The Impact of Sleep Disorders on Driving Safety – Findings from the SHRP2 Naturalistic Driving Study

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ABSTRACT

This study is the first examination on the association between seven types of sleep disorder and driving risk using large-scale naturalistic driving study data involving more than 3,400 participants. Regression analyses revealed that females with restless leg syndrome or sleep apnea and drivers with insomnia, shift work sleep disorder, or periodic limb movement disorder are associated with significantly higher driving risk than other drivers without those conditons. Furthermore, despite a small number of observations, there is a strong indication of increased risk for narcoleptic drivers. The findings confirmed results from simulator and epidemiological studies that the driving risk increases amongst people with certain types of sleep disorders. However, this study did not yield evidence in naturalistic driving settings to confirm significantly increased driving risk associated with migraine in prior research. The inconsistency may be an indication that the significant decline in cognitive performance among drivers with sleep disorders observed in laboratory settings may not nessarily translate to an increase in actual driving risk. Further research is necessary to define how to incentivize drivers with specific sleep disorders to balance road safety and personal mobility.

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GENERAL AUDIENCE ABSTRACT

This study is the first examination on the association between seven types of sleep disorder and driving risk using large-scale naturalistic driving study data involving more than 3,400 participants. The study identified seven sleep disorders - narcolepsy, sleep apnea, insomnia, shift work sleep disorder, restless legs syndrome, periodic limb movement disorder, and migraine among the participants and revealed that that females with restless leg syndrome or sleep apnea and drivers with insomnia, shift work sleep disorder, or periodic limb movement disorder are associated with significantly higher driving risk than other drivers without those conditons. Furthermore, despite a small number of observations, there is a strong indication of increased risk for narcoleptic drivers. The findings confirmed most results from previous simulator and epidemiological studies that the driving risk increased amongst people with certain types of sleep disorders except for those with migraines – there is no evidence showing increased driving risk associated with drivers with migraine. The inconsistency may be an indication that the significant decline in cognitive performance among drivers with sleep disorders observed in laboratory settings may not nessarily translate to an increase in actual driving risk. The public and private sectors can use the results to target their investments in supporting high risk individuals. And physicians now have more representative data on the level of risk in real world driving and thus more able to practice evidence-based medicine in consulting their patients with sleep disorders regarding driving safety and personal mobility.

DEDICATION

To my parents, thank you for your unconditional love and support.

To my dearest, thank you for your trust.

To my best friend, thank you for encouraging me even though you are on the other side of the Pacific Ocean.

To my friends, you are always the best.

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1. INTRODUCTION

1.1 Background

According to a national report, 32,999 people were killed, 3.9 million people were injured, and 24 million vehicles were damaged in motor vehicle crashes in the United States in 2010. The total economic cost of these incidents was $242 billion, but the value climbed up to $836 billion if the quality of life is considered (Blincoe, Miller, Zaloshnja, & Lawrence, 2015).

Motor vehicle crashes have various causes that are mostly preventable (NHTSA, 2008). Therefore, knowledge of pre-crash information and driver state is imperative for road safety. The National Motor Vehicle Crash Causation Study (NMVCCS) by National Highway Traffic Safety Administration's (NHTSA) indicated that fatigue is one of the common contributing factors for crashes. Fatigued drivers were twice as likely to make performance errors (e.g., overcompensation, improper directional control, etc.) compared to unfatigued people (NHTSA, 2008). The NMVCCS also estimated that 7% of the 3,894,983 drivers involved in crashes between 2005 and 2007 were fatigued (NHTSA, 2008). Between 2005 and 2009, a fatigued driver was involved in approximately 1.4% of all motor vehicle crashes annually, and 2.2% of these crashes resulted in injuries. Among the fatal crashes between 2005 and 2009, 2.5% involved a drowsy driver resulting in 5,021 deaths (NHTSA, 2011).

Brown (1994) defined fatigue as "a subjectively experienced disinclination to continue performing the task at hand"; hence, fatigue is related to sleepiness, referred to as "sleep propensity" (Shen, Barbera, & Shapiro, 2006). Although fatigue and sleepiness are different, they can coexist as a consequence of sleep deprivation. Fatigue and sleepiness are often used interchangeably and even merged under more general terms such as "tired" (*ibid*). For example, the Visual Analogue Scales (VAS), a subjective sleepiness measurement technique, uses "sleepy" and "drowsy" to characterize "sleep propensity" (Monk, 1989; Shen et al., 2006). In the context of driving studies, researchers have used different terms – drowsy, fatigued, and sleepy – to describe the driver whose state is affected by sleep propensity and is exhibiting noticeable behavioral changes, such as reduced eye scanning behaviors and increased eye lid closures during driving (Hancock & Verwey, 1997; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006;

Wierwille & Ellsworth, 1994). To be consistent, this study refers to the state of "sleepiness", "drowsiness", or "fatigue" due to propensity to sleep as "sleepy".

The cognitive effects of sleepiness include decrements in vigilance, reaction time, memory, psychomotor coordination, information processing, and decision making (Lyznicki, Doege, Davis, & Williams, 1998). When driving, sleepiness can lead to progressive withdrawal of attention from road and traffic demands, thereby impairing ability of vehicle control and collision avoidance (Brown, 1994). In the worst scenario, drivers can be unaware of their sleepiness and close their eyes behind the wheel (*ibid*). Despite these adverse effects, sleepy drivers are common on the road. According to a 2009 nationwide poll, 28% of the 1,000 respondents indicated that they had driven sleepy at least once per month during the past year (National Sleep Foundation, 2009). Therefore, a deeper knowledge of sleepy drivers is crucial in helping the government and the public to prevent motor vehicle accidents resulting from sleepiness.

Previous studies have identified various risk factors of sleepy driving, such as youth (as teenagers tend to stay up late but get up early), alcohol use, medication consumption, undiagnosed or untreated sleep disorders, and night time and long distance driving (Lyznicki et al., 1998; Stutts, Wilkins, & Vaughn, 1999). Sleep disorders are considered as one of the major risk factors for motor vehicle accidents (Stutts et al., 1999). A large-scale survey revealed that 16.9% of regular highway drivers complained about having one or more sleep disorders (Philip et al., 2010).

1.2 Sleep Disorders and Driving Safety

Sleep disorders are neurological disorders that give rise to excessive daytime sleepiness thereby impairing daytime functions (Aldrich, 1989; Consens & Chervin, 2007). The symptoms of sleep disorders can lead to severe road safety problems such as motor vehicle accidents (American Academy of Sleep Medicine, 2001). Prior research has examined the effects of sleep disorders on driving safety.

Some studies examined the driving risk associated with multiple sleep disorders. For instance, Philip et al. (2010) conducted a survey showing that drivers with narcolepsy and hypersomnia (odds ratio (OR)=3.16) or other sleep disorders (OR=1.46) are at higher risk of accidents. In an interview study with 4,002 drivers, the habitually sleepy drivers had a significantly higher crash rate than the control group (OR=13.3; Masa, Rubio, & Findley, 2000). Further, the habitually sleepy driver had a higher prevalence of respiratory sleep disorders (i.e., apnea, hypopnea, and other respiratory effort-related arousals; OR = 6.0) and the driver group with respiratory sleep disorders had a much higher likelihood of crashes (OR=8.5; *ibid*).

The literature also includes some driving studies on one or two specific types of sleep disorders, such as sleep apnea, insomnia, and shift work sleep disorder (Barger et al., 2005; Ellen et al., 2006; Young, Blustein, Finn, & Palta, 1997). The prior driving studies have illustrated the different influences of individual sleep disorders, compelling this research to explore the impact of seven prominent sleep disorders on driving safety – narcolepsy, sleep apnea, insomnia, shift work sleep disorder, restless legs syndrome, periodic limb movement disorder, and migraine.

Narcolepsy. Narcolepsy is a disabling sleep disorder that exhibits symptoms of excessive daytime sleepiness, cataplexy which is the sudden loss of muscle strength control and movement ability, uncontrollably falling asleep at any time of day, and abnormal rapid eye movement during sleep (L. Lin et al., 1999; Mignot, 1998). Narcolepsy affects 0.03% to 0.16% of the general population (American Academy of Sleep Medicine, 2001; Longstreth Jr., Koepsell, Ton, Hendrickson, & Belle, 2007). In a driving simulator study, Findley et al. (1995) showed that participants with narcolepsy hit obstacles more frequently (7.7%±3.2%) in a highway driving task than age- and sex-matched participants without narcolepsy (1.2%±0.03%). In another simulator study, the accident rate was higher with narcoleptics than controls (Kotterba et al., 2004). Personal crash histories also revealed that patients with narcolepsy had higher crash rates due to sleepiness: 11 times greater in female and 7 times greater in male narcoleptics compared to controls (Aldrich, 1989). Although evidence of impaired driving performance resulting from narcolepsy is available, Kotterba et al. (2004) indicated that further research is necessary to address limitations such as the small sample size.

Sleep apnea. Sleep apnea is characterized by repetitive episodes of upper airway obstruction during sleep and reduced levels of in blood oxygen (American Academy of Sleep Medicine, 2001; Ellen et al., 2006). Sleep apnea may lead to excessive daytime fatigue and impaired vigilance and attention (American Academy of Sleep Medicine, 2001). In Western countries, sleep apnea is more prevalent in males (3 to 7%) than in females (2 to 5%) and mostly affects middle-aged people (Punjabi, 2008; Young, Peppard, & Gottlieb, 2002). Reviews of epidemiologic studies indicated significantly higher crash risk of drivers with sleep apnea than for those without (Ellen et al., 2006; Findley, Unverzagt, & Suratt, 1988; Tregear, Reston, Schoelles, & Phillips, 2009). However, driving exposure is neglected in these studies as indicated by Ellen et al. (2006). Simulator studies also showed that sleep apneics drove worse compared to controls (George, 2004; Strohl et al., 1994).

Insomnia. Insomnia is the most prevalent sleep disorder in the general populations, affecting about 30% of adults (Roth, 2007) and causing difficulty in initiating sleep or staying asleep (Leger et al., 2014; Ohayon, 2002). Females are twice as likely as males to have insomnia (Ohayon, 2002; Ohayon & Roth, 2002). A large-scale survey conducted in sleep disturbed populations showed that untreated insomniacs were associated with a higher risk of accidents compared to the controls (OR=1.87; Leger et al., 2014; Sagberg, 2006). A review of 18 studies on cognitive dysfunctions indicated that insomniac patients had reduced performance in attention and vigilance tasks, but simulator research with insomniacs appears non-existent (Fulda & Schulz, 2001).

Shift work sleep disorder (SWSD). SWSD is a common but under-recognized sleep disorder due to misalignment of sleep/wake patterns with the endogenous circadian rhythm (Schwartz & Roth, 2006). Frequent night or early morning shifts can disrupt circadian rhythms. The American Academy of Sleep Medicine (2001) estimated that 2 to 5% of Americans may suffer from SWSD but the gender effect remains unknown. A survey study with new postgraduate interns in the US concluded that the crash odds of interns with extended work shifts doubled those with regular shifts (Barger et al., 2005). Some occupations are particularly prone to shift work, such as, nurses. Gold et al. (1992) conducted a cross-sectional survey study among female nurses in a hospital and discovered that ORs of automobile accidents were 2.24 for night shift nurses and 1.14 for rotators higher than day time shift nurses. Further, OR of near-crashes of night shift nurses (OR=1.92) and rotators (OR=2.63) were much higher than those of nurses without shift schedules. Other cross-sectional research using surveys and self-reports had similar conclusions that shift work schedules negatively impacted road safety (Garbarino et al., 2004; Wagstaff & Lie, 2011).

Restless leg syndrome (RLS). Another condition associated with chronic sleep deprivation is RLS, characterized by the irresistible urge to move lower extremities that usually occurs prior to onset of or during sleep (Gamaldo, Benbrook, Allen, Oguntimein, & Earley, 2009; Tan et al., 2001). The literature is inconsistent in the prevalence of RLS, reporting anywhere between 2.5 to 15% of the general population (Earley, 2003) but a lower rate in Asia (Tan et al., 2001). RLS is estimated to be more common in the middle-aged, the elderly, and women (Smolensky, Di Milia, Ohayon, & Philip, 2011). RLS has been suspected to contribute to car accidents, but the literature is limited in related research (Philip & Åkerstedt, 2006; Smolensky et al., 2011). For example, Aldrich (1989) reviewed data on sleep-related accidents of controls and drivers with sleep disorders but the sample only contained 4 out of 26 participants with RLS or periodic limb movement disorder that had been involved in crashes. Further, instead of discussing the impact of RLS or periodic limb movement disorder separately, the study included the two sleep disorders in the same driver group and was unable to isolate any effects of RLS (*ibid*).

Periodic limb movement disorder (PLMD). PLMD is defined by periodic episodes of repetitive and highly stereotyped limb movements during sleep that disturb sleep chronically (American Academy of Sleep Medicine, 2001). PLMD is comparatively prevalent (3.9%) in the general population (Ohayon & Roth, 2002). Previous research suggested an association between PLMD and car accidents. Data from a hospital emergency room showed that 7.7% of 40 injured drivers suffered from PLMD (Yee, Campbell, Beasley, & Neill, 2002). A driving simulator study suggested lower performance of PLMD patients compared to controls (Gieteling et al., 2012). However, similar to RLS, the current research is insufficient to conclude increased car accident rates due to PLMD (Philip & Åkerstedt, 2006; Pizza et al., 2010).

Migraine. The migraine is a sleep-related headache that is recurrent and widely varies in intensity, duration, and frequency with a common onset during patient's sleep (American Academy of Sleep Medicine, 2001). The estimated prevalence of migraines is 18.2% among women and 6.5% among men (Lipton, Stewart, Diamond, Diamond, & Reed, 2001). Up to 25% of patients have reported dizziness (Baloh, 1997). Studies in crash reports and medical history indicated a high accident risk among drivers with migraines. A multiple logistic regression analysis using personal driving history of 10,529 individuals indicated that migraines could be associated with a 50% increase in the risk of driver injury (Norton, Vander Hoorn, Roberts, Jackson, & MacMahon, 1997). In an epidemiological investigation involving military male drivers, migraine headache was found to be significantly associated with motor vehicle crashes (Lerman, Matar, Lavie, & Danon, 1995).

1.3 Summary of Current Research

The literature review highlights three key findings that reflect the state of current driving research. First, it is suggested by epidemiological and empirical (i.e., simulator) studies that sleep disorders disturb the normal sleep pattern, cause excessive sleepiness, result in temporary or chronic decrements in driving abilities, and thereby lead to decreased driving safety among patients (Aldrich, 1989; American Academy of Sleep Medicine, 2001; Consens & Chervin, 2007). Second, the prevalence rate of sleep disorders is dependent on demographic factors, particularly, age and gender. Finally, different sleep disorders are associated with different level of driving risk, but the paucity of epidemiological and empirical research limits the conclusiveness on the impact of sleep disorders on driving safety (e.g., PLMD and RLS research).

Besides the scarcity of related research mentioned above, prior studies have not addressed several areas. First, most studies relied on self-reported data or police reports that lacked pre-crash information and unbiased event descriptions (Neale, Dingus, Klauer, Sudweeks, & Goodman, 2005; Norton et al., 1997; Philip & Åkerstedt, 2006; Philip et al., 2010; Tregear et al., 2009). For example, although these reports demonstrate the association between sleep disorders and increased driving risk, they cannot provide the details of driver behavior prior to the event that are needed to analyze driving performance decrements. In another example, the police report might list the cause of a rear-end collision as "following too close" when the actual contributing factor was sleepiness which resulted in failure to maintain a proper following distance (Neale et al., 2005). Second, empirical and epidemiological studies investigated crashes but omitted near-crashes. Near-crashes share similar causal factors with crashes; therefore, both should be considered as safety critical events (Guo, Klauer, Hankey, & Dingus, 2010). Third, most driving studies on sleep disorders were limited in their participant samples, preventing investigation into any interactions between demographic factors and sleep disorders on crash risks (Barger et al., 2005; Ellen et al., 2006; Lerman et al., 1995). Finally, the driving exposure is neglected in virtually all the studies (Ellen et al., 2006). Driving exposure can be vital to road risk associated with sleep disorders as driving risk would not exist if patients do not drive.

The review of current research points to several knowledge gaps. First, there is no research examining the association between sleep disorder and driving risk under real driving conditions.

Although researchers have shown that sleep disorders can impair some cognitive functions in laboratory studies, such as vigilance performance and executive function that are necessary for driving (Fulda & Schulz, 2001), there has not been any strong empirical evidence gathered in naturalistic driving situations to confirm that the impact of sleep disorders translate into real risk on the road. Second, as stated above, Ellen et al. (2006) found that driving exposure is missing in current literature which can be vital to meaningful research conclusions ascertaining risks. Third, most previous epidemiological studies collected data on crash rates but mostly omitted the data on sleeping (e.g., sleep quality) and driving (e.g., frequency of night time trips) habits that would be essential to understand the association between sleep disorders and driving risks.

To address the research gaps in the literature on relationships between sleep disorders and road safety, this study investigates seven types of sleep disorder and their impacts on driving safety using a Naturalistic Driving Study (NDS) and can contribute to the literature as follows:

1) Provide crash/near-crash risk estimates for drivers with sleep disorders in a naturalistic driving research paradigm
2) Provide crash/near-crash risk estimates that can account for driving exposure and leverage information prior to the safety-critical events that was recorded while driving (e.g., quality of driver maneuvers in a crash-imminent situation)
3) Provide descriptive statistics on sleeping and driving habits of drivers with sleep disorders to aid in the interpretation of crash risks
4) Reduce sampling limitations associated with prior work through a large scale and longitudinal NDS

1.4 SHRP2 Naturalistic Driving Study

Naturalistic Driving Study (NDS) is an innovative method to collect large-scale data on driver behavior, driving environment, and vehicle performance (e.g., speed, braking information) by installing unobtrusive cameras and other instruments that can record and store the data under real driving situations (Klauer, Perez, & McClafferty, 2011; Neale et al., 2005). Large-scale NDS provides researchers with two major advantages: (a) accurate details of pre-event information, and (b) exposure information that includes frequency of driver behaviors under normal driving conditions and the context of contributing factors on safety (Campbell, 2012). Unlike empirical research where driver behaviors may be modified by the presence of experimenters and epidemiological research where important details leading up to crashes may be lacking, NDS can limit the experimenter effect and provide pre-event data to examine factors contributing to safety critical events (Klauer et al., 2006; Neale et al., 2005).

The Second Strategic Highway Research Program (SHRP2), completed in 2014, is currently the largest existing NDS in the US (Campbell, 2012). SHRP2 has collected nationwide data from more than 3,400 male and female passenger-vehicle drivers over a three-year period, providing a large sample size to investigate myriad risk factors. Driver ages ranged from 16 to 98, and most volunteers participated for one to two years (Campbell, 2012; Victor et al., 2015). The onboard data acquisition system (DAS) installed on each vehicle continuously collected vehicle performance data (e.g., vehicle speed, acceleration, and braking), vehicle controls, lane position, forward radar, and video with different views (e.g., forward, rear, and on driver's face and hands) under real driving conditions (*ibid*). In addition to real time recording of driving behaviors, SHRP2 administered several questionnaires to collect driver demographics (e.g., age and gender) and medical conditions (e.g., sleep disorder conditions). Professional data reductionists at Virginia Tech Transportation Institute (VTTI) coded driver performance, behavior metrics, situational characteristics, and environmental characteristics for SHRP2 data for statistical analyses (Hankey, Perez, & McClafferty, 2016).

1.5 Research Hypotheses

SHRP2 provides the empirical data to address the paucity and methodological limitations of current research on sleep disorders and driving safety. Specifically, the SHRP2 data enable empirical investigation into the following research hypotheses:

Hypothesis 1. Do drivers with sleep disorders have different sleep and driving habits? Specifically, are there differences between people with sleep disorders and those without in terms of amount of night time driving, frequency of sleepy driving, sleep schedule, quality of sleep, and sleep duration?

Hypothesis 2: Do drivers with sleep disorders have higher risk in their naturalistic driving environment? Does driving risk differ with type of sleep disorder?

Hypothesis 3. Do gender and age interact with individual sleep disorders in moderating driving risk in naturalistic driving?

2. METHOD

2.1 SHRP2 NDS Data

SHRP2 provides four classes of data for hypothesis testing and exploratory data analysis in this study:

1. **Participant demographics:** Gender, age, and self-reported data on sleepy driving and sleep habit (see APPENDIX A, *Table A 1*).
2. **Sleep disorder(s) of participants:** Type of sleep disorder suffered by each participant.
3. **Event details.** Observations of crash, near-crash, and baseline (i.e., a randomly sampled control period representing normal driving condition), driver maneuver prior to the safety critical event, crash severity, etc (see APPENDIX A, *Table A 2*).
4. **Aggregated trip information:** Driving time of day, number of trips in day, average trip duration (see APPENDIX A, Table A *3*).

2.2 Descriptive Statistics of Driver Groups

The literature review suggests differences between driver groups with sleep disorders in sleeping and driving habits because sleep disorders influence drivers' circadian rhythms and behaviors. These differences between the driver groups were examined with ORs and associated 95% confidence intervals (CI) to learn about self-reported sleeping and driving habits, which in turn relate to roadway safety.

For example, the exposure and output information in the SHRP2 dataset can be arranged into contingency tables. Table 1 is a contingency table representing numbers of nighttime and daytime driving trips between participants with and without sleep disorders.

Table 1
Frequency of Nighttime Driving

	Sleep Disorder (+)	**Sleep Disorder (-)**
Numbers of Nighttime Trips	83733	388291
Numbers of Daytime Trips	930687	3699070

From Table 1, OR of having nighttime trips for drivers with sleep disorders over drivers without those conditions is computed as $(83733/930687)/(388291/3699070) = 0.86$. The contingency table also allow for the calculation of the CIs.

2.3 Regression Models for Driving Risk

To assess risks for drivers with sleep disorders, regression models were built with four safety outcome measures (i.e., dependent variables):

1. The first measure is risk of crash/near-crash which specifies whether or not the driver actually had a crash/near-crash in a driving observation. This measure is binary (i.e., 1 = crash/near-crash, 0 = baseline which is not a crash), relevant for assessing the risk of having crash/near-crashes associated with different sleep disorders. The outcome of driving observation is available in the dataset of **Event details** (see APPENDIX A, *Table A 2*).
2. The second measure is crash/near-crash rate which is calculated by number of crashes/near-crashes divided by total time traveled by the driver, relevant for predicting the road risk while accounting for driving exposure. In the dataset of **Trip aggregated information** (see APPENDIX A, Table A *3*) the count of events and driving time are available to calculate the exact exposure. The driving activity of a participant in SHRP2 NDS was recorded for at least one year, so the event rate is reliable to be considered as normal event rate of the driver.
3. The third variable is driver maneuver, which is a four-level rating on driver maneuver prior to a crash/near-crash according to a trained SHRP2 data reductionist. This safety outcome is relevant to assess risk factors associated with inferior driving performance. The driver maneuver is recorded in **Event details** (see APPENDIX A, *Table A 2*). The driver maneuver is ordered in four levels: "1" as "legal and safe", "2" as "illegal but safe", "3" as "legal but unsafe", and "4" as "illegal and unsafe".
4. The fourth safety outcome measure is severity of a crash/near-crash, which is a five-level rating on the severity of safety-critical events with respect to the magnitude of vehicle dynamics, the presumed amount of property damage, and the level of risk posed to the drivers. This safety outcome is relevant to assess the level of harm, rather than likelihood of risk associated with sleep disorder. The severity information is available in **Event**

details (see APPENDIX A, *Table A 2*). Five levels of crash/near-crash severity are: "1" as "not a crash", "2" as "low risk tire strike", "3" as "minor crash", "4" as "police reportable crash", and "5" as "most severe crash".

Given the three types of scale for the four outcome measures, this study employed three regression methods: 1) Logistic regression model, 2) Poisson log-linear regression model, 3) Ordinal logistic regression model. All models were built in R with a significance level at 0.05.

2.3.1 Logistic Regression Model

Logistic regression is suitable for modelling risk of having crashes/near-crashes since its outcome is binary – a crash/near-crash or a baseline. Such model accommodates multiple predictors and addresses confounding and interactive effects (Guo & Hankey, 2009). In the model, the dependent variable is coded as "1" if the outcome was a crash/near-crash or "0" if it was a baseline. A random intercept is assigned to each driver to account for within-participant variances. The independent variables are described in Table 2.

Table 2

The Independent Variables of the Mixed-Effect Logistic Regression Model

Independent Variable	Description
The seven sleep disorders	$\begin{cases} 1 = \text{is a patient} \\ 0 = \text{not a patient} \end{cases}$
Gender	$\begin{cases} F = \text{female} \\ M = \text{male} \end{cases}$
Age group	Categorical variable with 17 levels
Average trip duration in second	Continuous variable
Frequency of sleepy driving	Self-reported rating of frequency of sleepy driving
Participant ID	The unique ID assigned to each participant
Interaction of sleep disorder and gender	Combination of the above description
Interaction of sleep disorder and age	Combination of the above description
Interaction of sleep disorder, gender and age	Combination of the above description

2.3.2 Poisson Log-linear Regression Model

The Poisson log-linear regression is appropriate to model rate - the count of events with an offset of total driving exposure in time and thus predicts the crash/near-crash rate using the parameter estimates of each predictor. In this model, the random effect in the model is the participant factor. *Table 3* is the list of independent variables.

Table 3

The Independent Variables of the Poisson Log-linear Regression Model

Independent Variable	Description
The seven sleep disorders	$\begin{cases} 1 = \quad is\ a\ patient \\ 0 = not\ a\ patient \end{cases}$
Gender	$\begin{cases} F = female \\ M = \quad male \end{cases}$
Age group	Categorical variable with 17 levels
Frequency of sleepy driving	Self-reported rating of frequency of sleepy driving
Participant ID	The unique ID assigned to each participant
Interaction of sleep disorder and gender	Combination of the above description
Interaction of sleep disorder and age	Combination of the above description
Interaction of sleep disorder, gender and age	Combination of the above description

2.3.3 Ordinal Logistic Regression Model

The proportional odds ratio regression (a type of ordinal logistic regression for modeling multilevel and ordered categorical response) predicts the driver maneuver ratings and severity ratings associated with crashes/near-crashes. The regression coefficients predict the probability of an independent variable associated with an outcome/rating in the higher category. In other words, this regression method calculates adjusted odds ratio (AOR) that predicts the odds of more unsafe driver maneuver or more severe safety-critical event of drivers with sleep disorders while taking other factors such as demographics into consideration. The independent variables are listed in Table 4.

Table 4

The Independent Variables of the Ordinal Logistic Regression Model

Independent Variable	Description
The seven sleep disorders	$\begin{cases} 1 = \quad is\ a\ patient \\ 0 = not\ a\ patient \end{cases}$
Gender	$\begin{cases} F = female \\ M = \quad male \end{cases}$
Age group	Categorical variable with 17 levels
Frequency of sleepy driving	Self-reported rating of frequency of sleepy driving

Average trip duration	Continuous variable
Rate of nighttime driving	Continuous variable of nighttime driving rate
Sleep quality	Categorical variable, self-reported
Sleep duration	Categorical variable of driver's satisfaction of sleep duration, self-reported

3. RESULTS

3.1 Descriptive Statistics

The SHRP2 data set includes more than 24,000 observations (i.e., crashes, near-crashes, and baselines) involving drivers with and without any of the seven types of sleep disorders (Table 5). As the literature indicates differences in sleeping and driving habits due to sleep disorders, driver groups with and without sleep disorders were compared using OR with 95% CI to examine such differences among the participant population.

Table 5
Number of baselines, crashes/near-crashes, and total observations categorized by sleep disorder

Driver Category	Number of observations			
	Drivers	Baselines	Crashes/Near-crashes	Total
All drivers	3,541	20,000	4175	24,175
Sleep disorder	646	4,085	920	5,651
Narcolepsy	5	34	6	45
Sleep apnea	188	1,202	245	1,635
Insomnia	170	1,153	332	1,655
Restless leg syndrome	119	692	150	961
Shift work sleep disorder	16	108	36	160
Periodic limb syndrome	8	48	4	60
Migraine	297	1,940	468	2,705
No sleep disorder	2,895	15,915	3255	22,065

3.1.1 Frequency of sleepy driving

In SHRP2, drivers self-reported their frequency of feeling sleepy or finding it hard to keep eyes open while driving in the past 12 months as "never", "rarely", "sometimes", and "often". In addition, the drivers also reported whether they have nodded-off or fallen asleep when driving as either "yes" or "no". Table 6 presents the OR and 95% CI for all sleep disorders.

Table 6

Odds ratio of frequency of sleepy driving for drivers with sleep disorders (drivers without sleep disorders were treated as "non-disease" and the response "never" is treated as non-exposure)

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrome	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Rarely	1.10 0.80-1.15	2.11 0.19-23.25	0.93 0.69-1.27	1.01 0.72-1.41	0.86 0.58-1.28	4.23 0.90-19.94	0.63 0.15-2.64	1.34 * 1.03-1.73
Sometimes	1.42 0.98-1.78	5.41 0.34-86.78	0.64 0.34-1.21	1.85 * 1.43-2.98	0.94 0.48-1.87	16.52 * 3.32-82.28	N/A	2.06 * 1.40-3.03
Often	1.61 0.47-4.47	107.86 * 6.42-1811.89	1.11 0.14-8.57	1.41 0.18-10.84	3.92 0.87-17.80	N/A	N/A	1.90 0.42-8.54

Note. * denotes significant results at $p < 0.05$. N/A means the numerator in OR calculation is 0.

Table 7

Odds ratio of having nodded-off or fallen asleep for drivers with sleep disorders (drivers without sleep disorders were treated as "non-disease" and "no" was treated as non-exposure)

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrome	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Have nodded-off or fallen asleep	1.04 0.82-1.32	7.74 * 1.29-46.45	1.13 0.76-1.67	1.37 0.93-2.02	0.76 0.44-1.32	5.20 * 1.94-13.92	1.17 0.35-8.52	0.97 0.70-1.35

Note. * denotes significant results at $p < 0.05$.

Table 7 shows that only some sleep disorders are associated with significantly more (self-reported) frequent sleepy driving and having nodded-off or fallen asleep during driving. Aggregating drivers with any type of sleep disorders into a single group shows no significant difference in increased frequency of sleepy driving.

3.1.2 Difference in sleep related habits

The drivers reported their sleep related habits by responding to three questions. First, the drivers answered “yes” or “no” to whether the drivers kept a fairly regular sleep schedule (Table 8). Second, drivers were asked to describe problems they had with their total sleep duration that happened at least three times per week in the last month. The answer was “sufficient” if there was no problem and was used as baseline in OR calculation. Other descriptions are “slightly insufficient”, “markedly insufficient”, and “very insufficient or didn’t sleep at all” (Table 8). Finally, the drivers reported how frequently they felt fatigue immediately upon awakening as “never” (i.e., baseline), “rarely”, “1-2/month”, “1-2/week”, “3-4/week”, or “nearly everyday” (Table 10).

Table 8

Odds ratio of having irregular sleep schedule for drivers with sleep disorders (driver without sleep disorder were treated as “non-disease” and the response “regular” was treated as non-exposure)

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrome	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Irregular sleep schedule	1.44 * 1.17-1.77	0.99 0.11-8.89	1.02 0.70-1.48	2.55 * 1.85-3.53	1.19 0.76-1.87	4.01 * 1.50-10.72	N/A	1.88 * 1.45-2.44

Note. * denotes significant results at $p < 0.05$. N/A means the numerator in OR calculation is 0.

Table 9

Odds ratio of sleep duration for drivers with sleep disorders (driver without sleep disorder were treated as “non-disease” and the response “sufficient” was treated as “non-exposure”)

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrome	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Slightly insufficient	1.45 * 1.21- 1.73	1.02 0.17-6.13	1.60 0.85-1.60	2.55 * 1.77-3.67	0.95 0.63-1.42	2.46 0.80-7.55	0.61 0.12-3.16	1.43 * 1.11-1.85
Markedly insufficient	2.10 * 1.53-2.89	N/A	1.65 0.98-2.79	5.64 * 3.49-9.10	1.45 0.75-2.79	4.98 * 1.17- 20.86	1.65 0.19-14.19	1.84 * 1.99-2.82

Very insufficient or did not sleep at all	2.01 * 2.69-18.89	N/A	1.13 0.15-8.65	31.07 * 11.50-83.95	3.60 0.81-16.06	N/A	N/A	3.65 * 1.17-11.34

Note. * denotes significant results at $p < 0.05$. N/A means the numerator in OR calculation is 0.

Table 10

Odds ratio of feeling fatigued immediately upon awakening for drivers with sleep disorders (drivers without sleep disorders were treated as "non-disease" and the response "never" was treated as "non-exposure")

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrome	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Rarely	1.29 0.91-1.84	N/A	1.13 0.65-1.96	N/A	1.11 0.53-2.35	0.15 0.01-1.67	0.15 0.01-1.67	0.81 0.50-1.31
1-2 times/month	1.55 * 1.03-2.33	N/A	1.10 0.57-2.13	N/A	1.61 0.70-3.68	0.89 0.12-6.34	0.89 0.12-6.34	1.20 0.69-2.09
1-2 times/week	1.64 * 1.12-2.39	N/A	1.10 0.57-2.13	N/A	1.35 0.61-2.99	1.20 0.22-6.59	N/A	1.62 0.99-2.65
3-4 times/week	1.53 * 1.01-2.31	N/A	1.03 0.52-2.03	N/A	1.30 0.54-3.14	0.97 0.14-6.93	0.48 0.04-5.36	1.37 0.79-2.37
Nearly everyday	2.53 * 1.74-3.67	N/A	1.33 0.73-2.44	N/A	1.60 0.72-3.55	1.70 0.33-8.80	0.34 0.03-3.73	2.32 * 1.43-3.76

Note. * denotes significant results at $p < 0.05$. N/A means the numerator in OR calculation is 0.

Results show that drivers with sleep disorders generally have higher likelihood of irregular sleep schedule, insufficient sleep duration, and feeling fatigued immediately upon awakening. However, only some types of sleep disorder are associated with ORs significantly greater than one.

Some ORs are not available due to different reasons. None of drivers with PLMD reported to have irregular sleep schedule while none of narcoleptic participants reported to have problems of "markedly insufficient" and "very insufficient or did not sleep at all" in sleep duration. None of the drivers with SWSD or PLMD reported problems of "very insufficient or did not sleep at all" in sleep duration. Finally, there were no drivers who have narcolepsy or insomnia had “never” felt fatigued immediately upon awakening.

3.1.3 Propensity of Nighttime Driving

In SHRP2, all driving trips were marked by start and end time of day. The trips from 9 PM to 5AM are considered nighttime driving when driving risk is generally considered higher than other times of the day (Centers for Disease Control and Prevention, 2016). Table 11 presents the ORs and 95% CIs of nighttime driving trips.

Table 11

Odds ratio of propensity of nighttime driving for drivers with sleep disorders (drivers without sleep disorders were treated as “non-disease” and daytime trips were treated as “non-exposure”)

	Odds Ratio 95% CI							
	All sleep disorder	Narcolepsy	Sleep apnea	Insomnia	Restless leg syndrom e	Shift work sleep disorder	Periodic limb movement disorder	Migraine
Trips by start time	0.86 0.85-0.86	0.95 0.88-1.02	0.62 * 0.61-0.63	1.06 * 1.04-1.07	0.83 * 0.81-0.84	1.40 * 1.35-1.46	0.24 * 0.21-0.27	1.06 * 1.05-1.08
Trips by end time	0.86 0.85-0.87	0.97 0.90-1.04	0.63 * 0.62-0.64	1.06 * 1.05-1.07	0.81 * 0.79-0.82	1.36 * 1.32-1.41	0.25 * 0.23-0.28	1.08 * 1.07-1.09

Note. * denotes significant results at $p < 0.05$.

As an aggregated group, drivers with sleep disorders drove less nighttime trips than drivers without sleep disorders. Again, the ORs are different across type of sleep disorders. Specifically, the ORs by start and end time are both non-significant for narcoleptic drivers while their ORs and CIs are very close to 1.0. Drivers with sleep apnea, insomnia, RLS, or PLMD, drive significantly less at night than drivers without the sleep disorder. Drivers with insomnia, migraine, and especially SWSD have significantly more nighttime driving.

3.1.4 Summary of descriptive statistics

The descriptive statistics indicate that different sleep disorders yield different odds in frequency of sleepy driving. Second, most drivers with sleep disorders reported some kind of sleep related problem (i.e., irregular sleep schedule, insufficient sleep duration, and feeling fatigued upon awakening). Aggregating across the seven types, drivers with sleep disorders drove less in the nighttime than those without. When separated individually, drivers with sleep apnea, restless leg syndrome, and periodic limb movement disorder drove less at nighttime. Drivers with insomnia, migraine, and especially shift work sleep disorder had significantly more nighttime trips. These findings suggest that the degree of sleepy driving, problems in sleep related habits, and propensity of nighttime driving depends on the type of sleep disorder.

3.2 Driving risk

The safety outcome measures in SHRP2 permits regression modeling to assess driving risk associated with different sleep disorders and demographics factors. Four outcome measures were modelled in mixed-effect logistic regression model, Poisson log-linear regression model, and ordinal logistic regression model.

3.2.1 Risk of crashes/near-crashes

A mixed-effect logistic regression model provides the AORs with 95% CIs for crash/near-crash associated with every sleep disorder, interaction between a sleep disorder and a demographic factor, and other independent variables, such as frequency of sleepy driving (Table 12).

Table 12
Adjusted odds ratio for a crash/near-crashes

Statistically Significant Independent Variables	AOR (95% CI)
Female with restless leg syndrome	2.26 (1.20-4.26)
Insomnia	1.49 (1.07-2.06)
Narcolepsy ($p < 0.1$)	10.24 (0.86-122.24)
Frequency of sleepy driving - “Never”	1.53 (1.01-2.31)
Frequency of sleepy driving - “Rarely”	1.31 (1.02-1.68)
Frequency of sleepy driving - “Sometimes”	1.42 (1.11-1.94)

Note. All results presented are significant at $p < 0.05$ except for Narcolepsy which is marginally significant ($p < 0.1$).

Table 12 shows that female drivers with RLS, drivers with insomnia are associated with significantly and narcolepsy are associated with marginally significantly increased risk of having crashes/near-crashes. These findings confirm Hypothesis 2 and 3 that some types of sleep disorders have higher driving risk and the risk interacts with demographic factors. The results also show that drivers who reported frequency of sleepy driving as “never”, “rarely”, and “sometimes” have AORs greater than one - higher driving risk.

3.2.2 Risk of increased crash/near-crash rate

Poisson log-linear regression model estimated the influence of independent variables on crash/near-crash rate which accounts for driving exposure (i.e., total time traveled by the driver). The parameter estimation yields a predicted risk ratio for each independent variable (of which greater than one indicates increased rate of crash/near-crash). Table 13 presents crash/near-crash rates that are greater than one and the p-value.

Table 13
Predicted risk ratio for crash/near-crash rate

Statistically and Marginally Significant Independent Variables	p-value	Predicted Risk Ratio
Shift Work Sleep Disorder (SWSD)	0.029	7.50
20 – 24 Years Old with SWSD	0.053	0.10

Drivers with SWSD are predicted to have 7.5 times of crash/near-crash rate compared to those who without, except for 20 – 24 years old SWSD drivers who have much lower rate.

3.2.3 Driver Maneuver prior to Crashes/near-crashes

Ordinal logistic regression modeled the multilevel and ordered outcome of driving maneuvers (i.e., “1” as “legal and safe”, “2” as “illegal but safe”, “3” as “legal but unsafe”, and “4” as “illegal and unsafe”). The analysis estimated AORs to show the likelihood of less safe maneuver right before crashes/near-crashes. Table 14 presents the significant risk factors.

Table 14
Ordinal logistic regression model for the likelihood of having less safe maneuver prior to crashes/near-crashes

Statistically Significant Independent Variables ($p < 0.05$)	Estimate	S.E.	AOR
Female with sleep apnea	0.31	0.07	1.36
Female with restless leg syndrome	1.22	0.00	3.38
Shift work sleep disorder	1.26	0.05	3.53
Age group			

16 – 19	0.32	0.00	1.37
75 - 79	0.42	0.01	1.52
80 - 84	0.29	0.08	1.34
85 - 89	0.40	0.00	1.50
90 - 94	1.28	0.00	3.60
Nighttime driving rate	1.90	0.11	6.71
Sleep duration – "very insufficient or did not sleep at all"	0.67	0.07	1.95
Frequency of sleepy driving – "Never"	0.34	0.06	1.40
Frequency of sleepy driving – "Rarely"	0.29	0.06	1.34
Frequency of sleepy driving – "Sometimes"	0.14	0.08	1.15
Frequency of sleepy driving – "Often"	-0.27	0.02	0.76

Note. All results presented are significant at $p < 0.05$.

The analysis suggests that females with sleep apnea (AOR = 1.36) and RLS (AOR = 3.38), and drivers with SWSD (AOR = 3.53) are more likely to perform unsafe maneuver prior to crashes/near-crashes.

Consistent with the literature, the results also show that young drivers, senior drivers and nighttime driving are associated risk of having less safe maneuver.

3.2.4 Severity of crashes/near-crashes

Ordinal logistic regression was used to analyze the severity of a crash/near-crash that is ranked from level one to five – "1" as "not a crash", "2" as "low risk tire strike", "3" as "minor crash", "4" "police reportable crash", and "5" as "most severe crash". Table 15 presents the significant results.

Table 15
Ordinal logistic regression model for the likelihood of more severe crashes/near-crashes

Statistically Significant Independent Variables ($p < 0.05$)	Estimate	S.E.	Adjusted Odds Ratio
Periodic limb movement disorder (PMLD)	0.36	0.004	1.43
Age group			
16 – 19	0.57	0.07	1.77
20 – 24	0.25	0.07	1.28

60 - 64	0.55	0.15	1.74
70 - 74	0.62	0.17	1.87
75 - 79	0.75	0.14	1.87
80 - 84	1.01	0.14	2.11
85 - 89	0.63	0.03	1.88
90 - 94	1.00	0.004	2.73
95 - 99	0.60	0.003	1.83
Nighttime driving rate	0.48	0.03	1.61

Note. All results presented are significant at $p < 0.05$.

The results show that drivers with PLMD have a higher risk of having more severe crashes. Other significant results include that young drivers, senior drivers and nighttime driving are associated with more severe safety-critical events, consistent with the findings for driver maneuver prior to crashes/near-crashes and the literature.

3.2.5 Summary of driving risk associated with sleep disorders

Table 16 summarizes the significant results of the four regression analyses. The analyses find narcoleptic, insomniac, and female with RLS drivers are significantly more likely to have crashes or near-crashes. The Poisson log-linear regression model predicts drivers with SWSD have significantly higher crash/near-crash rate while those who are 20 to 24 years old in this driver group are the exception and actually predicted to be safer. Females with sleep apnea and RLS have significantly higher likelihood of performing more unsafe maneuvers prior to a crash/near-crash. Drivers with PLMD disorder are at risk of more severe safety-critical events.

Table 16
Summary of significantly increased driving risk associated with sleep disorders and gender/age

Sleep Disorders	Risk of crashes/near-crashes AOR	Crash/near-crash rate Predicted rate	Driver maneuver AOR	Crash/near-crash severity AOR
Narcolepsy	10.24	-	-	-
Sleep apnea	-	-	1.36 (female)	-
Insomnia	1.49	-	-	-
Restless leg syndrome	2.26 (female)	-	3.38 (female)	-
Shift work sleep disorder	-	7.50 (main effect) 0.10 (20-24 years old)	-	-

Periodic limb movement disorder	-	-	-	1.43

Note. AOR of narcolepsy is marginally significant. Gender/age in parenthesis stands for interaction between the sleep disorder and gender/age.

4. DISCUSSION

The objective of this research is to investigate the driving risk associated with sleep disorders and their interaction with gender and age in a naturalistic driving environment. The literature indicates that sleepiness leads to crashes (Brown, 1994) while sleep disorder is one of the contributing factors to sleepiness (Lyznicki et al., 1998; Stutts et al., 1999). This study does indicate that frequent sleepy driving is significantly associated with higher risk of crashes/near-crashes and less safe driver maneuvers. Thus, driving risk associated with sleep disorders deserves research attention. However, only drivers with narcolepsy, insomnia, SWSD, and migraine self-reported to be associated with significantly more frequent sleepy driving. Furthermore, among groups significantly associated with higher frequency of sleepy driving, drivers with migraine are not associated with significantly increases in any of the driving risks. Surprisingly, drivers who reported "never" drive sleepy are at higher risk of having crashes/near-crashes and more unsafe driver maneuvers. These findings suggest that assuming driving risk based on self-reported data on driving and sleeping habits requires extreme caution. Further, the variations in driving risks, sleeping and driving habits point to discussion of individual sleep disorders.

4.1 Driving risks associated with sleep disorders

4.1.1 Narcolepsy.

Drivers with narcolepsy have a marginally significant ($p < 0.1$) higher likelihood of crashes/near-crashes (AOR=10.24, 95% CI: 0.86-122.24) that deserves research attention. The sample size of 45 observations and five narcoleptic participants (i.e., 0.14%) in SHRP2 mostly likely contributed to the wide CI. Statistical significant findings on narcolepsy are always challenging to reveal given the low prevalence rate of disease - 0.03% to 0.16% in general population (Longstreth Jr. et al., 2007). Negative impacts of narcolepsy, including excessive daytime drowsiness, uncontrollably falling asleep, and cataplexy, may also contribute to driving risk. As indicated by the SHRP2 questionnaire results, drivers with narcolepsy also have higher likelihood of having nodded-off or fallen asleep while driving (OR=7.74, 95% CI: 1.29-46.45). This finding confirms a survey study of 180 narcoleptic participants, who reported higher likelihood of falling asleep behind the wheel (66%) than the matched control group (Broughton et al., 1981). Further, 29% and 12% of the 180 participants experienced cataplexy and sleep paralysis while driving, respectively. In brief, this study provides the naturalistic driving empirical evidence on the increased crash risk experienced by narcoleptic drivers as suggested by previous simulator research (Aldrich, 1989; Kotterba et al., 2004).

4.1.2 Sleep Apnea

The ordinal logistic regression model of unsafe maneuvers indicates female drivers with sleep apnea (AOR=1.36, $p < 0.05$) have significantly higher likelihood of performing more unsafe maneuvers prior to crashes/near-crashes. The analysis does not yield a significant main effect of sleep apnea. Being more likely to have less safe reactions in the crash-imminent scenarios indicates driving performance is compromised among female sleep apneics, although sleep apnea is more prevalent in males (3% to 7%) than females (2% to 5%) among the general western population (Punjabi, 2008; Young et al., 2002). Also, 3.7% of female and 6.9% of male SHRP2 participants are apneics, matching the prevalence rate of the general population. However, the regression models do not indicate any significant increase in risk of having crashes/near-crashes or crash rate. This finding may be consistent with the literature. George (2004) reviewed five simulator studies of sleep apnea patients and found their driving performance was worse than controls although some participants never had collisions on the road. The review also indicated that driving performance of patients receiving treatment improved to the average crash rate (*ibid*). For this reason, some SHRP2 participants may not exhibit higher crash risk except for the most vulnerable groups. In SHRP2, only 34 out of 188 sleep apneics received prescription or over the counter medication, and some of them reported using multiple medicines. This study omits the investigation into the impact of medication given lack of medication prescription details. The regression model on crash rate also addresses the lack of empirical evidence concerning risk with respect to driving exposure for sleep apneics (Ellen et al., 2006), although the results indicate no significant findings. In brief, female sleep apneics are associated with higher likelihood of unsafe maneuvers, but not all drivers with sleep apnea are exhibiting significantly increased risk of crashes/near-crashes or high crash rate.

4.1.3 Insomnia

Drivers with insomnia are found to have significantly increased risk of having crashes/near-crashes (OR=1.49, 95%CI: 1.07-2.06). This result confirms the higher risk of insomniac drivers in epidemiological studies (Leger et al., 2014; Sagberg, 2006). The descriptive statistics suggest that insomnia affects sleep habits and increases frequency of sleepy driving. First, drivers with insomnia are 1.85 times (95%CI: 1.43-2.98) more likely to "sometimes" drive sleepy than those without. Second, insomniac people have higher risk of irregular sleep schedule (OR=2.55, 95%CI: 1.85-3.35). Third, insomnia is associated with increased likelihood of insufficient sleep duration – slightly insufficient (OR=2.55, 95%CI: 1.77-3.67), markedly insufficient (OR=5.64, 95%CI: 3.49-9.1), and very insufficient or did not sleep at all (OR=31.07, 95%CI: 11.50-83.95). The irregular sleep schedule and insufficient sleep schedule are likely related to insomnia and lead to more frequent sleepy driving. Fulda and Schulz (2001) reviewed eighteen insomnia studies indicating patients with reduced performance in attention and vigilance tasks. While such cognitive decrements may negatively impact driving (Brown, 1994), SHRP2 insomniac drivers are not associated with more unsafe maneuvers prior to crashes/near-crashes. In conclusion, drivers with insomnia are more likely to have crashes/near-crashes.

4.1.4 Shift Work Sleep Disorder (SWSD)

The Poisson log-linear regression model predicted the crash/near-crash rate of drivers with SWSD to be 7.5 times higher than drivers without SWSD. However, 20 to 24 years old drivers with SWSD is an exception as the predicted crash/near-crash rate of this group is 0.1. The whole SWSD group (0.45% of participants) is underrepresented in SHRP2 as the American Academy of Sleep Medicine (2001) estimated that 2 to 5% of Americans have SWSD. Further study with more SWSD patients is necessary to verify the association between SWSD and age. Prior research on rotating and night shift workers found the crash odds can be as high as two times that of regular shift workers (Barger et al., 2005; Gold et al., 1992). However, these studies failed to indicate driving exposure and SWSD diagnosis for the rotating and night shift workers. Taking exposure into account, this SHRP2 analysis confirms that drivers with SWSD are at high risk. The descriptive statistics also reveal that SWSD drivers have increased chance of sleepy driving – "sometimes" driving sleepy (OR=16.52, 95%CI: 3.32-82.28), having had nodded-off or fallen asleep during driving (OR=5.20, 95%CI: 1.94-13.92), irregular sleep schedule (OR=4.01, 95%CI: 1.50-10.72), "markedly" insufficient sleep duration (OR=4.98, 95%CI: 1.17-20.86), and the highest propensity of nighttime driving trips among all seven sleep disorders (based on trip start time: OR=1.40, 95%CI: 1.35-1.46; trip end time: OR=1.36, 95%CI: 1.32-1.41). In summary, SWSD drivers are heavily compromised with their sleeping and driving habits (i.e., driving exposure). The findings suggest that the employers should pay attention to SWSD vulnerable workers, and the government should assist these workers with public transportation to reduce high risk driving.

4.1.5 Restless leg syndrome (RLS)

The impact of restless leg syndrome on driving tends to affect female patients specifically. First, female drivers with RLS have significantly increased risk of crash/near-crash (OR=2.26, 95%CI: 1.20-4.26). Second, the likelihood of females with RLS to perform more unsafe maneuvers prior to crashes/near-crashes is significantly higher (AOR=3.38, $p < 0.05$) than other drivers. These findings can be related to higher prevalence of RLS among females in general population (Smolensky et al., 2011) and in SHRP2. However, the descriptive statistics do not reveal any differences in sleeping and driving habits between drivers with and without RLS. This study is able to reveal the increased driving risk of females with RLS, addressing the lack of empirical evidence in existing literature (Philip & Åkerstedt, 2006; Smolensky et al., 2011),.

4.1.6 Periodic limb movement disorder (PLMD)

The ordinal logistic regression model for crash/near-crash severity reveals that drivers with PLMD are associated with more severe safety-critical events (AOR=1.43, $p < 0.05$). Similar to RLS, descriptive statistics on drivers with PLMD indicate no significant difference in frequency of sleepy driving and sleep related habit of drivers with PLMD. Note that PLMD is underrepresented in SHRP2 dataset because the prevalence rate of PLMD is 3.9% of the general population (Ohayon & Roth, 2002) but only 0.23% of the SHRP2 participants and four crashes/near-crashes relate to PLMD. For this reason, drawing strong conclusions on the increased safety risk for all drivers with PLMD in the US requires caution, even though a previous simulator study found decreased performance among PLMD patients compared to the control group (Gieteling et al., 2012).

4.1.7 Migraine

The analyses of SHRP2 data do not suggest any increased risk related to migraine in contrast to previous epidemiological studies indicating that drivers with migraine have significantly higher risk of having crashes. The descriptive statistics indicate that migraine is associated with higher likelihood of "sometimes" driving sleepy, insufficient sleep duration, and feeling fatigued immediately upon awakening which are some indications of the negative impact of migraine. About 8.4% of SHRP2 participants have migraine, matching the prevalence rate in general population. Although drivers with migraine self-reported to drive sleepy more frequently, they seem insensitive to the negative effect of sleepy driving. The presence of pain for people with migraine may have distorted their perception and thus self-report of sleep behaviors that are commonly associated with driving risk. Further investigation is necessary to examine why strong indication about lack of sleep does not translate to detectable driving risk for this sleep disorder.

4.1.9 Other findings

Consistent with the literature (Anstey, Wood, Lord, & Walker, 2005; Williams, 2003), the regression models confirm that young and senior drivers are associated with higher likelihood of more unsafe maneuvers and more severe crashes/near-crashes.

In addition, the fact that nighttime driving is considered more dangerous than driving during the day (M.-L. Lin & Fearn, 2003) is also confirmed in the study, which indicates an increase in nighttime driving rates yield higher chances of more unsafe maneuver (AOR=6.71, $p < 0.05$) and more severe safety-critical events (AOR=1.61, $p < 0.05$). In the descriptive statistics, the OR of nighttime driving of drivers with sleep apnea, RLS, PLMD, or with any type of the seven sleep disorders is smaller than one. This is might be the indication that drivers with certain sleep disorders are driving less in the night arguably to mitigate their risk because drivers with SWSD drive more in the night (OR=1.40, 95%CI: 1.35-1.46) and high predicted event rate of 7.5.

Though not central to the thesis of this study, these findings provide assurance on the key results on sleep disorders.

4.2 Research Contribution

This is the first study investigating sleep disorder and driving risk with naturalistic driving study data, augmenting current empirical evidence collected from police reports, epidemiological studies, and simulator experiments. Specifically, this study takes driving exposure into account for the assessment of driving safety associated with sleep disorders that are neglected in simulator experiments and potentially biased in epidemiological studies (due to self-report of detailed driving behaviors). Further, the recorded details of vehicle dynamics and videos of the driving in SHRP2 permit assessments of driving maneuvers and crash severity with respect to sleep disorders that are not published in the literature. Finally, the scale and longitudinal nature of the SHRP2 study yield a comparatively large sample size and illustrate representative driving behaviors that are unprecedented in the literature to provide a level of assurance and completeness for studying differences in crash risks between people with and without sleep disorders.

4.3 Implications

The findings in this study not only contribute to empirical research on sleep disorders and road safety but also have practical implications for a variety of stakeholders. First, the study indicates drivers with shift work sleep disorder have 7.5 times higher crash/near-crash rate and drive much more often in nighttime. Hence, employers should consider providing low-cost or alternative transportation for their shift workers and rotators. The public sector might also be able to expand transportation options to aid both employers and employees, thereby improving road safety. Centers for Disease Control and Prevention (2014) estimated that each crash-related emergency department visit costs an average of about $3,300 and each hospitalization about $57,000. The high costs warrant serious consideration for alternative transportation. This high risk factor may also be relevant to insurance company in estimating premiums for some employers with different practice of supporting their workers.

Second, the results on more unsafe driving maneuvers by females with sleep apnea or restless leg syndrome, and more crashes for drivers with insomnia are informative to physicians consulting their patients upon diagnosis. Doctors should inform both driver groups about their significant risk level so they can take greater caution in choosing when to drive. On the other hand, doctors should avoid introducing *undue* fear to low risk patients with other sleep disorders and thereby limiting mobility unnecessarily.

Finally, policy makers should devote attention to licensing individuals with high risk sleep disorders. Currently, Federal Motor Carrier Safety Administration (FMCSA) requires medical qualifying examination to determine if commercial vehicle drivers have a condition – such as sleep apnea – that would affect their ability to safely operate the vehicle. Although some policies related to sleep deprivation exist, there appears to be no standard regulations on issuing passenger vehicle driver’s license in the US. For example, the California Department of Motor

Vehicles (DMV) may revoke a driver's licenses if he or she is sleep deprived. DMVs may also consider instituting doctor examination or training when issuing non-commercial driver's license to those diagnosed with risky sleep disorders. In addition, DMVs may provide additional training to aid patients with sleep disorders in choosing to drive in less risky environment (e.g., day vs night time). Coherent and formal policy can then translate to improved public awareness about sleepy driving in general.

4.4 Limitations

Four limitations are identified. First, the sample size of narcolepsy, shift work sleep disorder, and periodic limb movement disorder are small. While narcoleptic participants match the prevalence rate of narcolepsy, participants with SWSD and PLMD are underrepresented in SHRP2. Further study with adequate sampling is recommended to confirm findings in this study. Second, the association of a sleep disorder and driving risk does not indicate *how* the sleep disorder is negatively affecting the roadway safety. For example, cataplexy is one of most deleterious symptom of narcolepsy, but the current data analysis does not address such symptoms during driving. Research needs to use other assessment methods, such as Observer Rating of Drowsiness (ORD) Scale and PERCLOS, to investigate sleep disorder symptoms for NDS. Third, the effects of medication or other treatments are omitted in this study due to limited information. In other words, the moderating effect of medical treatment of sleep disorders on driving risks is unknown for the naturalistic driving environment. Finally, some non-intuitive predictors are significant such as drivers who "never" drive sleepy are associated with significantly increased driving risk. The cause of motor vehicle crashes, as well as near-crashes, is multifactorial. Given the models in this study were not all-encompassing, significant risk factors that cannot be attributed to sleep disorders are likely associated with those "never" drive sleepy but this study cannot explain such variability.

5. CONCLUSION

This research is the first examination into the association between sleep disorders and driving risk with the SHRP2 Naturalistic Driving Study. SHRP2 provides empirical data that can address some limitations of police reports, epidemiological studies and simulator experiments on driving risks associated with sleep disorders. The results indicate that sleepy driving is generally associated with increased driving risk. However, sleepy driving is not necessarily more common amongst all types of sleep disorders. Driving risks also vary with different sleep disorders. On one hand, significantly higher risks on the road are associated with female with restless leg syndrome or sleep apnea, drivers with insomnia, shift work sleep disorder, and periodic limb movement disorder. On the other, migraine is not associated with increased driving risk. These findings are the first evidence gathered in naturalistic driving environment investigating the negative impact on driving due to the most prominent sleep disorders in the US. These findings can help inform the public sectors in setting transportation policies and regulations, medical professionals in consulting their patients, and the private sector in supporting their employees particularly those who suffer from or are vulnerable to SWSD.

REFERENCES

Aldrich, M. S. (1989). Automobile accidents in patients with sleep disorders. *Sleep*.

American Academy of Sleep Medicine. (2001). International classification of sleep disorders,revised: Diagnostic and coding manual. Chicago, Illinois: American Academy of Sleep Medicine.

Anstey, K. J., Wood, J., Lord, S., & Walker, J. G. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical psychology review, 25*(1), 45-65.

Baloh, R. W. (1997). Neurotology of migraine. *Headache: The Journal of Head and Face Pain, 37*(10), 615-621.

Barger, L. K., Cade, B. E., Ayas, N. T., Cronin, J. W., Rosner, B., Speizer, F. E., & Czeisler, C. A. (2005). Extended work shifts and the risk of motor vehicle crashes among interns. *New England Journal of Medicine, 352*(2), 125-134.

Blincoe, L., Miller, T. R., Zaloshnja, E., & Lawrence, B. A. (2015). *The economic and societal impact of motor vehicle crashes, 2010 (Revised)* (DOT HS 812 013). Retrieved from Washington, DC: http://www-nrd.nhtsa.dot.gov/Pubs/812013.pdf

Broughton, R., Ghanem, Q., Hishikawa, Y., Sugita, Y., Nevsimalova, S., & Roth, B. (1981). Life effects of narcolepsy in 180 patients from North America, Asia and Europe compared to matched controls. *Canadian Journal of Neurological Sciences/Journal Canadien des Sciences Neurologiques, 8*(04), 299-304.

Brown, I. D. (1994). Driver fatigue. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 36*(2), 298-314.

Campbell, K. L. (2012, 2012-9). The SHRP 2 naturalistic driving study: Addressing driver performance and behavior in traffic safety. *TR News,* 30-35.

Centers for Disease Control and Prevention. (2014, October 7). Motor Vehicle Crash Injuries | Vital Signs | CDC. Retrieved from https://www.cdc.gov/vitalsigns/crash-injuries/index.html

Centers for Disease Control and Prevention. (2016, July 28). Graduated Driver Licensing Night Driving Restrictions and Drivers Aged 16 or 17 Years Involved in Fatal Night Crashes — United States, 2009–2014 | MMWR. Retrieved from https://www.cdc.gov/mmwr/volumes/65/wr/mm6529a1.htm

Consens, F. B., & Chervin, R. D. (2007). Sleep Disorders *Textbook of clinical neurology* (Vol. 355, pp. 1267 - 1283). Atlanta, GA: Elsevier Health Sciences.

Earley, C. J. (2003). Restless legs syndrome. *New England Journal of Medicine, 348*(21), 2103-2109.

Ellen, R., Marshall, S. C., Palayew, M., Molnar, F. J., Wilson, K., & Man-Son-Hing, M. (2006). Systematic review of motor vehicle crash risk in persons with sleep apnea. *J Clin Sleep Med, 2*(2), 193-200.

Findley, L. J., Unverzagt, M., Guchu, R., Fabrizio, M., Buckner, J., & Suratt, P. (1995). Vigilance and automobile accidents in patients with sleep apnea or narcolepsy. *CHEST Journal, 108*(3), 619-624.

Findley, L. J., Unverzagt, M. E., & Suratt, P. M. (1988). Automobile accidents involving patients with obstructive sleep apnea. *American Review of Respiratory Disease, 138*(2), 337-340.

Fulda, S., & Schulz, H. (2001). Cognitive dysfunction in sleep disorders. *Sleep medicine reviews, 5*(6), 423-445.

Gamaldo, C., Benbrook, A. R., Allen, R. P., Oguntimein, O., & Earley, C. J. (2009). Evaluating daytime alertness in individuals with Restless Legs Syndrome (RLS) compared to sleep restricted controls. *Sleep medicine, 10*(1), 134-138.

Garbarino, S., Mascialino, B., Penco, M. A., Squarcia, S., De Carli, F., Nobili, L., . . . Ferrillo, F. (2004). Professional shift-work drivers who adopt prophylactic naps can reduce the risk of car accidents during night work. *Sleep, 27*(7), 1295-1302.

George, C. (2004). Sleep· 5: Driving and automobile crashes in patients with obstructive sleep apnoea/hypopnoea syndrome. *Thorax, 59*(9), 804-807.

Gieteling, E. W., Bakker, M. S., Hoekema, A., Maurits, N. M., Brouwer, W. H., & van der Hoeven, J. H. (2012). Impaired driving simulation in patients with periodic limb movement disorder and patients with obstructive sleep apnea syndrome. *Sleep medicine, 13*(5), 517-523.

Gold, D. R., Rogacz, S., Bock, N., Tosteson, T. D., Baum, T. M., Speizer, F. E., & Czeisler, C. A. (1992). Rotating shift work, sleep, and accidents related to sleepiness in hospital nurses. *American journal of public health, 82*(7), 1011-1014.

Guo, F., & Hankey, J. (2009). *Modeling 100-car safety events: A case-based approach for analyzing naturalistic driving data*. Retrieved from Blacksburg, VA: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.184.6266&rep=rep1&type=pdf

Guo, F., Klauer, S., Hankey, J., & Dingus, T. (2010). Near crashes as crash surrogate for naturalistic driving studies. *Transportation Research Record: Journal of the Transportation Research Board*(2147), 66-74.

Hancock, P., & Verwey, W. B. (1997). Fatigue, workload and adaptive driver systems. *Accident Analysis & Prevention, 29*(4), 495-506.

Hankey, J. M., Perez, M. A., & McClafferty, J. A. (2016). *Description of the SHRP 2 Naturalistic Database and the Crash, Near-Crash, and Baseline Data Sets*. Retrieved from Blacksburg, VA: https://vtechworks.lib.vt.edu/handle/10919/70850

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The impact of driver inattention on near-crash/crash risk: An analysis using the 100-car naturalistic driving study data*. Retrieved from Washington, DC: https://vtechworks.lib.vt.edu/handle/10919/55090

Klauer, S. G., Perez, M., & McClafferty, J. (2011). Naturalistic driving studies and data coding and analysis techniques. *Handbook of traffic psychology*, 73-85.

Kotterba, S., Mueller, N., Leidag, M., Widdig, W., Rasche, K., Malin, J.-P., . . . Orth, M. (2004). Comparison of driving simulator performance and neuropsychological testing in narcolepsy. *Clinical neurology and neurosurgery, 106*(4), 275-279.

Leger, D., Bayon, V., Ohayon, M. M., Philip, P., Ement, P., Metlaine, A., . . . Faraut, B. (2014). Insomnia and accidents: cross‐sectional study (EQUINOX) on sleep‐related home, work and car accidents in 5293 subjects with insomnia from 10 countries. *Journal of sleep research, 23*(2), 143-152.

Lerman, Y., Matar, M., Lavie, B., & Danon, Y. L. (1995). Effect of valvular heart diseases, migraine headaches, and perianal diseases on the risk of involvement in motor vehicle crashes. *Journal of Trauma and Acute Care Surgery, 39*(6), 1058-1062.

Lin, L., Faraco, J., Li, R., Kadotani, H., Rogers, W., Lin, X., . . . Mignot, E. (1999). The sleep disorder canine narcolepsy is caused by a mutation in the hypocretin (orexin) receptor 2 gene. *Cell, 98*(3), 365-376.

Lin, M.-L., & Fearn, K. T. (2003). The provisional license: nighttime and passenger restrictions—a literature review. *Journal of safety research, 34*(1), 51-61.
Lipton, R. B., Stewart, W. F., Diamond, S., Diamond, M. L., & Reed, M. (2001). Prevalence and burden of migraine in the United States: data from the American Migraine Study II. *Headache: The Journal of Head and Face Pain, 41*(7), 646-657.
Longstreth Jr., W. T., Koepsell, T. D., Ton, T. G., Hendrickson, A. F., & Belle, G. v. (2007). The epidemiology of narcolepsy. *Sleep, 30*(1), 13-26.
Lyznicki, J. M., Doege, T. C., Davis, R. M., & Williams, M. A. (1998). Sleepiness, driving, and motor vehicle crashes. *Jama, 279*(23), 1908-1913.
Masa, J. F., Rubio, M., & Findley, L. J. (2000). Habitually sleepy drivers have a high frequency of automobile crashes associated with respiratory disorders during sleep. *American journal of respiratory and critical care medicine, 162*(4), 1407-1412.
Mignot, E. (1998). Genetic and familial aspects of narcolepsy. *Neurology, 50*(2 Suppl 1), S16-S22.
Monk, T. H. (1989). A visual analogue scale technique to measure global vigor and affect. *Psychiatry research, 27*(1), 89-99.
National Sleep Foundation. (2009). 2009 Sleep in America Poll Highlights & Key Findings. Retrieved from https://sleepfoundation.org/sites/default/files/2009%20POLL%20HIGHLIGHTS.pdf
Neale, V. L., Dingus, T. A., Klauer, S. G., Sudweeks, J., & Goodman, M. (2005). *An overview of the 100-car naturalistic study and findings*. Retrieved from http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2005/100Car_ESV05summary.pdf
NHTSA. (2008). *National Motor Vehicle Crash Causation Survey: Report to Congress.* (DOT HS 811 059). Retrieved from Washington DC: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811059
NHTSA. (2011). *Traffic Safety Facts: Drowsy Driving* (DOT HS 811 449). Retrieved from Washington, DC: https://crashstats.nhtsa.dot.gov/Api/Public/Publication/811449
Norton, R., Vander Hoorn, S., Roberts, I., Jackson, R., & MacMahon, S. (1997). Migraine: a risk factor for motor vehicle driver injury? *Accident Analysis & Prevention, 29*(5), 699-701.
Ohayon, M. M. (2002). Epidemiology of insomnia: what we know and what we still need to learn. *Sleep medicine reviews, 6*(2), 97-111.
Ohayon, M. M., & Roth, T. (2002). Prevalence of restless legs syndrome and periodic limb movement disorder in the general population. *Journal of psychosomatic research, 53*(1), 547-554.
Philip, P., & Åkerstedt, T. (2006). Transport and industrial safety, how are they affected by sleepiness and sleep restriction? *Sleep medicine reviews, 10*(5), 347-356.
Philip, P., Sagaspe, P., Lagarde, E., Leger, D., Ohayon, M. M., Bioulac, B., . . . Taillard, J. (2010). Sleep disorders and accidental risk in a large group of regular registered highway drivers. *Sleep medicine, 11*(10), 973-979.
Pizza, F., Contardi, S., Antognini, A. B., Zagoraiou, M., Borrotti, M., Mostacci, B., . . . Cirignotta, F. (2010). Sleep quality and motor vehicle crashes in adolescents. *J Clin Sleep Med, 6*(1), 41-45.
Punjabi, N. M. (2008). The epidemiology of adult obstructive sleep apnea. *Proceedings of the American Thoracic Society, 5*(2), 136-143.

Roth, T. (2007). Insomnia: definition, prevalence, etiology, and consequences. *Journal of clinical sleep medicine: JCSM: official publication of the American Academy of Sleep Medicine, 3*(5 Suppl), S7.
Sagberg, F. (2006). Driver health and crash involvement: A case-control study. *Accident Analysis & Prevention, 38*(1), 28-34.
Schwartz, J. R., & Roth, T. (2006). Shift work sleep disorder. *Drugs, 66*(18), 2357-2370.
Shen, J., Barbera, J., & Shapiro, C. M. (2006). Distinguishing sleepiness and fatigue: focus on definition and measurement. *Sleep medicine reviews, 10*(1), 63-76.
Smolensky, M. H., Di Milia, L., Ohayon, M. M., & Philip, P. (2011). Sleep disorders, medical conditions, and road accident risk. *Accident Analysis & Prevention, 43*(2), 533-548.
Strohl, K., Bonnie, R., Findley, L. J., Fletcher, E., Getsy, J., Kryger, M., . . . Walsleben, J. (1994). Sleep-Apnea, Sleepiness, and Driving Risk. *American journal of respiratory and critical care medicine, 150*(5), 1463-1473.
Stutts, J. C., Wilkins, J. W., & Vaughn, B. V. (1999). *Why do people have drowsy driving crashes*. Retrieved from Washington, D.C. : https://m.www.aaafoundation.org/sites/default/files/sleep.PDF
Tan, E., Seah, A., See, S., Lim, E., Wong, M., & Koh, K. (2001). Restless legs syndrome in an Asian population: a study in Singapore. *Movement Disorders, 16*(3), 577-579.
Tregear, S., Reston, J., Schoelles, K., & Phillips, B. (2009). Obstructive sleep apnea and risk of motor vehicle crash: systematic review and meta-analysis. *J Clin Sleep Med, 5*(6), 573-581.
Victor, T., Dozza, M., Bärgman, J., Boda, C.-N., Engström, J., Flannagan, C., . . . Markkula, G. (2015). *Analysis of naturalistic driving study data: Safer glances, driver inattention, and crash risk* (0309274230). Retrieved from https://trid.trb.org/view.aspx?id=1323585
VTTI. (2016). Virginia Tech Transportation Institute | Virginia Tech. Retrieved from http://www.vtti.vt.edu/research/cdras/index.php
Wagstaff, A. S., & Lie, J.-A. S. (2011). Shift and night work and long working hours-a systematic review of safety implications. *Scandinavian journal of work, environment & health, 37*(3), 173-185.
Wierwille, W. W., & Ellsworth, L. A. (1994). Evaluation of driver drowsiness by trained raters. *Accident Analysis & Prevention, 26*(5), 571-581.
Williams, A. F. (2003). Teenage drivers: patterns of risk. *Journal of safety research, 34*(1), 5-15.
Yee, B., Campbell, A., Beasley, R., & Neill, A. (2002). Sleep disorders: a potential role in New Zealand motor vehicle accidents. *Internal medicine journal, 32*(7), 297-304.
Young, T., Blustein, J., Finn, L., & Palta, M. (1997). Sleepiness, driving and accidents: sleep-disordered breathing and motor vehicle accidents in a population-based sample of employed adults. *Sleep, 20*(8), 608-613.
Young, T., Peppard, P. E., & Gottlieb, D. J. (2002). Epidemiology of obstructive sleep apnea: a population health perspective. *American journal of respiratory and critical care medicine, 165*(9), 1217-1239.

APPENDIX A

Descriptions of SHRP 2 NDS Data

Table A 1

Descriptions of Participant Demographics Data from SHRP 2 Used in This Investigation

Number	Description (below are the questions for each participant)
1	Participant ID
2	Participant's gender
3	Participant's age group
4	The participant's associated risk with sleepy driving, rank ranges from 1 to 7. 1 is no greater risk, 4 is moderately greater risk, and 7 is much greater risk.
5	Self-reported frequency of sleepy driving in the past 12 months.
6	The number of crashes in the last three years
7	Sleep schedule. "Y" is regular schedule and "N" is not regular schedule.
8	Average sleep hours per 24 hours when .
9	Average sleep hours per 24 hours when not working.
10	Average sleep needed per 24 hours.
11	Sleepy during daytime.
12	Number of nod off or fall asleep when not driving in the last month.
13	Number of nod off or fall asleep when driving in the last month.
14	Number of nod off or fall asleep when not driving in the last year.
15	Number of nod off or fall asleep when driving in the last year.
16	Frequency of using sleep aids in the last month.
17	Frequency of using sleep aids in the typical month.
18	Sleep aid type.
19	Frequency of being awake for more than 30 hours in the last month.
20	Frequency of being awake for more than 24 but less than 30 hours in the last month.
21	Frequency of being awake for more than 20 but less than 24 hours in the last month.
22	Hours spent on working in the past week.
23	Hours spent on sleeping in the past week.
24	Frequency of fleeing sleepy upon waking.
25	Whether has nodded off or fallen asleep while driving.
26	Subjective problem description of sleep duration in the last month.
27	Subjective problem description of sleep quality in the last month.
28	Subjective description of sleepiness while awake in the last month.

Table A 2

Descriptions of Event Details Data from SHRP 2 Used in This Investigation

Number	Description of Details of Each Event
1	Participant ID
2	Event ID

3	Event details: crash, or near-crash, or baseline (non-event).
4	Crash severity: the severity of crashes.
5	The timestamp, in milliseconds after the start of the file, when the subject vehicle and other object of conflict first make impact. In the case of a near crash, the timestamp when the subject vehicle and other object of conflict are at their closest distance to each other. If more than one incident type occurs, this is coded for the most severe (crash or near crash) or the first incident type if both are the same severity.
6	The pre-event driver maneuvers include safe and legal, safe but illegal, unsafe and illegal, unsafe but legal, and unknown.
7	The subject driver's reaction or avoidance maneuver (if any) in response to the event/incident(s). This is independent of maneuvers associated with or caused by the resulting crash or near-crash. This is a vehicle kinematic measure--based on what the vehicle does.
8	Types of conflict(s) that the subject vehicle has with other objects of conflict for the most severe type of crash, near-crash, or safety-related incident that occurred. The types include animal-related, backing into traffic, backing into fixed object, opposite direction, other, pedal cyclist-related, pedestrian-related, rear-end striking, rear-end struck, road departure (Longstreth Jr. et al.), road departure (left or right), sideswipe, same direction (left or right), straight crossing path, turn across path, turn into path (opposite direction), turn into path (same direction), unknown.
9	Driver behaviors (those that either occurred within seconds prior to the Precipitating Event or those resulting from the context of the driving environment) that include what the driver did to cause or contribute to the crash or near-crash. Behaviors may be apparent at times other than the time of the Precipitating Event, such as aggressive driving at an earlier moment which led to retaliatory behavior later. If there are more than 3 behaviors present, select the most critical or those that most directly impact the event as defined by event outcome or proximity in time to the event occurrence. Populate this variable in numerical order. (If there is only one behavior, name it Behavior 1; if there are two, name them Behaviors 1 and 2.)
10	Best description of the surroundings that influence or may influence the flow of traffic at the time of the start of the precipitating event. If there are ANY commercial buildings, indicate as business/industrial or urban area as appropriate (these categories take precedence over others except for church, school, and playground). Indicate school, church, or playground if the driver passes one of these areas (or is imminently approaching one) at the same time as the beginning of the Precipitating Event (these categories take precedence over any other categories except urban, and divided highway).

Table A 3

Descriptions of Trip Aggregates Data from SHRP 2 Used in This Investigation

Number	Description
1	Participant ID
2	Count of the number of trips that started at hour n, based on UTC time.

3	Count of the number of trips that ended at hour n, based on UTC time.
4	Count of the number of trips that started at hour n, in local time.
5	Count of the number of trips that ended at hour n, in local time.
6	Average trip duration.
7	Mean speed of the entire trip.
8	Maximum speed recorded during the trip.
9	The distance traveled during the trip.
10	The proportion of the trip duration spent in the urban 2 lane class.
11	The proportion of the trip duration spent in the rural 2 lane class.