PROACTIVE FATIGUE PREDICTION AND HEALTH MONITORING SYSTEMS FOR ROAD FREIGHT TRANSPORT IN THE EUROPEAN UNION: TOWARD A PREVENTIVE SAFETY FRAMEWORK

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Summary

Poor health conditions and driver fatigue continue to be a major contributor to road traffic accidents in the transport and logistics industries across the European Union (EU). Despite great technological and regulatory advancements in driver systems and safety technologies, most approaches towards management of fatigue among professional drivers remain reactive, rather than proactive, with physiological and behavioral indicators being the basis of detecting fatigue. This paper proposes a preventive framework for the management of fatigue, where fatigue risk factors are identified by integrating wearable sensors, predictive analytics, and health monitoring systems. A detailed literature review illustrates gaps in the current systems of fatigue management, laying emphasis on the need for progressive, real-time health data, and prediction models based on machine learning. The proposed system presents a combination of driver scheduling information, environmental data, and physiological monitoring information to predict the probability of fatigue and offer adaptive interventions. This paper also discusses policy implications for EU transport regulations, driver privacy, and management of data, suggesting its implementation using a multi-stakeholder approach. This paper highlights the potential of proactive management of fatigue towards reduction of road accidents and enhancement of occupational and logistics well-being in EU. Findings indicate that proactive monitoring plays a key role in improving early risk detection, improving well-being of drivers, and reducing accident rates, thus promoting safer and sustainable logistics operations.

Keywords: proactive monitoring, health monitoring systems, fatigue prediction, eu policy, driver health, transportation safety, machine learning, wearable sensors, logistics, preventive safety framework

Introduction

Road freight transport is the pillar of the internal market of the European Union, accounting for more than 75% of inland freight transport (European Commission, 2023). Even so, the logistics industry continues to face serious safety challenges relating to health deterioration, stress, and driver fatigue. According to Akerstedt et al. (2021), this usually emanates from either sedentary lifestyles, chronic stress, irregular schedules, or extended driving hours that cause fatigue, and thus increase risk levels of road accidents. Fatigue alone is responsible for about 20% of commercial road accidents, with the most affected being delivery and truck drivers (European Transport Safety Council, 2023).

Traditional fatigue management systems (reaction-time tests, lane deviation alerts, camera-based driver monitoring, regulatory enforcement and post-accident investigations) aim at detecting fatigue the moment symptoms become evident, rather than before, thus offering very limited preventive opportunities (European Commission, 2022).

The advancement of smart technologies provides a shift towards proactive fatigue management, by adapting smart technologies such as telematics, artificial intelligence (AI), wearable biosensors, IoT-based sensors. These technologies go a long way in continuously assessing behavioural and physiological indicators, before the occurrence of performance deterioration. According to Sahayadhas et al. (2020), fatigue likelihood can be forecasted by predictive models using variables such as driving schedules, sleep quality, electrodermal activity, and heart rate variability (HRV).

This paper investigates and proposes the operationalization of health monitoring systems and proactive fatigue prediction framework to improve driver safety, reduce rate of accidents, and align the logistics industry with the EU Vision Zero policy on road fatalities. The research explores policy requirements, data analytics approaches, system architecture, and technological foundations needed for effective implementation of such systems.

The primary databases used were Google Scholar and ScienceDirect, using the keywords listed above. Boolean operators (AND, NOT, and OR) were used to refine the search for relevance. 74 articles published between 2018 and 2025 were initially accessed based on titles and abstracts. Using thematic analysis and data extraction, 20 key articles and institutional reports used, based on their major themes. Editorials, conference abstracts, studies published before 2018, and non-peer-reviewed literature were all excluded.

Research aim: to examine how proactive fatigue prediction and health monitoring systems can improve road safety in EU by supporting a data-driven safety management framework, enabling preventive risk detection, and reducing drive-related accidents.

The following **objectives** have been set to achieve the aim:

1. To analyse the current state of driver fatigue and health-related risks in the road freight transport sector in EU.

2. To highlight the role and effectiveness of proactive fatigue prediction and health monitoring technologies in improving road freight safety.

3. To develop a preventive safety framework integrating health monitoring systems into the road freight transport operations in EU.

Research object and methods

Research object: proactive fatigue prediction and health monitoring systems within EU road freight transport.

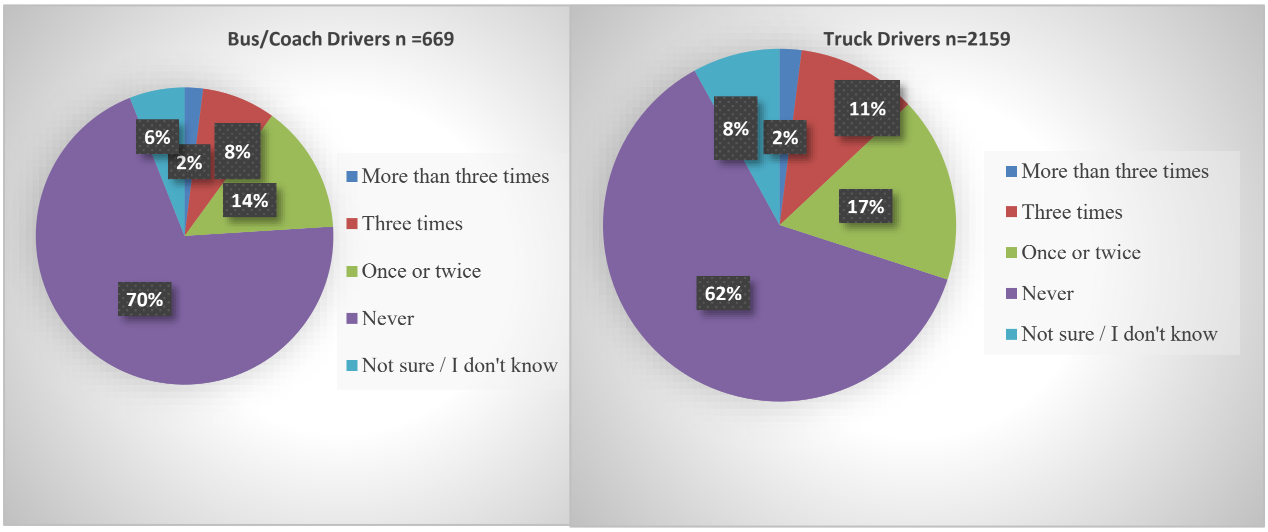
To assess and highlight the use and benefits of artificial intelligence solutions in logistics customer service, the article employs literature analysis, synthesis of existing data, and analysis of relevant scholarly works. This research method allows gathering of applicable information from online databases, reports and academic journals. This review will be useful in providing a comprehensive understanding of proactive fatigue prediction and health monitoring systems within EU road freight transport, including the challenges of implementing smart technologies solutions, and identifying the gaps in the literature. To this end, data was obtained by reviewing literature findings in various scientific peer reviewed papers, published between 2018 and 2025.

Research results and discussion

Driver Fatigue and Health Risks in EU Road Freight Transport

Fatigue is a psychological and physiological state characterized by impaired decision-making, slower reaction times, reduced alertness, and physical tiredness (Phillips, 2020; Philip et al., 2018). In commercial transport, factors responsible for fatigue include physical strain, disruption of circadian rhythm, and cumulative sleep debt.

A 2021 Eurostat report opined that more than 35% of long-haul drivers in Europe suffer moderate to severe fatigue at least once a week, owing to inadequate rest breaks, monotony, night shifts, and irregular schedules. Fatigue is blamed for 20-25% of fatal road accidents involving heavy trucks in the EU (ETSC, 2022). Under the EU regulations, drivers should drive for up to 4.5 hours consecutively, and then take a compulsory break for 45 minutes. The figure (Figure 1) below shows how often drivers fall asleep while driving.



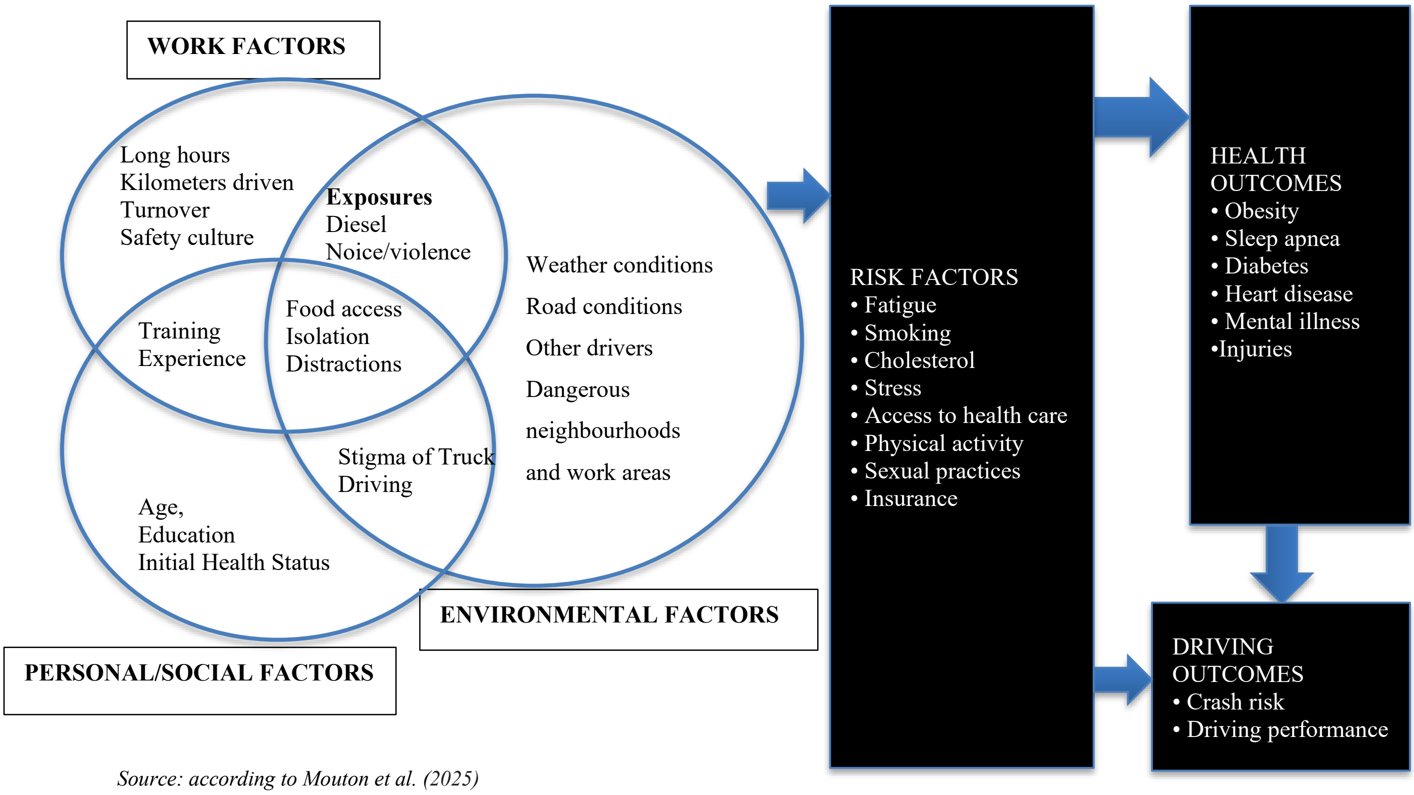
Source: according to European Transport Workers' Federation (2021)

Fig. 1. How often drivers fell asleep while driving (extended driving periods of 9-10 hours per day)

Freight drivers face a myriad of risks factors, ranging from work, personal/social, and environmental factors, as shown in figure 2. According to Apostolopoulos et al. (2020), health conditions like musculoskeletal, sleep disorders, obesity, and cardiovascular diseases not only compromise the well-being of drivers, but also directly affect their driving performance, with sleep apnea significantly increasing the probability of delayed hazard recognition and micro-sleeps. The figure (Figure 2) below references *work factors, personal/social factors,* and *environmental factors,* as well as the corresponding *risk factors, health outcomes,* and ultimately, *driving outcomes,* which include crash risk and driving performance.

As shown in the table below, the present fatigue management strategies in EU logistics are primarily regulatory and reactive, outlining rest driving hour limits and rest periods, while warnings based on facial recognition and steering patterns are provided using Attention Assist and Driver Drowsiness Detection (DDD). Although these measures reduce immediate risks, they are still limited to detecting symptoms, with a fatigued driver already limited further by a wasted opportunity for prevention (Williamson et al., 2019). It is important to note that although the risk factors are numerous as shown in figure 2, fatigue tops the list of risk factors, whose driving outcomes include crash risk and driving performance.

Driver compliance to the EU regulations is largely reliant on tachographs and does not offer direct assessment of the drivers' health status or physiological fatigue, thus a regulatory gap that calls for proactive monitoring solutions, and referenced in the table (Table 1) below.



Source: according to Mouton et al. (2025)

Fig. 2. Factors affecting health and driving outcomes among truck drivers

Table 1. Traditional Fatigue Management Systems in EU

	Traditional system	Regulation	Key Purpose
1	Medical screening programs	Directive 2007/59/EC	Health-based fatigue risk detection
2	Self-assessment logs	Regulation (EC) No 561/2006	Subjective fatigue reporting
3	Manual shift scheduling	Regulation (EU) No 165/2014	Operational fatigue prevention
4	Working time directive	Directive 2002/15/EC Directive 2003/88/EC)	Control of total working hours
5	Tachograph monitoring	Regulation (EU) No 165/2014	Recording and enforcing work/rest
6	EU drivers' hours regulation	Regulation (EC) No 561/2006	Legal control of driving/rest times

Source: Compiled by author (2026)

Proactive Fatigue Prediction and Health Monitoring Technologies and their Effectiveness

Recent research puts emphasis on predictive analytics as a gateway towards proactive fatigue management, using devices which can continuously monitor biometric signals, and permitting machine learning models to predict onset hours of fatigue way before it happens (Zhao et al., 2021). The integration of contextual data (such as work schedule, temperature and route conditions) and physiological data provide for individualization of fatigue risk forecasting. On the other hand, cloud-based telematics systems are gradually becoming capable of analysing and aggregating large scale health data of drivers. Fatigue prediction accuracy was improved by a prediction accuracy of 30% compared to behavioural monitoring alone, according to a study be Li et al. (2021). Some of the technologies and their effectiveness are discussed here below:

1. **Wearable and biometric monitoring devices:** such devices include *smartwatches, heart rate sensors, EEG headbands, smart clothing, and chest straps,* and are effective for monitoring heart rate variability (HRV), sleep patterns, and body temperature. In particular, HRV is effective for early detection of fatigue and responses to stress (Zhao et al., 2021).
2. **Telematics and Internet of Things (IoT) Integration:** telematics systems integrate physiological inputs, vehicle data, and driving behaviour into a unified platform. Connectivity with IoT enables transmission of real-time data to safety platforms and fleet managers, who can then provide requisite interventions immediately (Molloy and McDonald, 2022).
3. **Predictive Analytics and Artificial Intelligence (AI):** AI models rely on health, sleep, and historical driving data to predict the risk of fatigue before it actually happens. Machine learning progressively adapts to individual driver patterns to enhance prediction accuracy (Wang et al., 2023).

4. **Vision-Based Driver Monitoring Systems:** This includes use of camera-based systems to track head position, frequency of yawning, gaze direction, and eye closure rate, with the view of helping detect drowsiness in real-time. These parameters are analysed by AI algorithms, which then provide alerts before fatigue thresholds reach a critical stage.

This effectiveness is referenced in the figure (Figure 3) below.

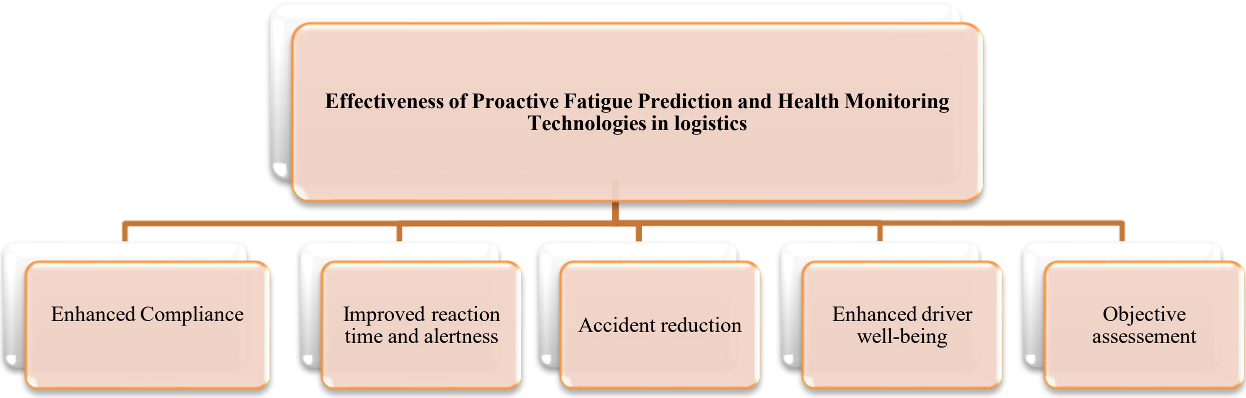


Fig. 3 Effectiveness of proactive fatigue prediction and health monitoring technologies in improving road freight safety
Source: compiled by author (2026)

Benefits of Proactive Fatigue Prediction and Health Monitoring Systems

a) Operational Efficiency and Compliance: Fleet operators become beneficiaries of reduced downtimes related to accidents, enjoy enhanced compliance with EU safety regulations, and reap big from lower insurance costs. Based on driver fatigue risk, route planning is also optimized using predictive systems.

b) Improved Driver Health and Well-being: Continuous monitoring of drivers' health promotes early detection of stress-related illnesses, hypertension, and sleep disorders. This proactive approach helps in reducing cases of chronic absenteeism and long-term costs of medication.

c) Reduction of Accidents and Safety Enhancement: A study by Wang et al. (2023) showed that real-time fatigue detection systems play an important role in reducing incidents related to fatigue by up to 40%. This is because early alerts allow drivers to take critical breaks before the occurrence of cognitive impairment.

Challenges and Ethical Considerations for Proactive Fatigue Prediction and Health Monitoring Systems

a) **Cost and Infrastructure Barriers:** the initial investment costs for smart technologies can be high, and digital infrastructure for small and medium-sized logistics companies, which hamper technological implementation in large scale. Additionally, physiological monitoring systems are rarely integrated with EU transport compliance systems or fleet management software.

b) **Data Privacy and Compliance with General Data Protection Regulation (GDPR):** under the GDPR, health data is classified as sensitive personal data. It is also important to note that on data privacy and governance, there is limited clarity under GDPR on how drivers' personal biometric data should be managed. In view of this, transport companies must implement strict access controls, as well as ensuring informed consent and encrypted data storage (European Union, 2018).

c) **Acceptance of Technology among Drivers:** drivers tend to resist technological monitoring due to perceived surveillance and privacy concerns. For successful adoption of proactive fatigue prediction and health monitoring systems, worker involvement and transparent communication remain critically essential (Montoro et al., 2021).

d) **Interoperability:** there are no standardized data formats to support cross-border and cross-fleet implementation. Additionally, there are few systems which integrate medical health parameters (such as sleep disorders or cardiovascular) into fatigue risk modelling.

Proposed Predictive Fatigue Management System Framework

The primary objective of this framework is to provide prevention through prediction, minimizing accidents by identifying precursors of fatigue, before the occurrence of behavioural impairment. Secondary objectives would include using personalized health insights to enhance driver well-being, aligning rest schedules with physiological needs to improve logistics efficiency, and supporting EU transport safety goals under the "Vision Zero" initiative.

The proposed model integrates three major dimensions: *physiological monitoring, contextual analytics,* and *predictive modelling.* This methodology is anchored on the empirical findings from other studies on fatigue detection and monitoring occupational health. Secondary data from literature review should be combined with a system architecture to illustrate a feasible model for fatigue prediction. A mixed methods framework is recommended in order to implement testing, including physiological data collection (quantitative) and driver feedback (qualitative).

For acquisition of physiological data, non-invasive wearable biosensors will be used; they should have the capability to record the following parameters which according to Li et al. (2022), correlate with fatigue onset and recovery cycles. Data should be recorded continuously, to capture both driving time and resting periods in order to develop individualized baselines:

Heart Rate (HR) and Heart Rate Variability (HRV)

Skin Temperature and Electrodermal Activity (EDA)

Blood Oxygen Saturation (SpO_2)

Eye blink and head movement frequency (via lightweight headbands)

Sleep duration and quality (through accelerometer and actigraphy data)

On contextual and environmental data, other stressors to be considered include weather conditions, type of roads used, time of the day, and duration of driving. It is proposed that data sources should also include:

a) Vehicle telematics: engine idling, braking patterns, and speed
b) Route information: elevation of terrain, and traffic congestion
c) Scheduling data: urgency of delivery, and work-rest cycles.

Instead of simply relying on biometric thresholds only, the integration of these datasets using a telematics interface will allow for contextualized fatigue prediction. In this regard, the framework will consider data privacy compliance, regulatory oversight, integration with fleet management systems, real-time drive alerts and feedback, fatigue prediction based on AI, and a continuous behavioural and physiological monitoring.

Apart from the developers, other stakeholders will have specific roles in the proposed framework:

a) Technology providers: continuous innovation and assurance on cyber-security
b) Regulators: development of ethical guidelines and monitoring standards
c) Fleet operators: invest in technology and safety policy enforcement
d) Drivers: take an active role in safety decision-making and self-monitoring.

Conclusions

1. Driver fatigue remains a significant health and safety risk in the European Union Road freight transport. Current systems used to monitor fatigue and health are only reactive, thus offering very limited preventive capacity.

2. Continuous advancements and integration of smart technologies not only address traditional road freight transport challenges but also creates endless possibilities for logistics companies and all stakeholders, especially drivers.

3. Shifting from reactive detection to proactive prevention of fatigue management systems in the EU transport sector will help the region achieve healthier and more sustainable working conditions for drivers, as well as fewer accidents. Although there are challenges related to user acceptance, cost and privacy, the overall economic and safety benefits significantly outweigh the limitations.

4. The proposed proactive fatigue prediction framework leverages machine learning, contextual analytics, and physiological sensing, to forecast fatigue risk way before its occurrence. The framework aligns with the objectives of EU policy for road safety and digital transformation, while upholding ethical norms and data protection. Successful implementation of the proposed framework requires collaboration among driver unions, logistics operators, technology developers, and policymakers in the industry.

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