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Original Article

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Acute sleep deprivation and culpable motor vehicle crash involvement

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Abstract

Study Objectives: To quantify the relationship between acute sleep deprivation and culpable involvement in motor vehicle crashes.

Methods: Participants were 6845 drivers involved in a representative sample of crashes investigated by the US Department of Transportation in years 2005–2007. A modified case–control study design was used to compare self-reported hours of sleep in the 24 hr before crashing between drivers deemed culpable versus nonculpable. Analyses controlled for fatigue-related, driver-related, and environmental factors. Specific errors that led to crashes were also examined.

Results: Drivers who reported having slept for 6, 5, 4, and less than 4 hr in the 24 hr before crashing had 1.3 (95% confidence interval [CI] = 1.04 to 1.7), 1.9 (1.1 to 3.2), 2.9 (1.4 to 6.2), and 15.1 (4.2 to 54.4) times the odds, respectively, of having been culpable for their crashes, compared with drivers who reported 7–9 hr of sleep. Drivers who had slept less than 4 hr had 3.4 (95% CI = 2.1 to 5.6) times the increase in odds of culpable involvement in single-vehicle crashes compared with multiple-vehicle crashes. Recent change in sleep schedule, typically feeling drowsy upon waking, and driving for 3+ hr were also associated with culpability (all $p \leq 0.013$). Assuming nonculpable drivers comprised a representative sample of all drivers present where crashes occurred, these odds ratios approximate incidence rate ratios for culpable crash involvement per unit of time driving.

Conclusions: Driving after having slept less than 7 hr in a 24 hr period is associated with elevated risk of culpable crash involvement. Risk is greatest for drivers who have slept less than 4 hr and is manifested disproportionately in single-vehicle crashes.

Statement of Significance

This is the first study in the peer-reviewed literature to quantify a dose–response relationship between drivers' sleep in the past 24 hr and their risk of causing a motor vehicle crash in a representative sample of crashes involving the general driving population. Risks were elevated measurably for all drivers who slept for less than 7 hr and increased further with decreasing sleep. Drivers who slept for less than 4 hr were found to have crash risk comparable to that reported in previous studies for drivers with blood alcohol concentration roughly 1.5 times the legal limit effective in all US states. These findings could be used to educate drivers, healthcare providers, and policymakers about how sleep deprivation affects driving safety.

Key Words: sleep deprivation; motor vehicle; automobile; crash; accident; driving

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Introduction

Experts recommend that adults should sleep for 7–9 hr per night to promote optimal health [1, 2], yet surveys indicate that approximately one in five US adults sleeps for less than 7 hr on any given night [3], and one in three report usually sleeping for less than 7 hr daily [4]. An estimated 7 per cent of all motor vehicle crashes in the United States and 16 per cent of fatal crashes involve driver drowsiness [5]. The National Transportation Safety Board has identified fatigue as a probable cause, a contributing factor, or a finding in 40 per cent of all of its major highway accident investigations [6].

Studies using laboratory-based measures of attention and reaction time have found that participants kept awake for prolonged periods of time experience longer and more frequent lapses in attention [7]. Studies comparing the effects of sustained wakefulness and alcohol consumption on tasks including reaction time, hand-eye coordination, and simulated driving performance have found similar performance decrements associated with both [8–10]. Case–control studies have compared binary measures of acute sleep deprivation (e.g. ≤5 hr of sleep in the past 24 hr) among drivers involved in real-world crashes versus among controls sampled from the population of non–crash-involved drivers on the road [11, 12]. However, case–control studies to date have not quantified a dose–response relationship between a measure of sleep deprivation and real-world crash risk, largely due to the rarity of encountering drivers who report having slept very little in population-based samples of non-crash-involved drivers, the size of which is typically constrained by resources.

A study design sometimes used to estimate the association of some factor of interest with the risk of causing a motor vehicle crash, in the absence of data on the prevalence of the factor in the general population, is quasi-induced exposure or the related culpability analysis [13–18]. These study designs involve comparing the prevalence of the factor of interest (e.g. sleep deprivation) among drivers found "culpable" or "responsible" (hereafter "culpable") for their crashes versus among drivers found not culpable. From an analytic standpoint, this is analogous to a modified case–control study in which the "disease" is culpability for a crash rather than simple involvement in a crash. The resulting odds ratio (OR) is the ratio of the odds of being culpable versus nonculpable for a crash among crash-involved drivers with versus without the risk factor. While this OR is typically not of substantive interest in itself, under certain assumptions, it approximates a more useful quantity. Specifically, if nonculpable drivers are assumed to have been involved in crashes solely due to the chance occurrence that they were driving at a time and place at which factors outside of their control caused the crash to occur, then they should approximate a random sample of all drivers present at the times and places of crashes. If this assumption holds, the OR for culpability given a crash approximates the OR for culpable crash involvement per unit of time spent driving. Because nonculpable drivers are sampled from among drivers present when new cases arise (i.e. when culpable drivers crash), this OR approximates an incidence rate ratio [19, 20].

In a report published by the AAA Foundation for Traffic Safety (AAAFTS), the author of the current study used the culpability study design to estimate the relationship between the number of hours that drivers had slept in the 24 hr before crashes and their odds of culpability [21]. The current study builds upon and refines the analysis presented in the AAAFTS report by examining the relationships between sleep deprivation and the odds of culpable involvement in single-vehicle crashes and multiple-vehicle crashes separately, by examining the specific types of driving errors committed by culpable drivers in relation to the number of hours that they reported having slept, and by controlling for additional fatigue-related covariates not examined in the AAAFTS study.

Materials and Methods

Design, setting, and participants

This study examined the relationship between the number of hours that crash-involved drivers reported having slept in the 24 hr before crashing and the odds that the drivers were culpable for their crashes, using a modified case–control study design in which cases were drivers classified as culpable and controls were drivers classified as nonculpable.

The current study involved secondary analysis of data collected in a previous study by the US Department of Transportation (DOT) [22–25]. In that study, a sample of 5470 motor vehicle crashes that occurred between July 2005 and December 2007 and involved 10 239 drivers were subject to in-depth multidisciplinary crash investigations that included interviews with drivers by trained investigators independent of law enforcement. Inclusion criteria for the DOT study were that the crash occurred on a public roadway between the hours of 6:00 am and 11:59 pm; involved at least one car, pickup truck, van, minivan, or sport utility vehicle that was towed due to damage; and resulted in emergency medical services dispatch to the scene. Crashes were sampled from 24 central cities, large counties, or groups of counties across the United States stratified by region and extent of urbanization. The sample was designed to be representative of all crashes nationwide subject to the inclusion criteria; a detailed description is available in a report by the US DOT [25].

The data collection performed by the US DOT was authorized under the National Traffic and Motor Vehicle Safety Act of 1966 (Public Law 89–563, Title 1, Section 106) and approved by the US Office of Management and Budget (Control Number 2127-0021). The current study was exempt from IRB review because the DOT study data are available for public use and the author had no interaction with participants nor access to any personal identifying information.

Variables

Outcome variables

The main outcome variable was a binary indicator of whether each driver was classified as culpable or nonculpable for the crash. In some analyses, the outcome variable was the cross-classification of culpability and crash type (single-vehicle versus multiple-vehicle crash).

The author classified each driver as culpable or nonculpable on the basis of specific precrash actions and events documented by the on-scene crash investigators for the DOT study [23, 24]. Specifically, a driver was classified as culpable if the investigators reported that the event that made the occurrence of the crash inevitable (termed "critical precrash event" in the DOT study) was an action by the driver, and the reason for the occurrence of that event (the "critical reason") was an unsafe or illegal action, inaction, or error committed by that driver. Examples of frequently cited critical reasons include the driver's failure to look (e.g. before entering an intersection), driving too fast for conditions or too fast to respond to another driver's actions, and misjudgment of a gap in traffic or of another vehicle's speed. In a small number of crashes, investigators reported that the critical reason for the crash was that the driver was asleep at the onset of the critical precrash event. However, aside from determination that the driver was actually asleep, investigators' judgment of whether a driver was fatigued or drowsy was not considered in their determination of the critical reason [24], nor in the authors' assignment of culpability.

The purpose of the culpability assessment in the context of the current study was solely to differentiate between drivers who played a clear active role in the occurrence of the crash versus drivers who were involved in crashes mainly due to factors beyond their immediate control. The word "culpability" is used only for brevity and consistency with other traffic safety literature; it is not intended to imply a determination of whether a driver was *legally* culpable or "at fault" for the crash. (The DOT investigators did not assign fault [24].)

Explanatory variables

The main explanatory variable was the number of hours that a driver reported having slept in the 24 hr before the crash. This variable was derived from the start and end times of the driver's main sleep and all naps longer than 30 minutes in the 24 hr before the crash, which drivers reported to crash investigators in interviews conducted at the crash scene or elsewhere (e.g. a medical facility) shortly after the crash [24]. Sleep was not the focus of the interview; only a small portion of all interview questions pertained to sleep.

For analysis purposes, the number of hours that the driver had slept in the 24 hr before the crash was grouped into 1 hr intervals. Few drivers reported less than 3 hr of sleep, thus drivers who reported less than 3 hr of sleep were grouped with drivers who reported having slept for 3 hr. Drivers who reported having slept for 7–9 hr in the past 24 hr were used as the reference group because this is the amount of sleep that experts recommend for healthy adults [1, 2].

Fatigue-related covariates included in the study were:

- A binary indicator of whether the driver reported having changed his or her sleep or work hours in the 7 days preceding the crash, to capture the potential effect of Circadian disruption.
- A binary indicator of whether the driver reported that he or she typically felt fatigued or drowsy upon waking (in general, not specifically on the day of the crash), to reflect effects of possible chronic sleep restriction, sleep disorders, chronotype, or other medical issues not recorded in the data.
- The number of hours that the driver reported having been driving prior to the crash (<1, 1, 2, 3+), to reflect possible task-related fatigue.

Potential confounders included in analyses were as follows: driver age in years (modeled using age and age squared to account for the curvilinear relationship between age and crash rate [26]), sex; vehicle type (car or light truck versus large truck or bus); road type (one way, two-way undivided, two-way with center left turn lane, two-way without positive median barrier; two-way with positive median barrier), speed limit (<35; 35–40; 45–50; 55+ miles per hour), weather conditions (binary indicators for presence of rain, sleet or freezing rain, snow, and fog), roadway surface conditions (dry; wet; other), and lighting conditions (daylight; dark-unlit; dark-lit; dawn; dusk). In addition, hour of day, day of week, season of year, and jurisdiction in which the crash occurred were included in models to increase the plausibility of the assumption that nonculpable drivers were representative of all drivers present at the times and places at which the culpable drivers crashed.

Inclusion and exclusion criteria

Drivers from the original DOT study were included in the current study if they were:

- Driving a car or truck, and
- Involved in a crash in which a driver of a car or truck (i.e. this driver or another driver) was classified as culpable per the criteria outlined previously.

Drivers were excluded from the current study if they:

- Were not driving a car or truck (e.g. driving a motorcycle, farm equipment, construction equipment, or other/unknown vehicle type), or
- Suffered an incapacitating medical event (e.g. heart attack, stroke, or seizure) immediately prior to the crash, or
- Were involved in a crash in which no eligible driver was classified as culpable. These included crashes in which:
    - The culpable driver was driving an ineligible vehicle type, or
    - No driver was culpable because investigators determined that the critical reason for the critical precrash event was vehicle mechanical failure, an environmental condition, or an action by a pedestrian or bicyclist, or
    - No driver was classified as culpable because investigators were unable to determine the critical reason for the critical precrash event.

Of the 10 239 drivers in the original DOT study, 801 were excluded per the criteria outlined above (52 were not driving a car or truck; 611 were involved in a crash in which no eligible driver was classified as culpable; 138 suffered an incapacitating medical event immediately prior to the crash). After these exclusions, 9438 drivers remained for analysis.

Statistical analysis

The relationship between the number of hours that a driver reported having slept in the 24 hr before the crash and the odds that the driver was deemed culpable for the crash was quantified using logistic regression. Ordinary logistic regression was used to estimate the relationship between sleep and the overall odds of culpability for any crash irrespective of crash type. Multinomial logistic regression was used to quantify the effects of sleep deprivation on the odds of culpable involvement in single-vehicle crashes and multiple-vehicle crashes specifically [15, 27].

Data were weighted to account for each crash's probability of selection for the original DOT study [24]. All analyses were based on the weighted data. Statistical tests accounted for the stratification and clustering of the sample. The statistical significance of bivariate comparisons was evaluated using chi-square tests adjusted for stratification and clustering and converted to F statistics [28]. Variances of ORs were estimated using the robust variance estimator. Heterogeneity of the effect of sleep deprivation and covariates on culpability for single-vehicle versus multiple-vehicle crashes was evaluated using Wald tests of differences of the respective ORs after estimating the multinomial logistic regression model [29]. Analyses were performed using Stata version 15.0 (StataCorp LP, College Station, TX).

The distributions of the critical reasons for crashes among culpable drivers in relation to the number of hours that they had slept were examined *post hoc*.

Missing values

Drivers with missing values for variables needed to classify hours of sleep (n = 2593; 27.5% of eligible drivers) were excluded from statistical analysis. The proportions of drivers missing data on sleep did not differ statistically nor practically between nonculpable drivers, drivers culpable for single-vehicle crashes, and drivers culpable for multiple-vehicle crashes (27.4%, 28.0%, and 27.4%, respectively; p = 0.90). The majority of these drivers (n = 1903; 73.4% of drivers with missing sleep) simply were not interviewed and thus had no opportunity to report their sleep.

A small portion of eligible drivers who reported their hours of sleep had missing values for one or more covariates or confounders (number missing: time driving before crash, 222; speed limit, 76; feeling fatigued/drowsy upon waking, 55; changed sleep/work schedule, 30; age, 2). Missing values of these variables were imputed so that all eligible drivers who reported their sleep could be included in analyses. Imputation was performed 10 times using the method of chained equations [30], producing 10 independent data sets with missing values replaced by imputed values. All variables included in the above-described analyses were included in the imputation model for each variable; missing values were assumed missing at random conditional upon the covariates included in the model. The above-described analyses were performed on each imputed data set separately and were then combined to incorporate the uncertainty in the imputed values into the estimates of variances [31].

Assessment of possible biases

Three potential sources of bias in the current study are violation of the assumption that nonculpable drivers comprise a representative sample of all drivers present at the times and places where crashes occur, bias in self-reported hours of sleep, and lack of data on alcohol and drug use for most drivers.

Representativeness of nonculpable drivers

To test the assumption that nonculpable drivers comprised a representative sample of all drivers present at the times and places where crashes occurred, the characteristics of the nonculpable driver sample were compared between three distinct groups of nonculpable drivers:

1. Nonculpable drivers involved in two-vehicle crashes,
2. Nonculpable driver involved first in crashes involving three or more vehicles, and
3. Nonculpable drivers involved later in crashes involving three or more vehicles.

The rationale behind this comparison is that nonculpable involvement later in the sequence of events in a chain-reaction crash arguably is influenced more by random chance and less by driver behavior or performance than is involvement as the first nonculpable driver in a crash. Thus, similarity between these three groups supports the assumption that nonculpable drivers comprise a representative sample of all drivers present when and where crashes occur, whereas dissimilarity refutes that assumption [32, 33].

Bias in self-reported hours of sleep

The sensitivity of the main results to biases in self-reported hours of sleep was examined by simulating various hypothetical scenarios in which 0, 10, or 25 per cent of culpable and/or nonculpable drivers exaggerated how much they had slept by an average of 1 hr. For each scenario, 500 simulations were performed in which the main analysis was replicated with hypothetical overreporting of sleep, modeled as a truncated normal distributed random variable with mean 1 hr; SD 1 hr; and minimum 0, subtracted from the self-reported sleep of a random sample of the drivers indicated for that scenario. Odds of culpability were then calculated in relation to drivers' hypothetical "actual" hours of sleep rather than the number of hours that they reported. Results reported for each scenario are the median OR from the 500 simulations and the 95 per cent simulation interval of the OR (2.5th and 97.5th percentiles) adjusted for random error [34].

Lack of data on alcohol and drugs

The DOT study did not collect blood samples to test for alcohol or drugs; thus, the only source of data available for most drivers regarding alcohol or drug use was the police report associated with the crash, which in most instances was not verified by chemical tests. To attempt to gain some insight into possible bias due to lack of data on alcohol and drug use, the main analysis was replicated with drivers for whom the police affirmatively indicated alcohol or illegal drug use excluded (n = 195).

Results

Description of sample

Table 1 shows the number of hours that drivers reported having slept in the 24 hr prior to crashes, fatigue-related covariates, and selected confounders in relation to driver culpability for the crash and crash type among the 6845 drivers included in the final study sample. Overall, 78 per cent of nonculpable drivers and 70 per cent of culpable drivers reported having slept for 7–9 hr in the 24 hr before crashing, 7 per cent of nonculpable and 8 per cent of culpable drivers reported 6 hr of sleep, and small percentages reported less than 6 hr of sleep. The distribution of hours of sleep in the 24 hr before the crash varied significantly between culpable and nonculpable drivers (p < 0.0001). Notably, all but 5 of the 80 drivers who reported less than 4 hr of sleep were classified as culpable.

The proportion of drivers who had changed their sleep or work schedule in the past 7 days (6% of culpable versus 4% of nonculpable; p < 0.0001), the proportion who reported usually feeling fatigued or drowsy upon waking (9% of culpable versus 4% of nonculpable; p = 0.0001), the age distribution (p < 0.0001), and the distribution of crashes by time of day (p = 0.025) differed significantly between culpable versus nonculpable drivers as well. Culpable and nonculpable drivers differed marginally with respect to the day of week on which they crashed (p = 0.067) and the number of hours that they had been driving prior to crashing (p = 0.085). They did not differ with respect to sex (p = 0.22).

The distribution of hours of sleep also differed significantly between drivers culpable for single-vehicle versus multi-vehicle

Table 1. Hours of sleep in 24 hr before crash involvement and selected covariates in relation to culpability for crashes and crash type, drivers involved in sample of crashes subject to in-depth investigations, United States, 2005–2007

	Nonculpable drivers (*n* = 3245)		Culpable drivers (*n* = 3600)		*P*	Culpable drivers in multiple-vehicle crashes (*n* = 2727)		Culpable drivers in single-vehicle crashes (*n* = 873)		*P*
Hours of sleep in 24 hr before crash	Unweighted *N* (Weighted column %)									
<4:00	5	(<1)	75	(3)	<0.0001	34	(1)	41	(6)	0.006
4:00–4:59	20	(<1)	51	(1)		33	(1)	18	(2)	
5:00–5:59	51	(1)	102	(2)		69	(2)	33	(2)	
6:00–6:59	260	(7)	329	(8)		236	(8)	93	(9)	
7:00–9:59	2396	(78)	2417	(70)		1863	(71)	554	(68)	
≥10:00	513	(13)	626	(16)		492	(17)	134	(13)	
Changed sleep/work schedule in past 7 days										
Yes	135	(4)	226	(6)	<0.0001	147	(5)	79	(8)	0.12
No	3102	(96)	3352	(94)		2564	(95)	788	(92)	
Typically feels fatigued/drowsy upon waking										
Yes	166	(4)	373	(9)	0.0001	247	(8)	126	(14)	0.067
No	3054	(96)	3197	(91)		2462	(92)	735	(86)	
Hours of driving on trip before crash										
<1:00	2948	(93)	3184	(91)	0.085	2454	(92)	730	(87)	0.039
1:00–1:59	138	(5)	173	(5)		113	(4)	60	(6)	
2:00–2:59	37	(1)	56	(2)		31	(1)	25	(2)	
≥3:00	31	(1)	56	(3)		33	(2)	23	(4)	
Age (years)										
<25	652	(20)	1214	(35)	<0.0001	853	(33)	361	(41)	0.034
25–44	1388	(43)	1243	(33)		942	(33)	301	(35)	
45–64	940	(29)	733	(19)		584	(21)	149	(16)	
≥65	265	(9)	408	(12)		347	(14)	61	(8)	
Sex										
Female	1413	(44)	1612	(47)	0.22	1236	(48)	376	(44)	0.18
Male	1832	(56)	1988	(53)		1491	(52)	497	(56)	
Time of day										
6:00–8:59 am	543	(16)	624	(19)	0.025	440	(16)	184	(26)	0.0002
9:00–11:59 am	434	(14)	464	(13)		365	(15)	99	(8)	
12:00–2:59 pm	1003	(31)	1045	(29)		844	(33)	201	(20)	
3:00–5:59 pm	627	(17)	667	(14)		531	(15)	136	(13)	
6:00–8:59 pm	485	(17)	575	(19)		413	(18)	162	(22)	
9:00–11:59 pm	153	(5)	225	(7)		134	(5)	91	(12)	
Day of week										
Monday–Friday	2632	(81)	2837	(78)	0.067	2219	(81)	618	(70)	0.002
Saturday	354	(10)	437	(12)		296	(10)	141	(18)	
Sunday	259	(9)	326	(10)		212	(9)	114	(11)	

Data were weighted to account for differential sampling probabilities of crashes. Missing values not shown. Number of missing values: hours driving on trip before crash: 222; typically feels fatigued/drowsy upon waking: 55; changed sleep/work schedule within past 7 days: 30; age: 2. Data: National Highway Traffic Safety Administration (2008).

crashes ($p = 0.006$), with the shortest sleep durations more common among drivers culpable for single-vehicle crashes than multi-vehicle crashes. Culpable drivers involved in single-vehicle crashes also tended to have been driving for longer prior to the crash ($p = 0.039$), had a greater proportion of their crashes before 9:00 am and after 9:00 pm ($p = 0.0002$) and on the weekend ($p = 0.002$). Culpable drivers in single-vehicle crashes also tended to be younger than culpable drivers in multiple-vehicle crashes ($p = 0.034$) and were marginally more likely to report typically feeling fatigued or drowsy upon waking ($p = 0.067$).

Sleep deprivation and odds of culpability

Table 2 shows ORs for the associations of sleep in the past 24 hr and fatigue-related covariates with culpability for crashes. Compared with drivers who reported having slept for 7–9 hr in the 24 hr before the crash, drivers who reported less than 7 hr of sleep had statistically elevated odds of having been culpable for the crash, with ORs ranging from 1.3 (95% confidence Interval [CI] = 1.04 to 1.7) for drivers who reported having slept for 6 hr to 15.1 (95% CI = 4.2 to 54.4) for drivers who reported having slept for less than 4 hr. Odds of culpability were elevated slightly for drivers who reported having slept for 10 hr or more; however, this was not statistically significant (OR 1.3, 95% CI = 0.9 to 1.7). Odds of culpability were also elevated significantly for drivers who had changed their sleep or work schedule in the past 7 days (OR 1.3, 95% CI = 1.1 to 1.6), drivers who reported that they typically felt fatigued or drowsy upon waking (OR 2.2, 95% CI = 1.5 to 3.2), and drivers who had been driving for 3 hr or longer prior to the crash (OR 2.9, 95% CI = 1.4 to 6.1) relative to those who had been driving for less than 1 hr.

ORs for culpable involvement in single-vehicle and multiple-vehicle crashes differed significantly from one another ($p = 0.008$ for heterogeneity of all ORs for sleep by crash type). Post hoc comparisons revealed that the only statistically significant difference

Table 2. Odds ratios for driver culpability in relation to total hours of sleep in 24 hr before crash and fatigue-related covariates

	Odds ratio (95% confidence interval)
Hours of sleep in 24 hr before crash	
<4:00	**15.1 (4.2–54.4)**
4:00–4:59	**2.9 (1.4–6.2)**
5:00–5:59	**1.9 (1.1–3.2)**
6:00–6:59	**1.3 (1.04–1.7)**
7:00–9:59	1 (Reference)
≥10:00	1.3 (0.9–1.7)
Changed sleep or work schedule in past 7 days	
Yes	**1.3 (1.1–1.6)**
No	1 (Reference)
Typically feels fatigued/drowsy upon waking	
Yes	**2.2 (1.5–3.2)**
No	1 (Reference)
Hours of driving on trip before crash	
<1:00	1 (Reference)
1:00–1:59	1.2 (0.7–2.1)
2:00–2:59	1.0 (0.5–2.1)
≥3:00	**2.9 (1.4–6.1)**

Odds ratios estimated using logistic regression. All odds ratios adjusted for driver age, sex, vehicle type, road type, speed limit, weather conditions, roadway surface conditions, lighting conditions, hour of day, day of week, season of year, jurisdiction in which crash occurred, and all other variables in table. Odds ratios statistically significant at 95% confidence level are shown in bold. Data: National Highway Traffic Safety Administration (2008).

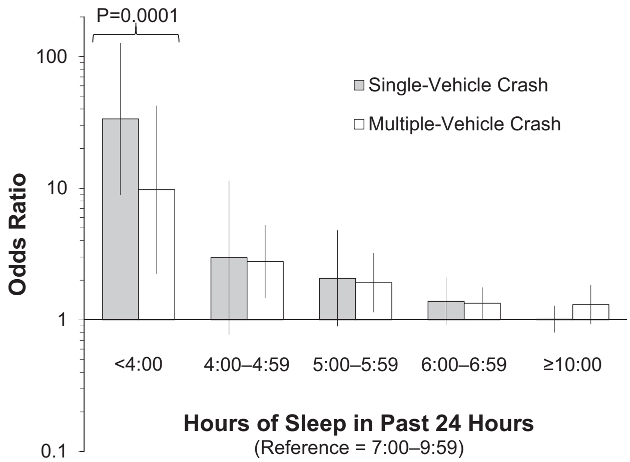

Figure 1. Odds ratios and 95% confidence intervals for driver culpability for single-vehicle crashes and multiple-vehicle crashes in relation to total hours of sleep in 24 hr before crash. Odds ratios estimated using multinomial logistic regression (base outcome: nonculpable involvement in a multiple-vehicle crash). Odds ratios adjusted for driver age, sex, vehicle type, road type, speed limit, weather conditions, roadway surface conditions, lighting conditions, hour of day, day of week, season of year, jurisdiction in which crash occurred, recent change in sleep schedule, usually feeling fatigued or drowsy upon waking, and hours of driving on trip before crash. Value of *p* is from Wald test of difference between odds ratios for culpability for single-vehicle versus multiple-vehicle crash. Data: National Highway Traffic Safety Administration (2008).

between ORs for culpable involvement in single-vehicle versus multiple-vehicle crashes was for drivers who had slept for less than 4 hr (Figure 1). Compared with drivers who had slept for 7–9 hr, drivers who had slept for less than 4 hr had 33.6 times the odds of culpable involvement in single-vehicle crashes (95% CI = 8.9 to 126.8) and 9.7 (95% CI = 2.2 to 42.4) times the odds of culpable involvement in multiple-vehicle crashes (ratio of ORs 3.4, 95% CI = 2.1 to 5.6, $p = 0.0001$). Ratios of ORs for culpable involvement in single-vehicle versus multiple-vehicle crashes for drivers who reported 4, 5, 6, and 10+ hr of sleep relative to drivers who reported 7–9 hr of sleep were 1.1 (95% CI = 0.4 to 3.1), 1.1 (95% CI = 0.5 to 2.2), 1.0 (95% CI = 0.7 to 1.6), and 0.8 (95% CI = 0.5 to 1.1), respectively.

ORs for culpable involvement in single-vehicle crashes did not differ significantly from those for culpable involvement in multiple-vehicle crashes for drivers who reported having changed their sleep or work schedules in the 7 days preceding the crash (ratio of ORs 1.0, 95% CI = 0.7 to 1.4). The OR for culpable involvement in single-vehicle vehicle crashes associated with typically feeling fatigued or drowsy upon waking (OR 3.1, 95% CI = 1.6 to 6.1) appeared considerably larger than the corresponding OR for culpable involvement in multiple-vehicle crashes (OR 1.9, 95% CI = 1.3 to 3.0); however, these did not differ significantly from one another (ratio of ORs 1.6, 95% CI = 0.8 to 3.3). ORs for culpable crash involvement in relation to hours of driving prior to the crash did not differ between single-vehicle versus multiple-vehicle crashes ($p = 0.89$ for heterogeneity of all ORs for hours of driving by crash type).

Critical reasons for crash involvement in relation to hours of sleep

Table 3 shows the types of driving actions, inactions, and errors recorded by DOT investigators as the critical reasons for culpable drivers' involvement in crashes in relation to the number of hours that they reported having slept. The distribution of the types of critical reasons differed significantly in relation to hours of sleep ($p = 0.0003$). Notably, the proportion of culpable drivers who were reported to have actually been asleep at the time of the critical precrash event increased monotonically with decreasing hours of sleep, ranging from 1.4 per cent (CI = 1.0% to 2.0%) among drivers who reported having slept for 7+ hr to 32 per cent (CI = 24% to 41%) among drivers who reported having slept for less than 4 hr ($p = 0.0001$ for trend). Overcompensation and poor directional control, possibly suggestive of a driver recovering from a microsleep, were also cited much more frequently among culpable drivers who reported less than 4 hr of sleep (overcompensation: 23%, CI = 13% to 37%; poor directional control: 14%, CI = 6% to 28%) than among those who reported 4 or more hours of sleep (overcompensation: 5%, CI = 4% to 7%; poor directional control: 4%, CI = 3% to 5%). Excluding crashes in which the culpable driver fell asleep, the distributions of critical reasons were similar among drivers who reported 5, 6, and 7+ hr of sleep ($p = 0.36$).

Assessment of possible biases

Representativeness of nonculpable drivers

Table 4 compares sleep, fatigue-related covariates, and driver demographics between three groups of nonculpable drivers: those involved in two-vehicle crashes, those involved first in crashes with three or more vehicles, and those involved later in crashes with three or more vehicles. Neither nonculpable drivers in two-vehicle crashes nor nonculpable drivers involved first in crashes with three or more vehicles differed significantly from nonculpable drivers involved later in crashes with three or more vehicles. While some comparisons approached statistical significance, all differences were small in a practical sense (e.g. drivers involved later in crashes with three or more vehicles were slightly more likely to report 7–9 hr of sleep and slightly less likely to report 6 or 10+ hr of sleep than the other two groups). Assuming that nonculpable involvement later in the sequence

Table 3. Critical reasons for crashes in relation to hours of sleep in the 24 hr before the crash among drivers classified as culpable

	Hours of sleep in 24 hr before crash					
	<4:00 (*n* = 75)	4:00–4:59 (*n* = 51)	5:00–5:59 (*n* = 102)	6:00–6:59 (*n* = 329)	≥7:00 (*n* = 3043)	Total (*n* = 3600)
	Weighted column %					
Failed to look/look but did not see	6	17	14	34	27	27
Excessive speed	6	8	14	15	13	13
In-vehicle distraction	7	14	24	14	12	12
Misjudgment (e.g. gap, speed, others' actions)	0.4	3	8	8	11	10
Overcompensation	23	4	5	3	5	6
External distraction	1	2	3	3	5	5
Poor directional control	14	5	2	3	4	4
Inattention/daydreaming	3	4	2	4	4	4
Decision error (e.g. turned with obstructed view)	1	2	6	3	4	4
Driver sleeping (i.e. actually asleep)	32	24	11	7	1	3
Incorrect or inadequate evasive action	4	11	4	1	3	3
Illegal maneuver	2	0	0.2	1	3	3
Other/unknown action, error, or inaction	2	7	6	3	6	6

The critical reason was the reason for the critical precrash event that made the occurrence of the crash unavoidable as assessed by on-scene crash investigators. Data were weighted to account for differential sampling probabilities of crashes; thus, some percentages in table do not equate to whole numbers of drivers. Data: National Highway Traffic Safety Administration (2008).

Table 4. Comparison of sleep and selected covariates between three groups of nonculpable drivers

	Nonculpable driver in 2-vehicle crash (*n* = 2218)	First nonculpable driver in 3+ vehicle crash (3V_1st) (*n* = 551)	Later nonculpable driver in 3+ vehicle crash (3V_Later) (*n* = 476)	P value: 2-vehicle vs. 3V_Later	P value: 3V_1st vs. 3V_Later
Hours of sleep in 24 hr before crash		Column %			
<4:00	0.1	0.0	0.1	0.16	0.26
4:00–4:59	0.4	0.5	0.4		
5:00–5:59	0.7	2.2	0.9		
6:00–6:59	8.3	5.1	4.9		
7:00–9:59	77.1	77.5	83.3		
≥10:00	13.5	14.7	10.5		
Changed sleep/work schedule within past 7 days					
Yes	3.4	3.7	4.8	0.31	0.43
No	96.6	96.3	95.3		
Typically feels fatigued/drowsy upon waking					
Yes	3.9	4.5	5.1	0.42	0.63
No	96.1	95.5	94.9		
Hours driving on trip before crash					
<1:00	92.7	94.7	92.5	0.71	0.54
1:00–1:59	5.0	3.3	4.1		
2:00–2:59	1.3	0.3	2.7		
≥3:00	1.0	1.6	0.7		
Age (years)					
<25	19.6	23.7	16.9	0.45	0.19
25–44	42.8	42.0	45.8		
45–64	29.1	26.0	28.2		
≥65	8.5	8.3	9.1		
Sex					
Female	43.0	47.0	45.9	0.51	0.89
Male	57.0	53.0	54.1		

Data were weighted to account for differential sampling probabilities of crashes; thus, some percentages in table do not equate to whole numbers of drivers. Data: National Highway Traffic Safety Administration (2008).

of events in a crash involving many vehicles is more plausibly a random occurrence than is the involvement of the first nonculpable driver, this similarity supports the assumption that the nonculpable drivers approximate a random sample of the drivers present at the times and places at which crashes occurred [32, 33].

Bias in self-reported hours of sleep

Table 5 shows ORs from simulations of various scenarios in which 0, 10, or 25 per cent of culpable and/or nonculpable drivers were assumed to have overreported how much they had slept by an average of 1 hr. The upper left quadrant of the table shows results obtained assuming no systematic overreporting of sleep by culpable nor nonculpable drivers (i.e. the main results from Table 2). The other groups of ORs on the main diagonal represent nondifferential overreporting of sleep by culpable and nonculpable drivers. In these scenarios, simulated results suggest that nondifferential overreporting of sleep would cause the main study results to overestimate the magnitude of the effect of sleep deprivation on culpable crash involvement, but preserve the correct general pattern of the associations.

Values above the main diagonal represent differential overreporting in which culpable drivers were more likely than nonculpable drivers to exaggerate how much they had slept. Simulation results suggest that this type of differential overreporting of sleep would cause the main results to underestimate the effect of sleep deprivation on culpable crash involvement, with the possible exception of drivers who slept less than 4 hr. Because so few nonculpable drivers reported having slept for less than 4 hr, the misclassification of even a small number of nonculpable drivers who actually slept for less than 4 hr into other sleep categories could still bias this OR away from the null, even if similar exaggeration of sleep were considerably more common among the culpable drivers.

Values below the main diagonal represent differential overreporting in which nonculpable drivers were more likely than culpable drivers to overreport their sleep. These simulated results indicate that this type of differential overreporting of sleep would cause the main study results to overestimate the effect of sleep deprivation on culpable crash involvement.

Lack of data on alcohol and drugs

Removing 195 drivers for whom police reported presence of alcohol or drugs had minimal statistical and practical impact on the main study results. The overall OR for culpability associated with 6 hr of sleep did not change in magnitude but was no longer statistically significant (OR 1.3, 95% CI = 0.9 to 1.8). The ORs for culpability associated with less than 4 hr of sleep remained statistically significant but decreased slightly in magnitude to 12.6 (95% CI = 3.2 to 51.7) for all crashes, 8.7 (95% CI = 2.0 to 38.5) for multiple-vehicle crashes, and 25.0 (95% CI = 5.3 to 116.9) for single-vehicle crashes.

Discussion

This study quantified a dose–response relationship between the amount that a crash-involved driver reported having slept in the 24 hr preceding crash involvement and the odds that the driver was found culpable for the crash. Drivers who reported having slept for less than 7 hr had a statistically detectable increase in the odds of having been culpable, the magnitude of which increased as hours of sleep decreased. If nonculpable drivers comprise a representative sample of all drivers present where crashes occur, these ORs approximate incidence rate ratios for culpable crash involvement per unit of time spent driving.

The current study builds upon and refines previous work by the same author [21], producing several new findings. Drivers who had slept for less than 4 hr experienced a significantly greater increase in odds of culpable involvement in single-vehicle crashes than multiple-vehicle crashes. This finding is consistent with previous literature [5, 35] and is important because single-vehicle crashes are over three times as likely as multiple-vehicle crashes to result in fatalities [36]. Another novel finding of the

Table 5. Odds ratios for driver culpability in relation to hours of sleep under scenarios in which various proportions of culpable and/or nonculpable drivers overreported how much they had actually slept

	Culpable drivers		
	No overreporting	Overreported by 10%	Overreported by 25%
Nonculpable drivers	Odds ratio (95% confidence interval)		
No overreporting			
<4:00	**15.1 (4.2–54.4)**	**18.9 (5.3–56.4)**	**25.2 (7.2–85.2)**
4:00–4:59	**2.9 (1.4–6.2)**	**4.4 (2.1–9.1)**	**6.9 (3.5–15.4)**
5:00–5:59	**1.9 (1.1–3.2)**	**3.3 (2.0–5.6)**	**6.0 (3.3–9.8)**
6:00–6:59	**1.3 (1.0–1.7)**	**1.6 (1.3–2.0)**	**2.0 (1.5–2.7)**
≥10:00	1.3 (0.9–1.7)	1.2 (0.9–1.6)	1.1 (0.8–1.5)
Overreported by 10%			
<4:00	**5.7 (1.7–21.6)**	**7.4 (2.0–29.1)**	**8.6 (2.8–32.3)**
4:00–4:59	1.3 (0.6–2.6)	2.0 (0.8–4.6)	**2.8 (1.1–5.7)**
5:00–5:59	0.8 (0.4–1.3)	1.4 (0.8–2.5)	**2.0 (1.1–3.5)**
6:00–6:59	1.0 (0.8–1.3)	1.2 (0.9–1.6)	**1.5 (1.1–2.0)**
≥10:00	1.3 (1.0–1.7)	1.2 (0.9–1.6)	1.2 (0.8–1.6)
Overreported by 25%			
<4:00	2.7 (0.6–8.8)	**4.2 (1.2–17.7)**	**4.5 (1.2–17.6)**
4:00–4:59	0.7 (0.3–1.4)	1.2 (0.5–2.8)	1.6 (0.6–3.5)
5:00–5:59	0.4 (0.2–0.7)	0.8 (0.5–1.5)	1.2 (0.7–2.2)
6:00–6:59	0.7 (0.6–0.9)	1.0 (0.8–1.3)	1.1 (0.8–1.6)
≥10:00	1.3 (1.0–1.7)	1.3 (0.9–1.7)	1.2 (0.9–1.6)

Odds ratios are medians from 500 simulations in which hypothetical overreporting of sleep was modeled as a truncated normal distributed random variable (mean 1 hr; SD 1 hr; minimum 0) subtracted from self-reported hours of sleep for a randomly selected subset of drivers as indicated for each row/column of table. Endpoints of 95% confidence interval are 2.5th and 97.5th percentile odds ratios from simulation adjusted for random error. All odds ratios are adjusted for driver demographics, environmental factors, and fatigue-related covariates as in main analysis. Odds ratios in upper left quadrant of table are the main study results as reported in Table 2. Odds ratios statistically significant at 95% confidence level are shown in bold.

current study is that while most culpable crashes of drivers who had slept for less than 4 hr were attributed to the driver having fallen asleep or to distinctive driving errors arguably suggestive of microsleeps, most culpable crashes of drivers who reported 4–6 hr of sleep were attributed to driving errors of the same general variety as those of culpable drivers who had slept for 7 hr or longer. This finding illustrates that in addition to the obvious risk of falling asleep while driving, sleep deprivation also increases drivers' risk of committing the types of driving errors that also lead non-sleep-deprived drivers to crash. The current study also found that drivers who had changed their sleep or work schedule in the previous 7 days, typically felt fatigued or drowsy upon waking, or had been driving for 3 or more hours without a break had significantly elevated odds of culpable crash involvement. Furthermore, adjustment for these fatigue-related covariates also enhances the robustness of the main results with respect to sleep deprivation relative to those reported previously [21].

The results of the current study confirm and extend the results of previous work by others as well. Laboratory-based studies have found sleep deprivation—typically operationalized in terms of hours of continuous wakefulness—is detrimental to participants' reaction time, response accuracy, and lapses in attention [7], all of which are clearly critical to safe driving. One study that examined simulated driving performance found that drivers' variability in speed and lane position were as impaired after 21 hr of continuous wakefulness as they were at a blood alcohol concentration (BAC) of 0.08 grams of alcohol per deciliter of blood (g/dL) [10]. The latter finding regarding lane position is entirely consistent with the current study's finding that overcompensation and poor directional control were much more likely to be cited as the critical reasons for the crashes of drivers who had slept for less than 4 hr.

A case–control study conducted in New Zealand found that drivers who reported having slept for 5 hr or less in the past 24 hr had 2.7 times the crash risk of drivers who reported having slept for more than 5 hr [11]. A similar case–control study in Fiji found that drivers who reported having slept for less than 6 of the past 24 hr had 5.9 times the odds of crash involvement of drivers who reported having slept for 6 hr or longer [12]. For the sake of comparison, the main analysis from the current study was replicated with sleep recoded as in the two above-mentioned case–control studies: the resultant OR for culpable crash involvement associated with having slept for less than 6 hr vs. 6+ hr was 2.9 (95% CI = 2.2 to 3.8), similar to that reported in the New Zealand case–control study [11].

A source of impairment to safe driving ability whose dose–response relationship to motor vehicle crash risk has been studied extensively is alcohol. A large case–control study by the US DOT estimated that the relative risk of crash involvement for a driver with a BAC equal to 0.08 g/dL relative to a sober driver is approximately 3.9 [37]. That study, however, estimated the relative risk of involvement in any crash irrespective of culpability; the current study estimates the relative risk of *culpable* involvement in a crash, or colloquially, the risk of causing a crash. Another study applied the culpability analysis approach to the cases in the [37] to compare the results obtained by the two study designs, and estimated an OR of 5.6 for culpable crash involvement associated with a BAC of 0.08 [18]. The current study's ORs for culpable crash involvement associated with 5, 4, and less than 4 hr of sleep were similar to ORs estimated in that study for drivers with BACs of 0.03, 0.05, and 0.12, respectively [18]. This similarity of the effects of sleep deprivation estimated herein and the effects of alcohol estimated in previous studies [18, 37] is broadly consistent with the results of laboratory-based studies that have compared the effects of these two risk factors within the same experiment [8–10].

A panel of experts convened by the National Sleep Foundation in 2015 concluded based on review of evidence available at the time that "Drivers who have slept for two hours or less in the preceding 24 hours are not fit to operate a motor vehicle" [38]. The authors noted that members of the panel believed that laboratory-based data indicated that drivers would be significantly impaired by sleep loss after having slept for 3, 4, or 5 hr in a 24 hr period, but they found existing epidemiologic data on the relationship between sleep deprivation and involvement in real-world crashes insufficient to support labelling a driver who had slept for 3, 4, or 5 hr as unfit to drive. The results of the current study would arguably support extending a future revision of that statement to include drivers who have slept for less than 4 hr and possibly drivers who have slept for 4 hr as well.

Limitations

This study has several limitations that should be noted. Nonculpable drivers might not actually comprise a representative sample of all drivers present where crashes occur [39]. Sleep deprivation might impair drivers' crash avoidance skills and thus increase their risk of involvement as nonculpable drivers in crashes that they might have otherwise avoided altogether. If sleep deprivation were more common among nonculpable drivers involved in crashes than among drivers not involved in crashes, this would cause the current study to underestimate the impact of sleep deprivation on crash risk (i.e. bias the ORs toward the null). Bias away from the null would imply that sleep deprivation enhances drivers' crash avoidance skills, which is improbable.

Data on sleep were self-reported and might be biased if drivers exaggerated the amount that they slept to avoid implicating themselves in a behavior that might be construed as negligent. If culpable and nonculpable drivers were equally likely to exaggerate their sleep, the main results would overestimate the impact of sleep deprivation, but would be expected to preserve the correct general pattern of the association. If exaggeration of sleep was more common among nonculpable drivers than among culpable drivers—a counterintuitive scenario—the main results would overestimate the impact of sleep deprivation. If exaggeration of sleep were more common among culpable drivers than among nonculpable drivers—arguably the most likely scenario—the main results would underestimate the impact of sleep deprivation (with the exception of possible marginal overestimation of the OR for drivers who slept <4 hr).

The data analyzed for the current study excluded crashes that occurred between midnight and 5:59 am, precisely the hours during which both the prevalence [5, 35] and the impact [7] of driving while sleep-deprived would be expected to be the greatest. The estimated impact of sleep deprivation on the risk of culpable crash involvement likely would have been even greater had the study included data from early-morning crashes.

The majority of drivers in the source data were not tested for alcohol nor drugs. Removal from the analysis of drivers who police affirmatively reported to have consumed alcohol or illegal drugs had minimal impact on the main study results; however, it is possible that some drivers were under the influence of alcohol or drugs that went undetected. If undetected drug and/or alcohol use were disproportionately among culpable drivers who reported little sleep, the results could overestimate the effect of sleep deprivation on culpable crash involvement.

The study included too few fatal crashes to estimate the effects of sleep deprivation on fatal crashes; thus, the results of the current study should not be generalized to fatal crashes.

Conclusion

The findings of this study could be used to educate drivers about the nature of the relationship between sleep deprivation and the risk of causing a crash, for which purpose comparison to the crash risk associated with driving after drinking alcohol may be instructive given its familiarity. Drivers who reported having slept for 5, 4, and less than 4 hr in the past 24 hr had crash risks similar to those estimated in a large case–control study by the US DOT [37] for drivers with BACs of roughly 0.03, 0.05, and 0.12 g/dL, respectively, after accounting for differences in study design [18]. A small number of countries including Japan prohibit driving at BACs greater than or equal to 0.03 g/dL; many countries including most of Western Europe prohibit driving at BACs greater than or equal to 0.05; the United States prohibits driving at BACs greater than or equal to 0.08 [40]. Finally, it is important for drivers to be aware that falling asleep at the wheel is not the only risk associated with acute sleep deprivation.

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