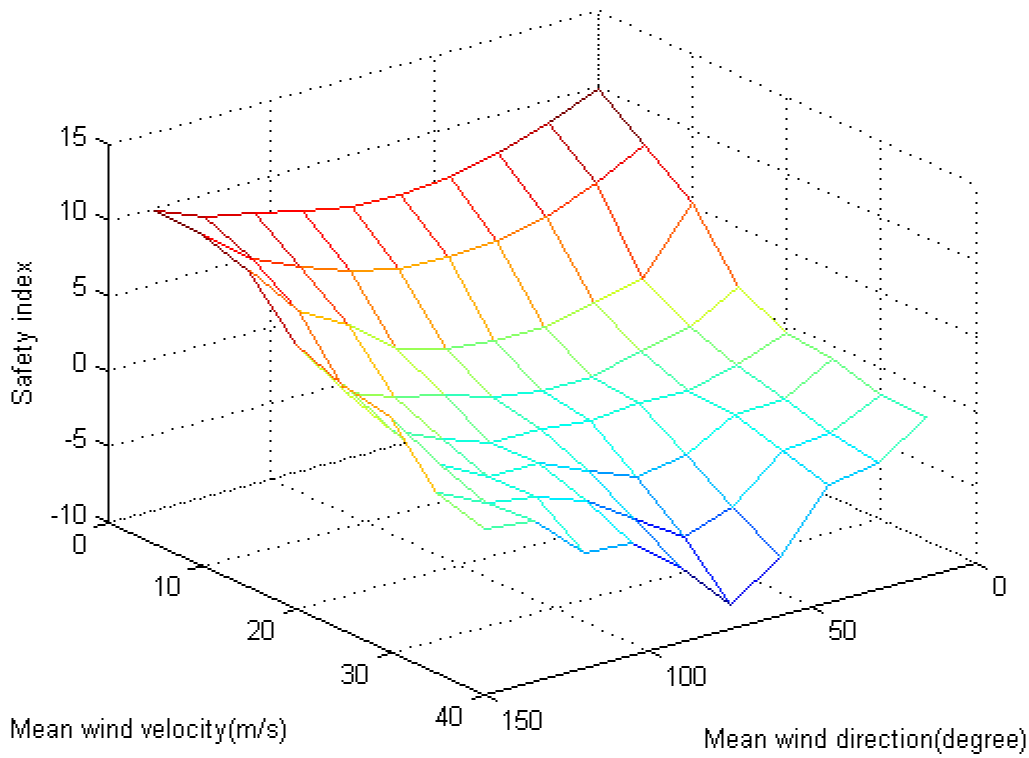


Fig. 5.3 Safety index as a function of the mean values of wind velocity and wind direction (straight route and mean driving speed $\mu_V = 90\text{km/h}$)

Fig. 5.4 demonstrates the influence of vehicle sprung mass and wind velocity on driving safety. With 10m/s mean wind velocity (μ_U), the safety index decreases considerably when the vehicle becomes partially-loaded (with the mean value of vehicle sprung mass equals to 10,433 sprung mass) from fully-loaded (with the mean value of vehicle sprung mass equals to 20,866kg sprung mass) situation. This result confirms the observation on highways that an empty truck is typically more prone to single-vehicle accidents (e.g. rollover) than the fully-loaded same truck under strong wind (USDOT 2000).

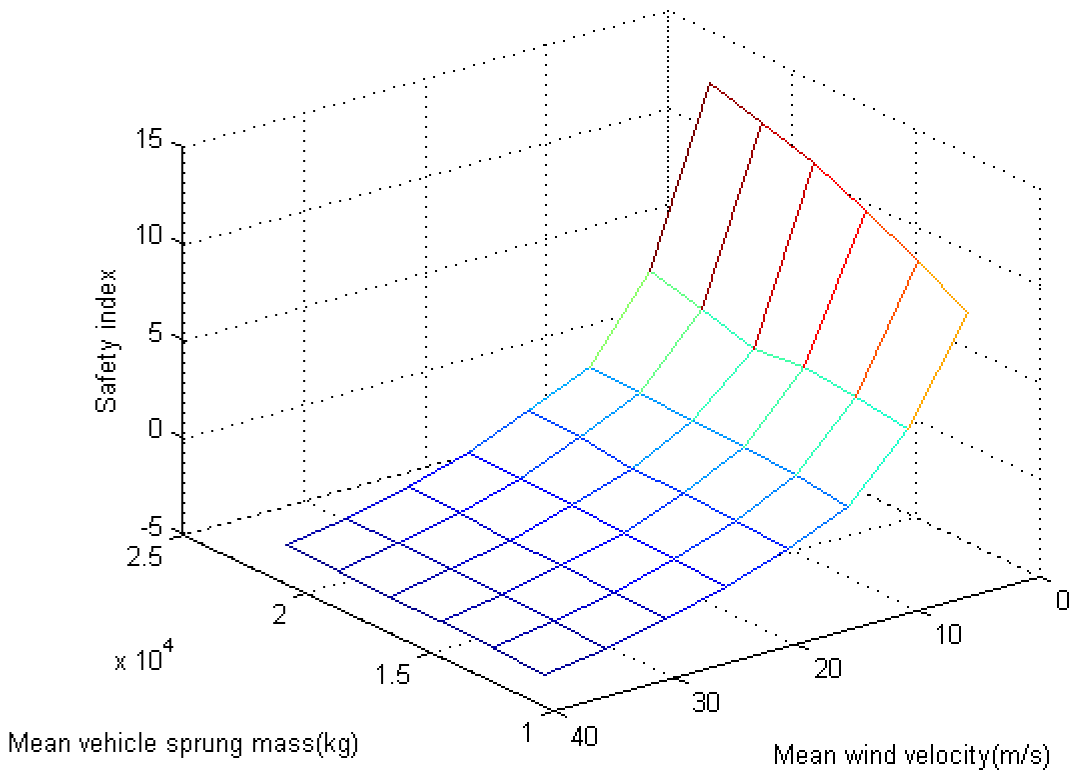


Fig. 5.4 Safety index as a function of the mean values of vehicle sprung mass and wind velocity (straight route and mean driving speed $\mu_V = 90\text{km/h}$)

Safety index also varies with different driving speeds and road friction coefficients (i.e. different road surface conditions). As shown in Fig. 5.5, considerable influence of various road surface conditions on driving safety can be observed when the mean value of friction coefficient of the road surface is below 0.4. With other random variables keeping their respective default mean values, sideslip accident will firstly occur in this situation**.** It can be found that under moderate wind condition (μ_U =15 m/s), the safety index drops dramatically when the mean value of road friction coefficient decreases. It can be found when the mean values of road friction coefficient are higher than 0.2, higher driving speeds have considerable lower safety index than lower driving speeds. When the road is very slippery (the mean value of road friction coefficient is lower than 0.2), sideslip accident is very prone to occur even at a low driving speed.

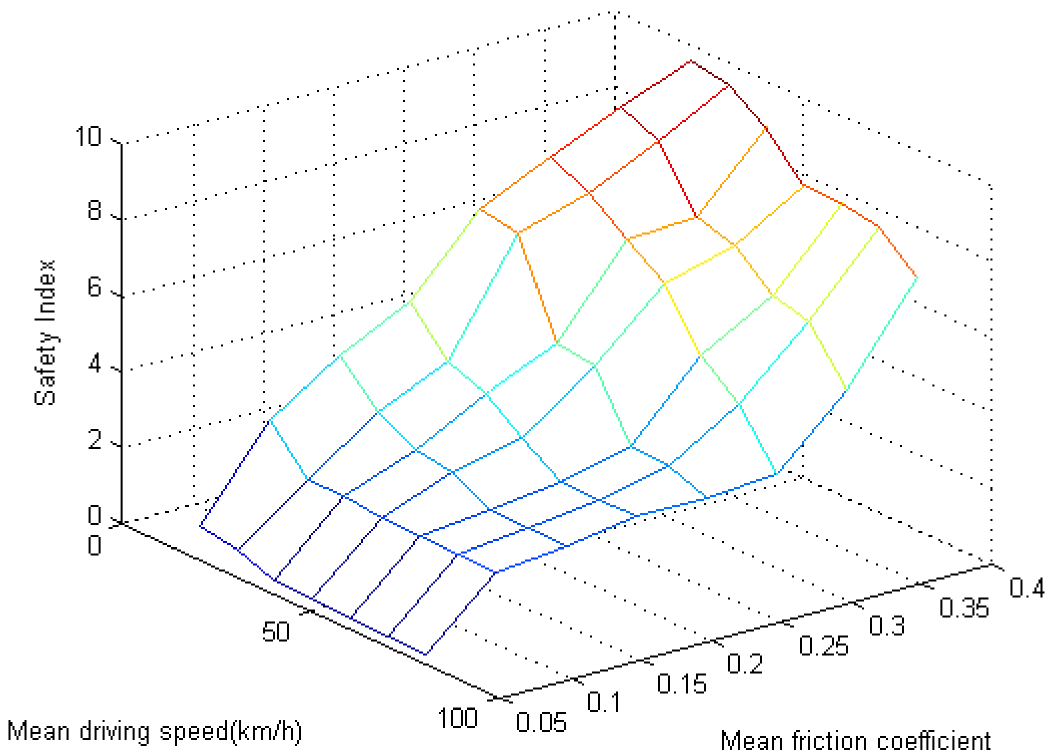


Fig. 5.5 Safety index as a function of the mean values of driving speed and friction coefficient (straight route and mean wind speed μ_U = 15m/s)

5.3.3.2 On curved road

The relationship between mean wind velocity, curving radius and the safety index has been studied and the results are displayed in Fig. 5.6. The vehicle model used in this chapter is assumed to be driven in neutral steer. Accordingly the steering angle δ can be expressed as $\delta = L/R$, where L is the wheelbase of the vehicle, R is the curving radius of the curved path. For the convenience of presentation, more straightforward variable R is chosen as the variable instead of δ in Figs. 5.6-5.9. Here, the truck is driven on a dry road and rollover accidents will usually happen earlier than sideslip accidents.

When wind is strong (μ_U = 30m/s or above), the influence of different curving radii on the accident risk is found to be trivial (Fig. 5.6). When μ_U is lower than 20m/s, the safety index drops dramatically with the decrease of the mean value of curving radius. It is found that the impact of wind velocity on accident risks dominates when wind is strong. When wind is moderate or weak, the influence of curving radii on accident risks gradually becomes dominant. Therefore, in addition to traditionally investigating the accident risks of large trucks on roads with sharp curves under normal weather, truck safety under relatively strong wind on mild curves could be critical as well.

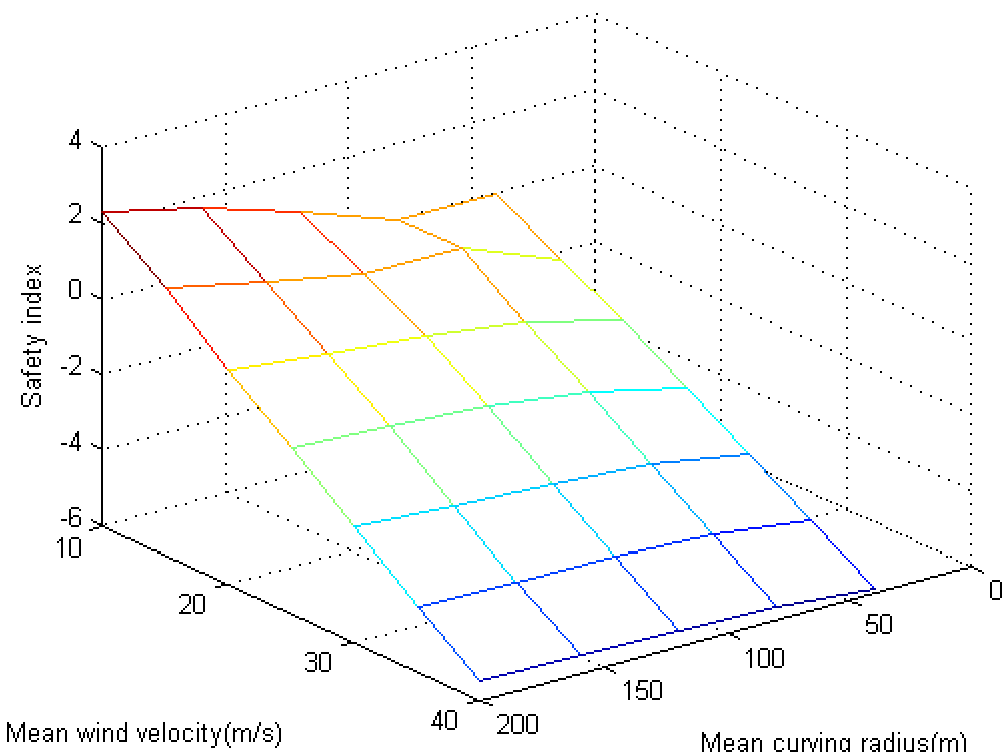


Fig. 5.6 Safety index as a function of the mean value of wind velocity and curving radius (mean driving speed $\mu_V = 90\text{km/h}$)

Fig. 5.7 illustrates the safety index results under different combinations of driving speeds and curving radii. Compared to Fig. 5.6, the influence of driving speed on accident index is less significant than that of wind velocity. It is also found that the impact of curving radius on safety index is more substantial for a higher driving speed (e.g. μ_V over 70 km/h).

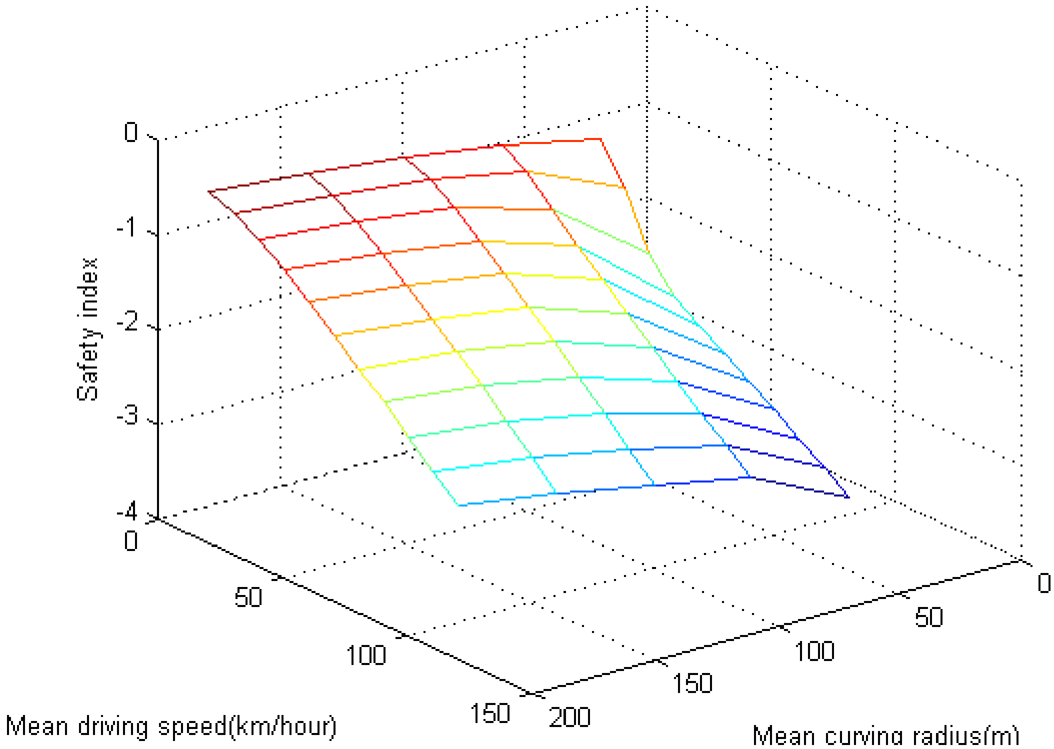


Fig. 5.7 Safety index as a function of the mean values of driving speed and curving radius (mean wind speed $\mu_U = 25\text{m/s}$)

Figs. 5.8-5.9 give the results when the road surface is covered by snow and ice, respectively. Under these particular driving conditions, sideslip accidents are found to occur more likely than rollover accidents. The results of safety index under different mean values of driving speed and curving radii when the road is covered by snow are displayed in Fig. 5.8. For snowy road surface, the friction coefficient is assumed to be a typical value of 0.35.

Generally, accident risk increases when driving speed increases or curve gets sharper (i.e. smaller curving radius) (Fig. 5.8). It is found that the curving radius plays a dominant role when the radius is 100m or less (i.e. sharp curves). When the curving radius is around 50 m (a typical value of highway ramp) and the vehicle velocity is as low as 40km/h, the safety index will be around 0, which is equivalent to the accident probability around 50%. It suggests that an appropriate selection of the curving radius for sharp curves (e.g. ramps of interstate) in the design stage is substantial to large truck safety in areas where snow is common. Comparatively, speed limits are not as critical as the radius itself for sharp curves. So for existing highways with sharp curves, to clean the snow in these locations using all possible measures as soon as possible is very critical to safety of vulnerable trucks. With the increase of the curving radius (i.e. less sharp curves), the driving speed becomes more critical (Fig. 5.8). Therefore, for a typical highway with moderate curves, appropriate advisory driving speeds or driving speed limits for trucks and other high-sided vehicles should be carefully evaluated for snow season.

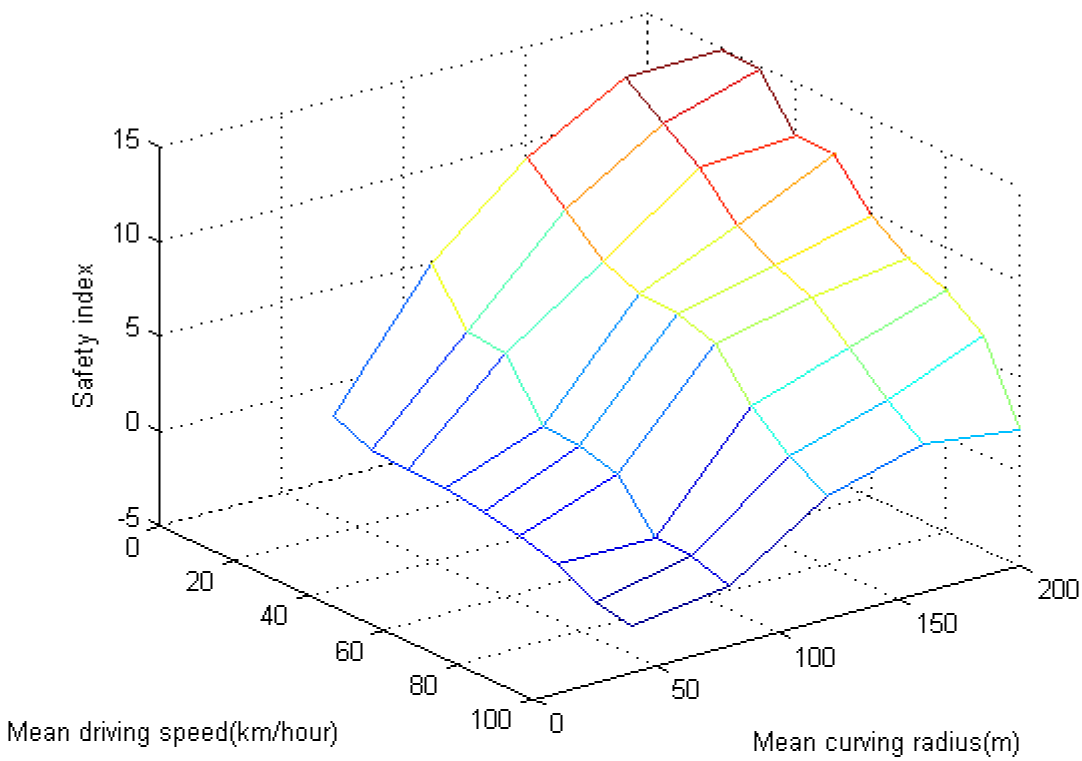


Fig. 5.8 Safety index as a function of the mean values of driving speed and curving radius on snowy roads (mean wind speed $\mu_U = 10$m/s)

Fig. 5.9 presents the results of safety index as a function of driving speed and curving radius on icy roads when the mean road friction coefficient equals to 0.1. Clearly, the safety index is much lower than that of snowy condition. For most situations, the safety index is below 0, which indicates the accident probability is more than 50% for those scenarios. In cold regions, the proposed model can be used to evaluate the potential safety risk of large trucks during winter. Based on the evaluation results, appropriate differential speed limits or variable speed limits may be decided.

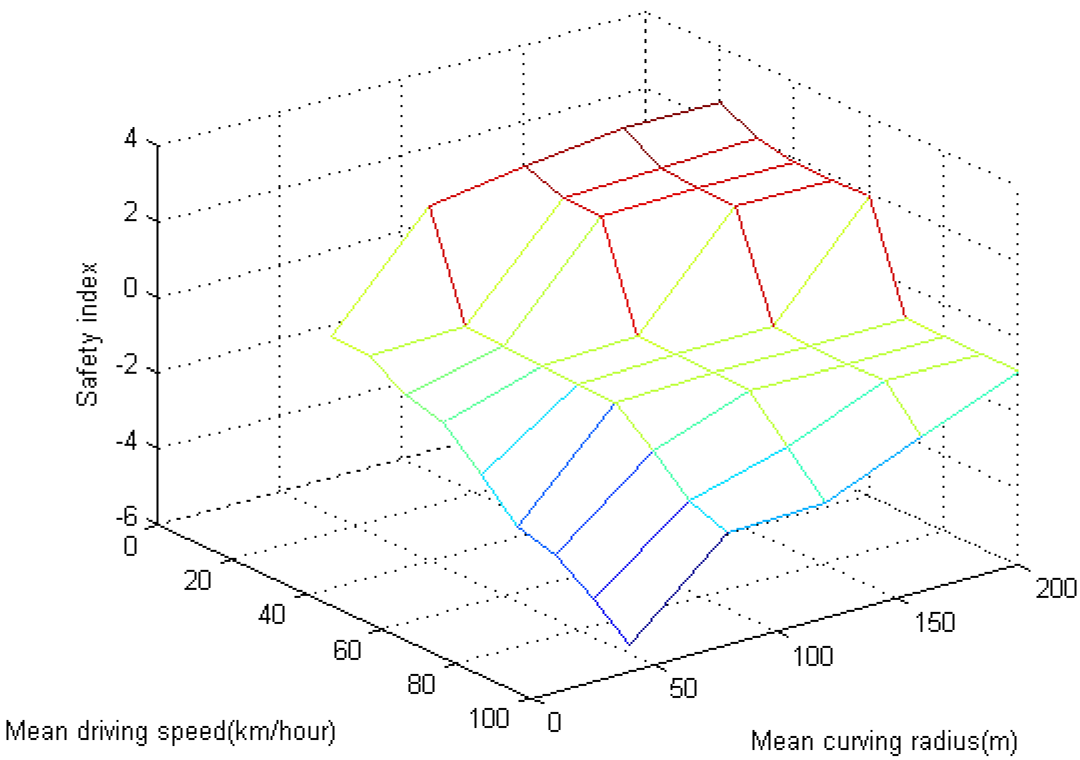


Fig. 5.9 Safety index as a function of the mean values of driving speed and curving radius on icy roads (mean wind speed $\mu_U = 10$m/s)

5.3.3.3 With excitations from supporting infrastructures

When a vehicle moves on roadways, vehicles will be excited to vibrate in several directions by the surface roughness on the roadway and these excitations are usually not significant (Guo and Xu, 2007; Chen and Cai, 2004) When a vehicle moves on a bridge, dynamic interactions between the bridge and the vehicle will result in more significant vibrations on the vehicle than those when the vehicle moves on roadways (Chen et al., 2009). In the present vehicle accident assessment model, safety behavior of the truck will be evaluated through a general consideration of excitations from supporting infrastructures by defining accelerations in the lateral direction a_y and that in rolling direction a_{roll} as base excitations. The relationship between safety index and the different mean values of a_y as well as a_{roll} (μ_U =20m/s, μ_V =80km/h) is shown in Fig. 5.10. It is found that the rolling excitation caused by interaction with supporting structures is relatively more critical to the truck safety than the lateral excitation. The existence of rolling excitations will considerably increase the rollover accident probability when all other conditions remain the same. Since substantial rolling excitations may exist on some bridges, the result suggests that the truck is more vulnerable to rollover accidents on a vibrating bridge than on roadways. The similar phenomenon has been observed in some other studies as well (Guo and Xu, 2007; Chen and Cai, 2004).

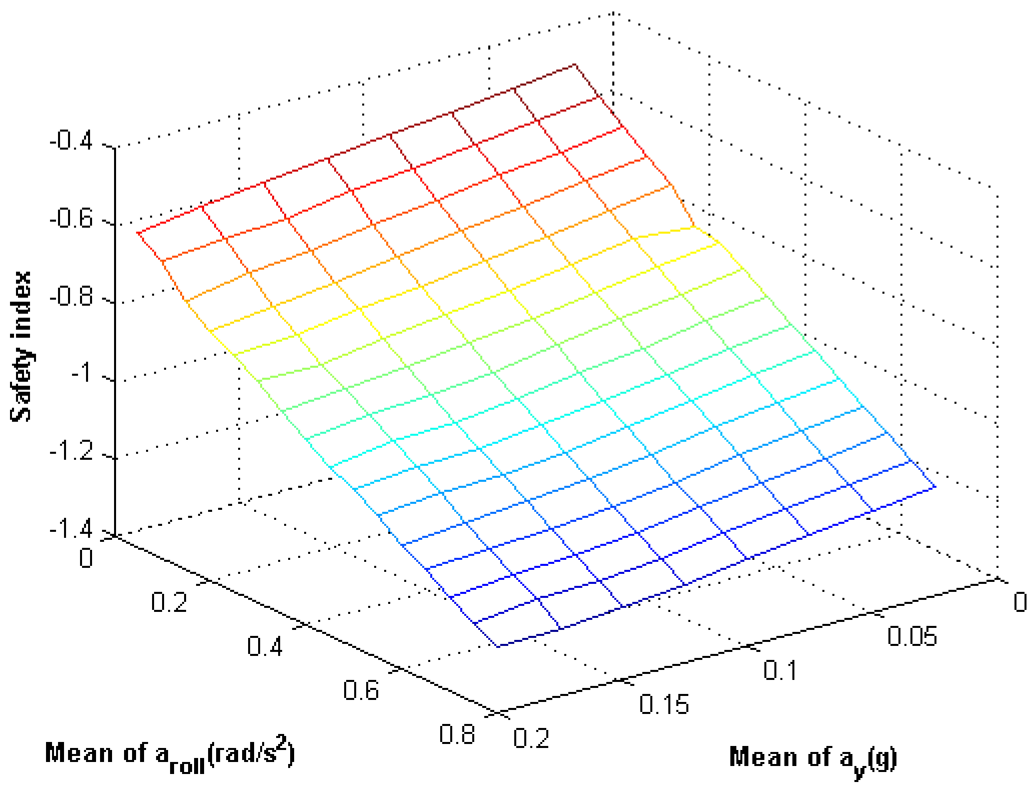


Fig. 5.10 Safety index as a function of the mean values of accelerations from supporting structures (mean driving speed $\mu_v = 80\mathrm{km/h}$, mean wind speed $\mu_U = 20\mathrm{m/s}$)

5.4 Conclusions

A general reliability-based single-vehicle accident risk prediction model of trucks was developed based on the improved deterministic dynamic vehicle model. It was found that the proposed model provides a tool to assess accident risk of a particular vehicle considering realistic driving conditions in nature such as specific topographic, wind and road surface conditions as well as associated uncertainties. Safety index was introduced to quantify the safety margins and associated accident probability based on the reliability theory.

After the analytical model is introduced, parametric studies of safety index and various variables defining adverse driving conditions were conducted. Both straight and curved roads were studied under different road surface conditions, driving speeds and wind conditions. The differences between the results from the dynamic model and the rigid-body model were also discussed. Some major observations from the parametric study are summarized as follows:

(1) Considerable non-conservative error may occur for analysis with the rigid-body vehicle model as compared to the dynamic vehicle model;

(2) Under strong wind, high-sided trucks are exposed to high rollover accident risk and the driving speed has little impact under such an extreme situation. But under moderate and low wind speeds, an appropriate driving speed can be critical to maintain acceptable accident risk.

(3) The developed reliability-based model can help deciding whether the traffic should be closed to a particular type of trucks under extreme events. It can also help on providing advisory speed limits under normal conditions based on the desired safety index (or acceptable accident risk);

(4) The simulation and risk study confirmed several field observations, such as higher vulnerability of an empty or partially-loaded truck as compared to the situation when it is fully-

loaded and high accident risk on slippery roads even with low driving speeds;

(5) In addition to the high accident risks of large trucks on roads with sharp curves under normal weather, truck safety under relatively strong wind on mild curves could be critical as well. With a higher driving speed, the impact of curving radius on safety is more substantial;

(6) An appropriate selection of the curving radius for sharp curves (e.g. ramps of interstate) in the design stage is critical to large truck safety in areas where road surface is often covered by snow in winter. For those existing sharp curves, to clean snow as soon as possible using all measures is critical to protect vulnerable vehicles. With snowy road surface, speed limits are not as critical as the radius for sharp curves;

(7) For typical highways with moderate curves, the driving speed becomes more critical and appropriate advisory driving speeds for vulnerable trucks should be rationally decided;

(8) The existence of rolling excitations from supporting structures (e.g. bridges) will considerably increase the rollover accident probability of trucks.

5.5 References

AASHTO. (2004). A Policy on Geometric Design of Highways and Streets. Washington, D.C.

Baker, C. J. (1986). "Simplified analysis of various types of wind-induced road vehicle accidents." Journal of Wind Engineering and Industrial Aerodynamics, 22(1), 69-85.

Baker, C. J. (1987). "Measures to control vehicle movement at exposed sites during windy periods." Journal of Wind Engineering and Industrial Aerodynamics, 25(2), 151-161.

Baker, C. J. (1991). "Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system." Journal of Fluids and Structures, 5, 221-241.

Baker, C. J. (1994). "Quantification of accident risk for road vehicles in cross winds." Journal of Wind Engineering and Industrial Aerodynamics, 52(1-3), 93-107.

Bucher, C.G. and Bourgund, U. (1990). "A fast and efficient response surface approach for structural reliability problems." Struct. Safety 7 (1), 57–66.

Cai, C. S., Chen, S. R. (2004). "Framework of vehicle-bridge-wind dynamic analysis," Journal of Wind Engineering and Industrial Aerodynamics, 92 (7-8), 579-607.

Chen, S. R. and Cai, C. S. (2004). “Accident assessment of vehicles on long-span bridges in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 92(12), 991-1024.

Chen, S. R., Cai, C. S. and Wolshon, B. (2009). “From normal operation to evacuation: single-vehicle safety under adverse weather, topographic and operational conditions”, Natural Hazards Review, ASCE, 10 (2), 68-76.

Chen, S. R. and Chen, F. (2010). “Simulation-Based Assessment of Vehicle Safety Behavior under Hazardous Driving Conditions”, J. of Transportation Engineering, ASCE, 136 (4), 304-315.

Chen, S. R., Chen, F., Liu, J. Wu, J. and Bienkiewicz, B. (2010). “Mobile mapping technology of wind velocity data along highway for traffic safety evaluation”, Transportation Research Part C: Emerging Technology, 19, 507-518.

Coleman, S. A., and Baker, C. J. (1994). “Experimental study of the aerodynamic behavior of high sided lorries in cross winds.” Journal of Wind Engineering and Industrial Aerodynamics, 53(3), 401-429.

Faravelli, L. (1989). “Response surface approach for reliability analysis.” J. Eng. Mech. 115 (12), 2763–2781.

Gaspar, P., Szaszi, I., and Bokor, J. (2004). “The design of a combined control structure to prevent the rollover of heavy vehicles.” European Journal of Control, 10(2), 148-162.

Gaspar, P., Szaszi, I., and Bokor, J. (2005). “Reconfigurable control structure to prevent the rollover of heavy vehicles.” Control Engineering Practice, 13(6), 699-711.

Guo, W. H. and Xu, Y. L. (2006). “Safety analysis of moving road vehicles on a long bridge under crosswind”, Journal of Engineering Mechanics, 132 (4), 438-446.

Haldar, A. and Mahadevan, S. (2000). Reliability assessment using stochastic finite element analysis, Wiley, New York.

Liu, Y.W. and Moses, F. (1994). “A sequential response surface method and its application in the reliability analysis of aircraft structural systems.” Struct. Safety 16, 39–46.

Rajashekhar, M.R. and Ellingwood, B.R. (1993). “A new look at the response surface approach for reliability analysis.” Struct. Safety 12 (3), 205–220.

Sampson, D. J. M. (2000). “Active roll control of articulated heavy vehicles.” PhD Thesis, University of Cambridge.

Sigbjornsson, R., and Snaebjornsson, J. T. (1998). “Probabilistic assessment of wind related accidents of road vehicles: A reliability approach.” Journal of Wind Engineering and Industrial Aerodynamics, 74-76, 1079-1090.

Snaebjornsson, J. T., Baker, C. J., and Sigbjornsson, R. (2007). “Probabilistic assessment of road vehicle safety in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 95, 1445-1462.

The National Academies. (2006). “Where the weather meets the road- a research agenda for improving road weather system.” Report in Brief, The National Academies.

The Road Information Program (2005). “Growing Traffic in Rural America: Safety, Mobility and Economic Challenges in America’s Heartland”, http://www.tripnet.org/RuralRoads2005Report.pdf, last accessed May 17, 2008.

Thomas D. G. (1992). Fundamentals of vehicle dynamics, SAE, Warrendale, PA, USA.

Transportation Research Board (TRB) (2007). “The domain of truck and bus safety research”, Transportation Research Circular, Number E-C117, May 2007.

USDOT (2000). “Comprehensive Truck Size and Weight (CTS&W) Study”, FHWA-PL-00-029 (Volume I), August 2000.

USDOT (2005). “Report to Congress on the Large Truck Crash Causation Study”, Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Winkler C. B., and Ervin R. D. (1999). Rollover of heavy commercial vehicles. SAE, Warrendale, PA, USA.

Xu, Y. L. and Guo, W. H. (2003). “Dynamic analysis of coupled road vehicle and cable-stayed bridge system under turbulent wind.” Engineering Structures, 25, 473-486.

Yao, T.H.J. and Wen, Y.-K. (1996). “Response surface method for time-variant reliability analysis.” J. Struct. Eng. 122 (2), 193–201.

CHAPTER 6: A CASE STUDY OF TRAFFIC SAFETY OF LARGE TRUCK ON I-70

6.1 Introduction

Extensive works have been conducted on the traffic safety and injury prevention related to multi-vehicle accidents of large trucks in past decades (e.g. Braver et al. 1997; Chang and Mannering 1999; Lyman and Braver 2003). Different from most passenger vehicles which are dominantly vulnerable to multi-vehicle traffic conflicts, large trucks are also prone to single-vehicle accidents on the mountainous interstate highways due to the complex terrain and fast-changing weather (USDOT 2005; Baker 1991). Although the absolute number of single-vehicle accidents is typically smaller than that of multi-vehicle accidents, single-vehicle accidents have caused serious injury and casualty (The National Academies 2006). For example, single-vehicle accidents were responsible for 57.8% of the total fatalities of traffic accidents in 2005 (USDOT 2005). This is especially true when complex terrain couples with inclement weather conditions, such as snow, ice or strong wind. Each year in the United States, adverse weather alone is associated with more than 1.5 million vehicular accidents, which result in 800,000 injuries and 7,000 fatalities (The National Academies 2006).

The primary causes of accidents involving large trucks on rural highways were found to be excessive speed and adverse driving conditions (The Road Information Program 2005). Different from passenger vehicles, it is known that the safety performance of large trucks in adverse driving conditions greatly depends on the specific terrain and local weather condition

(USDOT 2005; Baker 1991). Therefore, it is necessary to comprehensively evaluate the safety performance of large trucks on a mountainous highway by looking into not only the safety of individual trucks.

In the present chapter, an attempt is made to evaluate the safety performance of large trucks on mountainous highways. The I-70 corridor in Colorado is chosen to demonstrate the methodology because of its typical mountainous terrain and adverse weather conditions. Firstly, ten-year historical accident records will be analyzed to identify the accident-vulnerable-locations (AVLs) and critical adverse driving conditions specific to I-70. Secondly, simulation-based single-vehicle assessment will be performed for different inclement weather conditions at these AVLs along the whole corridor. The advisory critical vehicle speeds (CVS) will be compared to the corresponding speed limits along the highway to give some insights about single-vehicle safety performance of large trucks.

6.2 Simulation-based Analytical Models

Extensive works have been carried out on both multi- (USDOT 2005; AASHTO 2004) and single-vehicle accidents (Young and Liesman 2007a, b; Summerfield and Kosior 2001; Edwards 1998) with a focus on data analyses of historical accidents. In addition to analyses based on historical data, there were also studies using various simulation models on multi-vehicle traffic conflicts (Moussa 2005; Zhang et al. 2006) as well as single-vehicle accidents (Baker 1991; Chen and Cai 2004; Guo and Xu 2006). Compared to data-based accident analyses, simulation-based analyses of multi-vehicle or single-vehicle accidents have the advantage of exploring more comprehensive collections of possible scenarios, which may not be covered by the historical accident data (Baker 1991; Snaebjornsson et al. 2007; Chen et al. 2009). In this section, the simulation-based evaluation models of single-vehicle safety which will be used in the present chapter are already introduced in Chapter 3 and 5.

6.3 Historical Accident Data Analysis of I-70 in Colorado

6.3.1 I-70 Interstate corridor

The Interstate I-70 Mountain Corridor within the State of Colorado, from Denver to Grand Junction is a typical mountainous highway in rural areas as it is a gateway to recreation, commerce and everyday necessities for Colorado residents and visitors. At some locations along the corridor, very steep grades which are coupled with extreme weather conditions have been blamed for many accidents involving large trucks. Differential speed limits have been adopted at several locations where the terrains are complicated on the I-70 mountain corridor. Ten-year (1996-2005) historical accident data of I-70 in Colorado from Vail to Golden (Mile Post 179.90 to 258.60) were studied. The percentage of trucks in traffic is 5.7%-13% on this corridor in Year 2005. Average daily traffic (ADT) on I-70 in Colorado is 32,962. During the ten-year period, there were totally 1,565 accidents reported, out of which 762 and 639 accidents involved large trucks/bus as the first vehicle (vehicle 1) and the second vehicle (vehicle 2), respectively.

6.3.2 Data analysis and accident vulnerable locations (AVL)

Based on the comprehensive analysis of the historical accident data on I-70 corridor between 1996 and 2005, some accident vulnerable locations (AVL) experiencing a considerable number of past accidents are summarized in Table 6.1. AVLs are selected based on the number of accidents occurring on each segment (typically 0.1 mile long), which is identified with the beginning and ending mileposts (MP) (e.g. MP 184.4-185.4). Due to the limit of the space, Table 6.1 only gives detailed information for several selected AVL, including the mileposts (MP), the numbers of accidents associated with different vehicle types, accident types, geometric conditions, speed limits and adverse weather conditions. Most differential speed limits on I-70 are applied in the westbound direction, as shown in column 4 in Table 6.1. “No. of truck-initiated accidents (% of all accidents)” (column 5) is the number (and percentage) of accidents with large trucks (more than 10k lbs) as the first vehicle (vehicle 1). Column 6 shows the number of accidents occurring at different adverse road surface conditions (e.g. wet, icy or snowy). Column 7 gives the number of the accidents by accident type: single-vehicle accidents, including overturn and sideswipe accidents, and typical multi-vehicle accidents (rear-end accidents). By comparing the actual driving speeds reported in the accident record with the corresponding speed limits, the percentage of those trucks with the driving speeds at least 10 mph over the speed limits in the truck-initiated accidents was given in Column 8.

Some general observations from the accident data analysis of I-70 AVLs include: (1) trucks were more vulnerable to accidents than other vehicles (around 50%-70% of all accidents were initiated by trucks); (2) for multiple-vehicle accidents, rear-end collisions were dominant (over 80%); (3) adverse road surface conditions were found to have significant impacts on traffic safety (associated with up to 70% accidents); and (4) dominant accident types at different locations were sideswipe or overturn accidents (single-vehicle), rear-end accidents (multi-vehicle) or both. Based on these observations, the need and significance of the present study focusing on trucks and adverse driving conditions are well justified.

6.3.3 Accident analysis under adverse driving conditions

Historical accidents are firstly studied for different adverse driving conditions, such as windy, snowy, icy conditions of road surface and different terrains. Among all the adverse driving conditions, Figs. 6.1-6.3 give the statistics of historical accidents involving trucks under several most significant adverse driving conditions on I-70, including strong wind, snow-covered, ice-covered road surface and on grades, respectively. Different sizes of the dots on the maps represent different numbers of similar accidents happening at the same locations during the past ten years, as defined in the legend.

Table 6.1 Selected Accident Vulnerable Locations (AVLs) on I-70 (1996-2005)

(1) Milepost Range	(2) Terrain features	(3) Grade	(4) Speed limit (mph)	(5) No. of truck-initiated accidents (% of all accidents)	(6) No. of accidents under adverse road surface conditions	(7) Accident Types	(8) Percentage of trucks over speed limits by 10 mph or more
184.4-185.4	Curve R=1250 ft	6%	Truck 45 Others 65	24 (64.9%) EB3, WB21	Wet 2	Overturn 0	8.3%
					Icy 13	Sideswipe 11	
					Snowy 7	Rear-end 7	
204.8-205.14	Curve R=2130 ft	8%	Truck 30 Others 60	13 (56.5%) EB6, WB7	Wet 3	Overturn 0	38.5%
					Icy 4	Sideswipe 5	
					Snowy 2	Rear-end 4	
208.0-209.3	Straight	8%	Truck 30 Others 60	36 (69.2%) EB2, WB34	Wet 1	Overturn 8	86.1%
					Icy 2	Sideswipe 8	
					Snowy 5	Rear-end 12	
213.0-214.0	Straight	8%	Truck 30 Others 60	19 (48.7%) EB7,WB12	Wet 3	Overturn 0	0%
					Icy 3	Sideswipe 12	
					Snowy 12	Rear-end 10	
242.5-242.92	Curve R=690 ft	4%	All 55	18 (69.3%) EB12,WB6	Wet 3	Overturn 8	33.3%
					Icy 5	Sideswipe 5	
					Snowy 1	Rear-end 2	
243.4-244.7	Curve R=850 ft	4%	All 55	44 (70.3%) EB28,WB16	Wet 6	Overturn 15	22.2%
					Icy 5	Sideswipe 11	
					Snowy 1	Rear-end 7	
250.8-251.2	Curve R=1540 ft	3%	All 65	7 (58.3%) EB0,WB7	Wet 2	Overturn 1	0%
					Icy 3	Sideswipe 4	
					Snowy 2	Rear-end 2	

Note: EB=east bound vehicles; WB=west bound vehicles; R=curve radius

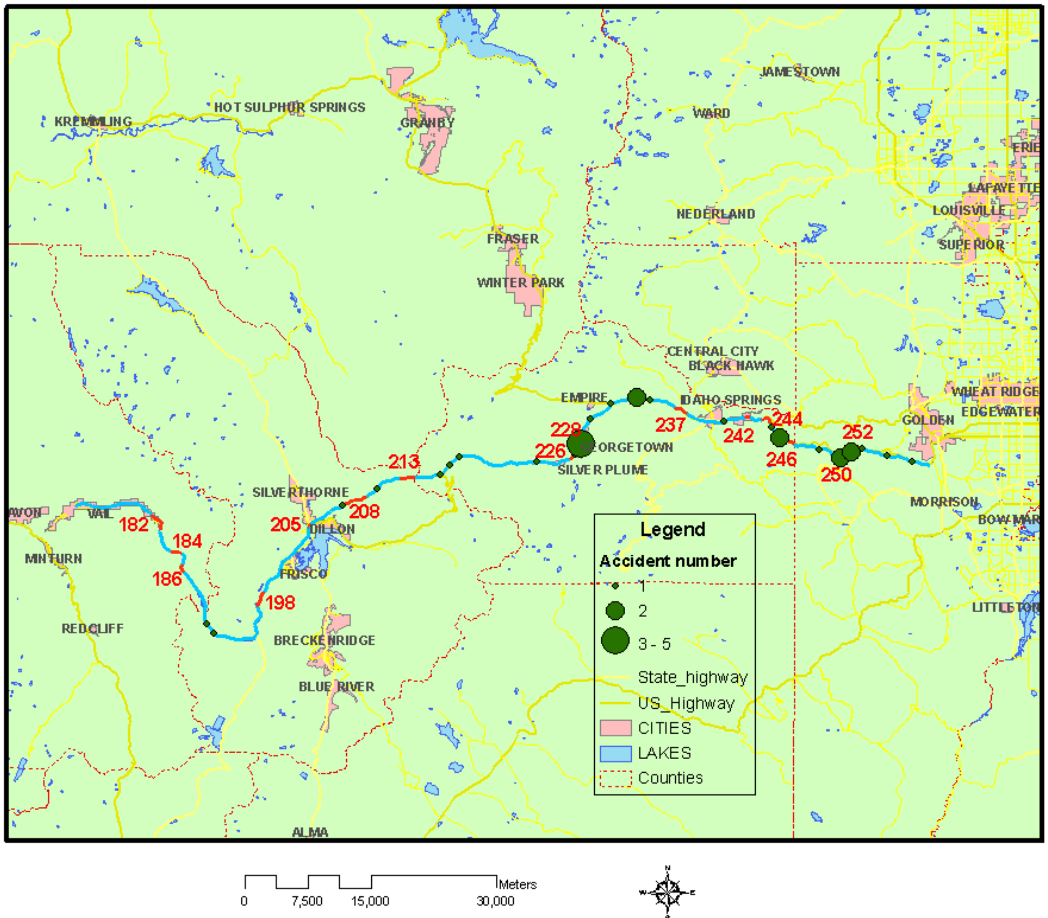


Fig. 6.1 Historical wind-induced accidents (1996-2005).

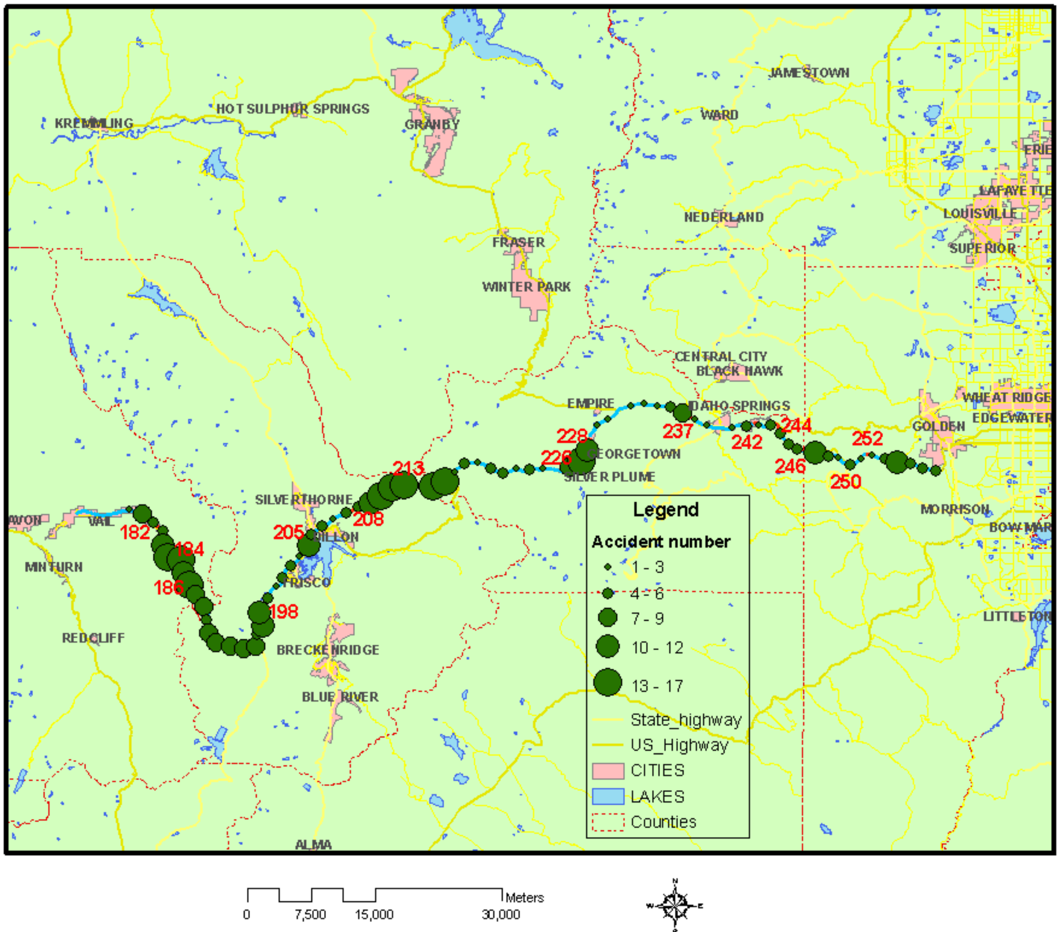


Fig. 6.2 Historical accidents on snow-covered road surface (1996-2005).

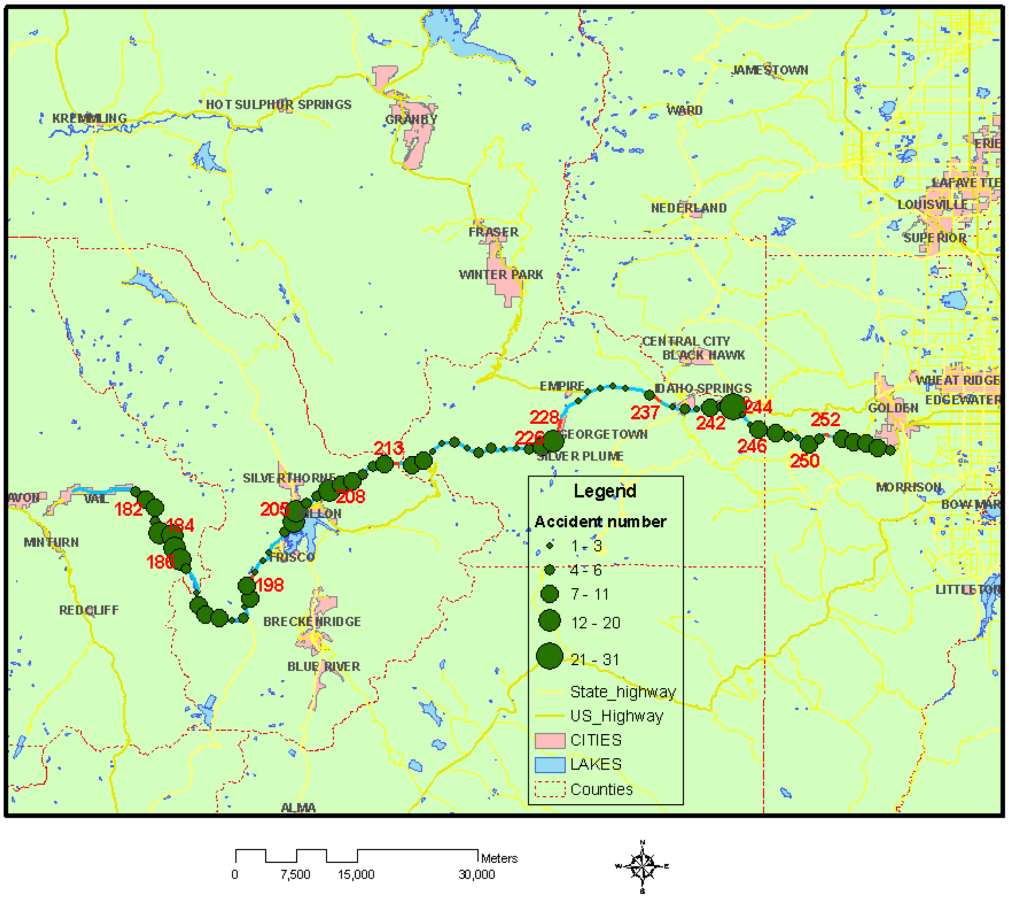


Fig. 6.3 Historical accidents on grade curves (1996-2005).

It is found in Fig. 6.1 that there are about 30 accidents identified as wind-induced ones in the accident records during the ten-year period. It is noted that the actual number may be higher since it is possible that some accidents were not identified as wind-induced ones on the accident report despite the fact that wind may also contribute to the accidents along with other reported factors. According to Fig. 6.1, except for some scattered locations along I-70, most of the wind-induced accidents happened in the east portion of the corridor. Repetitive accidents happened at several locations along I-70, such as MP 229, 244, and 250-252.

Fig. 6.2 shows the historical accidents happening on snow-covered roads. A large number of repetitive accidents happened frequently along the whole stretch between MP 182 and 228.

The accidents happening on curves with grades are also studied (Fig. 6.3). It can be found that the most vulnerable locations identified in Fig. 6.2 (snowy road) are similar to those shown in Fig. 6.3 (on grades). It is understandable since both scenarios cause challenges for the truck drivers to stop efficiently.

As shown in Fig. 6.3, MP 242-248 suffered from frequent accidents because of the well-known steep grades (6%) which are coupled with sharp curves. Based on the observations from Fig. 6.2 and Fig 6.3, it is obvious that both the road surface condition and the road geometric condition (e.g. grade and curves) have large impacts on the accident risk for trucks. The similarities between the observations in Figs. 6.2 and 6.3 suggest that such two critical conditions (i.e. road-surface and geometric) work interactively to pose threats on the safety of trucks under adverse driving environments. Given the fact that the complex terrain is common throughout the I-70 corridor in Colorado, the historical accidents on snow-covered road surface and grade curves were found to occur in nearly all the portions of the whole corridor with a comparatively higher number of accidents on the western part.

6.4 Single-vehicle Traffic Safety under Adverse Weather

The data analyses of the historical accidents in the last section identified several AVLs and the critical adverse driving conditions. In this section, with the single-vehicle accident simulation model introduced earlier, more comprehensive simulations of single-vehicle accidents under different adverse driving conditions are conducted along the whole I-70 corridor including those identified AVLs. As a result, different advisory critical vehicle speeds (CVS) are obtained under various weather and road surface conditions such as: (1) windy conditions (U=30 mph (13.4 m/s)); (2) snow storm (U=30 mph and snow-covered road); or (3) icy storm (U=30 mph and icy road). The results from the simulation will be compared with the observations from the data analysis of historical accidents.

In the following Figs. 6.4-6.6, the *x*-axis shows different milepost numbers along I-70. The *y*-axis is the dimensionless variable - the ratio between the critical vehicle speed (CVS) identified from the simulation and the corresponding posted speed limit at the same spot. The ratio of the “critical vehicle speed/speed limit” (called “speed ratio” for brevity purpose hereafter) as shown in Figs. 6.4-6.6 is not a variable intended to rigorously quantify the effectiveness or rationality of the posted speed limits for the adverse driving conditions. Rather, the speed ratio is only used to provide qualitative information about (1) the relationship between the CVS and the corresponding speed limit at the same location, and (2) the relative risk of single-vehicle accidents at different locations along the I-70. It is made possible by comparing the speed ratio and unit at one location, and the speed ratios at different locations.

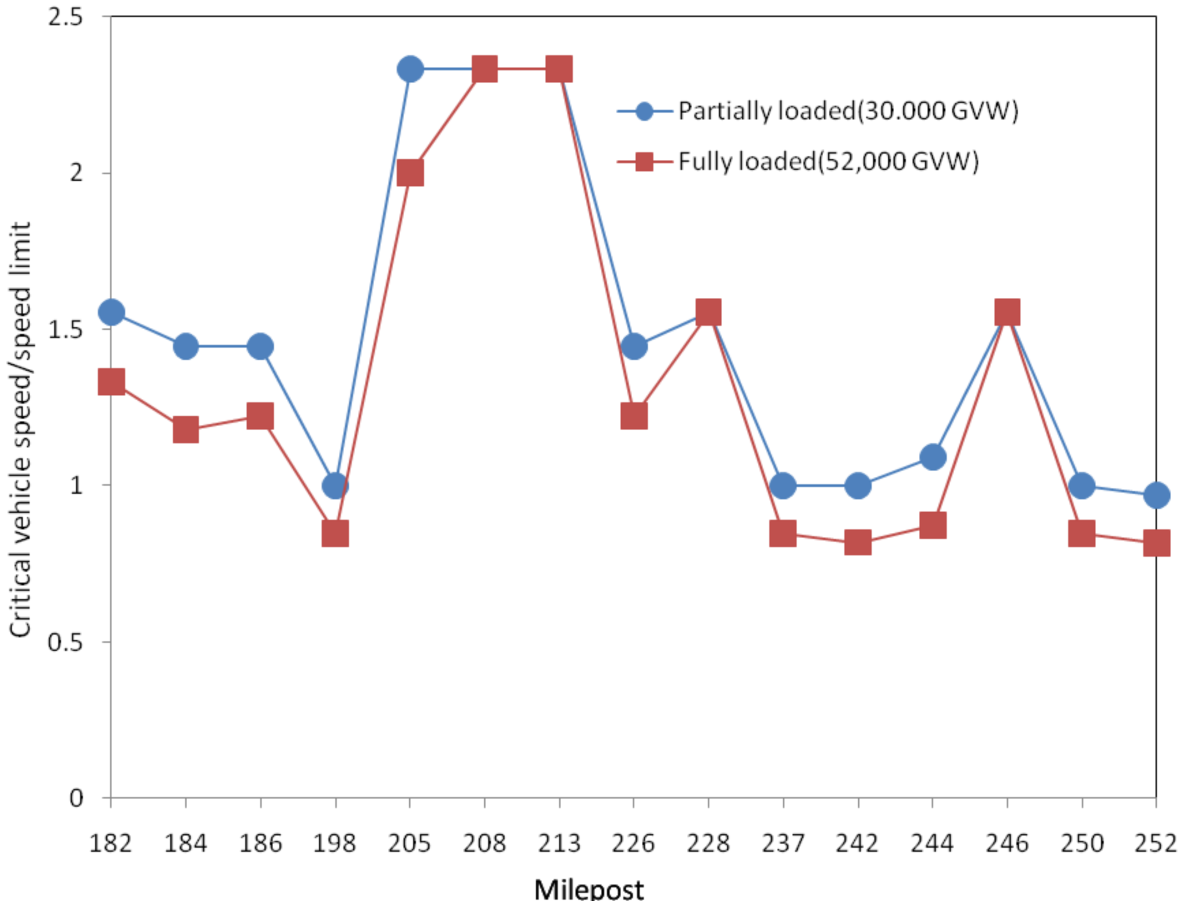


Fig. 6.4 Critical vehicle speed ratio of different mileposts in windy conditions (U=30 mph).

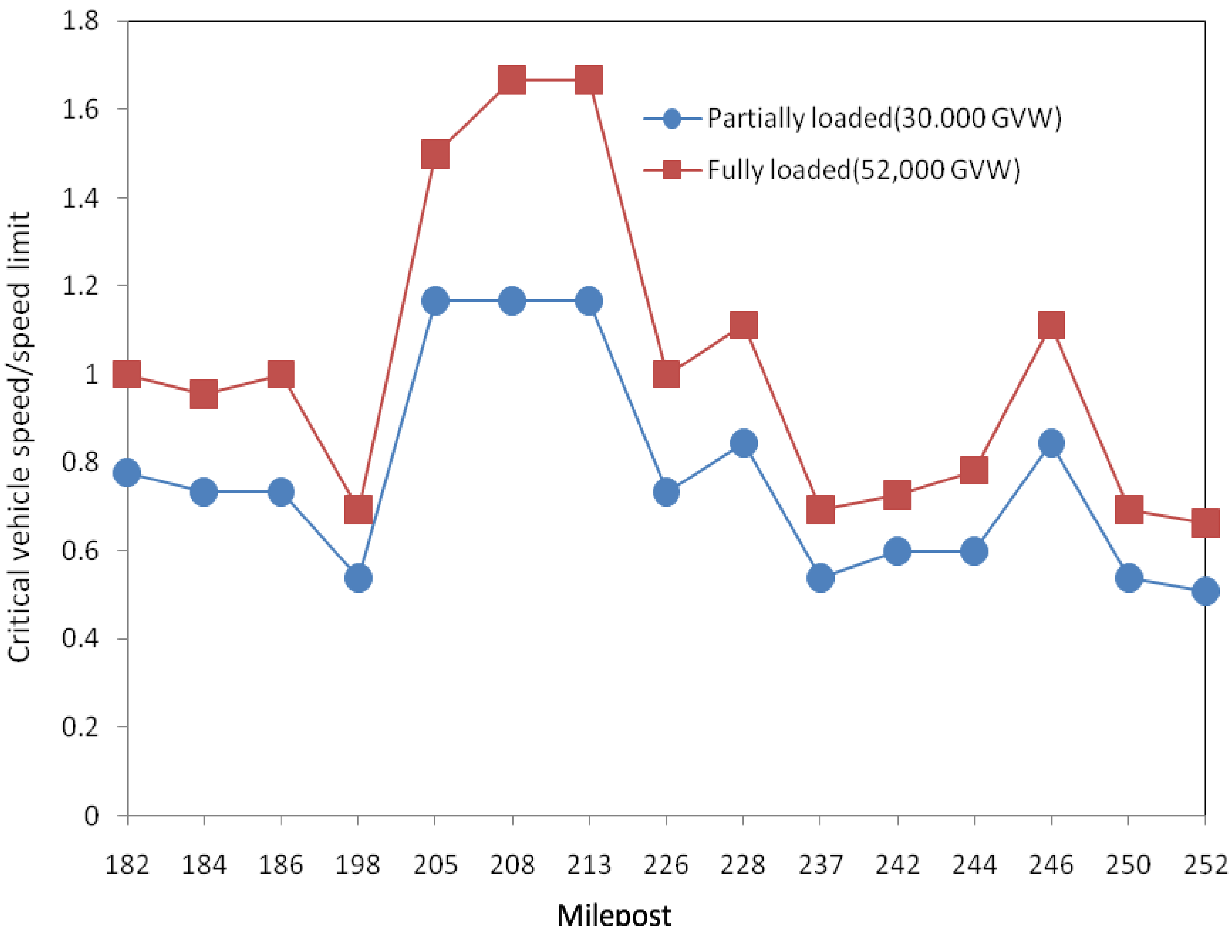


Fig. 6.5 Critical vehicle speed ratio of different mileposts in snowstorm
(U=30 mph and snow).

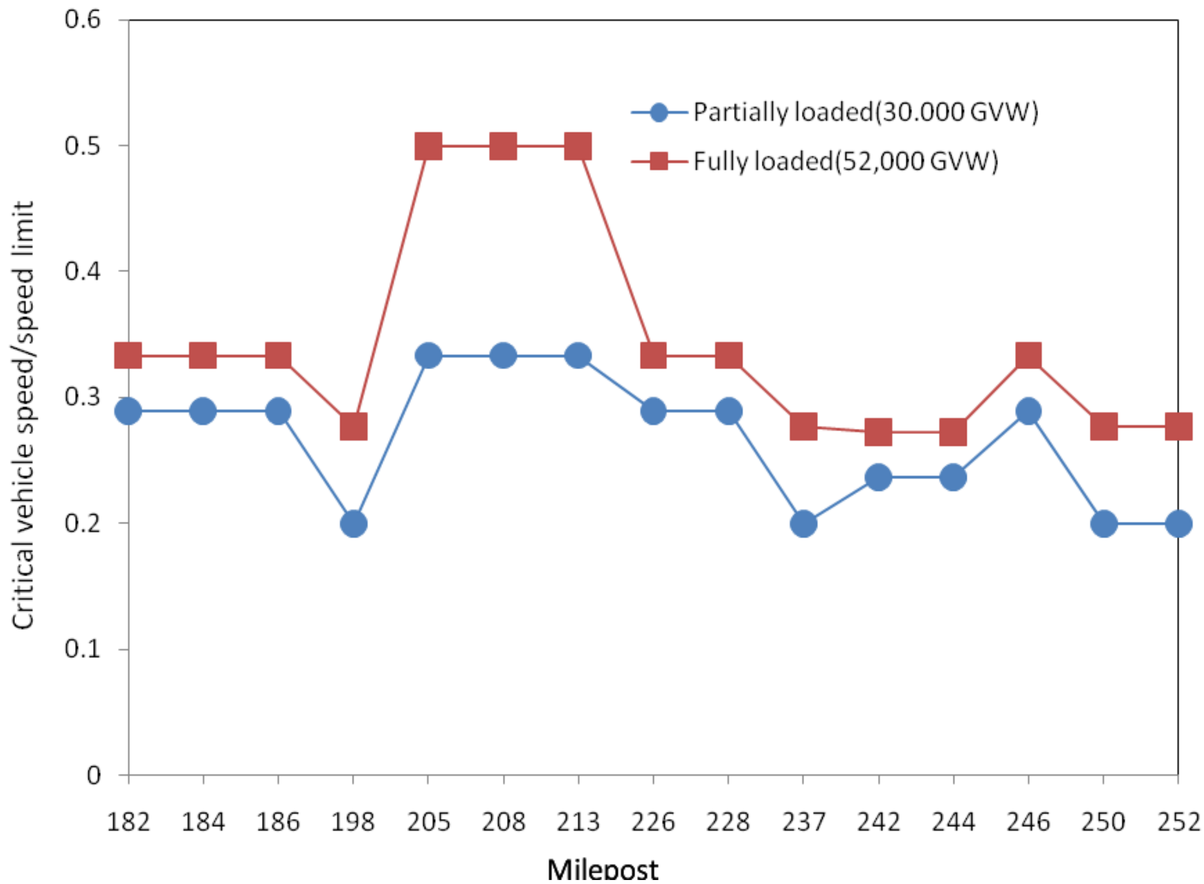


Fig. 6.6 Critical vehicle speed ratio of different mileposts in cold winter season (U=30 mph and icy road).

The CVS in windy conditions (U=30 mph) for a typical truck along the I-70 is identified considering the corresponding geometric condition for each segment along I-70 and the results are displayed in Fig. 6.4. It is known that 30 mph wind speed is pretty common for mountainous highways, especially during winter and spring seasons. As shown in Fig. 6.4, there are several locations with relatively low speed ratios, such as MP 244, MP 250-252. As compared to the historical accident results, these locations with lower speed ratios were also identified as AVLs in Table 6.1 as well as in Fig. 6.1. Pretty good correlations between the simulation results and the historical accident records can be found for most of the locations studied as displayed in Fig. 6.1. There is, however, one location (MP 198) which seems pretty vulnerable to single-vehicle accidents according to the simulation results in Fig. 6.4, while this observation is not well supported by the historical accident records (Table 6.1 and Fig. 6.1). It is possibly because that the unique terrain or surrounding near the MP 198 may improve the actual wind condition from the theoretical one. This observation underscores the importance of collecting site-specific wind and other environmental data for those locations with complex terrain or surroundings (Chen et al. 2010). One possible option is to use the mobile mapping technology to collect the site-specific wind and environmental data (Chen et al. 2010). A detailed investigation of this particular location involves significant data collection, which is beyond the scope of the present study.

Fig. 6.5 gives the CVS results on I-70 under snow storms (i.e. the road surface is covered by snow and the wind speed equals to 30 mph). It can be found that there are several locations with the speed ratios considerably lower than 1, such as MP 182-184, MP 250-252. Such a phenomenon observed from the simulation results is generally consistent with the historical accident records as shown in Table 6.1 and Fig. 6.2, except for MP 205-213. In Fig. 6.5, the speed ratios are all above 1 between MP 205-213, which seem to contradict with the fact as shown in Fig. 6.2 that there were many accidents happening during snowy conditions in that region. It is known that MP 208-213 involves very steep grades with the speed limits of 30 mph for trucks and 60 mph for other vehicles. A closer look of Table 6.1 discloses that for MP 204-209, 38.5% - 86.1% of those trucks which were involved in the accidents were actually driven at speeds at least 10 mph (16.1 km/h) higher than the speed limits according to the accident records. With the assumption that most large trucks were driven in speeds close to the posted speed limits, the speed ratios used in the present study were usually found to provide pretty accurate information about single-vehicle accident risks for most of locations (Fig. 6.5). However, the results of MP 204-213 in Fig. 6.5 also suggest the need of using the actual operational speeds of trucks instead of the posted speed limits in the study for those special regions where the actual driving speeds of the large trucks are considerably different from those of the posted speed limits.

The results of trucks under ice storm during winter seasons were reported in Fig. 6.6. The wind speed is assumed to be 30 mph and the road surface is covered with ice. For most locations of the whole corridor, the speed ratios are around 0.3-0.4 which suggests very large difference between the advisory CVS and the speed limits. It is thus found that during a sever snow storm, the closure of traffic to large trucks is probably the best solution. Most speed limits, primarily decided based on normal driving conditions, provide little information to the drivers about the appropriate driving speeds that the large trucks should maintain at a specific adverse driving condition. Therefore, adaptive (variable) speed limits for trucks which can automatically adjust with different extreme weather conditions at those critical locations will be helpful on improving truck safety on mountainous highways. The information gathered from the present study and the simulation methodology may help on developing the algorithm for the adaptive (variable) speed limit with ITS technology in the future.

In Figs. 6.4-6.6, the results for both fully-loaded and partially-loaded trucks (50% loaded) were plotted together. Although the results in Fig. 6.4-6.6 show relatively larger risk (lower speed ratio values) for partially-loaded trucks as compared to fully-loaded vehicles, it is premature to make a general conclusion about which one between a partially-loaded truck and a fully-loaded truck is more vulnerable. Compared to a partially-loaded truck, a fully-loaded truck has a higher center of gravity (C.G.) and also larger weight. A partially-loaded truck is lighter, but usually also has a lower C.G. than a fully-loaded truck. It is effortless to find out from the simulation model or even common sense that vehicles with larger weights or lower C.G. are less prone to overturn accidents. For a particular truck, therefore, it is not straightforward to tell which situation (i.e. fully-loaded or partially-loaded) is more vulnerable to single-vehicle accidents without a specific and detailed analysis. The single-vehicle simulation model (Chen and Chen 2010) can be used to conduct a detailed analysis on a case-by-case basis.

6.5 Conclusions

A case study was conducted to evaluate the traffic safety of large trucks. It includes investigating the advisory critical vehicle speeds of large trucks under site-specific adverse driving conditions as compared to the actual driving speed limits. Such a methodology, integrating historical accident data analysis and simulations with single-vehicle safety performance models, can be used on any mountainous highway experiencing complex driving conditions and high traffic volumes. The I-70 corridor in Colorado was chosen to demonstrate the methodology. The simulation results showed good correlations with the historical accident data. The specific findings are summarized in the following.

(1) It was found from the 10-year historical accident data analysis that snowy and icy road surfaces, windy weather and graded curves are the major critical adverse conditions for I-70.

(2) With the simulation model of single-vehicle accidents considering site-specific topographic conditions along the highway, the advisory critical vehicle speeds (CVS) were obtained for those critical adverse driving conditions identified from the data analysis. The ratios between the CVS and the corresponding posted speed limits can be used to qualitatively evaluate the accident risk as long as the actual operational speeds of large trucks are close to the posted speed limits.

(3) Although the general wind information can lead to reasonable predictions of the traffic safety performance for most of the locations on I-70, it is possible that the unique terrain or surrounding for some location may require site-specific wind and environmental data. The site-specific data may be obtained through the field data collection such as using the mobile mapping technology.

(4) For those special locations where the actual operational speeds of large trucks are significantly different from those of the posted speed limits, a specific analysis using the actual operational driving speeds rather than the posted speed limits is needed.

(5) For a particular truck, it is not straightforward to tell which situation (i.e. fully-loaded or partially-loaded) is more vulnerable to single-vehicle accidents without a specific analysis. The simulation study with the model introduced in the present study on a case-by-case basis is needed.

(6) Adaptive (variable) driving speed limits for trucks which can automatically adjust with different extreme weather conditions at those critical locations will be helpful on improving the truck safety on mountainous highways. The information gathered from the present study may help on the decisions about adopting advanced transportation management and ITS technology.

6.6 References

AASHTO. (2004). A Policy on Geometric Design of Highways and Streets. Washington, D.C.

Baker, C. J. (1991). "Ground vehicles in high cross winds. 3. The interaction of aerodynamic forces and the vehicle system." Journal of Fluids and Structures, 5, 221-241.

Braver, E., Zador, P., Thum, D., Mitter, E., Baum, H., Vilardo, F., (1997). "Tractor-trailer crashes in Indiana: a case-control study of the role of truck configuration". Accident Anal. Prevent. 29(1), 79–96.

Chang, L.-Y., Mannering, F., (1999). "Analysis of injury severity and vehicle occupancy in truck- and non-truck-involved accidents". Accident Anal. Prevent. 31 (5), 579–592.

Chen, S. R. and Cai, C. S. (2004). "Accident assessment of vehicles on long-span bridges in windy environments." Journal of Wind Engineering and Industrial Aerodynamics, 92(12), 991-1024.

Chen, S. R., Cai, C. S. and Wolshon, B. (2009). "From normal operation to evacuation: single-vehicle safety under adverse weather, topographic and operational conditions", Natural Hazards Review, ASCE, 10(2), 68-76.

Chen, S. R. and Chen, F. (2010). "Simulation-based assessment of vehicle safety behavior under hazardous driving conditions", J. of Transportation Engineering, ASCE, 136(4), 304-315.

Chen, S. R., Chen, F., Liu, J. and Bienkiewicz, B. (2010). “Mobile mapping technology of wind velocity data along highway for traffic safety evaluation”, Transportation Research Part C, 18, 507-518.

Chen, F. and Chen, S. R. (2009). “Assessment of vehicle safety behavior under adverse driving conditions”, 11th American Conference of Wind Engineering, June 22-26 2009, Puerto Rico.

Edwards, J.B. (1998). “The relationship between road accident severity and recorded weather”. Journal of Safety Research 29 (4), 249–262.

Guo, W. H. and Xu, Y. L. (2006). “Safety analysis of moving road vehicles on a long bridge under crosswind”, Journal of Engineering Mechanics, 132 (4), 438-446.

Harkey,D.L., Robertson, H.D. and Davis, S.E. (1990). “Assessment of Current Speed Zoning Criteria”. In Transportation Research Record 1281, Transportation Research Board, National Research Council, Washington, D. C., pp.40–51.

Lyman S., Braver E.R., (2003). “Occupant deaths in large truck crashes in the United States: 25 years of experience”. Accident Anal. Prevent. 35(5), 731-739.

Snaebjornsson, J. T., Baker, C. J., and Sigbjornsson, R. (2007). “Probabilistic assessment of road vehicle safety in windy environments.” Journal of Wind Engineering and Industrial Aerodynamics, 95, 1445-1462.

Summerfield, S., and Kosior, J., (2001). “Simulation of heavy trucks in inclement weather”. Canadian Transportation Research Forum

The National Academies (2006). “Where the weather meets the road- a research agenda for improving road weather system”, Report in Brief, The National Academies.

The Road Information Program (2005). “Growing Traffic in Rural America: Safety, Mobility and Economic Challenges in America’s Heartland”, http://www.tripnet.org/RuralRoads2005Report.pdf, last accessed May 17, 2008.

U. S. Department of Transportation (USDOT) (2005), “Report to Congress on the Large Truck Crash Causation Study”, Federal Motor Carrier Safety Administration, U.S. Department of Transportation.

Young, R. and Liesman, J. (2007a) "Intelligent Transportation Systems for Operation of Roadway Segments in High-Wind Conditions." Journal of Transportation Research Record 2000, 1-7

Young, R. and Liesman, J. (2007b) "Estimating the Relationship between Measured Wind Speed and Overturning Truck Crashes Using Binary Logit Model." Accident Analysis and Prevention, Vol. 39, Issue 3, pg. 574-580

CHAPTER 7: CONCLUSIONS AND RECOMMENDATION FOR FUTURE STUDY

7.1 Summary and Conclusions

The dissertation was to establish a general framework to systematically evaluate the traffic safety on rural highway through the rationalized reliability-based vehicle safety assessment model. To achieve this goal, following tasks were conducted:

(1) A mobile testing technology was developed to collect crosswind velocity data in both time and spatial domains along any highway, for traffic safety studies. The developed technology can be used for two primary purposes: acquisition of general site-specific wind velocity data along any highway, independent of the choice of the test vehicle and direct measurement of wind velocity at the roof height of a specific vehicle driven along a highway. A field test was carried out on I-70 corridor to evaluate the performance of the developed technology. Subsequently, wind tunnel investigation was performed, using a scaled model of the test truck, to investigate the effects of proximity of the car cabin surface on the anemometer (crosswind velocity) readouts. A wind tunnel test on a sedan car was also conducted to evaluate other alternatives of the test vehicle. The developed technology was proven to be feasible to collect wind velocity data in both time and spatial domains. Multiple runs under different wind conditions through the same highway of interests can generate a wind velocity surface;

(2) An integrated vehicle safety behavior simulation model was developed which adopts more realistic dynamic equations and accident criteria to characterize the transient process of accidents. Numerical analyses on one type of typical trucks under several representative scenarios were conducted. The new model can be used to predict the safety performance of vulnerable vehicles under various hazardous weather, topographic and road surface conditions by using the variables CST and CDS. For both straight and curved roads, rollover accidents usually happen first when the road surface is dry. When the wind speed is low, the difference of curvature has noteworthy impacts on CST and CDS. It was found that the road surface condition, wind speed and the curvature all play vital roles on the accident risks integrally. To accurate predict the safety risk under adverse driving conditions requires a detailed simulation with the developed model on a case by case basis;

(3) Ten-year detailed HSIS accident data on major interstate highways, US highways and state highways in Illinois were studied. The mixed logit model was adopted to analyze the injury severity of truck drivers on rural highways. The result of the likelihood ratio test indicates that the injury mechanisms of SV and MV accidents involving trucks are clearly distinct. A comprehensive collection of different risk factors including driver characteristics, vehicle characteristics, temporal characteristics, roadway characteristics, environmental characteristics, and accident characteristics were included in the mixed logit models. For the first time, SV and MV accidents involving trucks were studied separately to identify those risk factors which have significant influence on the driver-injury severity. The detailed findings on risk factors in MV and SV accidents will add to the existing knowledge of injury studies about truck drivers. Based on the improved understanding of the injury severity of truck drivers, it is expected that more rational and effective injury prevention strategies may be developed for truck drivers by trucking industry and related agencies, such as occupational safety and transportation agencies.

(4) A general reliability-based single-vehicle accident risk prediction model of trucks was finally developed based on the improved deterministic dynamic vehicle model established earlier in this dissertation. It was found that the proposed model provides a tool to assess accident risk of a particular vehicle considering realistic driving conditions in nature such as specific topographic, wind and road surface conditions as well as associated uncertainties. Safety index was introduced to quantify the safety margins and associated accident probability based on the reliability theory. After the analytical model is introduced, parametric studies of safety index and various variables defining adverse driving conditions were conducted. Both straight and curved roads were studied under different road surface conditions, driving speeds and wind conditions. The differences between the results from the dynamic model and the rigid-body model were also discussed. The developed reliability-based model can help deciding whether the traffic should be closed to a particular type of trucks under extreme events. It can also help on providing advisory speed limits under normal conditions based on the desired safety index (or acceptable accident risk);

(5) A case study was conducted to evaluate the traffic safety of large trucks. It includes investigating the advisory critical vehicle speeds of large trucks under site-specific adverse driving conditions as compared to the actual driving speed limits. Such a methodology, integrating historical accident data analysis and simulations with both single-vehicle accident, can be used on any mountainous highway experiencing complex driving conditions. The I-70 corridor in Colorado was chosen to demonstrate the methodology. The simulation results showed good correlations with the historical accident data.

7.2 Future Work

Based on the research experience accumulated from this study, the writer believes that the following issues can be addressed in the future work to improve the traffic safety of rural highways.

(1) The study about the injury severity of truck driver has some limitations, such as the fact that data reflect information from a single US state, were obtained from a single database, as well as the fact that the truck types investigated are limited by the available types from the database. Future studies with multiple states, data from different databases and more comprehensive truck types may be conducted, which may provide more comprehensive insights.

(2) Some special truck typical was not considered in the study, such as long-trailer truck. Part of the season was that the wind coefficients of these particular kinds of truck are still unknown. Future wind-tunnel experiments of these kinds of truck will improve the understanding of the safety performance of this type of special trucks.

(3) A reasonable accident rate prediction model based on historical data can possibly used to validate the simulation model. It is however understood that a rational accident prediction model which can consider different accident rates between different vehicles is still very challenging and is not available to the community. It is felt by the writer that future work about advanced truck accident prediction models may be important.