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Real-time feedback reduces the incidence of fatigue events in heavy vehicle fleets

Michael G Lenné[1,2*], Michael Fitzharris[2]
1. Seeing Machines, 1/11 Lonsdale St, Braddon ACT 2612, Australia. Country. Tel: +61 2 6103 4700,
email: mike.lenne@seeingmachines.com
2. Monash University Accident Research Centre, Australia

Abstract

Fatigue-related crashes are a persistent road safety problem. Advances in technology have permitted the development and fitment of continuous driver fatigue monitoring systems in vehicles. Using driver monitoring system data, this paper presents an evaluation of the impact of real-time feedback on the incidence of fatigue events in three long-haul trucking companies in South Africa. Fatigue events were defined as micro sleeps or prolonged eyelid closure events and verified in real-time by a dedicated monitoring centre. Forty-nine trucks were observed over a five-month period. The observation period included a 'baseline' where data were logged but no alerts were provided to the driver, and an 'intervention' period where alarms were provided to both the driver and the employer in real-time. Poisson regression analysis was used to examine the difference in the incidence of fatigue events in the intervention period relative to the baseline period. Analysis demonstrates that the rate at which fatigue events occurred during the intervention period was significantly lower than in the baseline period, adjusted for number of operating days, time spent in vehicle moving and distance travelled. The implications and feedback mechanisms in the context of broader safety management are discussed.

Keywords:
Driver fatigue, driver feedback, fatigue management.

Introduction

Driver fatigue resulting from reduced or compromised sleep continues to be a significant road safety concern and is implicated to be a casual factor in up to 20% of road traffic crashes (1,2). The risk of being involved in a crash increases with reduced amounts of sleep (2,3), and when fatigue is experienced while driving. By way of example, in a study of commercial vehicle drivers, those who reported that they were fatigued or that they fell asleep were 21 times more likely to be involved in a fatal crash than those drivers who reported neither (4). Objective physiological measures have been developed as a means of assessing fatigue, as distinct from driver self-report. Using the percentage eye closure metric as an index of fatigue (5), higher fatigue levels were seen amongst drivers found at-fault for safety-related driving events than those drivers classified as not at fault (6).

The measurement of driver fatigue represents a considerable challenge, and hence, so too does establishing accurate estimates of fatigue-related serious and fatal injury crashes. While crash-based studies employ various criteria to identify fatigue, researchers generally acknowledge derived values to be likely underestimates and lacking the desired levels of accuracy with regard to identifying a definite involvement of driver fatigue (7-9). With respect to pre-crash behaviours, it is known that significant proportions of long-haul drivers report having fallen asleep at the wheel in past 12 months (25%; 10). It has also been shown that drivers are very poor at predicting the onset of sleep (11), and may even continue to drive when recognising signs of fatigue. Given this is the case, it seems logical that any system that could assist a driver in recognising dangerous levels of fatigue would be of value. Such information would offer intrinsic safety value as it could be used by the driver (or company) to make an informed decision to continue to drive based on their objective fatigue state (12).

Establishing that a vehicle operator (or study participant) is fatigued remains the topic of much on-going research and development. Approaches widely used in the research literature include physiological measures such as EEG (13,14), subjective measures (15), vehicle-based performance measures (16), ocular-based measures (17), and eye-closure based approaches (13, 18) including the percentage of eye closure (PERCLOS, 5). As the evidence supporting the utility of these approaches for state assessments has grown, the strong need to develop fatigue assessment methods that will operate in real-time and in the real world has become even more critical.

Many real-world studies have shown that in-cab technologies can be used to both detect risky behaviours in real time and to provide feedback to drivers. These technology-based means of providing feedback have been shown to be an effective means of changing risky driver behaviours related to speeding (19) and seat belt use (20). Changing behaviour for a complex driver state such as fatigue has proven to be much more difficult primarily for two reasons. The first relates to the ability to detect fatigue events in real time and in real world conditions. The second relates to the complex nature of fatigue and the acknowledgement that there is an important role for fatigue management plans within corporate fleets to support the changes needed to obtain sustained reductions in fatigued driving. The study reported in this paper deals with both of these aspects.

For the reasons outlined above, very little data exist on the incidence of fatigue events in heavy vehicle operations. Those data that do exist are based on observational, survey, naturalistic and crash-based approaches where surrogate indicators of fatigue are used, such as time of day, which at best bear a reasonable relationship to actual levels of fatigue experienced in a vehicle at a specific point in time. In a recent review of fatigue detection technologies it was noted that evidence should be collected in laboratory and field studies, using large samples and undertaken in a sample of the population of interest such as heavy vehicle drivers (21). The field-based analysis reported here based in long haul settings is an initial step in this regard. This study analyses a large existing database of fatigue event data collected from long-haul trucking fleets. This study aims to establish the incidence of fatigue events in long-haul truck driving and to examine whether the provision of in-cab fatigue alerts to the driver, in combination with real time event feedback to the driver's employer, had an impact on the incidence of fatigue events.

Method

Data Set

The data are drawn from an existing dataset that contains fatigue-event data collected from over 4,000 mining and haul trucks worldwide. The data for the analysis presented in this paper was collected across three medium-sized long haul transport companies in South Africa. The companies involved each had a common insurance provider and their participation in this data collection was achieved via the insurer. Each of the three companies operates inter-city corridor trucking routes that involve driving a vehicle for between 10-12 hours per day. A driver monitoring and feedback technology, as described below, was fitted to a total of 49 trucks including in the analysis.

Monitoring and feedback technology

The data presented in this paper were collected using technology installed within truck cabins that was first development in 2007 and employs a VGA resolution 60Hz global shutter image sensor and a pair of pulsed 850nm infra-red lights to obtain images of the face and eyes of drivers in nearly all daytime and night-time conditions. The camera is placed upon a truck dashboard either directly in front of a driver, or to within a 30 degree angle to the left or right of their forward view direction. The system is placed so the camera is pitched up between 5 and 20 degrees below the face, ensuring a good view of the eye even when drivers are wearing wide-brimmed hats. The infra-red illumination system is designed to mitigate the effects of strong sunlight on the face and penetrate most sunglasses, although there remains a proportion of sunglasses that block the 850nm wavelength.

The system runs optimised real-time proprietary computer vision algorithms that measure the position and orientation of the head in three dimensions, as well as the extent of eyelid opening. Frames where the eyelids cannot be tracked are removed from any assessment of distraction or fatigue. The system is monocular with the distance to the head based on assumptions of scale derived from anthropomorphic facial dimensions, and the distance error to the camera is around 10% of the range. In mining and fleet truck settings the head-pose tracking is able to find and track any face within a few seconds, and can track head orientations out to 90 degrees in yaw; this is particularly important if the driver is distracted and looking out the window.

The system is primarily designed to identify driver distraction events and impairment due to fatigue, which in turn offers the potential for significant safety benefits. To do this the system generates events which can optionally be configured to alert the driver in real-time in the cabin, and which are also sent to a monitoring center over a wireless network. At the monitoring center a trained expert observes video of the driver's eyelids as well as historical information about the driver's tracked behavior and the truck's velocity, location and acceleration forces. The trained expert then confirms the automated event as either being true, re-classifies it as a different kind of event, or flags it as a false positive. If it is determined that the event is a real safety condition, that is, a verified fatigue event, a management plan established by the truck company is followed by the monitoring center. In most system configurations, this results in the company being notified of the fatigue event, and an advisory communication by the company to the driver takes place. The monitoring center staff undergo a structured training program prior to commencement and on-going performance assessment by the supervisor as part of the quality assurance process.

Feedback modes used in this study

For the three companies involved in this study, two levels of feedback were used. The first level of feedback was a warning issued to the driver when a fatigue event was detected. This feedback comprised an auditory message “fatigue detected” that was combined with vibration pulses issued at 1 Hz for 4 sec issued through a vibration motor under the base of the driver’s seat. These alerts were designed and tested so as to be easily perceptible warnings in mining and long-haul truck cabins. The second level of feedback involved the driver’s employer as part of the supporting fatigue management plan, as described above. In the event that a fatigue alert is received by the driver and verified by the monitoring center, a call is made to notify the driver’s employer. In line with the fatigue management plan developed for these companies, this contact was made for all fatigue events per vehicle per shift.

For the purposes of this paper, the ‘baseline’ / silent period’ refers to the period of time where the driver monitoring technology was fitted in the trucks and was logging data, but not providing alerts to the driver. The ‘intervention period’ refers to the time at which the drivers were provided with alerts and the company feedback mechanism was in place.

Data Analysis

Data were supplied individually for the three companies on a per-day aggregate basis along with the raw event data. Available data include the number of fatigue events detected, the number of operational hours, the number of hours the vehicle was moving and the number of stationary hours. Baseline and intervention periods used in the analysis were defined using the dates shown in Table 1. Summary statistics were calculated so as to compare differences, if any, between the two periods. The principal analysis is the number and rate of fatigue events in the baseline period and in the intervention period for the three companies combined.

Table 1 - Time periods of vehicles under observation

Company	Baseline period	Intervention period
Company A	15 February – 6th March 2015	7 March – 29th May 2015
Company B	1 January – 24th February 2015	25 February – 18th May 2015
Company C	1 January – 24th February 2015	25 February – 18th May 2015

Principal Statistical Analyses

To assess the difference, if any, in fatigue events in the baseline period and the intervention period, Poisson regression analysis was used incorporating an exposure variable (22), this being the number of operating days in the two periods, combined with either distance travelled and hours spent moving. Analysis was also conducted adjusting for days under observation on its own. Each model was parameterised in such a way as to allow direct comparison of driver fatigue events in the intervention period relative to the baseline period. In addition, to aid in interpretation, the model was reparametrised so that the comparison could be expressed as the fatigue event rate in the baseline period relative to the intervention period and Incidence Rate Ratios (IRR) are presented on a per distance travelled and per time driven basis. All analysis was conducted in STATA/MP 12.1 (23). Statistical significance was set at $p \leq 0.05$. Approval from the Monash University Human Research Ethics Committee was obtained for the analysis of the de-identified dataset.

RESULTS

The number of fatigue events detected in the 'baseline' and 'intervention' period was of principal interest. As described earlier, each fatigue event was verified by video review in the monitoring center by a trained monitor. Across the three companies, data were available for a combined 380 days of operation between 1 January 2015 and 29 May 2015.

Table 2 presents the total number of fatigue events detected in the baseline and intervention periods, as well as per-day summary statistics. Of note is the significantly lower number of fatigue events detected per day of operations in the intervention period (*Mean: 0.93, SD = 2.0)* compared to the baseline period (*Mean: 14.5, SD = 28.7)* ($p \leq 0.05$). As expected, exposure parameters indicate clear differences in the number of days under observation between the two periods; thus, differences exist in distance travelled and vehicle moving time in the baseline and intervention periods.

Table 2 - Fatigue event and fleet operational parameters

	Baseline period	**Intervention period**
Fatigue events detected		
Total number	1885	232
Per day		
Mean (*SD)*	14.5 (28.7)	0.93 (2.0)
Minimum observed	0	0
Maximum observed	196	12
Exposure		
Number of days under observation	130	250
Operating time (hours), total	64,716	100,839
Mobile time		
Total time (hours)	43,179	78,115
Mean (*SD)* (hours)	332.15 (749.5)	312.5 (737.7)
Distance travelled		
Total (km)	1,267,765	1,700,866
Per day		
Mean (*SD)* (km)	9752 (8468)	6803.5 (4939.5)
Total (mi)	787,754	1.056,870
Per day		
Mean (*SD)* (mi)	6059.6 (5251.7)	4227.5 (3069.3)

Adjusting for the exposure variables permits comparisons in the fatigue event rate between the baseline period and in the intervention period to be made. As seen in Table 3, the rate at which fatigue events occurred during the intervention period was substantially lower than in the baseline period.

While the event rate data presented in Table 3 indicate rate-based differences in fatigue events between the two periods, Poisson regression modelling that adjusts for the differences in exposure provides a robust method for assessing whether these differences are statistically significant. Table 4 presents the fatigue event incident rate ratios for the intervention period relative to the baseline (silent) period. These incident rate ratios can be seen to be emblematic of the effectiveness of the real-time feedback mechanism to companies and their drivers.

Table 3 - Rate of fatigue events in the baseline and intervention period

	Baseline period	**Intervention period**
Fatigue events detected		
Total number	1885	232
Rate of events		
Per day	14.5	0.928
Per mobile time (hours)	0.043	0.003
Per 1000 hours mobile	43.65	2.97
Per distance travelled (km)	0.002	0.0001
Per 1000 km travelled	1.48	0.136
Per distance travelled (miles)	0.002	0.0002
Per 1000 miles travelled	2.39	0.219

As shown in Table 4, after adjusting for the number of operational days, the rate at which fatigue events occurred in the intervention period was 6.4% that which occurred in the baseline period, representing a 93.6% reduction (IRR: 0.064, 95% CI: 0.055-0.073, p≤0.001). Conversely, this can be expressed as fatigue events occurred at a rate 15.6 times higher in the baseline period than they did in the intervention period, adjusting for the number of operational days (IRR: 15.6, 95th% CI: 13.63-17.91, p≤0.001).

Table 4 - Fatigue event rate in the intervention period relative to the baseline period (Poisson regression analysis)

	IRR	**95th % C.I**		
Fatigue event analysis	**Reference: baseline 1.0**	**Lower**	**Upper**	**P**
Rate per day	0.064	0.055	0.073	<0.001
Rate per mobile time	0.068	0.059	0.078	<0.001
Rate per distance travelled	0.091	0.080	0.105	<0.001

Table 4 also shows that fatigue events per hour driven were significantly lower in the intervention period (2.97 per 1000 moving hours) compared to the baseline period (43.65 per 1000 moving hours), translating to a 93.2% reduction in fatigue events in the intervention period (IRR: 0.068, 95th% CI: 0.059-0.078, p≤0.001).

Similarly, on a per distance travelled basis, fatigue events occurred at a significantly lower rate in the intervention period than in the baseline period; this reduction equates to 90.9% (IRR: 0.091, 95% CI: 0.080-0.105, p≤0.001. Expressed another way, fatigue events occurred at 11-times higher rate in the baseline period than in the intervention period (IRR: 10.9, 95^{th}% CI: 9.51-12.49, $p \leq 0.001$).

Discussion

This analysis of real-world fatigue event data aimed to establish the incidence of fatigue events in long-haul truck driving. A second aim was to examine whether the incidence of events changed in an intervention period where in-cab feedback was provided to the driver in combination with real-time feedback to the driver's employer. In short, the rate at which fatigue events occurred during the intervention period was substantially lower than was the case in the baseline period, adjusted for number of operating days, time spent in vehicle moving and distance travelled. Across all three denominators, the reduction was upwards of 90 percent.

The goal of fatigue monitoring should be two-fold. Firstly, these systems should identify instances where drivers are fatigued, in this case experiencing a micro sleep, and provide feedback to the driver so that safety at that point in time can be addressed. Secondly, the system should provide information that both a driver and their employer can use to manage fatigue in the longer-term. A fatigue management plan and involvement of a driver's employer are critically important in achieving these goals. A system should detect an event to help the driver to manage safety in real time, whilst also providing valuable data for both driver and employer to better manage fatigue so that the likelihood of fatigue events occurring in subsequent periods is reduced.

For the companies involved in this study, when a verified fatigue event occurred the driver and employer were encouraged to discuss possible contributors to that event(s) usually shortly after the shift concluded. The range of strategies used to manage safety at the time of the event typically include drivers pulling over immediately or at the next rest stop, and in cases of multiple events, driver's being 'swapped–out' with a new driver to continue the journey. Longer-lasting strategies are likely to also have emerged from these discussions that include drivers taking decisions to improve sleep quality through a reduction in alcohol consumption; drivers taking decisions to improve sleep duration when at home off-shift; and drivers being sent for medical review. It can be argued that it is these strategies that may have resulted in fewer fatigue events in the intervention period, and that the technology used to monitor and provide feedback represented an important trigger for the initiation of these supporting strategies.

As a road safety countermeasure, providing in-cab feedback to drivers has been found to be an effective approach to encouraging safer behaviours, for example, with seat belt usage and speeding behavior (19, 20, 24). Similarly, making a driver aware of their fatigue state via in-cab feedback is a crucial first step to reducing driver fatigue and has been shown to reduce self-reported fatigue events in real world driving (25). To achieve an even greater benefit it is important that this information is then incorporated into a broader safety framework, as was done by the companies involved in this study. This is consistent with the more recent discussions in the literature that emphasise the importance of integrating real time fatigue data within the context of fatigue risk management systems and safety management systems (26). Clearly, real-time fatigue data will likely be most effective when implemented as one component of a broader safety risk management system with multiple levels of control (21). It is therefore likely in the current study that the broader involvement of the three companies in managing fatigue events substantially contributed to the observed reductions in verified fatigue events in the intervention period, in addition to the direct auditory and tactile warnings to the driver.

The influence of 'outside-the-cab' company monitoring and feedback is an interesting issue not only for fleet settings where feedback through an employer's organisation is possible, but it may also provide interesting insights for the vehicle manufacturers (OEMs) generally. Current passenger fleet OEM approaches to drowsiness alerting center on providing an alert to driver, be it visual or auditory. While it is helpful to know when a driver is tired, the response to that warning is currently entirely in the hands of that driver's motivation – do they 'press on' with their journey, or do they take a break. A subset of drivers may likely continue driving even when they are made aware of their drowsy state. Considerable thought therefore needs to be given to how to replicate our findings in a passenger fleet setting where feedback through a driver's employer, as is in the case in fleet and mining settings, is not possible.

There are a number of limitations and therefore avenues that need further exploration. It is known that time of day impacts accident rates (1), and time into trip influences the rate of involvement in safety critical events for heavy vehicle drivers (27). As this analysis did not examine time-of-day effects, further research examining the impact of trip timing and duration with respect to time of day, the time into the trip of event occurrence, and the relationship between events within trips is warranted. It is also important to further explore each company's safety culture and maturity with respect to safety management systems so as to further tease apart the influence of the direct device warnings to the driver from the influence of company involvement in managing fatigue events.

A strength of this paper is the availability and use of continuous monitoring of driver behavior and driver state data, as well as the external verification of fatigue events. With contemporary road safety research being increasingly focused on studying behaviour in naturalistic settings, a dataset of the type used here can provide unique insights into driver state not otherwise possible. For practitioners and regulators this type of information would provide an important evidence base to inform policy discussions around working hours and timing, and durations of rest breaks, within the context of both company and regulatory-level managements systems (28,29).

This study has found that real-time driver monitoring can be used to successfully measure and manage fatigue events in long-haul truck fleets. This represents novel information about the incidence of verified fatigue events in the real world. Providing real time feedback to drivers and their employers has been shown in this paper to reduce the rate of fatigue events. Despite the large observed reduction in fatigue events, fatigue events continue to occur. This finding warrants continued efforts in exploring additional strategies to further reduce risk.

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