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An analysis of driving and working hour on commercial motor vehicle driver safety using naturalistic data collection

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ABSTRACT

Current hours-of-service (HOS) regulations prescribe limits to commercial motor vehicle (CMV) drivers' operating hours. By using naturalistic-data-collection, researchers were able to assess activities performed in the 14-h workday and the relationship between safety-critical events (SCEs) and driving hours, work hours, and breaks. The data used in the analyses were collected in the Naturalistic Truck Driving Study and included 97 drivers and about 735,000 miles of continuous driving data. An assessment of the drivers' workday determined that, on average, drivers spent 66% of their shift driving, 23% in non-driving work, and 11% resting. Analyses evaluating the relationship between driving hours (i.e., driving only) and SCE risk found a time-on-task effect across hours, with no significant difference in safety outcomes between 11th driving hour and driving hours 8, 9 or 10. Analyses on work hours (i.e., driving in addition to non-driving work) found that risk of being involved in an SCE generally increased as work hours increased. This suggests that time-on-task effects may not be related to driving hours alone, but implies an interaction between driving hours and work hours: if a driver begins the day with several hours of non-driving work, followed by driving that goes deep into the 14-h workday, SCE risk was found to increase. Breaks from driving were found to be beneficial in reducing SCEs (during 1-h window after a break) and were effective in counteracting the negative effects of time-on-task.

1. Introduction

The first United States (U.S.) government issued hours-of-service (HOS) regulations addressing how long a commercial motor vehicle (CMV) driver may drive and work over days and work weeks went into effect in 1938. Since 1938, the U.S. HOS regulations have been revised three times. In the 2005 regulations CMV drivers may drive a maximum 11 h after 10 h off duty and may not drive beyond the 14th hour after coming on duty (Federal Motor Carrier Safety Administration, 2008). Drivers may also use the sleeper berth provision to take breaks; the sleeper berth provision allows drivers to use the sleeper berth for at least 8 h, plus an additional off duty period of at least 2 h, to restart their work day calculations. The 2005 HOS regulations also regulate the total driving time over 7 or 8 days to 60 or 70 h, respectively.

The majority of the research dealing with crash risk and HOS regulations has examined time-on-task. In a study by the American Transportation Research Institute (ATRI) to evaluate the safety impacts of the 2005 HOS regulations, incidents and reportable crashes occurring in 2009 (per vehicle mile of travel [VMT]) as reported by the fleets surveyed were collected and compared to similar data collected from 2004 (American Transportation Research Institute, 2006, 2010). Results indicated that total crashes per million VMT (11.7% reduction), preventable crashes per million VMT (30.6% reduction), and driver injuries per million VMT (1.6% reduction) all experienced a significant reduction in 2009 as compared to 2004. The ATRI-conducted analysis of crashes per driving hour used data collected in October 2009 and January 2010. These results indicate that the majority (approximately 87%) of reportable crashes occurred in the first 8 driving hours (American Transportation Research Institute, 2010). While this analysis did not account for driving exposure, it does provide a useful overview of crash frequency per hour. The ATRI study also examined the use of driving hours 9–11. The majority (more than 60%) of drivers used the 9–10 driving hour and 10–11 driving hour epochs. Slightly more than 50% of drivers used the entire 10–11 driving hour (American Transportation Research Institute, 2010).

A study by the Virginia Tech Transportation Institute evaluated the effect of time-on-task on SCE risk in CMV drivers (Hanowski et al., 2008). This research utilized naturalistically collected driving data gathered from 103 drivers (102 males, 1 female) between May 2004 and September 2005. Key safety analyses conducted included examining SCEs as a function of driving hours, SCEs as a function of driving hour for drivers who drove into the 11th hour, and SCEs

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as a function of time of day. Results indicated that there were significantly more SCEs during the first driving hour as compared to all other driving hours. However, comparisons of all other driving hours failed to reach statistical significance. Similar findings were present for the analysis of SCEs as a function of driving hour for drivers who drove into the 11th hour. The first driving hour represented an increase in SCE risk, but the comparison of all other driving hours (including the 11th hour) did not reach significance. The time-of-day analysis suggested there was a significant time-of-day effect on SCE risk. However, Hanowski and colleagues note that other explanatory factors (primarily traffic density) may have influenced the findings.

Research from non-driving domains indicate that time-on-task is highly associated with fatigue (Williamson et al., 1996). The topic of time-on-task is also highly related to shift duration, which has been widely studied in both medical and industrial domains. Research in the medical domain has indicated that for shifts longer than 12.5 h, self-reported frequency of errors is three times greater than for shorter shift durations, and working more than 40 h per week is associated with a significant increase in self-reported errors among nurses (Dembe et al., 2005). When these extended schedules lead medical personnel into working during nighttime shifts, errors can become more frequent. One study of trainee physicians found that lapses in attention (a precursor to errors) occur between 1.5 times (during the day) and twice as often (during the night) under a 30-h physician trainee duty schedule as opposed to a 16-h duty schedule (Lockley et al., 2004). Industrial workers on a rotating shift (12 h in a 16-day rotation period) got less sleep during the initial days of the shift. During the night-shift period, workers reported lower perceived alertness levels and increased difficulty working (Budnick et al., 1994). This is an important finding, as other research has indicated that sleep debts (including self-perceived sleep debts) are associated with both driving and non-driving accidents (Carter et al., 2003). Furthermore, impaired or shortened sleep is noted as a major cause of workplace accidents in industrial settings (Philip and Akerstedt, 2006).

Unsafe driving is assessed by the presence of a safety-critical event, defined as a crash, near-crash, crash-relevant conflict, or unintentional lane deviation. Although crashes and near-crashes are the typical variables of interest in a safety evaluation such as the present study, less severe events can also provide valuable information. For example, unintentional lane deviations present additional safety concerns and have been shown to be a valid measure of performance decrement in prior research on HOS regulations and fatigue (Van Dongen et al., 2010). Additionally, unintentional lane deviations represent "driver errors." While much less serious than crashes, these may reflect potential time-on-task issues. Previous research by Wylie et al. (1996) and Hanowski et al. (2008) has suggested that there are no differences in safety events across driving hours. If similar findings are present in this analysis, which includes minor events that are sensitive to time-on-task, then this would provide strong evidence for the veracity of previous findings.

In naturalistic data collection, drivers operate vehicles with integrated data collection equipment as they would normally operate a vehicle. The sensors and cameras continuously record data when the vehicles are on and in motion, allowing researchers to assess driving behaviors and accurately determine the number of hours a participant has been driving a CMV at any point in time. Without naturalistic driving data, the knowledge of driver work day, driving hours, working hours, and breaks would be extremely limited and likely inaccurate in some areas. The current study used naturalistic-data-collection methods to evaluate several issues regarding the 2005 HOS regulations for CMV drivers. Researchers wanted to characterize the average workday for long-haul and line-haul drivers and investigate whether a relationship exists between workday characteristics and risk of safety-critical events (SCEs). Specifically, researchers considered workday characteristics of time-on-task, as defined by driving hour or working hour, and breaks from the driving task, including breaks used to perform work-related tasks and breaks used for rest.

2. Material and methods

The data used in this report was collected in the Naturalistic Truck Driving Study (NTDS) and reduced by Blanco et al. (2011, 2012). Blanco et al. (2012) collected and analyzed more than 14,500 h of naturalistically collected CMV driving data as well as sleep data collected via Actigraph watches. The NTDS driving data was augmented with previously collected activity register data in Blanco et al. (2011), which investigated the relationship between driving hours, work hours, and breaks on SCE occurrence. The data collection and reduction is outlined in this section.

2.1. Participants

Data collection for the NTDS took place from November 2005 to March 2007. A total of 100 drivers were involved in the study, however three drivers were removed due to missing data that were necessary for analyses. This left 97 drivers for analyses. Of these 97 drivers, 96 provided demographic information. Of the 96 drivers that provided demographic information, 91 were male and 5 were female. The average age was 44 years old (range: 21–73 years), and the drivers had an average of 9.13 years experience driving CMVs (range: 4 weeks to 54 years). Four for-hire trucking companies participated in the study. Long-haul (on the road for an extended period of time) and line-haul (usually out for a day or day/night) trucking operations were both represented in the study: 75 drivers were primarily long-haul and 21 drivers were primarily line-haul. All drivers and companies were volunteers and recruited for the study. Virginia Tech served as the Institutional Review Board of record. Drivers signed an Informed Consent prior to participation, and a Certificate of Confidentiality (from the National Institutes of Health) was in place. As with any study that uses volunteers, there is a chance the sample of participating drivers may not be representative of the general population of commercial drivers.

2.2. Procedure

2.2.1. Data collection

A naturalistic-data-collection approach was used to collect data. Study participants drove instrumented company trucks during their normal revenue-producing runs. The instrumented trucks were fitted with unobtrusive data-collection equipment consisting of a data acquisition system (DAS), sensors to measure driver performance, and video cameras that recorded the driver's face, steering wheel, and three views outside of the truck (Fig. 1). The data-collection equipment recorded data when the vehicle was on and in-motion. Each driver was assigned to one of nine instrumented trucks and drove the truck for approximately 4 weeks. After a driver completed their time in the study, a different driver was assigned to the instrumented truck until data collection was complete for all participants. Drivers assigned to the same truck did not have overlapping time in the truck. The resultant data set consisted of approximately 735,000 miles of driving data (comprised of both video and dynamic sensor data).

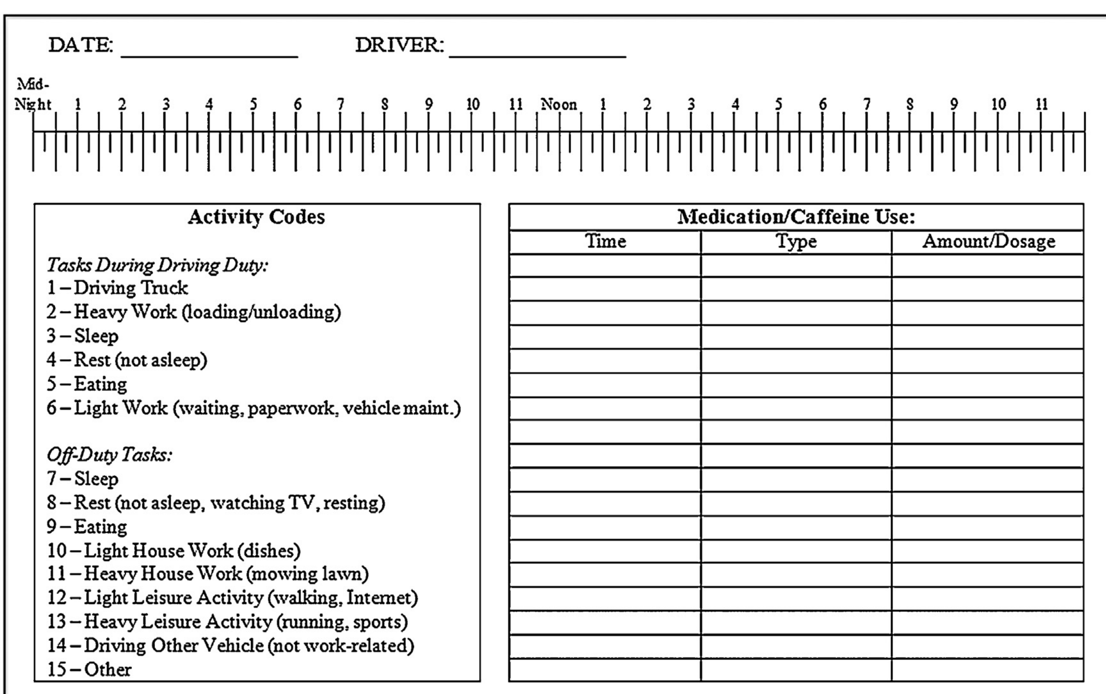
In addition to the vehicle data, each participant was asked to fill out an activity register (including both during-duty and off-duty periods) for the entire 4 weeks he or she participated in the study. A sample page of the activity register is shown below in Fig. 2. The top part of the daily activity register was a 24-h timeline, which began at midnight and ended at 11:59 p.m., scaled with 15-min

Fig. 1. Photo. Five camera images multiplexed into a single image.

increments (see Fig. 2). As participants went about their day, they were to record their activities by marking the corresponding activity code number (1 of the 15 activity codes from the left side of the form) and duration on the timeline. The tasks during driving duty included codes 1–6, while the off-duty activities were coded as 7–15. Researchers met regularly with participants to review the completed activity register and provide participants with a new activity register to complete.

2.2.2. Driver performance measures and data cleaning

Driver performance was assessed through the occurrence of SCEs. While the driver drove an instrumented vehicle, the DAS continuously acquired sensor values. After data collection was complete, computer software filtered the data by identifying driving episodes with sensor values associated with safety-critical driving (Table 1). Data reductionists visually inspected video of the triggered driving episodes and identified any valid SCEs that occurred.



DATE: ________ DRIVER: ________

Mid-Night 1 2 3 4 5 6 7 8 9 10 11 Noon 1 2 3 4 5 6 7 8 9 10 11

Activity Codes

Tasks During Driving Duty:
1 – Driving Truck
2 – Heavy Work (loading/unloading)
3 – Sleep
4 – Rest (not asleep)
5 – Eating
6 – Light Work (waiting, paperwork, vehicle maint.)

Off-Duty Tasks:
7 – Sleep
8 – Rest (not asleep, watching TV, resting)
9 – Eating
10 – Light House Work (dishes)
11 – Heavy House Work (mowing lawn)
12 – Light Leisure Activity (walking, Internet)
13 – Heavy Leisure Activity (running, sports)
14 – Driving Other Vehicle (not work-related)
15 – Other

Medication/Caffeine Use:

Time	Type	Amount/Dosage

Fig. 2. Illustration. Daily activity register sheet used to record activities.

Table 1
Trigger types used to identify SCEs.

Trigger type	Description
Longitudinal acceleration	Deceleration equal to or greater than −0.20 g. Speed equal to or greater than 1 mi/h.
Time-to-crash	A forward time-to-crash value of less than or equal to 2 seconds (s), coupled with a range of less than or equal to 250 ft, a target speed of equal to or greater than 5 mi/h, a gyro rate of less than or equal to $\|6^{\circ}/s\|$, and an azimuth of less than or equal to $\|0.12^{\circ}\|$.
Swerve	Swerve value of equal to or greater than 2 rad/s^2. Speed greater than or equal to 5 mi/h.
Lane deviation	Lane tracker status = abort. Distance from center of lane to outside of lane line less than 44 in.
Critical-incident button	Activated by the driver upon pressing a button, located by the driver's visor, when an incident occurred that he/she deemed critical.
Analyst-identified	Event that was identified by a data reductionist viewing video footage; no other trigger listed above identified the event (longitudinal acceleration, time-to-crash, etc.).

Data reductionists also recorded the exact start and end time (date and time of day) of each SCE.

Safety-critical events included crashes, near-crashes, crash-relevant conflicts, and unintentional lane deviations. The SCE types are defined as:

- Crash: Any contact with an object, either moving or fixed, at any speed, including another vehicle, roadside barrier, object on or off of the roadway, pedestrian, pedalcyclist, or animal.
- Near-crash: Any circumstance that required a rapid, evasive maneuver (e.g., hard braking, steering) by the subject vehicle or any other vehicle, pedestrian, pedalcyclist, or animal, in order to avoid a crash.
- Crash-relevant conflict: Any circumstance that required a crash-avoidance response on the part of the subject vehicle, any other vehicle, pedestrian, pedalcyclist, or animal that is less severe than a rapid evasive maneuver (as defined above), but greater in severity than a normal maneuver. A crash-avoidance response can include braking, steering, accelerating, or any combination of control inputs.
- Unintentional lane deviation: Any circumstance where the subject vehicle crosses over a solid lane line (e.g., onto the shoulder) where no hazard (e.g., guardrail, ditch, vehicle, etc.) is present.

In order to calculate the drivers' work hours for a duty period, or shift, it was necessary to use the data from the activity register to determine what the drivers were doing when they were not driving the truck. The activity register data and the vehicle time-stamped video data were combined to form a single data set that included both driving and non-driving activities. The hybrid activity register became a validated, accurate timeline of drivers' activities over the course of their participation in the study, with driving, non-driving work, and rest activities, and off duty periods marked for each day. The 2005 HOS regulations were converted into an algorithm to identify duty periods over the course of a driver's participation. The algorithm worked by pinpointing breaks that, under the 2005 HOS regulations, allowed drivers to begin a new duty period (10 or more hours of rest or the use of the sleeper berth provision) and by identifying the start of the following duty period.

The collected and cleaned data was managed in several ways to address the research questions. To determine the average work day for the sample of CMV drivers, researchers pulled the timeline of activities occurring during duty period for each shift.

Table 2
SCEs and total opportunities by driving hour for hours 1–11.

Driving hour	SCEs per driving hour	Total opportunities per driving hour	Rate of SCE/total opportunities
1	218	1864.60	0.117
2	230	1826.97	0.126
3	235	1786.90	0.132
4	285	1715.56	0.166
5	263	1612.94	0.163
6	265	1477.66	0.179
7	248	1261.41	0.197
8	154	1021.06	0.151
9	125	808.78	0.155
10	98	553.16	0.177
11	76	321.48	0.236

Researchers assembled the data sets used for the time-on-task analyses by first determining the duty period driving time and working time preceding each SCE. For each SCE, the SCE start time was overlaid on to the hybrid activity register and researchers recorded the driving time and working time up until the start of the SCE. The driving time and working time was recorded as a continuous variable (the actual time, fractions of drive and work hours acceptable) and as a discrete variable (drive hour or work hour reached). For example, if at the start of an SCE the driving time was 10.5 h, the continuous driving time would be 10.5 h and the discrete would be "in the 11th hour of driving" or 11 h. The calculations are the same for working time.

To fully investigate the relationship between the occurrence of SCEs and time-on-task as a function of driving hours, multiple analyses were conducted. There are three data sets that will be referred to in the Results section. In the first data set, all shifts with driving were included. These shifts could have total driving times of less than 11 h, as long as some driving occurred. All SCEs from these shifts were used in the analysis. This included 2197 SCEs: 4 crashes, 7 curb strikes, 46 near-crashes, 1022 crash-relevant conflicts, and 1118 unintentional lane deviations recorded over 1881 shifts and 735,000 VMT. Table 2 shows a summary of the first driving hour data set, which included all SCEs and all driving opportunities (in hours) that occurred in the 1st–11th driving hours. The table lists driving hours 1–11, the number of SCEs per driving hour and the total opportunities (time in hours) per driving hour across all shifts, and the rate of SCEs over total opportunities. Fig. 3 illustrates the rate of SCE occurrence as a function of driving hour for hours 1–11, broken down by SCE type.

A second data set consisted of only the 429 shifts (approximately 23% of all shifts) where drivers drove into the 11th hour. This data set included drivers who had a full opportunity (drove throughout the entire driving hour) to drive into hours 1 through 10 and a partial to full opportunity to drive into the 11th hour. Since a driver's performance could be calculated for each of their 11 h of driving, this data set allowed researchers to evaluate whether a driver's performance changed across the 11 driving hours. The data set is summarized in Table 3; the table lists the number of SCEs per driving hour and the total opportunities (in hours) over all included shifts and the rate of SCEs over total opportunities.

In the two previously described data sets, if a driver was involved in multiple SCEs per driving hour, all SCEs were used to describe the rate of SCE occurrence in that driving hour for that driver. A third data set removed the multiple cases to set up a dichotomous variable. A drive hour was labeled as either "yes, at least one SCE occurred" or "no SCE occurred." This data set removed any bias of associated with multiple SCEs and provides a controlled approach for assessing the impact of driving hour across all hours of a shift, therefore identifying effects specific to driving hour.

In the working hour data set, each driving hour was classified based on when it occurred during the 14-h workday. For example,

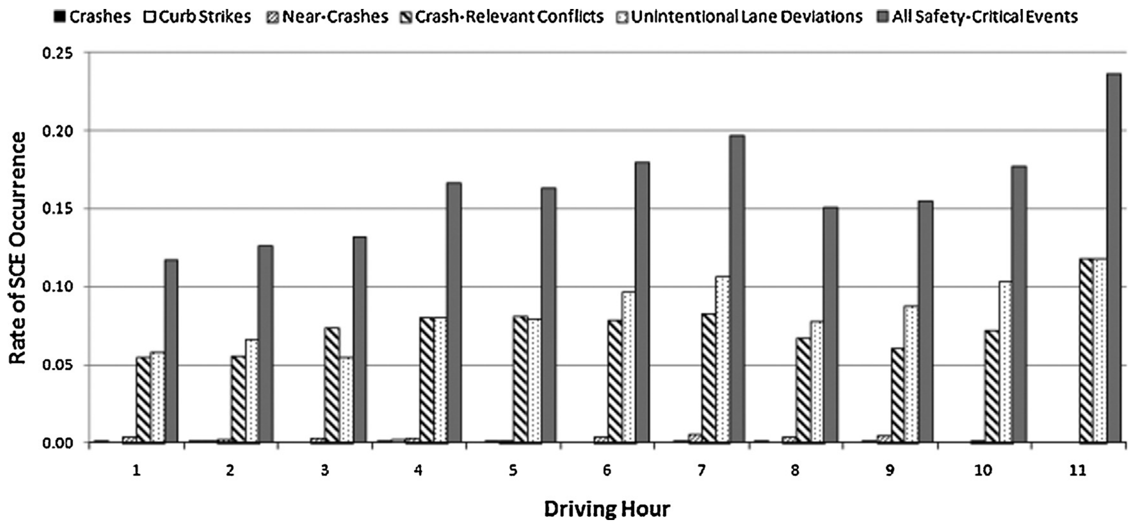


Fig. 3. Bar Graph. Rate of SCE occurrence as a function of driving hour.

consider a driver who performs 2 h of non-driving work (e.g., paperwork) at the start of a shift, followed by 3 h of driving. In this example, the driver has accumulated 3 h of driving time, but 5 h of work time. Additionally, the 1st driving hour began in the 3rd working hour, the 2nd driving hour began in the 4th working hour, and the 3rd driving hour began in the 5th working hour. At this point in time, the driver would be 5 h into his 14-h workday. There were 99 different driving hour–work hour combinations in the current data set, many of which had a very small sample size such that it was not possible to analyze every combination independently. Therefore, the 14-h workday was divided into three categories: Beginning (work hours 1–5), Middle (work hours 6–9), and End (work hours 10–14). Translating this work hour grouping strategy from individual work hours, the combination 'driving hour 1-work hour 1′ (i.e., a driver started the workday by driving 1 h) would be 'driving hour 1-work hour *Beginning*.' The combination 'driving hour 5-work hour 10′ (i.e., the driver was in their 5th hour of driving at the 10th hour of his shift) would be 'driving hour 5-work hour *End*.' Therefore, the work hour categories Beginning, Middle, and End can be thought of as intervals within the 14-h workday that the driver was driving. All shifts were used in the analyses. Shifts could have less than 11 driving hours (but greater than 0 driving hours) to be included. Following a similar method to the one used to analyze driving hours, a dichotomous approach was used to label each drive hour–work hour combination as either "yes, at least one SCE occurred" or "no SCE occurred."

Table 3
SCEs and total opportunities by driving hour for hours 1–11, for shifts that went into the 11th driving hour.

Driving hour	SCEs per driving hour for 11th driving hour shifts	Total opportunities per driving hour for 11th driving hour shifts	Rate of SCE/total opportunities
1	53	429	0.124
2	71	429	0.166
3	63	429	0.147
4	67	429	0.156
5	72	429	0.168
6	82	429	0.191
7	86	429	0.200
8	75	429	0.175
9	62	429	0.145
10	66	429	0.154
11	76	321.48	0.236

In the driving hour and drive hour–work hour combination dichotomous data sets, the number of "yes, at least one SCE occurred" shifts and the number "no SCE occurred" shifts are recorded for each of the driving hours or drive hour–work hour combinations. To calculate the odds of at least one SCE occurring in a specific drive hour or drive hour–work hour combination, the number of shifts with "yes, at least one SCE occurred" in the hour or combination is divided by the number of shifts with "no SCE occurred" in the same hour or drive hour–work hour combination. The dichotomous data and odds for each drive hour and drive hour–work hour combination are shown in Table 4 and Table 5, respectively.

Breaks in driving were identified by finding periods of non-driving activities during the duty period bordered on both sides by driving. To constitute a break from driving, the activities had to total at least 30 min in duration. Four different types of breaks from driving were identified: Break 1 or Rest During Duty Period, Break 2 or Work During Duty Period, Break 3 or Rest During Duty Period/Off Duty, and Break 4 or Off Duty. Break 1 consisted of activity codes 3, 4, or 5, Break 2 consisted of activity codes 2 or 6, Break 3 consisted of activity codes 3, 4, or 5 adjacent to 7–15 (and blank off duty periods), and Break 4 consisted of activity codes 7–15 (and blank off duty periods). There were 3171 breaks (of 30 min or longer) in the data used for the break analysis.

3. Results

All data were screened for normalcy and violations of test assumptions prior to analysis. All analyses were conducted with SAS 9.2 for Windows, using a significance level set at $\alpha = .05$.

3.1. The average CMV driver workday

The breakdown of activities during a CMV driver's workday has not been extensively studied in the literature. Until now, the most detailed knowledge available for a CMV driver's workday was for Local/Short-Haul operations (Hanowski et al., 2000). Using the activity register data, researchers examined the average 14-h work day across all drivers. The majority of their day, 65.7%, was spent driving while 4.1% was spent doing heavy work (e.g., loading/unloading), 18.7% was spent doing light work (e.g., paperwork), and 11.5% was spent resting (e.g., 4.4% spent sleeping, 4.7% spent resting, and 2.4% spent eating). These last three categories (heavy work, light work, and resting) were considered "breaks

Table 4
Driving hour dichotomous data for driving hours 1–11 used to calculate odds ratios.

Driving hour	Number of shifts with at least one SCE in driving hour	Number of shifts with no SCEs in driving hour	Total number of shifts	Odds of at least one SCE in driving hour
1	151	1730	1881	0.087
2	144	1701	1845	0.085
3	159	1650	1809	0.096
4	146	1615	1761	0.090
5	147	1522	1669	0.097
6	133	1424	1557	0.093
7	130	1265	1395	0.103
8	99	1029	1128	0.096
9	74	849	923	0.087
10	55	643	698	0.086
11	31	398	429	0.078

Table 5
Drive hour–work hour combination dichotomous data for driving hours 1–11 and work hours 1–14 used to calculate odds ratios.

Driving hour	Work hour category	Number of shifts with at least one SCE	Number of shifts with no SCEs	Total number of shifts per drive hour–work hour	Odds of at least one SCE in drive hour–work hour
1	Beginning	157	1682	1839	0.093341
1	Middle	0	31	31	0
1	End	1	10	11	0.1
2	Beginning	144	1603	1747	0.089832
2	Middle	8	74	82	0.108108
2	End	1	15	16	0.066667
3	Beginning	140	1436	1576	0.097493
3	Middle	24	184	208	0.130435
3	End	1	24	25	0.041667
4	Beginning	108	1145	1253	0.094323
4	Middle	50	413	463	0.121065
4	End	6	39	45	0.153846
5	Beginning	33	674	707	0.048961
5	Middle	113	743	856	0.152086
5	End	13	93	106	0.139785
6	Middle	134	1202	1336	0.111481
6	End	18	203	221	0.08867
7	Middle	100	893	993	0.111982
7	End	42	360	402	0.116667
8	Middle	33	559	592	0.059034
8	End	75	461	536	0.16269
9	Middle	13	240	253	0.054167
9	End	65	605	670	0.107438
10	End	59	639	698	0.092332
11	End	37	392	429	0.094388

from driving." It is noteworthy, and perhaps somewhat surprising, that approximately 23% of the CMV drivers workday involved non-driving, and unpaid (pay-per-mile fleets), work.

3.2. Safety critical events as a function of driving hours

The focus of the driving hour analysis was to investigate if there were significant differences in the rate of being involved in an SCE as a function of driving hour. That is, does the 11th hour of driving present a higher rate of SCEs as compared to the 10th hour or any other driving hour?

The following analysis used the first driving hour data set, which included SCE and driving data for all shifts, and treated driving hour as a continuous variable. A mixed-effect negative binomial (NB) regression model was used to assess the impact of driving hour on SCE rate, where the data were stratified by subject, shift, and driving hour and the number of SCEs and exact driving time was calculated for each stratum. The SCE rate was defined as the number of SCEs divided by the driving duration in the drive hour and was calculated for each driving hour, in each duty period, for each participant. The model assumes the number of SCEs is from an NB distribution. A driver's specific random intercept was used to account for the driver shift effect. The results of the NB model are shown in Table 6. The driving hour effect was statistically significant ($p_{\text{driving hour}} = 0.0014$). The point estimate of the effect of the driving hour is positive (0.03625), implying that as the driving hour increases, the SCE rate will also increase. This result indicates only that there is a significant difference across hours, but does not provide the power to determine which specific driving hours have significantly different SCE rates. In addition, this model assumes that there is one constant rate of increase between each adjacent hour; that is, the increase in SCE rate from the 1st hour to the 2nd hour is exactly the same as the increase in SCE rate from the 10th hour to the 11th hour. A follow-up analysis was conducted to address these limitations.

In the follow-up analysis, the first driving data set was re-analyzed with driving hour measured as a discrete variable. A mixed-effect NB regression model, using driving hour as a discrete

Table 6
SCE rate as a function of driving hour as a continuous variable, using total opportunities for driving hours 1–11.

Effect	Estimate	SE	df	t	p
Intercept	−2.8581	0.1506	96	−18.98	<0.0001
Driving hour	0.0363	0.0113	14841	3.20	0.0014

Table 7
Comparing individual driving hours for differences in SCE rates.

Contrast between driving hours	Estimate	P	α	LCL	UCL
11 versus 1	0.4684	0.0202	0.05	0.0730	0.8638
11 versus 2	0.4839	0.0162	0.05	0.0896	0.8782
11 versus 3	0.3912	0.0515	0.05	−0.0026	0.7851
11 versus 4	0.3367	0.0932	0.05	−0.0564	0.7298
11 versus 5	0.3050	0.1313	0.05	−0.0912	0.7012
11 versus 6	0.1831	0.3635	0.05	−0.2119	0.5781
11 versus 7	0.0459	0.8213	0.05	−0.3524	0.4442
11 versus 8	0.2619	0.2149	0.05	−0.1520	0.6757
11 versus 9	0.4221	0.0550	0.05	−0.0091	0.8533
11 versus 10	0.2378	0.3005	0.05	−0.2124	0.6881

variable, does not rely on the assumption of one constant increase in SCE rate across driving hours. In the resulting model the overall effect of driving hours was still significant ($F = 2.08$, $p = 0.02$), indicating a relationship between driving hour and SCE rate. However, when comparing the 11th driving hour and all other driving hours (Table 7), the only significant results were between the 11th driving hour and the 1st and 2nd driving hours. The SCE rate in the 11th driving hour was not significantly different from the SCE rate in the 3rd through 10th driving hours (all p's > 0.05).

An analysis was performed on the second driving data set, which only included duty periods with driving into the 11th driving hour, to compare how a driver's performance changes over driving hours 1–11. For each shift included in the analysis, the SCE rate was calculated for driving hours 8–11. The focus of the analysis was on driving hours 8–11, given that the "normal" duration of a workday for a full-time employee is commonly known as an 8-h day and it would be unlikely that anyone would suggest that truck operations drive less than 8 h. This data was analyzed using a mixed-effect NB regression model with logarithm link, to compare in a pair-wise fashion the rate of SCE occurrence across the driving hours 8–11 for each shift. In this method, the shift is a constant, which allows for control of individual driver behaviors as well as factors like time-of-day and location. Table 8 shows the results of the NB analysis. The results indicate that the rate of SCE occurrence for the 11th driving hour was not statistically different from the rate of SCE occurrence for driving hours 8, 9, or 10 ($p_{8\text{th hour}} = 0.7689$, $p_{9\text{th hour}} = 0.4079$, $p_{10\text{th hour}} = 0.4221$). Drivers do not seem to experience a driving performance decrement over hours 8–11.

To further compare the risk of SCE occurrence between driving hours, odds ratios with 95% confidence intervals were calculated for two driving hours at a time, using the data described in Table 4. The results of this analysis found no statistically significant effect for the 11th driving hour ($p > 0.05$ for all comparisons). Comparing the 11th driving hour to the 8th, 9th and 10th driving hours gives the following odds ratios, with lower and upper confidence limits in parentheses: 0.70 (0.43, 1.13), 0.85 (0.52, 1.40), 0.80 (0.49, 1.31), respectively. The 11th driving hour did not present an increase in risk of SCE occurrence as compared to the 8th, 9th, or 10th driving hour.

Table 8
NB model: pair-wise SCE rate comparison of driving hour 11 to hours 8, 9, and 10.

Comparison of driving hours	Estimate	SE	df	t	p
11 versus 8	0.0840	0.2858	428	0.29	0.7689
11 versus 9	0.2323	0.2804	428	0.83	0.4079
11 versus 10	0.2038	0.2536	428	0.80	0.4221

3.3. Safety-critical events as a function of work hour

To assess time-on-task effects as a function of work hour, analyses considered the full work shift, including driving and non-driving activities. To compare risk of SCE occurrence between driving hour–work hour combinations, odds ratios were calculated on two driving hour–work hour combinations at a time. Odds ratios with 95% confidence intervals were calculated using the data shown in Table 5, and the signficant odds ratios from this analysis can be seen in Table 9. The results show a trend of the risk of an SCE statistically increasing as the work hour value increases. The key points of comparison are when a driving hour of interest is compared against that same driving hour at two different points of work hours. For example, when the 5th driving hour is performed during the End of the shift (between 10 and 14 h from when the shift started) a driver is more than two times more likely to be involved in an SCE than when the 5th hour of driving is performed in the Beginning of the shift. Another point of interest are when a driving hour/work hour combination is compared to a later drive hour/earlier work hour combination. For example, when drive hour 4 at the End of shift was compared to drive hour 9 at the Middle of a shift, the driver is 2.84 times more likely to be involved in an SCE.

3.4. Breaks from driving

To address whether breaks from driving have an impact on the risk of SCEs and whether breaks from driving used to perform work-related tasks impact SCEs in a similar manner as breaks to rest, the SCE rate in the time period 1 h before and 1 h after each break type and all break types combined was calculated and compared. For each break type and all break types combined, the total number of SCEs was counted in the before and after time periods. The number of SCEs was then divided by the break opportunities, or total number of breaks of each break type, to get the before break and after break SCE rate. To calculate the magnitude of the decrease in rate before to rate after, the following equation was used: Magnitude equals [($SCE\ Rate_{before}$ minus $SCE\ Rate_{after}$) divided by $SCE\ Rate_{before}$] times 100.

Table 10 presents a comparison of SCE rates during the 1-h window occurring both before and after a break. It should be noted that because multiple break types could make up a single break, the summation of break frequency by types can be more than the total number of breaks. As shown in Table 10, the SCE rate for the 1-h window after a break is consistently lower than the before period, regardless of the break type. The magnitude of the decrease in SCE rate ranges from 28% to more than 50%. The break-level analysis indicates a 29% reduction in SCE rate in the 1-h window after a break compared to the 1-h window before a break for All Break types. The largest reduction in SCE rate was observed after Break Type 4 (Off Duty). The SCE rate after the break is half that of before the break (a reduction of more than 51%). Breaks from driving used to perform work-related tasks does reduce SCE rate by more than 30% and impacts SCEs in a similar manner as breaks from rest.

4. Discussion

The results from this study are profound as they provide information not available from previous research. By combining driving data from the NTDS with an activity register of non-driving tasks (off-duty and during-duty period activities), a more complete picture of the driver's workday was developed. This accurate hybrid data set allowed researchers to study driving hours and working hours in new ways, leading to several key findings relevant to HOS. These results include information on the potential for an increase

Table 9
Significant results from the drive hour–work hour combination odds ratio analysis.

Driving hour	Work hour category	Driving hour	Work hour category	Odds ratio	LCL	UCL
1	Beginning	5	Beginning	1.91	1.30	2.80
1	Beginning	8	Middle	1.58	1.07	2.33
2	Beginning	5	Beginning	1.83	1.24	2.71
2	Beginning	8	Middle	1.52	1.03	2.25
3	Beginning	5	Beginning	1.99	1.35	2.94
3	Beginning	8	Middle	1.65	1.12	2.44
3	Beginning	9	Middle	1.80	1.00	3.23
3	Middle	5	Beginning	2.66	1.54	4.62
3	Middle	8	Middle	2.21	1.27	3.84
3	Middle	9	Middle	2.41	1.19	4.86
4	Beginning	5	Beginning	1.93	1.29	2.88
4	Beginning	8	Middle	1.60	1.07	2.39
4	Middle	5	Beginning	2.47	1.57	3.90
4	Middle	8	Middle	2.05	1.30	3.24
4	Middle	9	Middle	2.24	1.19	4.20
4	End	5	Beginning	3.14	1.24	7.95
4	End	8	Middle	2.61	1.03	6.59
4	End	9	Middle	2.84	1.02	7.91
5	Middle	1	Beginning	1.63	1.26	2.11
5	Middle	2	Beginning	1.69	1.30	2.20
5	Middle	3	Beginning	1.56	1.20	2.03
5	Middle	4	Beginning	1.61	1.22	2.13
5	Middle	5	Beginning	3.11	2.08	4.64
5	Middle	6	Middle	1.36	1.05	1.78
5	Middle	6	End	1.72	1.02	2.89
5	Middle	7	Middle	1.36	1.02	1.81
5	Middle	8	Middle	2.58	1.72	3.86
5	Middle	9	Middle	2.81	1.55	5.08
5	Middle	9	End	1.42	1.02	1.96
5	Middle	10	End	1.65	1.18	2.30
5	Middle	11	End	1.61	1.09	2.39
5	End	5	Beginning	2.86	1.45	5.62
5	End	8	Middle	2.37	1.20	4.67
5	End	9	Middle	2.58	1.15	5.77
6	Middle	5	Beginning	2.28	1.54	3.37
6	Middle	8	Middle	1.89	1.27	2.80
6	Middle	9	Middle	2.06	1.15	3.70
6	End	5	Beginning	1.81	1.00	3.28
7	Middle	5	Beginning	2.29	1.52	3.43
7	Middle	8	Middle	1.90	1.26	2.85
7	Middle	9	Middle	2.07	1.14	3.75
7	End	5	Beginning	2.38	1.48	3.83
7	End	8	Middle	1.92	1.23	3.18
7	End	9	Middle	2.15	1.13	4.10
8	End	1	Beginning	1.74	1.30	2.34
8	End	2	Beginning	1.81	1.34	2.44
8	End	3	Beginning	1.67	1.24	2.25
8	End	4	Beginning	1.72	1.26	2.36
8	End	5	Beginning	3.32	2.17	5.09
8	End	6	Middle	1.46	1.08	1.97
8	End	6	End	1.83	1.07	3.15
8	End	7	Middle	1.45	1.06	2.00
8	End	8	Middle	2.76	1.80	4.23
8	End	9	Middle	3.00	1.63	5.52
8	End	9	End	1.51	1.06	2.16
8	End	10	End	1.76	1.23	2.53
8	End	11	End	1.72	1.14	2.61
9	End	5	Beginning	2.19	1.42	3.38
9	End	8	Middle	1.82	1.18	2.81
9	End	9	Middle	1.98	1.07	3.66
10	End	5	Beginning	1.89	1.22	2.93
10	End	8	Middle	1.56	1.01	2.43
11	End	5	Beginning	1.93	1.19	3.13

in risk in the 11th driving hour, the impact of work hour on SCEs, and the impact that breaks can have on safety.

A key take-away from the set of various analyses on driving hours was a lack of statistical significance for an increase in SCE rate for the 11th driving hour when compared to the 10th driving hour. Results from the NB model using all shifts with driving and measuring drive hour as a continuous variable did show a statistically significant time-on-task effect for driving hour. However, three follow-up analyses provided crucial findings. A NB model using all shifts and measuring drive hour as a discrete variable found the 11th drive hour was only significantly different from the 1st and 2nd drive hours. A pair-wise analysis, in which drivers who drove into the 11th drive hour were compared to themselves in terms of performance over drive hours 8–11, found no time-on-task performance decrement. An odds ratio analysis showed no difference in risk of involvement in at least one SCE for driving hour 11 versus all other driving hours. These findings suggests that perhaps another variable (in addition to driving

Table 10
SCE rate before/after: all break types.

Break type	Metric	Before break	After break	SCE ratio (before/after)	Magnitude of reduction
All break types	SCE frequency	429	305	–	–
All break types	Opportunities	3171	3171	–	–
All break types	SCE rate	0.135	0.096	1.406	28.889
Type 1: rest during duty period	SCE frequency	118	85	–	–
Type 1: rest during duty period	Opportunities	789	789	–	–
Type 1: rest during duty period	SCE rate	0.150	0.108	1.389	28.000
Type 2: work during duty period	SCE frequency	339	237	–	–
Type 2: work during duty period	Opportunities	2518	2518	–	–
Type 2: work during duty period	SCE rate	0.135	0.094	1.436	30.370
Type 3: rest during duty/off duty	SCE frequency	3	2	–	–
Type 3: rest during duty/off duty	Opportunities	15	15	–	–
Type 3: rest during duty/off duty	SCE rate	0.200	0.133	1.504	33.500
Type 4: off duty	SCE frequency	35	17	–	–
Type 4: off duty	Opportunities	211	211	–	–
Type 4: off duty	SCE rate	0.166	0.081	2.049	51.205

hours) may provide a more complete explanation for the statistically significant increasing SCE rate over time. The results from this study with regard to driving hour concur with the findings of Hanowski et al. (2008), with respect to non-significant differences when comparing the 10th and 11th driving hours.

Analyses of work hours indicate that time-on-task across 14 h of work impacts risk. The risk of being involved in an SCE generally increased as work hour increased. That is, driving time that occurred later in the driver's workday, due to performing non-driving tasks earlier in the workday, had a negative safety effect. Therefore, though driving hour, in and of itself, may not have shown an increase in risk when comparing the 10th and 11th driving hours, the combination of driving hour–work hour did show a negative time-on-task effect for driving hours that occurred late in the 14 h workday. These results suggest that perhaps the important question is not whether drivers should be allowed to drive 10 or 11 h, but rather: what are the safety implications of a 14-h workday? That is, though driving for 11 h was not shown to increase the risk of an SCE as compared to the 10th driving hour, if drivers drove deep into their 14-h shift, SCE risk increased. The significant time-on-task results from this study are not surprising and are consistent with findings from time-on-task research in other domains (Olds and Clarke, 2010; Rogers et al., 2004; Dembe et al., 2005).

The potential influence that non-driving work has on time-on-task effects and driving-related SCEs makes intuitive sense based on the results of the breakdown of the drivers' workday; though driving comprised the bulk of the workday—at 66%—non-driving work also was a factor at 23%. Therefore, focusing solely on driving hours (unless it represents 100% of a driver's workday) does not account for the entirety of work that drivers actually perform. This finding may raise other issues, beyond the scope of this research, including pay approaches (i.e., pay-per-mile), and related safety and equity implications, that do not account for the substantial amount of daily, non-driving work that truck drivers routinely perform. This is the first study the authors are aware of that has investigated work hours in combination with, and independent of, driving hours. Therefore, additional research is suggested to further evaluate this issue.

Breaks were found to be a successful countermeasure to address the negative effects of time-on-task. The 1-h window after a break from driving is associated with a considerable reduction (about 28–50%) in SCE rate as compared to the 1-h window before a break. Off-Duty (non-working) breaks are associated with the largest reduction in SCE occurrence. These results suggest that breaks from driving can reduce the SCE rate in the period following the break, whether the break consisted of work activities or restful activities.

While the primary focus areas that were investigated in the current study (i.e., workday characterization, driving, non-driving work, and breaks from driving) have provided important information to explain some of the parameters that may impact SCEs due to time-on-task, there are other factors, not investigated in the current effort, that must also be considered. Although outside the scope of this study, other factors that may impact SCE occurrence include, but are not limited to, sleep hygiene and off-duty activities. It must be noted that a drivers' activities during off-duty time cannot be controlled in a naturalistic study such as this. Previous research by Hanowski et al. (2007) suggested that providing more time to rest under the current HOS regulations allowed drivers to increase the amount of sleep they obtained, and that drivers usually received less than their own average amount of sleep in the time prior to an SCE. Therefore, there are key issues that bear addressing in addition to those investigated in this study. For example, educating drivers on the importance of sleep hygiene, company policies that allow drivers to rest when needed, and the implementation of a safety culture within fleets, as well as other countermeasures to address behind-the-wheel drowsiness, are additional critical components that would be important issues to consider for reducing risk in CMV operations.

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