Car crashes rank among the leading causes of death in the United States

Acute Sleep Deprivation and Risk of Motor Vehicle Crash Involvement

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Title

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About the Sponsor

Executive Summary

Previous research by the AAA Foundation for Traffic Safety has estimated as many as 7% of all crashes, 13% of crashes that result in hospital admission, and 21% of fatal crashes involve driver drowsiness. However, the relationship between specific measures of sleep deprivation and crash risk has not been quantified in the general driving population. This study examined data from a representative sample of crashes that occurred in the United States between 3 July 2005 and 31 December 2007, involved at least one light vehicle that was towed due to damage, resulted in an emergency medical services dispatch, and were subject to on-scene multidisciplinary investigations as a part of a special study by the U.S. Department of Transportation. Investigations included assessment of drivers' recent sleep.

This study quantifies the relationship between the number of hours that a driver had slept in the past 24 hours and the risk of crash involvement using a case-control study design. Cases were drivers who on-scene crash investigators found to have committed an unsafe or illegal action, inaction, or error that they determined was the critical reason for the critical event that led to the crash; controls were drivers not found to have contributed to the crash in such a way. Logistic regression was used to adjust for potential confounding by driver age, time of day, crash location, and recent changes in sleep schedule. Controls were assumed to have been sampled from among all drivers on the road in proportion to their exposure, thus the odds ratio associated with a particular amount of sleep approximates the ratio of the exposure-based crash involvement rates associated with that amount of sleep compared with a reference amount. The final sample comprised 7,234 drivers involved in 4,571 crashes.

Drivers who had slept for less than 4 hours, 4-5 hours, 5-6 hours, and 6-7 hours in the past 24 hours had an estimated 11.5, 4.3, 1.9, and 1.3 times the crash rate, respectively, of drivers who had slept for 7 hours or more in the past 24 hours. In an alternative analysis of drivers' usual daily hours of sleep and sleep in the past 24 hours relative to their own usual amount of sleep, drivers who reported that they usually slept for 4-5 hours daily had 5.4 times the crash rate of drivers who reported that they usually slept for 7 hours or more; drivers who reported that in the past 24 hours they had slept for 1-2 hours less than usual, 2-3 hours less than usual, 3-4 less than usual, and 4 or more hours less than usual had 1.3, 3.0, 2.1, and 10.2 times the crash rate, respectively, of drivers who reported that they had slept for at least their usual amount. This study may underestimate the risk of driving while sleep-deprived, because data on crashes that occurred between midnight and 6 AM were not available, and other studies have shown that the effects of sleep deprivation on attention and performance are greatest during the early morning hours.

Experts recommend that healthy adults should sleep for at least 7 hours daily. The results of this study indicate that drivers who usually sleep for less than 5 hours daily, drivers who have slept for less than 7 hours in the past 24 hours, and drivers who have slept for 1 or more hours less than their usual amount of sleep in the past 24 hours have significantly elevated crash rates. The estimated rate ratio for crash involvement associated with driving after only 4-5 hours of sleep compared with 7 hours or more is similar to the U.S. government's estimates of the risk associated with driving with a blood alcohol concentration equal to or slightly above the legal limit for alcohol in the U.S., and the increase in crash rate associated with driving after less than 4 hours of sleep is much greater.

Introduction

Sleep deprivation has been shown to slow reactions to stimuli, decrease the accuracy of responses, and lead to long lapses in attention (Lim & Dinges, 2008), all of which clearly have negative implications for safe driving. A multidisciplinary expert panel convened by the National Sleep Foundation recommended that healthy adults ages 18-64 should sleep for 7-9 hours daily (Hirshkowitz et al., 2015). A joint consensus statement by the American Academy of Sleep Medicine and Sleep Research Society similarly recommends that healthy adults aged 18-60 should sleep for at least 7 hours per night for optimal health, and noted that 9 or more hours may be appropriate for young adults and for people who are ill or are recovering from sleep debt (Watson et al., 2015). Another National Sleep Foundation consensus working group concluded that individuals who have slept for 2 hours or less in the past 24 hours "are not fit to operate a motor vehicle" (Czeisler et al., 2016).

According to a survey by the Centers for Disease Control and Prevention of more than 440,000 adults nationwide, 35% of U.S. adults usually sleep for less than 7 hours daily, including 12% who report usually sleeping for 5 hours or less (Liu et al., 2016). In any given 24-hour period from 2005 through 2014, an estimated 18% of all U.S. residents aged 16 and older slept for less than 7 hours, including 1.6% who slept for less than 4 hours and 0.3% who slept for less than 2 hours (American Time Use Survey, 2015, unpublished analysis by author).

Previous research by the AAA Foundation for Traffic Safety has estimated that as many as 7% of all crashes in which a vehicle is towed from the scene, 13% of crashes that result in hospital admission, and 16-21% of all fatal crashes involve a drowsy driver (Tefft, 2012 & 2014). However, there is little scientific literature that quantifies the relationship between specific measures of sleep deprivation and the risk of a motor vehicle crash in the general driving population.

Methods

Overview

The purpose of this study was to quantify the relationship between recent sleep and relative risk of involvement in a motor vehicle crash. The measure of recent sleep used for this study was the total amount that a driver had slept in the previous 24 hours. The risk of crash involvement associated with a given amount of sleep relative to the risk associated with the reference amount of sleep (7+ hours) was estimated by comparing the amount of sleep reported by drivers who on-scene crash investigators found to have committed an unsafe or illegal action, inaction, or error that was found to be the critical reason for the crash, to the amount of sleep reported by drivers who investigators found not to have contributed to the crash in such a manner. Assuming that drivers involved in crashes to which they did not contribute comprise a representative sample of all drivers on the road, the extent to which a given amount of sleep is more (or less) prevalent among drivers who contributed to crashes than among drivers involved in crashes to which they did not contribute reflects the extent to which drivers who had slept for that amount are over-involved (or under-involved) in crashes compared with the reference amount.

Data

The data analyzed for this study was from the NHTSA's National Motor Vehicle Crash Causation Survey (NMVCCS), which comprised a representative sample of police-reported crashes that occurred between July 2005 and December 2007; involved at least one car, pickup truck, van, minivan, or sport utility vehicle that was towed from the scene due to damage; and resulted in emergency medical services being dispatched to the scene (NHTSA, 2008a). Crashes were investigated by multidisciplinary teams of specially-trained investigators (hereafter NMVCCS investigators) for the purpose of the NMVCCS study, in addition to any routine investigation that may have been performed by law enforcement officers. The NMVCCS study only included crashes that occurred between 6 AM and 11:59 PM; crashes that occurred between midnight and 5:59 AM were not included in the NMVCCS. The sample design used for the NMVCCS is described in detail in NHTSA (2008b).

Sleep: As a part of the crash investigation, drivers were asked to report the start and end times of all of their sleep in the 24-hour period that preceded the crash, including any naps that were longer than 30 minutes. Using this information, NMVCCS investigators calculated the total amount of time that the driver had spent sleeping in the 24 hours before the crash (NHTSA, 2008c). For the current study, drivers' total sleep in the past 24 hours as coded in the NMVCCS database was compared to the start and end times of their last sleep interval and the amount of time between the end of their last sleep interval and the time of the crash. A small number of inconsistencies were identified; in these cases, the driver's total amount of sleep in the past 24 hours was recalculated using the reported start and end times of their sleep.

Drivers also reported their "normal average daily sleep interval" (hereafter usual daily amount of sleep), which NMVCCS investigators rounded to the nearest half hour. The difference between the driver's usual daily hours of sleep and their total sleep in the past 24

hours was calculated and categorized as: at least their usual amount of sleep, 1 – 59 minutes less than usual, 1h – 1hour: 59 minutes less than usual, 2 hours – 2 hours: 59 minutes less than usual, 3 hours – 3 hours: 59 minutes less than usual, or 4 or more hours less than usual.

Contribution to crash: For each vehicle in the crash, NMVCCS investigators determined the critical pre-crash event, defined as "the event which made the crash imminent," and also the critical reason for the critical pre-crash event (hereafter critical reason), defined as "the immediate reason for [the critical pre-crash event] and is often the last failure in the causal chain (i.e., closest in time to the critical pre-crash event)." (NHTSA, 2008c) The critical reason could be an action or inaction by a driver (e.g. an unsafe or illegal action, inaction, or error), a vehicle-related reason (e.g., a brake failure), or an environmental condition (e.g., a wind gust). For this study, a driver was considered to have contributed to the crash if the NMVCCS investigators assigned the critical reason for the crash to that driver and the critical reason was indicative of an unsafe or illegal action, inaction, or error by the driver. Coding of the driver's contribution to the crash was neither informed by nor intended to inform assessment of "fault" for legal or insurance purposes. NMVCCS investigator assessment of driver fatigue was not used to classify drivers' contribution to the crash; however, a driver was considered to have contributed to the crash if the critical reason for the crash was inaction by the driver due to the driver being asleep.

Analysis

A case-control study design (Rothman, Greenland, & Lash, 2008) was used to assess the relationship between a driver's total amount of sleep in the previous 24 hours and the relative risk of crash involvement. Cases were drivers who were found to have contributed to the crash in which they were involved; controls were drivers not found to have contributed to the crash.

Under the assumption that a driver involved in a crash to which he or she did not contribute was involved in a crash solely due to reasons external to that driver—for example, the actions of another driver, or a mechanical failure of the vehicle—a driver's probability of being "sampled" as a control would be proportional to his or her exposure (i.e., controls were assumed to be "density sampled," as described in Rothman, Greenland, & Lash, 2008, pp. 124-125). Thus, the distribution of sleep among controls was assumed to be representative of the distribution of sleep among all drivers on the road at the times and places where crashes occur. Under these assumptions, the ratio of the odds of a case versus a control having slept for a particular amount of time in the past 24 hours (e.g., 4 hours) relative to a reference amount (e.g., 7 hours) approximates the ratio of the rates of crash involvement associated with that amount of sleep relative to the reference amount, even though the outcome measure (contribution to a crash) was not rare (Greenland & Thomas, 1982).

For analysis purposes, amount of sleep in the past 24 hours was grouped into 1-hour categories. Few drivers reported less than 3 hours of sleep, thus drivers who reported less than 3 hours of sleep were grouped with drivers who reported between 3 and 4 hours of sleep. Drivers who reported having slept for 7 hours or more in the past 24 hours were the

reference group because experts recommend for healthy adults to sleep for at least 7 hours daily (Hirshkowitz et al., 2015; Watson et al., 2015).

Logistic regression was used to estimate odds ratios adjusted for potential confounding by driver age, driver sex, driver license status, driver illness, medical diagnosis of sleep apnea, recent change in sleep schedule, trip length, vehicle type, day of week, time of day, and several roadway-related variables (speed limit, access control, presence and type of divider, number of lanes, horizontal alignment, relation to intersection, and surface condition). A potential confounder was retained in the final model if its removal changed the odds ratio estimate for any category of sleep by more than 10% relative to its value in the model with all potential confounders included; otherwise it was removed from the model. Potential confounders were evaluated iteratively in this manner in order of increasing statistical significance (i.e., those with the largest P-values were tested for elimination first). The final multivariable model included driver age (modeled as age and age squared), relation to intersection (yes/no), a binary indicator for whether the driver had changed his or her sleep schedule in the past 7 days, and time of day (modeled using 7 categories shown in Table 1). Time of day was not found to be a confounder but was included in the model for substantive reasons. Other potential confounders examined had minimal effect on the odds ratio estimates for sleep and thus were not included in the final model.

A parallel analysis was performed with sleep quantified in terms of a driver's usual daily amount of sleep and amount of sleep in the past 24 hours relative to his or her usual amount of sleep, rather than absolute amount of sleep in the past 24 hours, to assess the relationship of crash risk with drivers' usual amount of sleep and deviations from their usual amount of sleep. This analysis excluded an additional 86 drivers whose usual daily amount of sleep was unknown.

Data were weighted to account for each crash's probability of selection for inclusion in the NMVCCS sample (NHTSA, 2008b). All counts of drivers and presented in this study are unweighted; all means, proportions, and measures of statistical association such as odds ratios are weighted unless noted otherwise. Standard errors and confidence intervals accounted for the stratification and clustering present in the NMVCCS sample (NHTSA, 2008b). Analyses were performed using Stata version 13.1 (StataCorp LP, College Station, TX).

Missing Data and Excluded Drivers

The complete NMVCCS database included 10,239 drivers. Drivers for whom NMVCCS investigators recorded the critical reason for the crash as unknown (n=260) were excluded from the study because their contribution to the crash could not be determined without this information.

An additional 138 drivers were excluded because they were coded as having suffered a heart attack, stroke, or other sudden incapacitating medical event immediately before the crash. NMVCCS investigators assigned all of these drivers the critical reason for the crash in which they were involved; however, the relationship between the driver's recent sleep and their contribution to the crash is unlikely to be informative in cases in which the driver suffered a heart attack or a stroke while driving.

Of the remaining 9,841 drivers, information about sleep in the previous 24 hours was missing for 2,573 drivers, who were thus also excluded. Of those, 1,987 (77%) were not interviewed by investigators; the remainder (n=586) were interviewed but were missing data on sleep for other reasons, likely because they were unable to recall specific details regarding their sleep in the 24-hour period before the crash. Drivers excluded due to missing data about sleep did not differ significantly from those included in the final study sample with respect to the proportion found to have contributed to the crash (54% vs 52%, P=0.36).

An additional 32 drivers were excluded because data on whether the driver had changed his or her sleep schedule was missing and 2 were excluded because driver age was missing. Results reported here are based on analysis of data from the remaining 7,234 drivers (3,579 cases and 3,655 controls) involved in 4,571 crashes.

Sensitivity Analysis

To assess the robustness of the results to the manner in which contribution to the crash was classified, contribution to the crash was re-classified using different criteria. In addition to the critical event and critical reason, NMVCCS investigators also documented other crash-associated factors (hereafter associated factors), defined as a, "factor that is likely to add to the probability of crash occurrence." Associated factors were coded according to NMVCCS investigators' determination of their presence, without regard to whether they had actually contributed to the specific crash being investigated (NHTSA, 2008a). In this sensitivity analysis, a driver was classified as having contributed to the crash if the driver was assigned the critical reason for the crash (as in the main analysis) or if any associated factors suggestive of any unsafe or illegal action, inaction, or error were coded as present, and was classified as having not contributed to the crash if the driver was neither assigned the critical reason for the crash nor had any associated factors suggestive of unsafe or illegal actions, inactions, or errors coded as present.

To ascertain that results were not biased by important differences between the driving exposure of contributing vs. non-contributing drivers, a matched case-control analysis was performed using a quasi-induced exposure method (Stamatiadis & Deacon, 1997) in which only drivers involved in two-vehicle crashes in which there was exactly one contributing driver, one non-contributing driver, and no other vehicles (often referred to in studies using the quasi-induced exposure method as "clean crashes") were included in the analysis. In this analysis, the matching of drivers involved in the same crash indirectly controls for all potential sources of confounding related to factors that were common to both drivers involved in the same crash, including factors that are not explicitly included in the model.

Results

Overall, a weighted 52.2% of all drivers in the study contributed to the crash in which they were involved; 47.8% did not (Table 1). A large majority of drivers reported having slept for 7 hours or more in the 24 hours before the crash. However, drivers who contributed to the crash in which they were involved were much more likely to report lower amounts of sleep compared with drivers who did not contribute to crashes. For example, 2.5% of drivers who contributed to crashes but only 0.2% of drivers who did not contribute to crashes reported less than 4 hours of sleep. Drivers who contributed to crashes were also much more likely than non-contributing drivers to report having slept less than usual in the 24 hours before the crash and to report having changed their sleep schedule in the past 7 days. The youngest and the oldest drivers were more heavily represented among drivers who contributed to crashes than among drivers who did not, whereas drivers who did not contribute to crashes were more likely to be middle-aged. Drivers who did not contribute to crashes were much more likely than contributing drivers to have crashed at intersection locations. (A much greater share of contributing drivers than non-contributing drivers were involved in single-vehicle crashes by virtue of the manner in which contribution to a crash was defined.) Slightly greater proportions of contributing drivers than non-contributing drivers crashed in the early morning and late evening hours.

Sleep in Past 24 Hours

After adjustment for driver age, relation to intersection, time of day, and recent change in sleep schedule, drivers who reported having slept for less than 4 hours in the past 24 hours had an estimated 11.5 times the odds of having contributed to the crash in which they were involved, compared with drivers who reported having slept for 7 or more hours in the past 24 hours (Odds Ratio [OR] 11.5; 95% Confidence Interval [CI] 2.9 – 45.7) (Figure 1). Drivers who reported having slept for 4:00 – 4:59, 5:00 – 5:59, and 6:00 – 6:59 had 4.3 (CI 2.2 – 8.3), 1.9 (CI 1.3 – 2.6), and 1.3 (CI 1.1 – 1.7) times the odds, respectively, of having contributed to the crash in which they were involved compared with drivers who had slept for 7 hours or longer.

Usual Daily Hours of Sleep and Deviation from Usual Hours of Sleep

Drivers who reported usually sleeping for between 4 and 5 hours daily had an estimated 5.4 (CI 1.6 – 17.6) times the odds of having contributed to the crash in which they were involved compared with drivers who reported usually sleeping for 7 hours or longer (Figure 2). Odds ratios associated with usually sleeping for less than 4 hours, 5-6 hours, and 6-7 hours daily were not statistically significant.

Independent of a drivers' usual daily amount of sleep, drivers who slept for up to 1 hour less than their usual amount in the past 24 hours had no statistically significant increase in the odds of having contributed to the crash in which they were involved relative to drivers who slept for at least their usual amount (OR 1.2; CI 0.9 – 1.6) (Figure 2). Drivers who slept for between 1 and 2 hours less than usual in the past 24 hours had a statistically significant 30% increase in the odds of having contributed to the crash (OR 1.3; CI 1.0 – 1.7) , and drivers who slept for 2-3 hours, 3-4 hours, and more than 4 hours less than usual had 3.0 (CI 2.0 – 4.3), 2.1 (CI 1.0 – 4.4), and 10.2 (CI 4.6 – 22.9) times the odds of having

contributed to the crash in which they were involved, respectively, compared with drivers who had slept for at least their usual amount in the 24 hours preceding the crash. A test for multiplicative interaction between drivers' usual amount of sleep and their sleep in the past 24 hours relative to their usual amount of sleep was not statistically significant (P=0.43).

Sensitivity Analyses

The results described previously and presented in Figures 1 and 2 were generally robust to changes in the classification of contribution to crashes and to changes in the analytical approach.

When classification of contribution to the crash took into account actions, inactions, and errors recorded by NMVCCS investigators as crash associated factors in addition to the critical reason for the crash, the odds ratio associated with the lowest levels of sleep (i.e., less than 4 hours in the past 24 hours) increased from 11.5 to 16.6 (Table 2). This is because of the very few (n=6) drivers who reported so little sleep and were not assigned the critical reason for the crash, half (n=3) had some form of unsafe or illegal action, inaction, or error coded as an associated factor (i.e., they were controls in the main analysis but became cases in this sensitivity analysis). Other odds ratios were similar in both analyses.

When drivers who contributed to crashes were matched to the non-contributing driver involved in the same crash, some odds ratios were larger and their confidence intervals were much wider than in the unmatched analysis. Most notably, in the main (unmatched) analysis, the odds ratio for 5-6 hours of sleep was 1.9 (95% CI 1.3 – 2.6), but increased to 4.1 (2.3 – 7.5) in the matched analysis. This was likely a function of sample size. In the main analysis (unmatched), the numbers of non-contributing drivers reporting <4 hours, 4-5 hours, and 5-6 hours of sleep in the 24 hours before the crash were 6, 22, and 59, respectively, whereas in the corresponding matched analysis, those same groups contained, respectively, only 2, 8, and 18 non-contributing drivers. Nonetheless, the direction and statistical significance of all estimates in the matched analyses were consistent with those in the corresponding unmatched analyses.

Results in the sensitivity analysis of usual amount of sleep and deviations from usual sleep were generally similar in the main analysis and in sensitivity analyses (Table 3), with the exception that odds ratios for the lowest two categories of usual daily hours of sleep became unstable in the matched analyses due to very small sample size. For example, in the matched analysis with contribution to the crash classified using both critical reason and associated factors, only 1 non-contributing driver reported usually sleeping less than 4 hours daily, and zero reported usually sleeping 4-5 hours daily.

Discussion

This study examined the relationship between acute sleep deprivation and the odds that a crash-involved driver had contributed to the crash in which he or she was involved. Drivers who did not contribute to the crash in which they were involved were assumed to approximate a random sample of all drivers on the road in the times and places where crashes occur, thus, the odds ratios from this study can be interpreted as ratios of the crash involvement rates of drivers who reported a given amount of sleep relative to the reference amount of 7 hours or more. Results showed that drivers who had slept for fewer than 7 hours in the past 24 hours had significantly elevated crash rates compared with drivers who had slept for 7 hours or more. Drivers who usually slept for between 4 and 5 hours daily were also found to have significantly elevated rates of crash involvement compared with drivers who usually sleep for 7 hours or more, and drivers who had slept for 1 or more hours less than their own usual amount in the past 24 hours also had significantly elevated crash rates independent of how much they usually slept.

A consensus working group convened by the National Sleep Foundation concluded that based on the totality of evidence available at the time of their meeting, drivers who have slept for 2 hours or less in the past 24 hours "are not fit to operate a motor vehicle" (Czeisler et al., 2016). The results of the current study generally support that recommendation, and might arguably support a recommendation that individuals who have slept for less than perhaps 4 or even 5 hours in the past 24 hours are likely to be substantially impaired. Indeed, this study estimates that drivers who have slept for between 4 and 5 hours in the past 24 hours have 4.3 times the crash rate of drivers who have slept for 7 hours or more, and drivers who have slept for less than 4 hours in the past 24 hours have 11.5 times the crash rate of drivers who have slept for 7 hours or more.

By way of comparison to another widely-acknowledged traffic safety problem—driving while impaired by alcohol—two large case-control studies by the NHTSA of the relationship between a driver's blood alcohol concentration (BAC) and the relative risk of crash involvement have estimated the risk of crash involvement at a BAC of 0.08 compared with a BAC of 0.00 is approximately $2.7 - 3.9$ (Blomberg et al., 2005; Compton & Berning, 2015). Thus, this study's estimate of the crash risk associated with driving after having slept for 4-5 hours in the past 24 hours compared with 7 hours or more is similar to the NHTSA's estimates of the crash risk associated with driving with a BAC equal to the level that all U.S. states have set as the per se legal limit, and the crash risk associated with having slept for less than 4 hours is comparable to the crash risk associated with a BAC of roughly $0.12 - 0.15$ as estimated by Blomberg et al. (2005) and Compton & Berning (2015).

Laboratory-based studies have compared research subjects' performance on various tasks while sleep deprived to performance after drinking alcohol. One study compared research subjects' performance on a computerized test of hand-eye coordination after a period of extended wakefulness with their performance on the same task after drinking alcohol, finding that performance after 17 hours of continuous wakefulness was similar to performance at a blood alcohol concentration (BAC) of 0.05 and performance after 24 hours continuously awake was similar to performance at a BAC of 0.10 (Dawson & Reid, 1997). Another study that used simulated driving found that drivers' variability in speed and lane position were similar after 18.5 hours awake to at a BAC of 0.05, and similar after 21 hours

awake to at a BAC of 0.08 (Arnedt et al., 2001). However, neither of these studies directly examined crash involvement as an outcome. Comparing the results of this study to previous real-world studies of crash involvement suggest that the extent of impairment associated with sleep deprivation may actually be somewhat greater than suggested by these laboratory-based studies.

This is the first study to quantify the relationship between specific measures of recent sleep and the risk of crash involvement in a representative sample of crashes of the general driving population. This study was performed by applying a well-established and relatively simple case-control study design to a unique database compiled by the NHTSA that included multiple quantitative measures of drivers' recent sleep as well as on-scene multidisciplinary crash investigators' assessment of each driver's actions and behaviors in the moments leading up to the crash. Rice et al. (2003) used a conceptually similar study design to investigate the relationship between passenger presence and crash risk for teenage drivers; Lenguerrand et al. (2008) also used a similar study design to investigate the crash risk associated with cannabis and alcohol use among drivers in France. However, no study to date has used this approach to examine the risk associated with a quantitative measure of acute sleep deprivation, likely because existing databases of motor vehicle crashes, with the exception of the NMVCCS, do not contain detailed data regarding the recent sleep of drivers involved in crashes.

It should be noted that crashes examined in this study were more severe than average, because this study was based on analysis of data from a sample of crashes in which EMS was dispatched and at least one light vehicle was towed due to damage. Police reported that at least one person was injured in 77% of crashes in the study sample. By way of comparison, only 28% of all police-reported crashes nationwide in 2015 resulted in any reported injuries (General Estimates System, 2016, unpublished analysis by author). It is possible that the relationship between sleep deprivation and crash risk might be different in less severe crashes; however, when odds ratios from the current study were tested for heterogeneity in relation to the maximum police-reported injury severity in the crash, no evidence of heterogeneity was found (P=0.69 for heterogeneity of odds ratios by maximum injury severity in crash).

Despite the many strengths of the NMVCCS database and case-control study design, this also entailed several limitations. One notable limitation was the small number of drivers with the exposure of interest: acute sleep deprivation. The purpose of this study was to quantify the relationship of crash risk with acute sleep deprivation. Drivers who had slept for less than 4 hours in the past 24 hours were found to have highly elevated crash rates relative to drivers who had slept for 7+ hours, but the estimate was very imprecise (Odds Ratio: 11.5, 95% Confidence Interval: 2.9 – 45.7), because only 80 drivers in the study sample (including only 6 controls) reported having slept so little.

A key assumption of this study was that drivers judged not to have contributed to the crashes in which they were involved were essentially a random sample of all drivers on the road, and thus that the distribution of the exposure of interest (sleep) among those drivers was a good approximation of its distribution among all drivers on the road at the times and places where crashes occurred. While this is not directly verifiable, the main study results were found to be robust to changes in the criteria used to classify drivers as cases versus controls, changes in the analytical approach (i.e., matching versus adjustment), and

changes in how sleep was quantified (absolute amount of sleep in past 24 hours versus usual amount of sleep and sleep in the past 24 hours relative to one's usual amount). Furthermore, controls reported having slept an average of 8 hours 19 minutes in the 24 hours before the crash, which agrees very well with the average of 8 hours 17 minutes of sleep in a 24-hour period reported by respondents who reported driving in a large unrelated survey of the general population by the Bureau of Labor Statistics (American Time Use Survey, 2015, unpublished analysis by author). In the event that the distribution of sleep among drivers who did not contribute crashes was not a good approximation of the corresponding sleep distribution among all drivers on the road at the times and places where crashes occur, the main study results would still be valid; however, the odds ratios would no longer be interpretable as ratios of exposure-based crash involvement rates.

Data on sleep were self-reported and in some cases may have been inaccurate due to errors in drivers' memories of recent sleep or due to deliberate misreporting. For example, drivers might have over-reported their sleep to avoid admitting to having committed a behavior that might be regarded as negligent. However, data on sleep were collected in interviews with investigators who were independent of law enforcement, which may mitigate any deliberate over-reporting of sleep. In fact, 16 drivers reported having not slept at all in the 24 hours before the crash, indicating that some drivers were willing to report extreme levels of sleep deprivation.

Another limitation is a lack of reliable data regarding driver's alcohol and drug use. Alcohol and many drugs (e.g., antihistamines) can cause drowsiness and impair one's ability to drive safely (Food and Drug Administration, 2014). However, in the data analyzed for the current study, fewer than 4% of drivers were tested for alcohol, and data on medications used was based on self-report by drivers and was likely subject to misreporting and under-reporting. For example, although the NMVCCS database enumerated over 500 specific drugs and medications, the single most common drug that drivers in the NMVCCS reported using was "other." Thus, the current study was not able to investigate whether results were confounded by alcohol and/or drugs nor quantify the interaction between alcohol and drugs, sleep deprivation, and crash risk.

Possibly the most significant limitation of the study was that crashes that occurred between midnight and 6 AM could not be examined because the NHTSA's NMVCCS study, which collected the data that were analyzed for the current study, did not include crashes that occurred during those hours. The prevalence of sleep-deprived drivers on the road and in crashes might have been different during those hours than during the hours that were examined. In another study of a different database that did not exclude any crashes based on the time at which the crash occurred, Tefft (2012) found that drivers involved in crashes between the hours of 1 AM – 5 AM were much more likely to have been drowsy than were drivers involved in crashes during the remainder of the day. In the data examined for the current study, drivers involved crashes in the first and last hours of data collection each day (i.e., 6:00 – 6:59 AM and 11:00 – 11:59 PM) reported having slept for an average of one full hour less in the past 24 hours than did drivers involved in crashes during the remainder of the day (7 hours 16 minutes vs. 8 hours 16 minutes; P=0.001), and drivers who reported having slept very little (e.g., less than 5 hours in the past 24 hours) were much more prevalent in crashes that occurred in the first and last hours of data collection than during the remainder of the day (8.0% vs. 1.9%; P=0.005), both of which suggest that the prevalence of sleep-deprived drivers on the road and in crashes might be higher during

the overnight and early morning hours absent from the current study than during the hours that were included in the study. Furthermore, although the mean amount of sleep reported by drivers in the current study agreed very well with that in the American Time Use Survey, very low amounts of sleep were substantially less prevalent in the current study than among drivers in the American Time Use Survey. For example, only 3.7% of drivers in the current study but 9% of drivers in the American Time Use Survey reported less than 6 hours of sleep in the 24-hour period about which each was queried (American Time Use Survey, 2015, unpublished analysis by author). While this discrepancy could plausibly be explained if drivers were simply less likely to drive after having slept little in the past 24 hours, another possibility is that trips taken by drivers who have slept little in the past 24 hours are disproportionately likely to occur during the overnight and early morning hours absent from the current study. Finally, there is evidence that the impairing effect of sleep deprivation on one's ability to respond quickly and appropriately to stimuli is greater during the early morning hours than during the daytime (e.g., Lim & Dinges, 2008). This suggests that the current study may have underestimated not only the prevalence but also the risk of driving while sleep deprived, especially if the prevalence and risk of driving while sleep deprived are both markedly higher during the early morning hours absent from the current study than during the hours that were examined.

Table 1. Hours of sleep in 24-hour period before crash and potential confounding variables in relation to contribution to the crash in a sample of crashes in which EMS was dispatched and at least one vehicle was towed, United States, 2005 – 2007.

	Contributed to Crash[a]					
	No (n=3,655)		Yes (n=3,579)		All (N=7,234)	
	N (weighted col %)					
Total sleep in 24 hours before crash (hours: minutes)						
< 4:00	6	(0.2)	74	(2.5)	80	(1.4)
4:00 – 4:59	22	(0.4)	49	(1.4)	71	(0.9)
5:00 – 5:59	59	(0.9)	99	(1.8)	158	(1.4)
6:00 – 6:59	286	(7.2)	331	(8.5)	617	(7.9)
≥ 7:00	3,282	(91.4)	3,026	(85.7)	6,308	(88.4)
Usual daily hours of sleep (hours: minutes)[b]						
< 4:00	3	(0.5)	10	(0.2)	13	(0.3)
4:00 – 4:59	6	(0.1)	24	(0.7)	30	(0.4)
5:00 – 5:59	34	(1.0)	68	(1.5)	102	(1.2)
6:00 – 6:59	235	(5.0)	259	(6.2)	494	(5.6)
≥ 7:00	3,340	(93.5)	3,167	(91.5)	6,507	(92.5)
Sleep in 24 hours before crash relative to usual number of hours[b]						
At least usual number of hours	2,826	(81.9)	2,654	(76.1)	5,480	(78.9)
0:01 – 0:59 less than usual	523	(12.1)	465	(12.6)	988	(12.4)
1:00 – 1:59 hours less than usual	210	(4.8)	223	(6.1)	433	(5.5)
2:00 – 2:59 hours less than usual	36	(0.8)	92	(2.1)	128	(1.5)
3:00 – 3:59 hours less than usual	15	(0.3)	31	(0.5)	46	(0.4)
≥ 4:00 hours less than usual	8	(0.2)	63	(2.5)	71	(1.4)
Changed sleep schedule in past 7 days						
Yes	152	(3.7)	224	(6.1)	376	(5.0)
No	3,503	(96.3)	3,355	(93.9)	6,858	(95.0)
Driver age (years)						
14-17	108	(2.8)	272	(7.9)	380	(5.5)
18-20	282	(7.8)	454	(14.7)	736	(11.4)
21-24	370	(10.1)	476	(12.4)	846	(11.3)
25-34	800	(22.0)	703	(20.6)	1,503	(21.3)
35-54	1,376	(36.3)	981	(24.7)	2,357	(30.2)
55-64	428	(12.6)	283	(7.7)	711	(10.0)
65-74	189	(5.8)	201	(6.8)	390	(6.3)
75+	102	(2.7)	209	(5.2)	311	(4.0)
Relation to intersection						
At or related to intersection	2,570	(70.6)	2,151	(56.1)	4,721	(63.0)
Not related to intersection	1,085	(29.4)	1,428	(43.9)	2,513	(37.0)
Time of day of crash						
6:00-7:59AM	445	(11.4)	421	(13.2)	866	(12.4)
8:00-9:59AM	339	(11.1)	342	(9.7)	681	(10.3)
10:00AM-1:59PM	1,142	(30.5)	1,085	(28.7)	2,227	(29.5)
2:00-4:59PM	849	(22.0)	790	(19.6)	1,639	(20.7)
5:00-7:59PM	604	(17.6)	600	(18.7)	1,204	(18.2)
8:00-9:59PM	192	(5.3)	223	(6.6)	415	(6.0)
9:00-11:59PM	84	(2.2)	118	(3.6)	202	(3.0)

Data: National Motor Vehicle Crash Causation Survey (National Highway Traffic Safety Administration, 2008a).
a. A driver was considered to have contributed to the crash if on-scene investigators assigned the driver the critical reason for the crash.
b. Excludes 88 drivers whose usual average daily sleep interval was unknown.

Table 2. Analysis of sensitivity of odds ratios to changes in study design, case-control study of contribution to crash in relation to total hours of sleep in the past 24 hours.

Cases	Critical reason for crash		Critical reason or associated factor	
Controls	Not critical reason for crash		Not critical reason & no associated factor	
Study design	Unmatched[a]	Matched[b]	Unmatched[a]	Matched[b]
Sample size	7,234	3,372	7,210	2,106
Total sleep in past 24 hours (hours: minutes)	Odds Ratio (95% CI)		Odds Ratio (95% CI)	
< 4:00	11.5 (2.9–45.7)	13.2 (2.2–80.2)	16.6 (4.7–58.7)	18.9 (2.7–134.2)
4:00 – 4:59	4.3 (2.2–8.3)	3.3 (1.2–9.2)	2.9 (1.1–8.0)	4.1 (0.9–19.0)
5:00 – 5:59	1.9 (1.3–2.6)	4.1 (2.3–7.5)	2.2 (1.3–3.9)	4.6 (2.0–10.3)
6:00 – 6:59	1.3 (1.1–1.7)	1.3 (0.9–1.8)	1.2 (0.9–1.5)	1.4 (0.8–2.4)
≥ 7:00	1.0 Ref	1.0 Ref	1.0 Ref	1.0 Ref

Data: National Motor Vehicle Crash Causation Survey (National Highway Traffic Safety Administration, 2008).
a. Odds ratios from unmatched analyses are adjusted for age, time of day of crash, intersection vs. non-intersection location, and recent change in sleep schedule.
b. Control was other driver involved in same crash as case in matched analysis; odds ratios from matched analysis are adjusted for age, recent change in sleep schedule, and all variables common to both drivers involved in the same crash.

Table 3. Analysis of sensitivity of odds ratios to changes in study design, case-control study of contribution to crash in relation to usual daily hours of sleep and sleep in past 24 hours relative to usual number of hours.
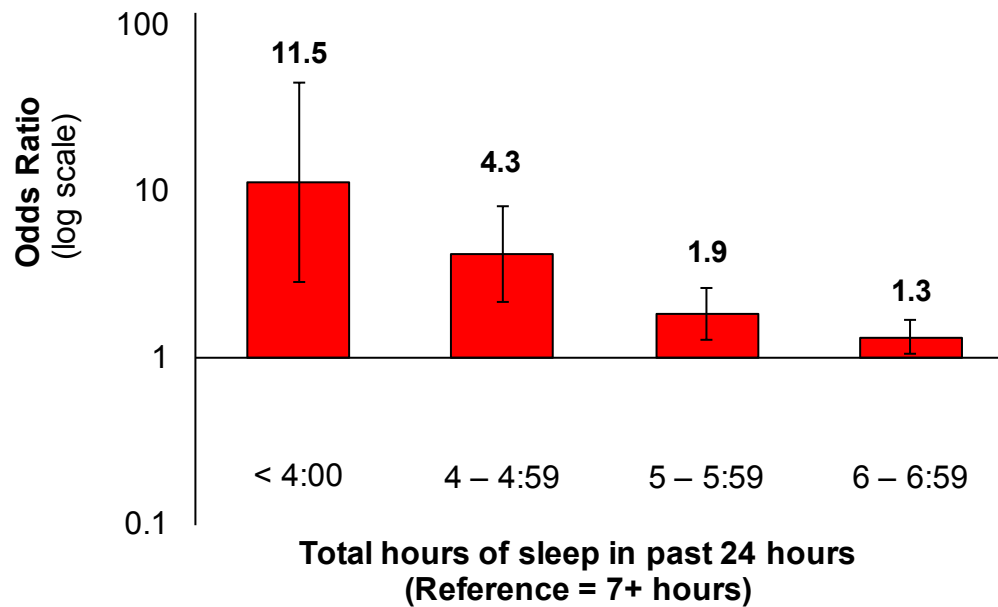
Cases	Critical reason		Critical reason or associated factor	
Controls	Not critical reason		Not critical reason & no associated factors	
Study design	Unmatched[a]	Matched[b]	Unmatched[a]	Matched[b]
Sample size	7,146	3,312	7,124	2,076
Usual daily hours of sleep	Odds Ratio (95% CI)		Odds Ratio (95% CI)	
< 4:00	0.8 (0.1–5.6)	0.1 (0.0–0.8)	5.4 (2.2–13.2)	0.2 (0.0–3.0)
4:00 – 4:59	5.4 (1.6–17.6)	5.4 (1.1–28.0)	5.9 (1.4–23.9)	*
5:00 – 5:59	1.4 (0.5–3.6)	1.8 (0.7–4.3)	1.4 (0.4–4.6)	1.1 (0.5–2.5)
6:00 – 6:59	1.4 (0.9–2.0)	1.4 (0.7–2.9)	1.3 (1.0–1.7)	1.6 (0.7–4.0)
≥ 7:00	1.0 Ref	1.0 Ref	1.0 Ref	1.0 Ref
Hours of sleep in past 24 hours relative to usual number of hours				
At least usual number	1.0 Ref	1.0 Ref	1.0 Ref	1.0 Ref
0:01 – 0:59 less	1.2 (0.9–1.6)	1.1 (0.7–1.9)	1.1 (0.9–1.3)	1.3 (0.7–2.2)
1:00 – 1:59 less	1.3 (1.0–1.7)	1.3 (0.9–1.7)	1.2 (1.0–1.5)	1.6 (0.9–2.9)
2:00 – 2:59 less	3.0 (2.0–4.3)	2.3 (1.2–4.2)	2.2 (1.4–3.3)	2.6 (1.1–6.3)
3:00 – 3:59 less	2.1 (1.0–4.4)	1.3 (0.3–5.6)	1.9 (0.7–4.9)	1.1 (0.2–5.5)
≥ 4:00 less	10.2 (4.6–22.9)	13.7 (2.6–71.5)	9.9 (3.2–30.4)	18.8 (3.0–120.3)

Data: National Motor Vehicle Crash Causation Survey (National Highway Traffic Safety Administration, 2008).
a. Odds ratios from unmatched analyses are adjusted for age, time of day of crash, intersection vs. non-intersection location, and recent change in sleep schedule.
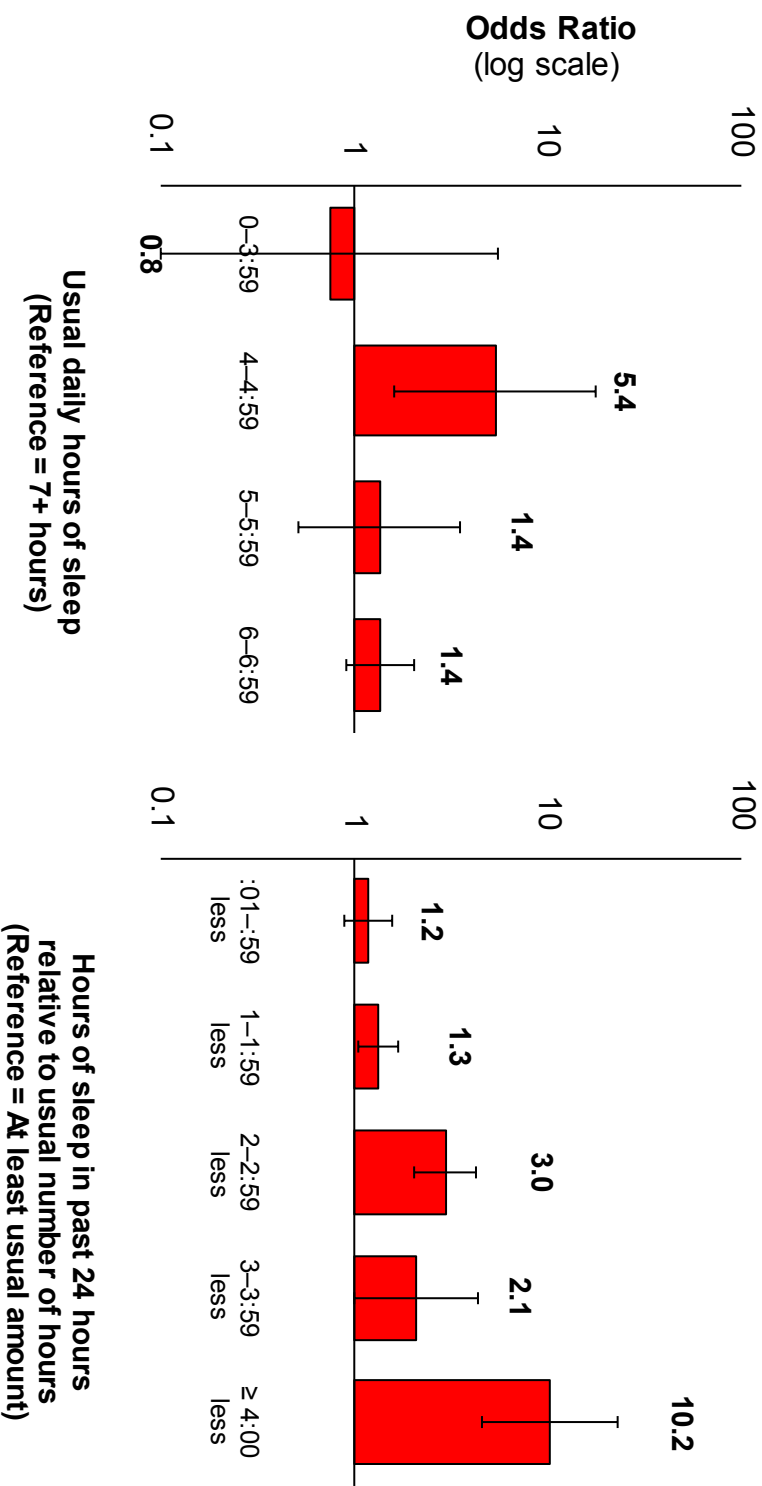b. Control was other driver involved in same crash as case in matched analysis; odds ratios from matched analysis are adjusted for age, recent change in sleep schedule, and all variables common to both drivers involved in the same crash.

Figure 1. Adjusted odds ratios for contribution to crash in relation to total hours of sleep in the past 24 hours, sample of 7,234 drivers involved in crashes in which EMS was dispatched and at least one vehicle was towed, United States, 2005 – 2007.

Data: National Motor Vehicle Crash Causation Survey (National Highway Traffic Safety Administration, 2008). Odds ratios are from a case-control study in which cases were drivers who on-scene investigators found to have contributed to the crash by means of an unsafe or illegal action, inaction, or error; controls were drivers not found to have contributed in such a way. Odds ratios were adjusted for driver age, time of day of crash, intersection vs. non-intersection location, and recent changes in sleep schedule.

Figure 2. Adjusted odds ratios for contribution to crash in relation to usual daily hours of sleep (left) and amount of sleep in past 24 hours relative to usual daily hours of sleep (right), sample of 7,146 drivers involved in crashes in which EMS was dispatched and at least one vehicle was towed, United States, 2005 – 2007.

Data: National Motor Vehicle Crash Causation Survey (National Highway Traffic Safety Administration, 2008). Odds ratios are from a case-control study in which cases were drivers who on-scene investigators found to have contributed to the crash by means of an unsafe or illegal action, inaction, or error; controls were drivers not found to have contributed in such a way. Odds ratios were adjusted for driver age, time of day of crash, intersection vs. non-intersection location, and recent changes in sleep schedule.

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