Journal of Transport and Supply Chain Management
ISSN: (Online) 1995-5235, (Print) 2310-8789

Fatigue risk associated with extended off-duty periods and circadian misalignment: An exploratory truck driver fatigue risk model

Authors:
Andries Mouton[1]
Leila L. Goedhals-Gerber[2]
Anneke de Bod[1]

Affiliations:
[1]Department of Logistics, Economics and Management Sciences, Stellenbosch University, Stellenbosch, South Africa

[2]Department of Industrial Engineering, Faculty of Engineering, Stellenbosch University, Stellenbosch, South Africa

Corresponding author:
Leila Goedhals-Gerber,
leila@sun.ac.za

Dates:
Received: 24 Feb. 2025
Accepted: 31 Mar. 2025
Published: 26 May 2025

How to cite this article:
Mouton, A., Goedhals-Gerber, L.L. & De Bod, A., 2025, 'Fatigue risk associated with extended off-duty periods and circadian misalignment: An exploratory truck driver fatigue risk model', *Journal of Transport and Supply Chain Management* 19(0), a1155. https://doi.org/10.4102/jtscm.v19i0.1155

Background: Road freight transportation in South Africa is vital to the economy, but truck driver fatigue poses safety risks, leading to crashes and reduced performance. Fatigue is influenced by work schedules, driver health and sleep patterns.

Objectives: This study analyses work scheduling factors contributing to fatigue, focussing on recovery between shifts, cumulative workload, waiting times and clock-in patterns.

Method: This study examines the risk of fatigue among truck drivers by applying logistic regression, fitted with ridge regression, to scheduling and fatigue telematics data from a South African road freight carrier. Hypotheses explored the association of scheduling practices that restrict truck drivers' rest and their fatigue risk.

Results: Longer recovery times were associated with increased fatigue risk, suggesting the quality of off-duty rest is more important than duration alone. Night-time rest between 00:00 and 06:00 was crucial in reducing fatigue risk, while working during these hours heightened the risk. A higher cumulative workload over the week, however, was associated with reduced fatigue risk, raising questions about drivers' use of off-duty time and the importance of routine schedules.

Conclusion: Fatigue management is complex – simply extending off-duty hours may not reduce fatigue if drivers struggle to readjust or use rest time ineffectively. Ensuring night-time rest and managing work hours are critical strategies.

Contribution: Carriers should go beyond extending rest periods by aligning schedules with circadian rhythms and prioritising driver well-being to enhance safety and performance.

Keywords: road freight; scheduling; recovery periods; truck driver well-being; logistic regression; fatigue management.

Introduction

South Africa's economy relies heavily on road freight transportation, which serves as the backbone of trade across the country (Havenga et al. 2014; Lalendle, Goedhals-Gerber & Van Eeden 2021). The truck drivers who traverse these extensive networks require sufficient quality sleep to mitigate risk associated with crashes, performance degradation and fatigue (Lemke et al. 2016). However, recovery opportunities for these drivers are influenced by work schedules, the timing of shifts, the drivers' health and how they utilise their time outside of work (Phillips et al. 2017). Fatigue, a critical issue in all industries, stems from a combination of work-, sleep- and health-related factors (Davidović, Pešić & Antić 2018), making effective management of these elements essential for ensuring road safety.

Logistic regression was employed in this study to examine the significance of work-related and sleep-related factors on the occurrence of fatigue events among truck drivers from a South African road freight carrier. The model is derived from scheduling and fatigue telematics data provided by the carrier, offering a unique South African perspective on truck driver fatigue risk – an area that is well studied globally but less so in this specific context. The study is further enriched by insights gathered from interviews conducted with the carrier.

The research is guided by four key hypotheses:

H1a: Carrier scheduling practices that reduce a truck driver's ability to receive sufficient recovery between shifts will increase the likelihood of a driver experiencing a fatigue event.

H1b: Recovery times before shifts, including the duration and timing of recovery periods, are negatively associated with the likelihood of truck drivers experiencing a fatigue event.

H1c: Cumulative weekly working hours, including the duration and timing of previous shifts, are positively associated with the likelihood of truck drivers experiencing a fatigue event.

H1d: Truck drivers who experience prolonged waiting times at the depot before a trip are more likely to experience a fatigue event.

The study revealed several key insights into how scheduling factors influence truck driver fatigue risk. Contrary to expectations, longer recovery times between shifts were associated with a higher risk of fatigue events, suggesting that extended rest periods may not always lead to better recovery and raise concerns about the drivers' activities outside of work. Conversely, increased rest during the critical night-time hours of 00:00 – 06:00 was significantly linked to a lower risk of fatigue, highlighting the importance of quality sleep during these hours. Interestingly, clocking in between 00:00 and 06:00 was not significantly associated with fatigue events, challenging the assumptions about the risk of early start times (Sirois 2012:10). In addition, while a higher cumulative workload over the past week was linked to a decrease in fatigue risk, more working hours during night-time periods were associated with an increased risk of fatigue.

These findings underscore the critical need for recovery during night-time hours and the importance of limiting work during these periods to mitigate fatigue risk. Furthermore, the results advocate for promoting sleep hygiene at home, ensuring that drivers use their off time productively to achieve sufficient quality rest. The evaluation of fatigue telematics data also revealed significant false positive errors, where human processing errors limit the effectiveness of fatigue risk measurement and monitoring within the carrier – questioning the value added to operations.

The study begins with a review of literature on road freight scheduling and fatigue monitoring, followed by a detailed explanation of the methodology, a discussion of results and concluding recommendations.

Theory and literature review

The backbone of road freight operations is scheduling, ensuring that deliveries are made on time and at the correct destination. Managing the efficient use of employees and vehicles is a challenging endeavour, where strain may be placed on the system. Truck driver fatigue is an outcome of such workplace strain and overwork, leading to detrimental safety performance outcomes. To improve the safety of truck drivers on the road, an ongoing trend is the installation of in-vehicle, real-time fatigue monitors. Such monitoring allows for real-time safety intervention, reactive investigation and proactive improvement of systems to mitigate fatigue risk.

Fatigue

Correctly defining fatigue is an essential task for accurate and consistent measurement (Phillips 2015:49). Fatigue can be categorised into three causal factors, namely work, sleep and health factors (Davidović et al. 2018:200). However, Phillips (2015:53) proposed the following definition that accounts for fatigue's complexity and expands upon the causal factors:

> Fatigue is a suboptimal psychophysiological condition caused by exertion. The degree and dimensional character of the condition depends on the form, dynamics and the context of exertion. The context of exertion is described by the value and meaning of performance to the individual; rest and sleep history; circadian effects; psychosocial factors spanning work and home life; individual traits; diet; health, fitness and other individual states; and environmental conditions. The fatigue condition results in changes in strategies or resource use such that original levels of mental processing or physical activity are maintained or reduced. (p. 53).

The key points highlighted by this broad definition are that fatigue is a result of exertion, its degree dependent on a variety of factors that hinder physiological and psychological performance. This defines fatigue as a symptom of certain conditions, rather than a behaviour, where its significance is determined by interactions between perceived fatigability and performance fatigability (Enoka & Duchateau 2016:3). Interestingly, fatigability is an individual's susceptibility to fatigue, which highlights the subjective nature of the symptom and supports Phillip's (2015) argument that the power of exertion is characterised by its context: circadian effects, health, work and home life, among others. Similarly, Enoka and Duchateau (2016:3) describe that individuals who are less fatigable can handle a higher physical or mental workload to reach the same level of fatigue as individuals with lower resistances. There are many contexts where exertion can lead an individual to experience fatigue; however, the interplay between perceived fatigability and performance fatigability dictates its force. From a truck driver's perspective, the demanding operational conditions may not take the same toll on all drivers and numerous individual factors will be influential.

Truck drivers, especially those working in developing countries, likely experience similar challenges as shift workers – low wages, inadequate housing and poor healthcare access (Fischer 2001). The method in which truck drivers are remunerated can lead to driving behaviours that manifest in fatigue – spending greater time driving for further distances and increasing the time between short rest breaks (Thompson, Newnam & Stevenson 2015). Mahajan et al. (2019) found that the majority of truck drivers from a study done in India (85%) have financial responsibilities to their families, and combined with a lack of understanding of the possible risks, lead to dangerous driving to earn higher earnings. The necessity of increasing working hours to support a driver's family will impact the duration and quality of sleep and contrary to management expectations, remuneration and incentive schemes aiming to increase performance may subsequently decrease driver performance and safety. As such, it is plausible that drivers may choose to work under self-imposed fatiguing conditions because of financial and family obligations.

Scheduling

Logistics and supply chain operations are a 24 h a day, 7 days a week (24 × 7) operation with deliveries at all hours of the day. As such, the effective scheduling of drivers is crucial when considering their health and safety. Li and Kwan (2003:334) define driver scheduling as the allocation of work periods into a set of legal shifts. The scheduling of truck drivers is a challenging task, as it is a short-term operational decision which may change daily (Baykasoğlu et al. 2019:640). There is also more leniency compared to passenger or rail transport systems that follow fixed timetables, where road transportation arrival times tend to be relatively flexible, which allows for the possibility to interrupt driving for rest breaks if required (Goel, Archetti & Savelsbergh 2012:1122). Effective scheduling must ensure that drivers have adequate rest time at home and that work arrangements minimise fatigue. Brown (1994) identifies key work factors contributing to driver fatigue, including the length of continuous work without breaks, total daily work hours, break duration and alignment with the circadian rhythm.

The primary challenge in truck driver scheduling lies in ensuring compliance with driver and working hour regulations, which are critical for managing driver fatigue. Goel et al. (2012:1123) outline these requirements as: (1) a minimum daily rest period of X_1 hours; (2) a maximum of X_2 driving hours between consecutive daily rests; (3) the initiation of the next rest period no later than X_3 hours after the previous one; and (4) mandatory short breaks of at least Y minutes after X_4 hours of driving. The complexity of truck driver scheduling increases significantly when considering factors such as circadian rhythms and the optimal timing of shifts to mitigate fatigue. Table 1 outlines the factors and associated recommendations for fatigue-resistant scheduling, aligning with the body's circadian rhythm.

Schedule regularity is also an essential aspect of health and safety. Schneider and Harknett (2019) highlight that unpredictable work schedules contribute to psychological distress, poor sleep quality and unhappiness – reducing overall well-being. However, achieving such consistency may not be feasible in the road freight industry, where schedule irregularity and short-notice delivery requirements are a common occurrence (Ren et al. 2023:1). Dorrian et al. (2022) suggest that schedule irregularity experienced by train drivers has the largest negative effect on performance and safety. This could be attributed to inconsistencies regarding scheduling impacting the driver's sleeping habits, which will negatively impact their circadian rhythm. Regarding the rotation of schedules, the changing of employee shift schedules, rapidly forward-rotating shifts are more advantageous compared to slowly backward-rotating shifts (Sallinen & Kecklund 2010:121). Sirois (2012:9) agrees that forward-rotating schedules (e.g., morning to evening to night shifts) are more aligned to circadian rhythms, although debate exists around the use of slow or fast rotations – each offering unique advantages. It is clear that optimal scheduling should be aligned with the circadian rhythm.

When developing schedules with circadian alignment in mind, it is crucial to consider individual truck driver fatigability, as some drivers may be better equipped to handle higher workloads or perform optimally at certain times. Declercq, Van Den Eede and Verbraecken (2022:5) discuss that healthy scheduling practices should include alignment to chronotypes. Chronotypes are an individual's tendencies towards preferring certain sleep and wake times, with each individual experiencing variances in the timing of optimal alertness and sleepiness (Hittle & Gillespie 2019:513). Chronotypes can be divided into three types: morning, evening and intermediate (Zou et al. 2022:3). Each chronotype prefers to be active during the respective period, while intermediate chronotypes have no preference (Zou et al. 2022:3). It appears reasonable that management should understand each truck driver's chronotype to, if feasible, allocate appropriate schedules to each employee. Chronotypes can be tested using the Morningness-Eveningness Questionnaire, Munich Chronotype Questionnaire and the Composite Scale of Morningness (Zou et al. 2022:3).

An additional concern regarding the scheduling of truck drivers is the possible variability of activities that occur during a delivery, such as delays because of congestion or

TABLE 1: Recommendations for fatigue-resistant scheduling.

Factors	Recommendations	Sources
Optimal morning shift start time	• Morning shifts should ideally start between 07:00 and 08:00. • Earlier start times may impair alertness.	• Sirois (2012:10)
Night shift end time	• Shifts should avoid ending between 00:00 and 06:00.	• National Heavy Vehicle Regulator (2013)
Critical sleep periods	• Ensure adequate sleep, particularly between 00:00 and 05:00.	• National Heavy Vehicle Regulator (2013); • Chen et al. (2016)
Reset break	• After accumulating 60 working hours in 7 days, truck drivers require a 34 h continuous break to eliminate sleep debt. • The 34 h reset must include two rest periods between 01:00 and 05:00.	• Sparrow et al. (2016:55); • Dawson, Blahous and Williamson (2019:18)
Post-reset shift recommendation	• After a reset break, truck drivers should ideally return to day shifts.	• Sirois (2012)

Note: Please see the full reference list of the article, Mouton, A., Goedhals-Gerber, L.L. & De Bod, A., 2025, 'Fatigue risk associated with extended off-duty periods and circadian misalignment: An exploratory truck driver fatigue risk model', *Journal of Transport and Supply Chain Management* 19(0), a1155. https://doi.org/10.4102/jtscm.v19i0.1155, for more information.

waiting at a customer's location. Goel (2010:432) emphasises the importance of robustness when scheduling truck drivers, as minor delays can disrupt the entire schedule, leading to an invalid schedule. Thus, schedules should be generated that account for the possibility of certain delays to not create further disruptions, hindering a driver's work-rest balance. This includes possibly uncontrollable queuing and waiting times at a customer's depot. However, the customer may not be motivated by the same responsibility to manage truck driver fatigue as the carrier, hampering optimal scheduling activities.

Queuing and waiting times present an important challenge challenge because of the impact on driver fatigue (Williamson & Friswell 2013), as it requires the driver to remain engaged and focussed while potentially increasing the daily working hours (Friswell & Williamson 2019:194). Minimising the involvement of truck drivers in the loading and unloading process is important for ensuring that maximum rest can be obtained before the next driving period (Friswell & Williamson 2019:205). Thus, collaboration between external customers, shippers and carriers is essential to improve scheduling and loading and unloading activities (Crum, Morrow & Daecher 2002). However, while scheduling and work allocation can assist in managing truck driver fatigue, their influence is limited.

Real-time fatigue monitoring

To manage fatigue and reduce crash risk, businesses often implement measures pertaining to scheduling and allowable work hours (Horberry et al. 2022:5350), often through prescriptive hours of service approaches. However, Hartley, Horberry and Mabbot (2000:27) suggest that hardware technologies can be used to expand a fatigue management system, as the information gathered can be integrated into scheduling to confirm the success or failure of certain scheduling practices. These technologies can be used for real-time monitoring of driver fatigue, detecting driver drowsiness through mounted cameras that observe facial features (eye state, head pose and mouth state) that indicate states of fatigue (Ngxande, Tapamo & Burke 2017). While real-time monitoring of driver fatigue can be used to assess scheduling, it also provides an opportunity to act as a warning system with cautionary and urgent alerts that give drivers auditory, visual and tactile warnings (Horberry et al. 2022:5357). However, Bowden and Ragsdale (2018:30) point out that a reactive approach with real-time fatigue detection will be more costly than proactively mitigating fatigue by developing a safer schedule that incorporates fatigue management. Although alerting the driver before fatigue is experienced is a method to prevent crashes (Asl et al. 2022:324), it is essential to leverage technology to enhance scheduling practices rather than relying on it solely as a safety device.

Behavioural fatigue monitoring

It is important to observe physical driver characteristics through behavioural measures, as these may be tell-tale signs that occur prior to the performance decrements identified with performance-based monitoring. Ngxande et al. (2017) identify four signals that suggest drowsy driving: frequent yawning, struggle to keep eyes open and focussed, swaying of the head and changes in face complexion because of blood flow. These signs encompass how continuous operator monitoring systems identify fatigue in drivers from a behavioural standpoint. The monitoring of driver fatigue within the vehicle cabin is an essential safety activity, as Fitzharris et al. (2017:75) and Lenné and Fitzharris (2016:7) showed that alerting a driver of fatigue reduced incident events by 66.2% and 90.3%, respectively. However, these systems must ensure accuracy to limit false classifications of alerts and ensure efficacy.

Detection versus prediction

An important distinction to consider with real-time fatigue monitoring is detection versus prediction. An issue attributed to the use of behavioural and vehicle-based measures is that drowsiness is usually detected after the onset of drowsiness, once a driver's eyes begin drooping or lane deviation occurs, allowing for the possibility of a crash (Perkins et al. 2023:1329). When developing a system to measure a driver's eyes to detect levels of drowsiness, Rusmin, Osmond and Syaichu-Rohman (2013) agreed that an alarm should sound after 4 s of eye closure. While it is crucial to avoid unnecessary alarms that could startle drivers, delayed warnings can also pose safety risks.

Hybrid fatigue monitoring

Utilising more than one measurement approach may also allow for better predictability. Jacobé de Naurois et al. (2019:100) designed a detection and prediction model, incorporating physiological, behavioural and vehicle-based signals, enabling it to predict a driver's state of drowsiness approximately 5 min in advance. However, the inclusion of driving time and driver information significantly enhanced the model's performance. This is an interesting consideration, as incorporating scheduling information into the detection process may allow for a better understanding of the driver's states of drowsiness and fatigability. Jacobé de Naurois et al. (2019:100) also discovered that the best predictability is seen with models incorporating multiple measurement systems, while, for instance, those utilising vehicle-based measures alone feature the worst predictability. Hybrid approaches may be essential to successful fatigue risk mitigation. Each of the monitoring measures used to detect drowsiness has advantages and limitations, as highlighted in Table 2. It is essential to integrate more than one measure within a drowsiness detection system, as it can lead to significantly more accurate results (Yaacob et al. 2020:1).

Implementation of fatigue monitoring technologies

Fatigue monitoring technologies require careful implementation rather than haphazard necessity to ensure the acceptance and efficacy of the system. Dawson, Searle and Paterson (2014:148) suggest that before such systems are implemented, independent, peer-reviewed studies should be investigated regarding the measured drowsiness signal, the seller should provide accuracy measures to avoid false classifications during operation and the selected devices should be applicable in real-world scenarios and work under the applicable driving conditions.

The individuals driving the vehicle will interact directly with the drowsiness detection systems influencing their driving behaviour in the process. As such, incorporating drivers into the design and implementation process is essential to ensure acceptance. Horberry et al. (2022) suggest a human-centred design process for the development, placing the drivers requirements as the central design approach and ensuring that end-users have a meaningful input in the development. Horberry et al. (2022:5357) recommend a two-level warning system for fatigue, where the first level is a cautionary and the second is an urgent warning. Table 3 specifies the type of warnings used for the two-level system. The system utilises auditory, visual and tactile warnings.

Laakmann et al. (2023:7) highlight the effectiveness of tactile warnings, noting the usefulness of vibrations in the seat belt, steering wheel, seat and pedals. It was also found that active seatbelts (that provide tensioning and consecutive pulls or vibrations) are the most noticeable, followed by vibrating seats. It is important that warnings do not negatively influence driving performance and safety. This is reflected where drivers tend to prefer tactile warnings through the seat, rather than the steering wheel, as the latter is perceived as being potentially dangerous (Horberry et al. 2022:5353). However, warning systems are more effective when utilising multiple types of warnings as well as adapting warnings to the urgency of the situation (Horberry et al. 2022). These fatigue monitoring technologies, to ensure efficacy, must be utilised in conjunction with a fatigue risk management system (FRMS) to holistically manage driver fatigue, as it allows for comprehensive fatigue monitoring data.

TABLE 2: Advantages and limitations of fatigue monitoring and detection measures.

Measures	Techniques	Advantages	Limitations
Vehicle-based measures	Steering wheel movement and standard deviation of lane position	Non-intrusive	Unreliable and dependent on environmental conditions
Behavioural measures	Percent eye closure (PERCLOS), blink rate, yawning, head nodding	Non-intrusive and easily adoptable by drivers	Depends on various human factors, illumination and background-dependent
Physiological measures	EEG, ECG and PPG	Reliable and accurate	Intrusive and difficult to use in real conditions.

Source: Adapted from Sikander and Anwar (2019) and Bajaj, Kumar and Kaushal (2021).

Note: Please see the full reference list of the article, Mouton, A., Goedhals-Gerber, L.L. & De Bod, A., 2025, 'Fatigue risk associated with extended off-duty periods and circadian misalignment: An exploratory truck driver fatigue risk model', *Journal of Transport and Supply Chain Management* 19(0), a1155. https://doi.org/10.4102/jtscm. v19i0.1155, for more information.

PERCLOS, percent eye closure; EEG, electroencephalography; ECG, electrocardiogram; PPG, photoplethysmography.

TABLE 3: In-vehicle fatigue warning system features.

Warning types	Level 1 (caution)	Level 2 (urgent)
Auditory	Warning tone followed by simple spoken message in a female voice (caution fatigue)	Louder, more pressing warning tone followed by spoken message in female voice (danger fatigue!)
Visual	Amber coffee cup symbol on windscreen	Larger, flashing red coffee cup symbol on windscreen
Tactile	Intermittent throbbing of seat	Whole seat vibration

Source: Adapted from Horberry, T., Mulvihill, C., Fitzharris, M., Lawrence, B., Lenne, M., Kuo, J. et al., 2022, 'Human-centered design for an in-vehicle truck driver fatigue and distraction warning system', *IEEE Transactions on Intelligent Transportation Systems* 23(6), 5350–5359. https://doi.org/10.1109/TITS.2021.3053096

Real-time monitoring systems provide a valuable tool to enhance fatigue management systems. Fitzharris et al. (2017) state that fatigue monitoring systems can support existing fleet management strategies using real-time information on driver performance that can be used to optimise scheduling by incorporating newfound known risks regarding drivers. Horberry et al. (2022:5353) agree that while these systems should effectively convey information to drivers in real-time, they should also record findings for training and management purposes. Fatigue detection technologies must be part of a broader FRMS with multiple controls, whereby constructive work and sleep schedules are initially developed (Dawson et al. 2014:149). Fatigue detection must be built on a culture of risk management, rather than punishment and the focus should be on how to manage fatigue effectively, rather than on identifying the reasons behind it. Only when fatigue occurrences for a specific driver occur regularly should root cause analysis be conducted (Dawson et al. 2014:149). A hybrid approach to fatigue detection technologies should be employed to inform necessary training and education, enhance scheduling and inform both the driver and employer of fatigue instances for improved long-term management.

Research methods and design

This study employed a logistic regression model fitted with ridge regression to explore the significance of features associated with truck driver fatigue events. The independent variables were derived from a 4-week scheduling dataset, while the binary dependent outcome, obtained from an in-vehicle telematics dataset, indicates whether a fatigue event occurred (1 = yes; 0 = no). Both datasets were sourced from a South African road freight carrier. To ensure the data were suitable for analysis, several pre-processing steps were undertaken. Data wrangling was conducted to improve data quality and formatting, as well as to create unique variables relevant to the study. In addition, structurally missing data were imputed using multiple imputation to prevent the loss of any observations, ensuring a complete dataset for analysis. The fundamental assumptions of logistic regression were tested and addressed, namely independence of errors, absence of multicollinearity, lack of influential outliers and linearity of the logit for continuous variables (Stoltzfus 2011). All data wrangling and analysis were conducted in R.

The independence of errors assumption was evaluated using the Durbin–Watson test (DW = 1.7571, p-value < 0.0001) to check for significant first-order serial correlation in the residuals (Penda, Djellout & Proïa 2014). However, an autocorrelation plot confirmed that the model did not considerably violate the autocorrelation assumption. Multicollinearity was assessed through variance inflation factor (VIF < 10) and generalised VIF (GVIF < 2.2). Parameters with high collinearity were removed to test their influence on the model and determine whether the problem must be addressed. Cook's distance was employed to examine influential outliers, ensuring that individual data points did not overly affect the model. Because of the class imbalance discussed in 'Results' section, there were many influential outliers (*n* = 135), but because 100% of the fatigue events are influential, removal was not an option. Linearity was tested using the Box–Tidwell procedure, which assesses the interaction between continuous variables and their log-transformed counterparts (Zeng 2022). Scatterplots fitted with loess curves were also generated to explore potential non-linear relationships. The model went through multiple iterations, and several alterations were made to address assumption violations.

Ridge regression was introduced to address multicollinearity by shrinking large coefficients, effectively reducing the impact of multicollinearity, while cross-validation was used to select the optimal regularisation parameter (λ = 0.0011) and balance the trade-off between bias and variance (Cule, Vineis & De Iorio 2011). Although influential outliers were detected, they were retained because of their relevance in understanding fatigue events. Testing with the weighted Bianco and Yohai estimator did not substantially improve model performance, justifying their inclusion without weights. In addition, a non-linear relationship between the continuous recovery break variable and the logit prompted its categorisation into five distinct bins: less than 9 h (the legal minimum in South Africa), 9 h to 12 h (used as the reference, aligning with Australian standards), 12 h to 24 h (sufficient rest), 24 h to 48 h (including a reset break) and more than 48 h (equivalent to a weekend rest). Categorisation mitigated nonlinearity while aligning with operational realities.

By combining logistic regression with ridge regression, this study aims to provide a robust analysis of the work scheduling factors contributing to truck driver fatigue – investigating risks associated with recovery between shifts, cumulative workload, waiting times and clock-in patterns. Table 4 outlines the independent parameters of the logistic regression model.

The equation of the logistic regression model is as follows (see Equation 1):

$$\log \frac{P(\text{fatigue\_event}=1)}{P(\text{fatigue\_event}=0)} = \beta_0 + \beta_1 \cdot \text{recovery\_break} + \beta_2 \cdot \text{night\_hours\_in\_recovery} + \beta_3 \cdot \text{yard\_1} + \beta_4 \cdot \text{is\_night-time\_clock\_in} + \beta_5 \cdot \text{cumulative\_weekly\_shift\_lengths} + \beta_6 \cdot \text{cumulative\_night\_hours\_shifted} \quad \text{[Eqn 1]}$$

TABLE 4: Independent parameters used in logistic regression model.

Characteristics	Parameters	Descriptions
Recovery	• Recovery break:	Recovery and rest time prior to shift
	▪ < 9 h	-
	▪ 9 h – 12 h (reference category)	-
	▪ 12 h – 14 h	-
	▪ 24 h – 48 h	-
	▪ > 48 h	-
	• Night hours in recovery	Time spent in recovery between 00:00 and 06:00.
Workload	• Cumulative weekly shift lengths	Cumulative weekly shift lengths prior to shift
	• Cumulative night hours shifted	Cumulative shift times between 00:00 and 06:00
Idle time (waiting)	• Yard 1	Waiting time at depot or distribution centre prior to driving task.
Clock-in time	• Is night-time clock in	Whether the driver clocked in between 00:00 and 06:00

h, hours.

To supplement the quantitative findings, semi-structured interviews were conducted at the same road freight carrier, with responses being coded into themes and quotations used to validate and contextualise the logistic regression model results. In addition, the logistic regression model development faced several constraints, which impacted both its predictive power and the confidence in its classifications. Despite these challenges, the results were contextualised and critically discussed considering existing literature and insights gathered from interviews, providing a balanced analysis of the findings.

Ethical considerations

An application for full ethical approval was made to the Social, Behavioural and Education Research Ethics Committee (REC: SBE) at Stellenbosch University, and ethics consent was received on 09 February 2024. The ethics approval number is LOG-2023-27699.

Results

This study proposed and tested four hypotheses, each addressing specific work-related and sleep-related factors contributing to truck driver fatigue.

Hypothesis 1a: Overview

The primary hypothesis (Hypothesis 1a) concerning the impact of scheduling practices on driver recovery is examined through the lens of its related sub-hypotheses (Hypotheses 1b, 1c and 1d). The results presented in Table 5 are based on logistic regression analyses and provide insights into the relationship between these factors and the likelihood of fatigue events. However, the overall aim of the study is to explore the various factors influencing driver fatigue and provide a deeper understanding that can help improve safety outcomes. The hypotheses served primarily to guide the discussion.

Hypothesis 1b: Recovery time before shifts and fatigue

A truck driver's recovery time prior to starting a shift plays a critical role in determining their fatigue risk. In this study,

TABLE 5: Logistic regression model with ridge regression (λ = 0.0011).

Parameter	Odds ratio	Standard error	95% CI lower	95% CI upper	*p*-value
Recovery_break < 9 h	0.6209	1.0028	0.0870	4.4327	0.6347
Recovery_break 12 h – 24 h	0.5322	0.2960	0.2980	0.9507	0.0331
Recovery_break 12 h – 24 h	2.5937	0.2707	1.5258	4.4091	0.0004
Recovery_break > 48 h	4.2226	0.4224	1.8451	9.6640	0.0006
Night_hours_in_recovery	0.9492	0.0233	0.9069	0.9936	0.0253
Yard_1	0.7636	0.0748	0.6596	0.8841	0.0003
Is_nighttime_clock_in1	0.9685	0.1878	0.6702	1.3994	0.8646
Cumulative_weekly_shift_lengths	0.9637	0.0123	0.9407	0.9873	0.0027
Cumulative_night_hours_shifted	1.1937	0.0401	1.1035	1.2914	0.0000

CI, confidence interval; h, hour.

categorical bins were used to assess how different ranges of recovery time impact fatigue risk, while a continuous variable was employed to evaluate the effect of night hours in recovery. It is hypothesised that longer recovery times between shifts and increased rest during night hours both reduce the risk of fatigue events. The reference category for recovery time was set between 9 h and 12 h, providing a baseline for comparison against other recovery ranges. The logistic regression results reveal a complex relationship between recovery time and the likelihood of experiencing a fatigue event. Interestingly, recovery times of less than 9 h do not exhibit a statistically significant difference in fatigue risk compared to the reference category, suggesting that shorter recovery periods may not drastically elevate fatigue risk. However, recovery times exceeding 12 h show a statistically significant impact on fatigue risk.

Specifically, the odds of a driver experiencing a fatigue event with a recovery time between 12 h and 24 h are approximately 47% lower than those resting between 9 h and 12 h. As such, moderate extensions in rest periods may have protective effects against fatigue. However, drivers who take longer breaks, ranging from 24 h to 48 h, or even greater than 48 h, are 2.59 and 4.22 times more likely to experience a fatigue event, respectively, compared to those in the reference category (resting between 9 h and 12 h). These findings align with the preliminary logistic regression model that measured recovery time continuously, which identified a counterintuitive positive relationship between recovery time and fatigue risk, indicating that as recovery time increases, so does the risk of a fatigue event. Such a paradoxical relationship raises questions on how drivers utilise extended rest periods and whether other factors, such as lifestyle choices or the disruption of sleep patterns, could influence fatigue risk.

In contrast, the analysis of night hours in recovery presents a different trend. The results show a negative relationship between night recovery time and fatigue risk, indicating that additional rest during the critical window of 00:00 and 06:00 correlates with a reduced likelihood of fatigue events. The odds ratio (OR) of 0.9492 suggests that for each additional hour of night rest, the odds of a fatigue event decrease by approximately 5.08%, underscoring the importance of quality sleep during night-time hours. In addition, the analysis revealed that clocking in between 00:00 and 06:00 does not have a statistically significant relationship with the occurrence of a fatigue event, challenging the assumption that early morning start times inherently increase fatigue risk.

Hypothesis 1b is rejected, as longer recovery times before shifts are positively associated with truck drivers experiencing a fatigue event, while reduced rest during night-time hours is negatively associated – highlighting the significant relationship between recovery duration and timing.

Hypothesis 1c: Cumulative weekly working hours

A truck driver's cumulative weekly hours worked before a shift significantly influence their ability to recuperate and may reflect their overall workload and potential work strain. Both cumulative weekly shift lengths and cumulative weekly night hours worked were found to be statistically associated with the occurrence of fatigue events ($p < 0.05$). It is hypothesised that increased cumulative weekly shift lengths and increased time spent working during night hours both increase the risk of fatigue events. Notably, cumulative weekly shift lengths demonstrated a negative association with fatigue events, with each additional hour worked reducing the odds of a fatigue event by approximately 3.63%. Such a counterintuitive finding suggests that increased overall working hours might lead to a routine or rhythm that mitigates fatigue, or it could reflect reduced time spent at home where rest quality may be unstable – supporting Hypothesis 1b.

In contrast, cumulative night hours worked between 00:00 and 06:00 had a much stronger and opposing effect, increasing the odds of a fatigue event by approximately 19.37% per additional hour. As such, night-time work has a pronounced impact on fatigue risk, emphasising the importance of adequate rest during night hours and the inherent dangers of sustained work during these periods. These findings suggest a nuanced relationship where longer working hours overall may not necessarily elevate fatigue risk, but working during night-time hours does. As a result, Hypothesis 1c is rejected, as cumulative weekly work hours are negatively associated with truck drivers experiencing a fatigue event, while increased night hours worked are positively associated – highlighting the significant relationship between work shift duration and timing.

Hypothesis 1d: Waiting times at depot

There is often a time gap between when a driver clocks in at the depot and when they depart with their assigned load. These discrepancies can result from delays in the picking and loading process or from drivers arriving early for their shifts. The waiting time before departing from the depot is statistically significant and negatively associated with the occurrence of fatigue events. Specifically, each additional hour spent waiting at the depot reduces the odds of experiencing a fatigue event by approximately 23.64%. These waiting periods may provide drivers with an opportunity to rest or prepare for their upcoming journey, thereby reducing their fatigue risk. The results do not support Hypothesis 1d, as increasing waiting times are significantly associated with a lower likelihood of truck drivers experiencing a fatigue event.

Discussion

The results highlight the potential inadequacy of simply providing truck drivers with extended recovery opportunities to mitigate fatigue risk, even resulting in adverse increases in fatigue risk. However, the importance of recovery time during night hours between 00:00 and 06:00 cannot be understated to ensure quality sleep – stressing the necessity of aligning to the body's circadian rhythm. The insignificance of clocking in during night hours suggests the possibility of circadian rhythm adaptation, whereby, because of fixed schedules, these truck drivers may be better adapted to working night shift hours, as well as differences in shift demands as these timings correspond with local, short-haul deliveries made at the carrier. The implications of a truck driver's previous workload on fatigue risk hint at an interesting dynamic between scheduling, circadian adaptation and a truck driver's home environment. Yet, working during unsafe night hours significantly influences fatigue risk, further advocating circadian alignment. While waiting time prior to the driving task generally increases daily hours worked, it seemingly provides a beneficial rest opportunity for drivers to prepare for their upcoming shift.

An interpretation of the logistic regression results, drawing on both existing literature and insights gathered from interviews with key personnel at the same South African road freight carrier from which the quantitative were was obtained is presented next. These interviews offer a practical perspective on the challenges of fatigue management, complementing the quantitative findings.

Sleep is an essential requirement for optimal health, safety and performance. Watson et al. (2015) recommend adults regularly obtain seven or more hours of sleep, as regularly obtaining less is associated with multiple adverse health outcomes. While this study was unable to incorporate actual sleep durations, the recovery period between shifts was used to indirectly measure a driver's ability to receive sufficient sleep. The results of the logistic regression correspond with Dawson and McCulloch (2005) who stated that fatigue is linked more to the timing and duration of sleep during a recovery period than the duration of the recovery period alone. As such, prolonged recovery periods do not necessarily mitigate fatigue but preferably also require quality rest during night-time hours. Lemke et al. (2016) support this finding by highlighting that sleep quality is better associated with driving while sleepy than sleep duration for truck drivers, concluding that sleep quality is better associated with safety-relevant performance. While increased night hours in recovery are significantly associated with fewer fatigue events, truck drivers, especially in developing countries such as South Africa, do not have the luxury of consistent quality sleep.

The home environment experienced by truck drivers can significantly impact their ability to receive sufficient quality rest. Interviews with the carrier highlighted multiple instances where family responsibilities inhibited rest opportunities. For example, one case involved a driver who, after finishing his evening shift, was unable to rest the required 9 h because of the demands of caring for his children following the passing of his partner. Despite his efforts, this driver often managed only 3 h – 4 h of sleep. Mutifasari and Ramdhan (2019) note the impact of unfavourable conditions at home on sleep quality: waking up because of heat and noise, lighting in the bedroom and children. Thus, while drivers may receive prolonged recovery opportunities, the timing and conditions at home may result in fatigue upon return to work. The challenges of a driver's home environment are further emphasised by the finding that increased weekly hours worked are associated with a reduced risk of fatigue events, suggesting that spending more time on the road, rather than at home, may inadvertently reduce fatigue risk.

A recurring theme among the interview responses was the truck drivers' desire to maximise their earnings, often at the expense of adequate rest. As one dispatcher explained, 'drivers forever want to make money, make hours and they don't even think about themselves [*to*] rest'. Potentially resulting in drivers taking on second jobs, which can impair their ability to manage fatigue (Khanehshenas et al. 2023). In addition, some drivers choose to sleep in their cars rather than go home, aiming to secure a long-distance delivery the following morning. It is also not uncommon for drivers to clock in 2 h – 3 h before their scheduled shift to accumulate extra work hours. The drive to earn more money is often tied to their financial responsibilities to their families (Mahajan et al. 2019). Given that truck drivers in developing countries are seemingly willing to sacrifice rest to increase their income, the possibility of some drivers working additional jobs outside of their driving shifts cannot be ignored, thereby raising the question: When salaries are low and financial burdens are high, what activities are drivers prioritising during prolonged recovery periods of more than a day?

The impact of prolonged recovery periods on fatigue risk is further exemplified by interviews with the carrier. In one extreme case, after 20 days of leave, a driver experienced a fatigue-related crash on their first day back on duty. When drivers regularly experience fatigue events, the carrier often adjusts their rostering or provides paid leave as a preventative measure. However, the study's results suggest that such practices may not always be beneficial. Jovanis, Wu and Chen (2011) support this by identifying an increase in a truck driver's crash odds after a recovery period of 34 h or more. The following interview response sheds light on this phenomenon:

> 'You'll find that a driver was supposed to start a shift after his three days off, and you know if you are off for such a [*long*] period you may spend a lot more time with your family. A lot of [*drivers*] are travelling from where they're staying. So, their home might be in KwaZulu-Natal, and on their last day off, they travel in a taxi all the way back [*to the depot*], and they sleep two or three hours and get into a truck.' (Operations Executive, pers. comm., 14 August 2024)

These accounts reveal how recovery periods, rather than ensuring quality rest, may instead become periods of additional strain because of travel and family commitments. While evidence generally concludes that restart breaks are an effective solution to mitigate cumulative fatigue and provide recovery from chronic sleep restriction (Dinges et al. 2017), these findings underscore the need to consider the quality and context of rest, rather than simply the duration. However, the importance of circadian-aligned schedules is of clear importance with the significance of night hours in recovery and cumulative weekly night hours worked. Figure 1 shows that the risk of fatigue for the carrier's truck drivers markedly increases from 00:00 to 06:00, potentially because of factors such as increased traffic congestion, a higher number of truck drivers on the road and circadian misalignment.

Activities that increase a truck driver's hours spent working are generally viewed as a fatigue risk, especially those that are unscheduled. Talebi, Rogers and Drews (2022) identified the risk of unscheduled activities, such as delays in operations causing additional waiting, on fatigue. Furthermore, Williamson et al. (2013) found unpaid waiting and queuing for loading or unloading were associated with longer working hours and were significant predictors of fatigue. However, different from other studies, this study investigated the influence of pre-trip waiting times on fatigue and not waiting times at customer stores. Picking and loading delays are a daily challenge at the carrier's depot, forcing the truck driver to either wait at the canteen, at designated benches, or in their cars. Interview responses with carrier operational staff suggest concerns that delays at the depot result in drivers getting tired. Despite this, the findings of this study highlight that waiting times could provide a brief opportunity to rest, as, importantly, drivers are also remunerated for this time.

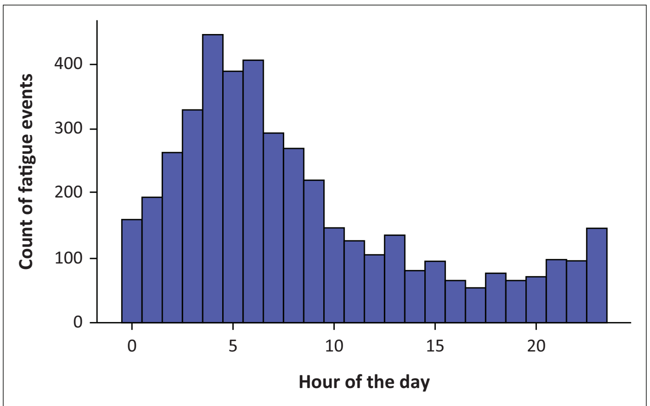

FIGURE 1: Positive fatigue events by hour of the day for the carrier (N = 882).

Opportunities exist for the carrier to further enhance the rest amenities at the depot, such as providing showers, comfortable seating, kitchen appliances, recreational activities and secure lockers, to better support drivers during their daily waiting periods. Interviews revealed that these facilities were available at the carrier's previous depot but are currently lacking at the present site, a concern noted by staff. The primary resting area, the canteen, offers drivers very inexpensive food options, mainly chicken, rice and vegetables. However, the low cost comes at the expense of nutritional value, with many interviewees frequently citing the food as detrimental to their health. One interviewee mentioned needing to visit the doctor because of stomach cramps after consistently eating the canteen meals. Presenting a cost trade-off where drivers prioritise affordability over their well-being.

Driver responsibility appears to be both the main challenge and solution to managing fatigue at the carrier. Management expects truck drivers to be 'professional drivers', emphasising fatigue awareness campaigns while placing the bulk of responsibility on drivers to change their behaviour. While this approach is understandable, management cannot micromanage what occurs outside of working hours; it is also limited. As one interviewee noted, there are 'uncontrollable factors that we cannot control'. However, solely monitoring and assessing driver behaviour may not be sufficient, as the choices drivers make often conflict with their well-being. The effectiveness of these awareness campaigns is in question, as one interviewee observed that 'management just put [*posters*] up and leave it', suggesting that while the campaigns provide critical information, they might not be engaging enough to drive meaningful behavioural change. The management of driver fatigue is a shared responsibility among all stakeholders (Gander et al. 2011), a principle central to the chain of responsibility concept.

The chain of responsibility concept recognises that the actions, inactions and demands of all parties in the supply chain – such as employers, loaders, pickers, managers, supervisors, dispatchers, schedulers and receivers – directly influence driver behaviour and road safety (Cikara et al. 2020). As such, while it is important for managers to view drivers as 'professionals' who carry out the majority of responsibilities, effective fatigue management requires collaboration and consistency across the entire organisation and its partners. For instance, lessons taught during fatigue management training should be understood and applied by dispatchers so that when issues arise, there are established standard operating procedures in place for handling them. Similarly, management has a responsibility to ensure that truck drivers are empowered to make healthy decisions.

Providing truck drivers with the resources and tools to make healthier behavioural choices is essential in improving their personal, social and home environments. One manager highlighted the importance of involving drivers' families in training, making them aware of the driver's roles and responsibilities and encouraging behavioural change. The effective management of truck driver fatigue requires collaboration from all stakeholders, extending beyond awareness and monitoring efforts to improve the drivers' home environment. In addition, driver schedules should be aligned with their body's natural circadian rhythm, minimising work and maximising rest during critical night hours.

Limitations

The study encountered numerous data constraints that limited its predictive capabilities as well as detailed analysis of the timing of fatigue events. As such, the logistic regression model is exploratory in nature and focussed on discussion rather than accurate prediction. Timestamp errors because of missing values or incorrect entries prevented the inclusion of fatigue event times, limiting the understanding of circadian rhythms and forcing the logistic regression to focus on pre-trip activities as a parameter of fatigue. As a result, working hours until the fatigue event could not be included. Because of the short timeframe of the retrieved scheduling data, significant class imbalance was present, where the non-event class (fatigue_event = 0) is vastly over-represented compared to the event class (fatigue_event = 1). Class imbalance reduces the model's predictive capabilities. Thus, precisely examining the coefficients and odds ratios may not convey the exact relationship but rather provide an indicative perspective that prompts valuable discussions on the risk of truck driver fatigue.

A challenge identified within the carrier was the abundance of false positive errors for fatigue event detection. Fatigue events are categorised as either 'possible' or 'critical' when reviewed by the fatigue detection systems company, which is then forwarded to the carrier for attention. However, there are suspicions of whether these events are thoroughly reviewed by the fatigue detection systems company, as there are constant influxes of fatigue alerts. Table 6 shows the possible positive and false positive fatigue events, highlighting a large imbalance, which makes it impossible to effectively measure and monitor truck driver fatigue for both the carrier and researchers. The carrier is also responsible for ensuring effective fatigue monitoring, aiming to minimise human processing errors when documenting the outcome of the fatigue event. The regular occurrence of false positive fatigue events presents limitations within this study's dataset.

TABLE 6: Frequency of fatigue event classifications (entire dataset).

Categories	Frequencies	Proportions (%)
Positive fatigue classification	1823	21.4
False positive fatigue classification	6714	78.6

Conclusion

This study aimed to investigate the relationship between a carrier's scheduling activities and truck drivers' ability to rest through multiple hypotheses using logistic regression. The analysis revealed that recovery times greater than 24 h between shifts are significantly associated with increased fatigue risk in comparison to the reference category, 9 h – 12 h recovery, contrary to initial expectations. However, recovery times between 12 h and 24 h are associated with a decreased risk of fatigue compared to the reference category, suggesting that the activities truck drivers prioritise during prolonged recovery may not be supportive of recuperative rest. The study confirms the importance of circadian rhythm alignment with recovery, between 00:00 and 06:00, being significantly associated with a decrease in fatigue risk, while working within those hours is significantly associated with an increase in fatigue risk. In contrast, truck drivers' clocking in within those same night hours is insignificantly associated with fatigue risk. The significance of waiting time at the depot reducing fatigue risk hints at an interesting opportunity to provide brief periods of additional rest before driving.

The findings present a complex relationship between recovery time, scheduling practices and fatigue risk, suggesting that the primary hypothesis cannot be fully confirmed. Other factors, possibly relating to socio-economic factors, quality of rest, health and the nature of work during these periods, may influence fatigue outcomes in ways not fully captured in the initial hypotheses. Tools and resources should be made available to facilitate healthy behaviours, as purely extending recovery periods is inadequate in mitigating fatigue. Scheduled recovery and work periods should align with the body's circadian rhythm and strategies must be pursued to improve drivers' home environment while incentivising safe and healthy behaviours. Focussing on fatigue awareness campaigns alone, supported by monitoring and assessment, is inadequate.

Practical applications

The findings of this study underscore several areas where fatigue management practices can be practically enhanced. Truck drivers should not be returning to work fatigued after prolonged recovery periods. To address this, road freight carriers should implement comprehensive tracking systems that monitor recovery times, with a particular emphasis on the amount of night rest obtained before shifts. However, the challenge of micromanaging a driver's behaviour during off-duty hours persists, necessitating fatigue management strategies that extend beyond awareness campaigns and theoretical training to genuinely influence behaviour change. To support quality rest and safe driving, work and rest schedules should be better aligned with the body's natural circadian rhythm. In addition, there is potential for carriers to enhance rest facilities at depots, providing drivers with opportunities for recovery and preparation amid daily delays.

Future research

Fatigue management in a developing country poses unique challenges that require further investigation. Understanding the specific socio-economic, infrastructural and cultural factors at play can provide valuable insights for tailored fatigue management interventions. Specifically, exploring the relationship between truck driver financial incentives, such as salary, in a developing country and the risk of fatigue-related incidents would be a valuable avenue for future research. In addition, integrating ethnographic research can offer a deeper understanding of the daily lives and challenges faced by truck drivers, including the potential impact of second jobs on fatigue risk. Future research should also aim to objectively measure the actual sleep obtained by truck drivers, perhaps through wearable sleep trackers or similar technologies. Expanding the sample size and incorporating fatigue event timestamps would further improve the model's predictive capabilities by allowing for more specific predictors related to activities leading up to fatigue events.

Acknowledgements

Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

L.L.G.-G. and A.d.B. contributed to the conceptualisation, project administration, resource provision, supervision and validation of the study. A.M., L.L.G.-G. and A.d.B. were responsible for data curation, formal analysis and methodology development. A.M. conducted the investigation, developed the software and handled visualisation. In addition, A.M. prepared the original draft, while L.L.G.-G. and A.d.B. reviewed and edited the manuscript. Funding acquisition was not applicable.

Funding information

This research did not receive a specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Data availability

The data that support the findings of this study are subject to commercial restrictions and are not publicly available.

Disclaimer

During the preparation of this work, the authors used ChatGPT and Perplexity to ensure readability and language. After using this tool and/or service, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

The views and opinions expressed in this article are those of the authors and are the product of professional research. The article does not necessarily reflect the official policy or position of any affiliated institution, funder or agency, or that of the publisher. The authors are responsible for this article's results, findings and content.

References

Asl, N.S., Baghdadi, G., Ebrahimian, S. & Haghighi, S.J., 2022, 'Toward applicable EEG-based drowsiness detection systems: A review', *Frontiers in Biomedical Technologies* 9(4), 323–350. https://doi.org/10.18502/fbt.v9i4.10426

Bajaj, J.S., Kumar, N. & Kaushal, R.K., 2021, 'Comparative study to detect driver drowsiness', in *2021 international conference on advance computing and innovative technologies in engineering*, IEEE, Greater Noida, March 04–05, 2021, vol. 7, pp. 678–683.

Baykasoğlu, A., Subulan, K., Taşan, A.S. & Dudaklı, N., 2019, 'A review of fleet planning problems in single and multimodal transportation systems', *Transportmetrica A: Transport Science* 15(2), 631–697. https://doi.org/10.1080/23249935.2018.1523249

Bowden, Z.E. & Ragsdale, C.T., 2018, 'The truck driver scheduling problem with fatigue monitoring', *Decision Support Systems* 110, 20–31. https://doi.org/10.1016/j.dss.2018.03.002

Brown, I.D., 1994, 'Driver fatigue', *Human Factors* 36(2), 298–314. https://doi.org/10.1177/001872089403600210

Chen, G.X., Fang, Y., Guo, F. & Hanowski, R.J., 2016, 'The influence of daily sleep patterns of commercial truck drivers on driving performance', *Accident Analysis and Prevention* 91, 55–63. https://doi.org/10.1016/j.aap.2016.02.027

Cikara, I., Dell, G., Toft, Y. & Dell, S., 2020, 'Who is responsible? An examination of the "Chain of Responsibility" in heavy vehicle crashes – An Australian perspective', *World Safety Journal* 29(4), 74–91.

Crum, M.R., Morrow, P.C. & Daecher, C.W., 2002, *Motor carrier scheduling practices and their influences on driver fatigu*e, Federal Motor Carrier Safety Administration, Washington, DC.

Cule, E., Vineis, P. & De Iorio, M., 2011, 'Significance testing in ridge regression for genetic data', *BMC Bioinformatics* 12, 1–15. https://doi.org/10.1186/1471-2105-12-372

Davidović, J., Pešić, D. & Antić, B., 2018, 'Professional drivers' fatigue as a problem of the modern era', *Transportation Research Part F: Traffic Psychology and Behaviour* 55, 199–209. https://doi.org/10.1016/j.trf.2018.03.010

Dawson, D., Blahous, A. & Williamson, A., 2019, 'A novel risk-based regulatory approach to managing fatigue-related risk in the Australian road transport industry', *Journal of Health, Safety and Environment* 35(1), 15–30.

Dawson, D. & McCulloch, K., 2005, 'Managing fatigue: It's about sleep', *Sleep Medicine Reviews* 9(5), 365–380. https://doi.org/10.1016/j.smrv.2005.03.002

Dawson, D., Searle, A.K. & Paterson, J.L., 2014, 'Look before you (s)leep: Evaluating the use of fatigue detection technologies within a fatigue risk management system for the road transport industry', *Sleep Medicine Reviews* 18(2), 141–152. https://doi.org/10.1016/j.smrv.2013.03.003

Declercq, I., Van Den Eede, F., Roelant, E. & Verbraecken, J., 2022, 'SHIFTPLAN: A randomized controlled trial investigating the effects of a multimodal shift-work intervention on drivers' fatigue, sleep, health, and performance parameters', *Trials* 23, 1–18. https://doi.org/10.1186/s13063-022-06573-6

Dinges, D.F., Maislin, G., Hanowski, R.J., Mollicone, D.J., Hickman, J.S., Maislin, D. et al., 2017, *Commercial Motor Vehicle (CMV) driver restart study: Final report*, Federal Motor Carrier Safety Administration, Washington, DC.

Dorrian, J., Chapman, J., Bowditch, L., Balfe, N. & Naweed, A., 2022, 'A survey of train driver schedules, sleep, wellbeing, and driving performance in Australia and New Zealand', *Scientific Reports* 12(1), 1–11. https://doi.org/10.1038/s41598-022-07627-0

Enoka, R.M. & Duchateau, J., 2016, 'Translating fatigue to human performance', *Medicine and Science in Sports and Exercise* 48(11), 2228–2238. https://doi.org/10.1249/MSS.0000000000000929

Fischer, F.M., 2001, 'Shiftworkers in developing countries: Health and well-being and supporting measures', *Journal of Human Ergology* 30(1–2), 155–160.

Fitzharris, M., Liu, S., Stephens, A.N. & Lenné, M.G., 2017, 'The relative importance of real-time in-cab and external feedback in managing fatigue in real-world commercial transport operations', *Traffic Injury Prevention* 18, 71–78. https://doi.org/10.1080/15389588.2017.1306855

Friswell, R. & Williamson, A., 2019, 'Management of heavy truck driver queuing and waiting for loading and unloading at road transport customers' depots', *Safety Science* 120(July), 194–205. https://doi.org/10.1016/j.ssci.2019.06.039

Gander, P., Hartley, L., Powell, D., Cabon, P., Hitchcock, E., Mills, A. et al., 2011, 'Fatigue risk management: Organizational factors at the regulatory and industry/company level', *Accident Analysis and Prevention* 43(2), 573–590. https://doi.org/10.1016/j.aap.2009.11.007

Goel, A., 2010, 'Truck driver scheduling in the European union', *Transportation Science* 44(4), 429–441. https://doi.org/10.1287/trsc.1100.0330

Goel, A., Archetti, C. & Savelsbergh, M., 2012, 'Truck driver scheduling in Australia', *Computers and Operations Research* 39(5), 1122–1132. https://doi.org/10.1016/j.cor.2011.05.021

Havenga, J.H., Simpson, Z.P., De Bod, A. & Viljoen, N.M., 2014, 'South Africa's rising logistics costs: An uncertain future', Journal of Transport and Supply *Chain Management* 8(1), 1–7. https://doi.org/10.4102/jtscm.v8i1.155

Hartley, L., Horberry, T. & Mabbott, N., 2000, *Review of fatigue detection and prediction technologies,* National Road Transport Commission, Melbourne.

Hittle, B.M. & Gillespie, G.L., 2019, 'Identifying shift worker chronotype: Implications for health', *Industrial Health* 56(6), 512–523. https://doi.org/10.2486/indhealth.2018-0018

Horberry, T., Mulvihill, C., Fitzharris, M., Lawrence, B., Lenne, M., Kuo, J. et al., 2022, 'Human-centered design for an in-vehicle truck driver fatigue and distraction warning system', *IEEE Transactions on Intelligent Transportation Systems* 23(6), 5350–5359. https://doi.org/10.1109/TITS.2021.3053096

Jacobé de Naurois, C., Bourdin, C., Stratulat, A., Diaz, E. & Vercher, J.L., 2019, 'Detection and prediction of driver drowsiness using artificial neural network models', *Accident Analysis and Prevention* 126, 95–104. https://doi.org/10.1016/j.aap.2017.11.038

Jovanis, P., Wu, K.-F. & Chen, C., 2011, *Hours of service and driver fatigue: Driver characteristics research,* Federal Motor Carrier Safety Administration, Washington, DC.

Khanehshenas, F., Mazloumi, A., Dabiri, R. & Adinevand, S.N., 2023, 'Fatigue in transportation operations: A contextual factors survey among Iranian suburban drivers', *Work* 75(4), 1439–1454. https://doi.org/10.3233/WOR-220272

Laakmann, F., Seyffert, M., Herpich, T., Saupp, L., Ladwig, S., Kugelmeier, M. et al., 2023, 'Benefits of tactile warning and alerting of the driver through an active seat belt system', in *27th International technical conference on the enhanced safety of vehicles*, Yokohama, April 03–06, 2023, pp. 1–24.

Lalendle, C., Goedhals-Gerber, L. & Van Eeden, J., 2021, 'A monitoring and evaluation sustainability framework for road freight transporters in South Africa', *Sustainability* 13(14), 1–22. https://doi.org/10.3390/su13147558

Lemke, M.K., Apostolopoulos, Y., Hege, A., Sönmez, S. & Wideman, L., 2016, 'Understanding the role of sleep quality and sleep duration in commercial driving safety', *Accident Analysis and Prevention* 97, 79–86. https://doi.org/10.1016/j.aap.2016.08.024

Lenné, M.G. & Fitzharris, M., 2016, 'Real-time feedback reduces the incidence of fatigue events in heavy vehicle fleets', in *23rd ITS world congress*, Melbourne, pp. 1–12.

Li, J. & Kwan, R.S.K., 2003, 'A fuzzy genetic algorithm for driver scheduling', *European Journal of Operational Research* 147(2), 334–344. https://doi.org/10.1016/S0377-2217(02)00564-7

Mahajan, K., Velaga, N.R., Kumar, A., Choudhary, A. & Choudhary, P., 2019, 'Effects of driver work-rest patterns, lifestyle and payment incentives on long-haul truck driver sleepiness', *Transportation Research Part F: Traffic Psychology and Behaviour* 60, 366–382. https://doi.org/10.1016/j.trf.2018.10.028

Mutifasari, R.S. & Ramdhan, D.H., 2019, 'Association between sleep quantity and quality with occupational stress among truck driver', *Malaysian Journal of Medicine and Health Sciences* 15(SP4), 153–158.

National Heavy Vehicle Regulator, 2013, *Risk classification system for advanced fatigue management evidence statement*, NHVR, Brisbane.

Ngxande, M., Tapamo, J.R. & Burke, M., 2017, 'Driver drowsiness detection using behavioral measures and machine learning techniques: A review of state-of-art techniques, in *2017 Pattern Recognition Association of South Africa and Robotics and mechatronics*, IEEE, Bloemfontein, South Africa, pp. 156–161.

Penda, S.V.B., Djellout, H. & Proïa, F., 2014, 'Moderate deviations for the Durbin-Watson statistic related to the first-order autoregressive process', *ESAIM – Probability and Statistics* 18, 308–331. https://doi.org/10.1051/ps/2013038

Perkins, E., Sitaula, C., Burke, M. & Marzbanrad, F., 2023, 'Challenges of driver drowsiness prediction : The remaining steps to implementation', *IEEE Transactions on Intelligent Vehicles* 8(2), 1319–1338. https://doi.org/10.1109/TIV.2022.3224690

Phillips, R.O., 2015, 'A review of definitions of fatigue – And a step towards a whole definition', *Transportation Research Part F: Traffic Psychology and Behaviour* 29, 48–56. https://doi.org/10.1016/j.trf.2015.01.003

Phillips, R.O., Kecklund, G., Anund, A. & Sallinen, M., 2017, 'Fatigue in transport: A review of exposure, risks, checks and controls*', *Transport Reviews* 37(6), 742–766. https://doi.org/10.1080/01441647.2017.1349844

Ren, X., Pritchard, E., Van Vreden, C., Newnam, S., Iles, R. & Xia, T., 2023, 'Factors associated with fatigued driving among Australian truck drivers: A cross-sectional study', *International Journal of Environmental Research and Public Health* 20(3), 2732. https://doi.org/10.3390/ijerph20032732

Rusmin, P.H., Osmond, A.B. & Syaichu-Rohman, A., 2013, 'Design and implementation of driver drowsiness detection system on digitalized driver system', in *3rd international conference on system engineering and technology*, IEEE, Shah-Alam, Malaysia, pp. 375–380.

Sallinen, M. & Kecklund, G., 2010, 'Shift work, sleep, and sleepiness – Differences between shift schedules and systems', *Scandinavian Journal of Work, Environment and Health* 36(2), 121–133. https://doi.org/10.5271/sjweh.2900

Schneider, D. & Harknett, K., 2019, 'Consequences of routine work-schedule instability for worker health and well-being', *American Sociological Review* 84(1), 82–114. https://doi.org/10.1177/0003122418823184

Sikander, G. & Anwar, S., 2019, 'Driver fatigue detection systems: A review', *IEEE Transactions on Intelligent Transportation Systems* 20(6), 2339–2352. https://doi.org/10.1109/TITS.2018.2868499

Sirois, W.G., 2012, *Biocompatible shift scheduling: The critical factors that influence the overall mental and physical fatigue risks of a core shift schedule*, Circadian, MA.

Sparrow, A.R., Mollicone, D.J., Kan, K., Bartels, R., Satterfield, B.C., Riedy, S.M. et al., 2016, 'Naturalistic field study of the restart break in US commercial motor vehicle drivers: Truck driving, sleep, and fatigue', *Accident Analysis and Prevention* 93, 55–64. https://doi.org/10.1016/j.aap.2016.04.019

Stoltzfus, J.C., 2011, 'Logistic regression: A brief primer', *Academic Emergency Medicine* 18(10), 1099–1104. https://doi.org/10.1111/j.1553-2712.2011.01185.x

Talebi, E., Rogers, W.P. & Drews, F.A., 2022, 'Environmental and work factors that drive fatigue of individual haul truck drivers', *Mining* 2, 542–565. https://doi.org/10.3390/mining2030029

Thompson, J., Newnam, S. & Stevenson, M., 2015, 'A model for exploring the relationship between payment structures, fatigue, crash risk, and regulatory response in a heavy-vehicle transport system', *Transportation Research Part A: Policy and Practice* 82, 204–215. https://doi.org/10.1016/j.tra.2015.09.016

Watson, N.F., Badr, M.S., Belenky, G., Bliwise, D.L., Buxton, O.M., Buysse, D. et al., 2015, 'Joint consensus statement of the American Academy of Sleep Medicine and Sleep Research Society on the recommended amount of sleep for a healthy adult: Methodology and discussion', *Journal of Clinical Sleep Medicine* 11(8), 931–952. https://doi.org/10.5664/jcsm.4950

Williamson, A. & Friswell, R., 2013, 'The effect of external non-driving factors, payment type and waiting and queuing on fatigue in long distance trucking', *Accident Analysis and Prevention* 58, 26–34. https://doi.org/10.1016/j.aap.2013.04.017

Yaacob, S., Izzati Affandi, N.A., Krishnan, P., Rasyadan, A., Yaakop, M. & Mohamed, F., 2020, 'Drowsiness detection using EEG and ECG signals', in *2020 IEEE 2nd international conference on artificial intelligence in engineering and technology*, Kota Kinabalu, Malaysia, September 26–27, 2020, pp. 1–5.

Zeng, G., 2022, 'A graphic and tabular variable deduction method in logistic regression', *Communications in Statistics – Theory and Methods* 51(16), 5412–5427. https://doi.org/10.1080/03610926.2020.1839499

Zou, H., Zhou, H., Yan, R., Yao, Z. & Lu, Q., 2022, 'Chronotype, circadian rhythm, and psychiatric disorders: Recent evidence and potential mechanisms', *Frontiers in Neuroscience* 16(August), 1–24. https://doi.org/10.3389/fnins.2022.811771