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The impacts of multiple rest-break periods on commercial truck driver's crash risk

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ABSTRACT

Introduction: Driver fatigue has been a major contributing factor to fatal commercial truck crashes, which accounted for about 10% of all fatal motor vehicle crashes that happened between 2009 and 2011. Commercial truck drivers' safety performance can deteriorate easily due to fatigue caused by long driving hours and irregular working schedules. To ensure safety, truck drivers often use off-duty time and short rest breaks during a trip to recover from fatigue. *Method:* This study thoroughly investigates the impacts of off-duty time prior to a trip and short rest breaks on commercial truck safety by using Cox proportional hazards model and Andersen–Gill model. *Results:* It is found that increasing total rest-break duration can consistently reduce fatigue-related crash risk. Similarly, taking more rest breaks can help to reduce crash risk. The results suggest that two rest breaks are generally considered enough for a 10-hour trip, as three or more rest breaks may not further reduce crash risk substantially. Also, the length of each rest break does not need to be very long and 30 min is usually adequate. In addition, this study investigates the safety impacts of when to take rest breaks. It is found that taking rest breaks too soon after a trip starts will cause the rest breaks to be less effective. *Practical applications:* The findings of this research can help policy makers and trucking companies better understand the impacts of multiple rest-break periods and develop more effective rules to improve the safety of truck drivers.

1. Introduction

1.1. Background

Based on a 2013 Federal Motor Carrier Safety Administration (FMCSA, 2013) report, there are 2983, 3271, and 3341 fatal crashes involving commercial trucks in 2009, 2010, and 2011, respectively. They account for about 10% of all fatal motor vehicle crashes during these three years. Also, the estimated total costs of all commercial truck crashes are $79 billion, $84 billion, and $87 billion in 2009, 2010, and 2011, respectively. These alarming facts show that commercial trucks are a major contributing factor to fatal motor vehicle crashes that cause significant losses of lives and productivity every year. Among the possible causes for fatal commercial truck crashes, driver fatigue has been identified as a major factor (FMCSA, 2006) because driver's performance can easily deteriorate due to long hours of driving or irregular working schedules. Sweeney, Ellingstad, Eastwood, Weinstein, and Loeb (1995) investigated 107 single-vehicle heavy truck crashes and categorized them as either fatigued-related or non-fatigued-related. He found that the duration of driver's last sleep period, number of trips made over the past 24 h, and the presence of split sleep schedule (i.e., separating sleep into two or more short periods each day) are significantly different between these two groups. Since 1938, FMCSA has enforced a series of safety rules on Hours-of-Service (HOS) to ensure commercial motor vehicle drivers get enough rest and to prevent driver fatigue and the crash risk associated with it. The safety rules for property-carrying Commercial Motor Vehicle (CMV) drivers include four basic terms related to off-duty. Specifically, drivers can make use of: (a) 10 consecutive off-duty hours, (b) 34 or more consecutive off-duty hours, (c) sleeper berths, and (d) rest breaks to recover and get ready for the next driving task. Among these, rest breaks were not included in previous versions of safety rules for property-carrying CMVs and were added recently. Although rest breaks have gained increasing attention in recent years, two remaining fundamental questions are how many hours of off-duty time and how many rest breaks are enough to prevent driver fatigue/drowsy driving from happening?

1.2. Experimental studies about driver fatigue

Several studies have shown that lack of sleep can seriously affect truck driver's safety performance. Dinges et al. (1997) conducted an experiment consisting of 16 young drivers. These young drivers were hired to perform various driving tasks for 9 consecutive days. The first day was used as the baseline and all drivers were given adequate sleep before it. In the following seven days, all drivers were given an

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average of only 5 h of sleep per night prior to their trips. Before the last day of trip, drivers were again given enough time to rest. Based on the experimental results, Dinges et al. (1997) found that these young drivers' levels of fatigue increased immediately and significantly with sleep restriction. Some aspects of Psychomotor Vigilance Test (PVT) showed a substantial elevation after the second day of sleep restriction. Also, they found that the restriction of sleep time to 4 ~ 5 h per night caused drivers' reaction times to increase significantly within three nights. Another similar study was conducted by Van Dongen, Maislin, Mullington, and Dinges (2003) with 48 adult participants. They concluded that restricting sleep time to 4 or 6 h per day for 14 days considerably affected drivers' safety performance. On the contrary, drivers with 8 h of sleep per night for over 24 days had almost no sign of declined behavioral alertness. Belenky et al. (2003) also conducted an experiment with 66 CMV drivers. They concluded that seven days of sleep restriction caused drivers' PVT results to deteriorate. Specifically, restricting sleep to 5 or 7 h caused drivers' performance to decline at the beginning and to stabilize at a lower level during the rest of the sleep restriction period. Also, restricting sleep time to 3 h resulted in continuous decline of driving performance. On the other hand, they found that drivers with 9 h of sleep every day generally showed no sign of fatigue or impaired ability to operate vehicles during driving. It was concluded that 8 h (or longer) of sleep is enough for CMV drivers to get adequate rest. The FMCSA requires that commercial truck drivers must have a minimum of 10 h of off-duty time between their HOS. Such a requirement seems reasonable, since most truck drivers cannot fully make use of the off-duty period for sleep. They also spend their off-duty time on other activities such as dining and entertainment.

1.3. Field study of off-duty time per trip

The term off-duty time per trip was initially introduced in the first edition of HOS rules and its length has been modified several times since then. It had been set to 8 h from 1962 to 2002 and to 10 h from 2003 to 2012. The off-duty time per trip was changed back to 8 h in July 2013. Many studies have been conducted to investigate off-duty time because of its significant impact on relieving truck drivers' fatigue. It is generally agreed that lack of enough rest is a major threat to truck drivers' driving performance and safety. Arnold, Hartley, Corry, Hochstadt, Penna, and Feyer (1997) conducted a study in Australia and surveyed 1249 truck drivers and 84 management representatives. He found that 32.4% of the drivers and 48.8% of the surveyed representatives considered lack of sleep as a major contributor to fatigue-related events. The survey showed that on average 12% of the drivers had less than 4 h of sleep; 20% of them had less than 6 h of sleep; and one third had more than 8 h of sleep. The author also found that 5% of the drivers had a fatigue-related event; and 20% of the drivers who had less than 6 h of sleep accounted for 40% of the events. Mitler, Miller, Lipsitz, Walsh, and Wylie (1997) conducted a study that monitored the 24-hour electrophysiological performance of 40 commercial truck drivers from the United States and 40 commercial truck drivers from Canada who worked day, night, or irregular shifts. Their study included 400 principal sleep periods for those drivers. Mitler et al. found that the average sleep times of these drivers were 5.18 h in bed per day and 4.78 h of electrophysiologically-verified sleep per day. Crum, Morrow, Olsqard, and Roke (2001) concluded that drivers require at least 5 h of uninterrupted sleep between driving stints. They also found that 5 h are the minimum requirement not the optimal length of sleep time. Another survey conducted by Hanowski, Wierwille, and Dingus (2003) used naturalistic data and targeted at local short-haul truck drivers. They concluded that drivers involved in at-fault incidents related to fatigue typically had less self-reported sleep time (5.33 h) than drivers who were not involved in fatigue-related at-fault incidents (6.13 h). In another study, Hanowski, Hickman, Fumero, Olson, and Dingus (2007) also used naturalistic data from 82 truck drivers. They found that the average sleep time for drivers involved in critical incidents (38 critical incidents) was 5.28 h compared to 6.63 h for other drivers. Also, the average sleep time was 5.25 h for drivers involved in at-fault incidents (29 truck drivers involved in at-fault incidents) compared to 6.70 h for other drivers. On average, most drivers surveyed only had 4 to 5 h of sleep.

Lin, Jovanis, and Yang (1993) collected 1942 observations with 694 crashes from a national less-than-truckload (Barnhart & Kim, 1995) company that usually transports shipments less than 10,000 lb. They developed several logistic regression models based on the data and concluded that off-duty time has little effect on crash risk when it is greater than 9 h. If the off-duty time is less than 9 h, drivers may have a 32% higher chance of being involved in a crash. In practice, it is difficult for FMCSA to enforce the HOS rules regarding the off-duty time for truck drivers to make sure that they receive enough sleep. What often happens is that truck drivers use other ways to recover from fatigue, for instance, rest breaks during trips.

1.4. Rest breaks per trip

Truck drivers can use rest breaks to recover effectively. However, rest breaks were not included in previous versions of HOS rules. The most recent HOS rules published in December 2011 did add the following term about rest breaks: “May drive only if 8 hours or less have passed since end of driver's last off-duty period of at least 30 minutes.” The compliance date of this new requirement was July 1, 2013. The inclusion of this new requirement indicates that rest breaks are equivalently important as other methods in preventing driver fatigue. A few studies on truck driver crash risk have investigated the influence of rest breaks on driver fatigue. There is no consensus regarding the appropriate length of a rest break for truck drivers. Lin et al. (1993) found that rest breaks, particularly those taken before the sixth or seventh one during a trip, helped to lower crash risk significantly. Harris and Mackie (1972) also performed a study to investigate the effectiveness of rest breaks when taken every 3 h. They concluded that the third break's impact on reducing crash risk is insignificant. Chen, Furth, and Dulaski (2012) used a Cox regression model with time-dependent covariates to analyze the effects of rest breaks on driver fatigue. They assumed a transient effect of rest breaks that combines both their fixed and variable effects on truck drivers' crash risk. Similar to the study by Harris and Mackie (1972), Chen et al. (2012) concluded that the first and second rest breaks have a significant impact on reducing drivers' crash risk but the effect of the third rest break is limited.

1.5. The objectives of this study

Due to the significant impact of rest breaks on driver fatigue, this paper aims to analyze the effects of rest breaks on truck driver's crash risk by using the Cox proportional hazards (PH) regression model. In this research, the impacts of the total duration of rest breaks, number of rest breaks, driving time from trip start to each rest break, and the duration of each rest break are investigated. Moreover, Andersen–Gill model is used to investigate the joint effects of both off-duty time and the total duration of rest breaks.

2. Method

This research is a case–control study using Cox proportional hazards (PH) and Anderson–Gill models to analyze the truck driver safety data collected from a national truckload carrier in 2010. Different from less-than-truckload carriers (Barnhart & Kim, 1995), a truckload carrier generally contracts an entire trailer-load to a single customer who has a substantial amount of freight to be loaded into a semi-trailer or container. Case–control studies are often used in epidemiology. In a case–control study, patients with and without a certain disease are categorized as *cases* and *controls*, respectively. The levels of exposure of each group to various risk factors are then compared and used to determine the relationship between the risk factors and the disease. In the context of commercial truck driver safety, drivers involved in crashes (i.e., *cases*) are matched with those who are not (i.e., *controls*). These two groups are compared to assess whether they are significantly different in terms of their previous exposure to risk factors (e.g., number of rest breaks, rest-break duration). Case–control studies are particularly suitable for rare outcomes (Carneiro & Howard, 2011; Mann, 2003) such as traffic crashes. In the rest of this section, the Cox PH and Anderson–Gill models are introduced first. The data used in this research are then described.

2.1. Cox proportional hazards model

Cox PH model was proposed by Cox (1972) to identify the relationship between the survival time (i.e., time before an event happens) of an individual and some explanatory covariates. This time-to-event analysis based on Cox PH model is commonly used in biological studies to describe the outcomes of various treatment groups. These treatment groups are equivalent to different rest-break patterns in this study and are represented by a set of explanatory covariates with different values. Let T be a non-negative random variable representing the survival time until the occurrence of an event with probability density function $f(t)$ and cumulative distribution function $F(t) = Pr\{T \leq t\}$ (i.e., probability of survival time $\leq t$). The survival function is defined as $S(t) = Pr(T > t) = 1 - Pr(T \leq t) = 1 - F(t)$, representing the probability of survival time $>t$. The hazard function of survival time is defined as $h(t) = \lim_{\Delta t \to 0} \frac{Pr(t \leq T < t + \Delta t | T \geq t)}{\Delta t} = f(t)/S(t)$. The hazard function can be considered as the instantaneous event rate at time t, given that no events have happened up to time t. Eq. (1) shows a typical Cox PH hazard function for individual i. The value of this hazard function is called hazard rate.

$$h_i(t|X) = h_0(t)\exp\left(\beta_1 x_{i1} + \ldots + \beta_p x_{ip}\right) = h_0(t)\exp(X\beta) \quad (1)$$

As shown in Eq. (1), the Cox PH model has two major components: a time-dependent baseline hazard function, $h_0(t)$, and a time-independent exponential part, $\exp(X\beta)$, that relates the hazard function to all covariates. A nice property of the Cox PH model is that the baseline hazard function doesn't have to be explicitly specified. The Cox PH model can estimate hazard ratio (HR) and its confidence interval. The HR is the probability that a driver will be involved in a crash in the next instant, given that she/he has survived up until time t and a number of explanatory covariates. It is calculated as the ratio of the hazard rates of two groups of explanatory variables as shown in Eq. (2) below and it is a constant in Cox PH model.

$$\mathrm{HR} = \frac{h_0(t)\exp\left(X_j\beta\right)}{h_0(t)\exp(X_i\beta)} = \exp\left[\left(X_j - X_i\right)\beta\right] \quad (2)$$

The hazard ratio is the key to interpreting Cox PH model results. Coefficient $\beta = 0$ (HR = 1) means the covariates do not contribute anything to the hazard ratio. Coefficient $\beta < 0$ (HR < 1) or $\beta > 0$ (HR > 1) means the covariates can decrease or increase the hazard ratio, respectively.

Based on the Cox PH model, a driver's crash probability is modeled as her/his hazard rate (i.e., value of the hazard function in Eq. (1)) divided by the sum of the hazard rates for all drivers. The coefficients in the Cox PH model are estimated by maximizing the partial likelihood as shown in Eq. (3). The partial likelihood is derived by taking the product of the conditional probability of a failure at time t_i, given the number of cases that are at risk of failing at time t_i.

$$L_i(\beta) = \prod_{i=1}^{N}\left(\frac{\exp(\beta X_i)}{\sum_{j \epsilon R(t_i)}\exp\left(\beta X_j\right)}\right)^{\delta_i} \quad (3)$$

where $\delta_i = 1$ if event i happened and $\delta_i = 0$ if censored. $R(t_i)$ represents the risk set at time t_i. The Cox PH model is suitable for analyzing matched case–control data (Cook, 2005).

In the Cox PH model, if time is continuous, tied events cannot happen. The partial likelihood is valid when there are no ties in the data set. Unfortunately, the time is discrete and tied events may happen. In this case, the Cox PH model can still be applied. However, the computation of the log-likelihood function involves permutations and requires a lot of time if ties exist. There are several ways to deal with the issue of tied events in the Cox PH model, including Breslow and Crowley (1974) approximation, Efron (1977) approximation, average likelihood or exact partial likelihood method, and exact discrete partial likelihood method. In this study, the Efron approximation shown in Eq. (4) is adopted. It is considered more precise than the Breslows approximation due to the following two main reasons: (1) it accounts for the risk set changes that are dependent on the sequence of tied events; and (2) it is based on the assumption that all possible sequences of tied survival times are equally likely. In Eq. (4), $R(t_i)$ represents the risk set at the ith survival time and r indexes D_i, which represents the set of d_i tied events (crashes) for the ith risk set.

$$L_i(\beta) = \prod_{i=1}^{K}\left(\frac{\exp\left(\sum_{l \epsilon D_i}\beta x_l\right)}{\prod_{r=1}^{d_i}\left(\sum_{j \epsilon R(t_i)}\exp\left(\beta x_j\right) - \frac{r-1}{d_i}\sum_{j \epsilon D_i}\exp\left(\beta x_j\right)\right)}\right)^{\delta_i} \quad (4)$$

Each individual driver may have zero, one, or multiple rest breaks during a trip, which can be considered as a case of multiple events per subject. Some popular methods in the area of biostatistics have been used to formulate such a case, which is often called ordered multiple events. Among these methods, the Andersen–Gill model (Andersen & Gill, 1982) in Eq. (5) is based on the assumption that the underlying baseline hazard is the same for all events per subject. Also, the event times are conditionally independent. Eq. (5) includes an at-risk indicator $Y_i(t)$. For survival data, a driver is no longer at risk when an event occurs and $Y_i(t)$ takes value zero, but for the Andersen–Gill (AG) model for recurrent events, the at-risk indicator $Y_i(t)$ is equal to one as an event occurs and is zero only when a crash happens.

$$Y_i(t)\lambda_0(t)\exp(X_i(t)\beta) \quad (5)$$

As shown in Table 1, each driver's trip may consist of multiple segments. Each segment has a start time, an end time before which all covariates remain unchanged, duration of rest break, and a status variable indicating whether a crash has happened (Status = 1) or not (Status = 0). For example, there were two drivers i and j. Driver i was not involved in any crashes and took three rest breaks after 4.75, 5.75, and 6.00 h of driving, respectively, during an 11-hour trip. Driver j was involved in a crash after 7.25 h of driving. He took two rest breaks after 2.50 h and 5.00 h of driving, respectively, before the crash occurred.

Other methods for ordered-multiple-events modeling include marginal risk set model (Wei, Lin, & Weissfeld, 1989) and conditional risk set model (Prentice, Williams, & Peterson, 1981). The marginal risk set

Table 1
Input data to Andersen–Gill model for multiple event cases.

Models	Start	End	Rest	Status
Driver i	0	4.75	0.50	0
	4.75	5.75	0.25	0
	5.75	6.00	0.75	0
	6.00	11.00	0	0
Driver j	0	2.50	0.25	0
	2.50	5.00	0.25	0
	5.00	7.25	0	1

model assumes that each event has its own stratum and each subject appears in all strata. The conditional risk set model (Prentice et al., 1981) is based on the assumption that each subject is not at risk of a second event until the first event has occurred and so on.

2.2. Data and variable description

The data set includes a total of 407 observations: 136 crash cases and 271 non-crash cases. For the crash cases, driving logs were obtained for the day of crash and the previous 7 days. The driving logs consisted of four types of driving activities: driving, on-duty not driving, off-duty, and sleeper berth for every 15 min. Additionally, two non-crash cases were chosen randomly from the same terminal as each crash-involved driver to help control for driving environment. The descriptive statistics of off-duty and rest breaks are listed in Table 2. The mean off-duty time is 21.41 h, which is almost one day. The off-duty time has a wide range. It has a large standard deviation of 21.76 h. Based on the collected data, some drivers had an off-duty time of more than seven days. The median off-duty time is 12.75 h, indicating 50% of the surveyed truck drivers had more than a half day off-duty before the last trip. For the durations of rest breaks, their median value is only 0.50 h. The 75th percentile of the first rest break duration is 0.5 h and the corresponding percentiles for the second and the third rest breaks are both 0.75 h. The data also suggests that most truck drivers spent a total of 0.5 to 0.75 h on rest breaks within a 10-hour driving period. For the driving time before the first rest break, the median and the 3rd quartile are 1.25 and 2.50 h, respectively. Thus, the first break generally happened shortly after the start of the trip. Such an observation is interesting as driver fatigue should not happen so soon. These rest breaks most likely were caused by factors other than fatigue. The median driving times for the second and the third rest breaks are 2.50 h and 3.25 h, respectively. The corresponding 3rd quartile for the second rest break is 4.25 h and the one for the third break is 5.00 h. A comparison with the first rest break data shows that the medians and 3rd quartiles for the driving times to the second and third rest breaks are considerably larger.

In this paper, the driving hours are considered as the driver survival time. Crash is a dummy variable for censoring status, where 1 = crash and 0 = censored. Table 2 shows the distributions of some of the covariates used for analysis in Tables 3 to 7. These categorical covariates are defined based on the ranges shown in Table 2 to guarantee each categorical group contains enough data points for analysis. Each of these categorical variables is further transformed into several binary variables. These binary variables are coded as 0 if the corresponding values are not true and 1 otherwise.

The new HOS rules published in 2011 require truck drivers to have at least 30 min of rest during at most 8 h of driving, suggesting the importance of rest-break duration. In this study, Sum_i ($i = 0, 1, 2, 3$) is used to investigate the safety influence of the total duration of rest breaks. In addition, S_i ($i = 0, 1, 2, 3$) is used to quantify the safety impact of the number of rest breaks. DR_{ij} ($i = 1, 2, 3$ and $j = 0, 1, 2$) is used to test the effect of the length of driving time from trip start to the beginning of a specific rest break. BR_{ij} ($i = 1, 2, 3$ and $j = 0, 1, 2$) is used to evaluate the influence of the duration of each rest break. The safety impacts of the last three categorical covariates (i.e., S_i, DR_{ij}, and BR_{ij}) were not considered in the new HOS rules directly. However, these factors may potentially have important effects on commercial truck safety. The analysis results in this study may be used to decide whether to include them in future revisions of HOS rules or not. Also, these three covariates complement the rest break duration covariate. Together they provide a more comprehensive description of the rest patterns of commercial truck drivers, which could be compared with the patterns of previous commercial truck driver rest data to assess the influence of different versions of HOS rules. In the following *Results* section, more detailed descriptions of these covariates are provided.

Table 3
Model estimates of the total duration of rest breaks.

	coef	exp(coef)	se(coef)	z	p-value	95% C.I. of HR	
Reference group includes trips without rest breaks.							
Sum_1 (0.00, 0.50]	−1.53	0.217	0.246	−6.22	5.00E-10	0.134	0.331
Sum_2 (0.50, 1.00]	−1.96	0.141	0.254	−7.73	1.10E-14	0.086	0.186
Sum_3 (1.00, 2.00]	−2.00	0.136	0.244	−8.17	3.30E-16	0.084	0.177
Sum_4 (more than 2.0 h)	−2.30	0.100	0.325	−7.08	1.40E-12	0.053	0.122

3. Results

The results of various Cox PH models are shown in Tables 3 to 6. In these tables, the estimated hazard ratios are listed under exp(coef). Table 3 lists the modeling results for the total duration of all rest breaks represented by Sum_i. In Table 3, variables Sum_1 through Sum_4 represent different total durations of rest breaks (0.0, 0.5], (0.50, 1.00], (1.00, 2.00], and more than 2 h, respectively. The reference group used in this analysis includes drivers who did not take any rest breaks during their last trips. As suggested by the p values in Table 3, the hazard rates of all durations (Sum_1 through Sum_4) are significantly different from the hazard rate of the reference group (Note that the rest break duration of the reference group is zero). Specifically, the hazard ratio of the period (0.00, 0.50) to the period without any rest breaks (i.e., reference group) is 0.217, suggesting that a brief rest break can substantially reduce the risk of crashes caused by driver fatigue. Similarly, the hazard ratios and p values of the other three periods all show that increasing the total rest break duration has a consistently and monotonically increasing impact on reducing fatigue-related crash risk. Although there is no significant difference in safety benefits between resting for 0.5 to 1 h and 1 to 2 h, having more than 2 h of rest does appear to substantially reduce commercial truck crash risk.

Table 4 shows the safety impact of number of rest breaks. S_i represents the number of rest breaks during each surveyed commercial truck driver's last trip. Specifically, S_1, S_2, and S_3 are for trips with one, two, and three or more rest breaks, respectively. Again, the reference group here is for trips without any rest breaks. As shown in Table 4, the hazard ratio of trips with only one rest break to trips without rest breaks is 0.304. This suggests that having one rest break can significantly lower drivers' risk of getting involved in fatigue-related crashes. The hazard ratios for trips with two (S_2) and three or more (S_3) rest breaks to trips without any rest breaks are 0.108 and 0.117, respectively. Compared to the value of 0.304 for trips with only one rest break, having two

Table 2
Descriptive statistics of off-duty and rest breaks of drivers' last trips.

	Sample Size		Mode	Mean	StDev	Minimum	1st quartile	Median	3rd quartile	Maximum
	Crashes	Non-crashes								
Off-duty	136	271	10.00	21.41	21.76	9.50	10.75	12.75	17.50	168.00
Duration of the 1st rest break	89	257	0.25	0.63	0.84	0.25	0.25	0.50	0.50	5.75
Driving time to the 1st rest break			0.25	1.70	1.46	0.25	0.50	1.25	2.50	7.00
Duration of the 2nd rest break	59	211	0.25	0.60	0.45	0.25	0.25	0.50	0.75	3.00
Driving time to the 2nd rest break			1.50	3.08	2.00	0.50	1.50	2.50	4.25	9.25
Duration of the 3rd rest break	43	152	0.25	0.61	0.49	0.25	0.25	0.50	0.75	3.75
Driving time to the 3rd rest break			2.00	3.79	2.14	0.75	2.25	3.25	5.00	9.75

Table 4
Model estimates of the number of rest breaks.

	coef	exp(coef)	se(coef)	Z	*p-value*	95% of C.I. of HR	
Reference group includes trips without rest breaks.							
S_1 (1 rest break)	−1.19	0.304	0.235	−5.07	3.90E-07	0.192	0.482
S_2 (2 rest breaks)	−2.23	0.108	0.293	−7.60	3.00E-14	0.061	0.191
S_3 (3 or more rest breaks)	−2.14	0.117	0.214	−10.04	0.00E + 00	0.077	0.179

or more rest breaks can further substantially reduce the crash risk. However, the difference in crash risk between having two breaks and three or more breaks is minor. This suggests that during the 10-hour driving period studied, it is important to have at least one rest break to prevent fatigue driving. In general, having two rest breaks would be optimal, since having three or more rest breaks does not appear to significantly further improve safety.

The safety effects of the length of driving time from trip start to each rest break are shown in Table 5. DR_{i1} and DR_{i2} are used to represent the driving time (not including the time for rest break(s)) from trip start to the *i*th rest break. More specifically, DR_{11} is for the driving time to the first rest break to be between 0.0 and 1.25 h and DR_{12} represents a driving time of more than 1.25 h to the first rest break. DR_{21} is for driving time between 0.0 and 2.5 h and DR_{22} is for driving time of more than 2.5 h. DR_{31} is for driving time between 0.0 and 3.25 h and DR_{32} is for driving time that is more than 3.25 h. The hazard ratio results for DR_{11} (0.515) and DR_{12} (0.266) in Table 5 suggest that having the first rest break in less than 1.25 h or after 1.25 h can both help to improve safety. Compared to having the first rest break in less than 1.25 h, it seems to be more helpful to take it after 1.25 h. The reason can be simple. Drivers usually do not get tired in the first 1.25 h of driving. The hazard ratios for DR_{21} and DR_{22} are 0.425 and 0.264, respectively. Again, this suggests that it is helpful to have a second rest break. Moreover, it is better to take the second rest break after 2.5 h (see definition of DR_{22}) of driving. The hazard ratio for DR_{31} is 0.989, suggesting that having the third rest break in less than 3.25 h of driving time may not bring any significant safety benefits. On the other hand, the hazard ratio for DR_{32} (0.576) shows that taking the third rest break after 3.25 h of driving time does seem to substantially improve safety. However, it should be noted that the *p* values for both DR_{31} and DR_{32} are greater than 0.10. Therefore, the interpretations on DR_{31} and DR_{32} values should be considered cautiously. With additional collected data in the future, we may be able to draw a more concrete conclusion regarding the driving time to the third rest break. Overall, the results show that it would be beneficial for commercial truck driver safety to take at least two rest breaks. Also, it is better not to take them too soon after the trip starts.

Table 6 shows the impact of the time duration of each rest break during surveyed drivers' last trip. BR_{11} represents that the length of the first rest break is between 0.0 and 0.5 h, while BR_{12} for this break to be more than 0.5 h. The other four variables (i.e., BR_{21}, BR_{22}, BR_{31}, and BR_{32}) are defined in the same way for the second and third rest breaks, respectively. Given the small *p* values for the estimated hazard ratios of BR_{11}, BR_{12}, BR_{21}, and BR_{22}, the results in Table 6 indicate that the first and second rest breaks can significantly reduce crash risk no matter whether their break durations were longer or shorter than 0.5 h. However, drivers who took three rest breaks did not seem to improve their safety performance unless the last break was longer than 0.5 h. A possible explanation of this is that drivers who took three rest breaks most likely were more tired compared to those who took one or two rest breaks. For these fatigued drivers, they are more prone to crashes unless they take longer rest breaks. Also, the *p* values for the estimated hazard ratios for BR_{31} and BR_{32} are all greater than 0.05, suggesting these two hazard ratios for the third rest break should be interpreted cautiously. A closer look at the hazard ratios of BR_{11} (0.299) and BR_{12} (0.321) shows that for the first rest break a duration of more than 0.5 h does not appear to bring any additional safety benefits compared to durations shorter than 0.5 h. Such an observation is interesting, as longer rest breaks are typically considered better than shorter rest breaks. The hazard ratios of BR_{21} (0.315) and BR_{22} (0.490) also suggest that 30 min is generally adequate for the second rest break.

So far, the analysis has been focused on the impacts of a single contributing factor, for instance, either the time duration of a rest break or the driving time from the beginning of a trip to each rest break. To further investigate the impacts of various rest-break related factors, it would be interesting to see if the impacts of different risk factors are interrelated. For this purpose, the AG model is considered to investigate the joint impacts of the off-duty time prior to the last trip and the total duration of rest breaks.

For the Andersen–Gill model, its input consists of four variables: Off_1, Off_2, Off_3, and *Rest*. Here Off_i ($i = 1, 2, 3$) represents the length of off-duty time prior to the last trip. More specifically, Off_1, Off_2, Off_3 are used to represent the following off-duty time intervals, respectively, (11, 13], (13, 18], and (18, 168] hours based on the quartile ranges in Table 2. *Rest* is for the total duration of all rest breaks and is a continuous variable. It is defined differently from the categorical variable Sum_i ($i = 1, 2, 3, 4$) in Table 3. Here, *Rest* is coded as a 407×39 matrix. Each row represents an observed trip. The maximum driving time from trip start to the last rest break is 9.75 h (see Table 3). This 9.75 h is divided into 39 intervals. Each interval is 15 min long and is represented by one column in the 407×39 matrix. If the *i*th truck driver

Table 5
Model estimates of the length of driving time to each rest break.

	coef	exp(coef)	se(coef)	z	*p-value*	95% C.I of HR	
Reference group includes trips without rest breaks.							
DR_{11}	−0.6643	0.515	0.307	−2.161	3.10E-02	0.282	0.939
DR_{12}	−1.326	0.266	0.245	−5.401	6.60E-08	0.164	0.429
Reference group includes trips without rest breaks or with one rest break.							
DR_{21}	−0.8562	0.425	0.458	−1.869	6.20E-02	0.173	1.042
DR_{22}	−1.3309	0.264	0.331	−4.018	5.90E-05	0.138	0.506
Reference group includes trips without rest breaks, one rest break, or two rest breaks.							
DR_{31}	−0.0113	0.989	0.417	−0.027	9.80E-01	0.437	2.239
DR_{32}	−0.5516	0.576	0.369	−1.493	1.40E-01	0.279	1.187

Table 6
Model estimates of the time duration of each rest break.

Parameter	coef	exp(coef)	se(coef)	z	*p-value*	95% C.I. of HR	
Reference group includes trips without rest breaks.							
BR_{11}	−1.209	0.299	0.243	−4.97	6.80E-07	0.185	0.481
BR_{12}	−1.137	0.321	0.299	−3.80	1.40E-04	0.179	0.576
Reference group includes trips without rest breaks or with one rest break.							
BR_{21}	−1.155	0.315	0.325	−3.56	3.70E-04	0.167	0.596
BR_{22}	−0.714	0.490	0.368	−1.94	5.30E-02	0.238	1.007
Reference group includes trips without rest breaks, with one rest break, or with two rest breaks.							
BR_{31}	0.204	1.226	0.309	0.66	5.10E-01	0.669	2.247
BR_{32}	−0.352	0.703	0.400	−0.88	3.80E-01	0.321	1.540

Table 7
Parameter estimates of Andersen–Gill model.

Parameter	DF	Parameter estimate	Standard error	Chi-square	Pr > chisq	Hazard ratio (HR)	95% C.I. of HR	
Off_1	1	0.04526	0.20126	0.0506	0.8221	1.046	0.705	1.552
Off_2	1	0.14502	0.20584	0.4963	0.4811	1.156	0.772	1.731
Off_3	1	0.31145	0.20282	2.3582	0.1246	1.365	0.918	2.032
Rest	1	−2.86215	1.38287	4.2837	0.0385	0.057	0.004	0.859

takes a rest break of 0.25 h after 3 h of driving, then the cell corresponds to Row *i* and Column 12 in the matrix is set to 0.25.

The Andersen–Gill model results are listed in Table 7. Based on the AG model, the hazard ratio for *Rest* is 0.057, suggesting that the total duration of rest breaks does reduce crash risk significantly. However, the off-duty time prior to the last trip does not appear to improve safety as its length increases. This is probably because the three categories (i.e., Off_1, Off_2, and Off_3) considered in this study are all greater than 11 h, suggesting that the minimum 10 h required in the HOS rules is sufficient for commercial truck drivers to recover from fatigue.

4. Discussion and conclusions

This paper aims to evaluate the safety impacts of various aspects related to rest breaks on commercial trucks, including the number of rest breaks, total duration of all rest breaks, driving time from trip start to each rest break, and the duration of each rest break. The Cox PH model is used to identify the potential impacts of these factors separately. In addition, Andersen–Gill model is utilized to further investigate the joint safety impacts of multiple factors.

Data collected from a national truckload carrier in 2010 is used in this study. The data set includes a total of 407 observations: 136 crash cases and 271 non-crash cases. Based on the driving logs, the median rest break duration is 0.5 h and the 3rd quartile of rest break duration is 0.75 h. An interesting observation of the data is that the first rest breaks for most drivers occurred shortly after the beginning of their trips. It is unclear why these truck drivers took rest breaks within such a short time period. In general, driver fatigue is caused by three major reasons: circadian rhythm effects, sleep deprivation and cumulative fatigue, and industrial fatigue (FMCSA, 2005). Drivers in this study might have used the first rest break for activities other than fatigue recovery. For drivers who took a second rest break, about 75% of them took it within 4.25 h. Fifty percent of the drivers took the second break within 2.50 h and took the third rest break in 3.25 h. In other words, the difference between the median times from trip start to the second and third breaks is 0.75 h. For the third rest break, about 75% of the drivers took it in 5.00 h.

The modeling results suggest that increasing the total duration of rest breaks does have an increasingly positive safety impact. However, this increasing trend is not linear. For instance, a total duration between 0.5 and 1 h is substantially better than a less than 0.5-hour duration. However, the difference between it and a total duration between 1 and 2 h is insignificant. During a 10-hour trip, taking one or two rest breaks can significantly reduce commercial truck drivers' crash risk. Compared to trips without any rest breaks, having one and two rest breaks can reduce the hazard ratio to 0.304 and 0.108, respectively. The results also show that it is not always helpful or cost-effective to increase the number of rest breaks. In fact, having three or more rest breaks does not appear to further improve commercial truck driver safety. This conclusion is consistent with what Harris and Mackie (1972) and Chen (2012) found.

The safety impacts of the length of driving time to each rest break have also been investigated. The modeling results show that the hazard ratios of DR_{11} and DR_{12} are 0.515 and 0.266, respectively. Also, the hazard ratios of DR_{21} and DR_{22} are 0.425 and 0.264, respectively. Based on the definitions of these variables, these hazard ratios indicate that it would be more beneficial or safer for drivers to wait a little longer before they take the first (e.g., $\geq$1.25 h) and second (e.g., $\geq$2.5 h) breaks. Other than the driving time from trip start to the first or second break, the durations of the first and second rest breaks can also have a significant impact on crash risk. The results suggest that 30 min is generally considered adequate and cost-effective for the first and second rest breaks. In both cases, increasing the rest break duration beyond 30 min does not really make any significant safety difference. For the duration of the third rest break, the *p* values for their estimated hazard ratios are very large, indicating that these values should be interpreted with caution. Nevertheless, based on these hazard ratios, the third rest break does not seem to bring any safety benefits within an 11-hour driving period unless it is more than 30 min. This may be explained by postulating that truck drivers who take three rest breaks are likely to be more tired than those who take one or two breaks. Overall, the rest break duration analysis results also support that two rest breaks are generally sufficient for preventing fatigue driving for a 10-hour drive.

In this study, the impact of off-duty time is also investigated. The results suggest that long off-duty times are not effective in reducing crash risk. This conclusion is consistent with the results found by Lin et al. (1993). Another possible reason is that drivers might use some of the long off-duty time or even the 34-hour restart time for recreational activities rather than sleeping. In many cases, these recreational activities cannot help truck drivers recover from fatigue. Interestingly, the new HOS rules include the following two terms: "(1) Must include two periods between 1 a.m.–5 a.m. home terminal time. (2) May only be used once per week." These new requirements are to ensure truck drivers can have enough rest at their home terminals instead of going out for other activities.

In this study, factors related to rest breaks are analyzed for commercial truck safety. Other than rest breaks, there are other important risk contributors related to commercial truck safety, such as time of day for rest breaks and on-duty time. In future studies, these risk contributors should also be incorporated for a more comprehensive analysis using the models proposed in this study. Moreover, additional commercial truck safety data can be collected before and after the implementation of the new rest break HOS rules to quantify their safety impacts.

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