EVERGREEN - Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 12, Issue 04, pp. 2046-2057, December, 2025

A Comparative Study of Mental Workload among Truck Drivers: The Effects of Truck Type and Age Using HRV Metrics

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(Received May 26, 2025; Revised September 02, 2025; Accepted December 16, 2025)

Abstract: This study explores the effects of truck type and driver age on mental workload and driving performance among professional truck drivers in Indonesia. Thirty drivers—operating wing box trucks, tanker trucks, and dump trucks—participated in a simulated motorcycle detection task while their heart rate variability (HRV) was continuously monitored. Performance metrics included response time, misses, and errors, while mental workload was assessed using HRV parameters such as LF power, HF power, and RMSSD. MANOVA results revealed significant differences across truck types, with dump truck drivers showing slower response times, more errors, and lower HRV, indicating higher cognitive and physiological workload. Age also played a role: drivers aged 40 and above exhibited greater performance decline and reduced HRV indices, suggesting diminished cognitive flexibility and stress resilience. Correlation analysis confirmed that longer response times and increased errors were associated with lower RMSSD, reinforcing the relationship between elevated workload and impaired performance. These findings highlight the importance of truck-type-specific and age-adaptive safety interventions, including targeted training, ergonomic design improvements, and physiological monitoring systems. The study contributes to the development of human-centered strategies for enhancing driver well-being and improving road safety in freight transport.

Keywords: driver age; driving performance; HRV; mental workload; truck type

1. Introduction

Truck-based freight transportation plays a vital role in sustaining a wide range of logistical operations, including the delivery of industrial products, construction materials, and energy supplies. As a backbone of supply chains, it supports economic productivity and infrastructure development across various sectors. However, despite its essential role, truck driving remains a cognitively demanding task. It requires sustained attention, rapid decision-making, and effective regulation of both physical and emotional stress. Elevated mental workload during truck operations has been associated with impaired driving performance, increased fatigue, and heightened risk of accidents, positioning it as a key concern in transportation safety research1). Mental overload has been shown to impair environmental awareness and decision-making, contributing to unsafe behaviors and accident risk, even among professional drivers2). Moreover, sustainable transport frameworks emphasize not only environmental and economic dimensions, but also human-centered factors such as safety, health, and workload, which are

Cite: S. Kurnia et al., "A Comparative Study of Mental Workload Among Truck Drivers: The Effects of Truck Type and Age Using HRV Metrics". Evergreen, 12 (04) 2046-2057 (2025). https://doi.org/10.5109/7402636.

critical for long-term system viability in both urban and freight contexts[3)].

Compared to smaller vehicles, driving a truck requires greater control, longer braking distances, larger blind spots, and results in significantly greater impact forces during collisions due to the vehicle's large size[4)]. Larger and heavier vehicles also pose a higher hazard to other road users[5,6)]. These factors suggest that the type of truck being operated may directly influence a driver's performance. High mental workload has been shown to impair driving performance and increase the risk of accidents[7,8)]. One of the key determinants of mental workload is the nature of the task demands[1,9)], which in this context is closely associated with the type of truck being driven.

Each truck type entails distinct operational task demands and risk profiles. Trucks transporting industrial or retail goods require increased driver vigilance to preserve cargo quality and ensure timely delivery. Drivers must maintain sustained attention, avoid abrupt maneuvers, and adhere to precise handling protocols. Trucks carrying hazardous materials demand even greater caution in route planning and vehicle operation, as these substances are highly flammable and pose serious environmental and safety risks in the event of leakage or collision. Such operations necessitate strict compliance with safety regulations and careful navigation on well-maintained roads. Meanwhile, trucks transporting bulk construction or mining materials—such as sand, gravel, or soil—typically operate under less stringent handling requirements. These vehicles often travel through poorly maintained or off-road routes, where cargo preservation is less critical, potentially resulting in a lower perceived cognitive burden for drivers. Over time, the distinct daily task demands associated with each truck type may shape specific driving behaviors and skill sets among drivers. These task-driven adaptations influence how drivers perceive, process, and respond to various road situations, thereby contributing to individual differences in cognitive load during driving tasks[10)].

In addition to vehicle-related factors, organizational context plays a critical role in shaping driver behaviour and mental workload[11,12)]. Drivers responsible for transporting regulated or high-value cargo are typically employed by large-scale companies that uphold strong safety cultures, offer regular training programs, and implement structured operational protocols. In contrast, drivers transporting bulk or low-sensitivity materials are often employed by smaller companies with less formalized safety practices. These organizational differences may influence drivers' risk perception, stress management strategies, and compliance with safety procedures[13)]. Similar patterns have been observed in last-mile delivery systems, where variations in organizational infrastructure, technological readiness, and operational planning significantly affect performance outcomes and can indirectly contribute to cognitive strain among logistics personnel[14)].

Another critical factor is driver age, which affects cognitive performance[15,16)]. While younger drivers may exhibit faster reaction times and higher cognitive flexibility, older drivers tend to benefit from greater experience but may experience declines in sustained attention, response inhibition, and decision-making under stress. Older adults may experience declines in cognitive flexibility and reaction time, impacting their ability to respond to critical traffic situations. Additionally, physiological resilience may diminish, affecting overall performance in the transportation sector[17–19)]. The inclusion of driver age as a core variable in this study is essential, given its well-established influence on accident risk. Research on heavy-vehicle operators reveals a U-shaped relationship between age and accident involvement, with elevated risk among both younger drivers (under ~27 years) and older drivers (around or above 63 years)[20)]. The interplay between truck type and driver age may thus yield important insights into the underlying mechanisms of driver's mental workload and driving performance.

The novelty of this research is twofold. First, while earlier studies have investigated HRV as an indicator of cognitive workload in drivers and pilots[21–23)], few have specifically examined professional truck drivers, especially in the Indonesian context where freight transport is dominated by an aging driver population. Second, unlike prior research that typically analyzes drivers as a homogenous group, this study differentiates between truck types—wing box, tanker, and dump trucks—highlighting how vehicle design and operational characteristics contribute to workload disparities. Finally, by incorporating driver age as a moderating factor, the study captures the interaction between aging-related cognitive changes and vehicle type, revealing how these jointly influence mental workload and driving performance. This integrated perspective provides new evidence to support the development of human-centered interventions tailored to both truck type and driver age.

Despite the relevance of these factors, empirical investigations that systematically examine the combined effects of truck type and driver age on mental workload and driving performance remain scarce, particularly in developing country contexts. To address this gap, this study aims to examine the relationship between truck types (specifically dump trucks, box trucks, and tanker trucks) and their effects on drivers' performance and mental workload. The objectives are:

- To analyze differences in driving performance metrics (e.g., response time and total number of misses and errors) across different truck types.
- To evaluate variations in mental workload using physiological measures such as heart rate variability (HRV).

By addressing these objectives, this research seeks to offer a comprehensive understanding of cognitive workload

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variations among different driver profiles. The findings will inform targeted strategies for fatigue monitoring, driver training programs, and evidence-based transportation safety policies.

2. Methods

2.1. Participants

The sample size was determined by considering the number of participants in related studies on mental workload[1,24,25,26,27] and calculated using G*Power software. Based on a MANOVA statistical test, the analysis indicated that at least 24 participants were required to detect a large effect size of 0.35, as classified by Cohen[28], with 80% statistical power and a 5% significance level. Therefore, a total of 30 professional truck drivers participated in this study.

The participants were recruited from three different companies, selected to represent diverse trucking industry conditions in Indonesia. The selection aimed to ensure variability in safety awareness and operational practices. Specifically, 10 drivers were from a company with high safety awareness and affiliated with the Indonesian Security and Safety Association, 10 drivers were from a company with high safety awareness but not affiliated with Indonesian Security and Safety Association, and 10 drivers were from a small company with relatively low safety awareness.

All participants possessed valid professional driving licenses. The average age was 38.63 years (SD = 9.23), and the mean duration of driving experience was 12.89 years (SD = 9.01). The participants were recruited from three different companies. Ten drivers operated wing box trucks, ten drivers drove fuel tanker trucks, and ten drivers operated dump trucks. All participants had either normal vision or corrected-to-normal vision and were in good health at the time of the experiment. Prior to commencing the study, all participants were provided with detailed information about the experimental procedures and voluntarily signed an informed consent form. This study has received ethics committee approval from The Ethics Committee on Social Studies and Humanities National Research and Innovation Agency (NRIA) with approval number 026/KE.01/SK/01/2024.

2.2. Apparatus

The experiment was conducted at the B. J. Habibie National Science and Technology Park under the National Research and Innovation Agency, using a controlled laboratory setup to ensure consistency in stimulus presentation and response measurement. The laboratory environment was carefully maintained, with temperature and lighting conditions standardized throughout the experiment to eliminate external variability. Participants viewed the video stimuli on a 24-inch high-resolution LCD screen, providing clear and detailed visuals to closely replicate real-world driving conditions. A standard keyboard was placed on the table, enabling participants to press the space bar to indicate motorcycle detection at a specific distance (see Figure 1). A Polar H10 heart rate sensor was used to monitor heart rate variability (HRV), capturing physiological responses related to cognitive workload. The strap was placed horizontally just below the chest across the sternum (see Figure 2), with moistened electrodes in direct skin contact to ensure accurate signal acquisition.

2.3. Procedure

Upon arrival, participants received a detailed explanation of the experimental procedure, including the tasks they would perform and the data collection methods. They then completed an informed consent form to confirm their voluntary participation, followed by a preliminary questionnaire to collect background information such as age, truck type, work experience, and health status. To minimize potential physiological effects on HRV, participants were instructed to refrain from consuming coffee, tea and smoking before and during the experiment. This step ensured a comprehensive understanding of participant characteristics, which could influence driving performance and mental workload.

A fatigue screening process was conducted before the experiment to account for potential variations in fatigue levels among participants. In addition to completing the demographic questionnaire, participants completed the Karolinska Sleepiness Scale (KSS) to assess their subjective alertness levels. The KSS, a widely used measure of sleepiness, ranges from 1 (extremely alert) to 9 (very sleepy, struggling to stay awake). Participants who reported a KSS score of 7 or higher were rescheduled to ensure that all drivers began the experiment in a comparable state of rest and alertness. Additionally, participants were instructed to get sufficient rest the night before the experiment and to avoid strenuous activities before arriving at the testing facility.

Before beginning the experiment, each participant was equipped with a Polar H10 heart rate sensor, which was securely attached to their chest. The operator verified that the device was transmitting a stable signal to ensure the accuracy of heart rate variability (HRV) measurements throughout the study. Participants were then provided with detailed task instructions and guided through a familiarization trial, allowing them to practice the experimental procedure before formal data collection began. This familiarization phase ensured that participants understood how to respond during the experiment, minimizing learning effects and variability in task performance.

The primary task required participants to identify motorcycles within the simulated driving scenario

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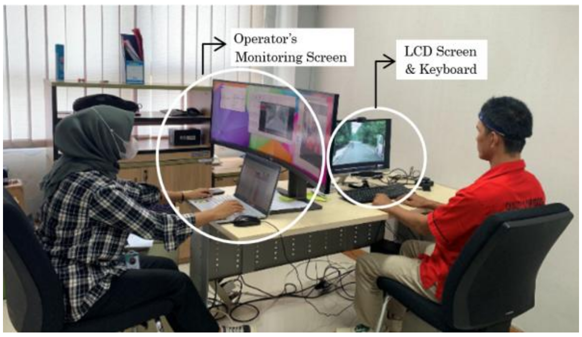


Fig. 1: Motorcycle Detection Experiment

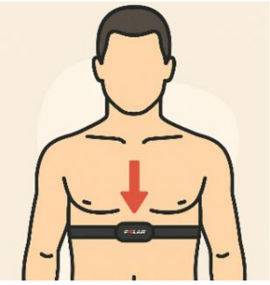


Fig. 2: HRV Sensor Placement

Fig. 3: Driving Video

presented in the video (see Figure 1). The driving scenario (see Figure 3) was structured into four distinct segments, each representing a different driving condition: rural-daytime, rural-nighttime, urban-daytime, and urban-nighttime, with each segment lasting 7 minutes and 30 seconds. A 5-minute break was provided between segments to minimize participant fatigue and maintain attentional performance throughout the experiment. In total, 145 stimuli were presented, consisting of motorcycles emerging from behind the truck, which appeared through the front windshield, left rearview mirror, or right rearview mirror. To control for potential order effects, the sequence of these segments was randomized across participants using a systematic counterbalancing approach. This method ensured a balanced distribution of conditions while maintaining consistency in data collection.

This structured approach allowed for a systematic evaluation of how truck type, age, and environmental conditions influenced both driving performance and cognitive demands, providing valuable insights into the interaction between these factors.

2.4. Data Acquisition

In this study, driving performance was assessed using response time (RT), the number of misses, and the number of errors. Response time refers to the interval between the moment a stimulus (e.g., a motorcycle appearing in the participant's field of view) is presented and the participant's response, measured by pressing the space bar on the keyboard. A shorter response time indicates a faster detection and response to potential hazards.

The number of misses was recorded when a participant failed to detect and respond to a motorcycle crossing their path within the given timeframe. A higher number of misses suggests reduced situational awareness or delayed hazard perception, which could be influenced by factors such as truck type, driver experience, or cognitive workload. The number of errors represented incorrect responses, such as pressing the space bar when no motorcycle was present or responding to a non-target stimulus. A higher error rate may indicate confusion, cognitive overload, or impaired decision-making during the task. Together, these three metrics provided a comprehensive evaluation of participants' driving performance, allowing for an analysis of how different truck types and driver characteristics influenced reaction speed, accuracy, and overall hazard perception.

Mental workload data will be derived from both time-domain and frequency-domain analyses of heart rate variability (HRV). The time-domain method will utilize the Root Mean Square of Successive Differences (RMSSD), measured in milliseconds (ms). This will be complemented by three features extracted from the frequency-domain approach, specifically employing the Fast Fourier Transform (FFT) spectrum: absolute Low Frequency (LF) power (ms^2), absolute High Frequency (HF) power (ms^2), and LF/HF ratio.

The LF band, characterized within the range of 0.04–0.15 Hz, signifies the aspect predominantly related to the engagement of the Sympathetic Nervous System (SNS), while the HF band (range of 0.15-0.4 Hz), signifies the aspect predominantly related to the engagement of the Parasympathetic Nervous System (PNS)[29]. RMSSD is the root mean square of the difference of all subsequent RR interval[30]. This comprehensive approach allows for a nuanced assessment of autonomic nervous system dynamics in response to mental workload variations.

3. Results

A Multivariate Analysis of Variance (MANOVA) was employed to evaluate group differences in driving performance and mental workload based on truck type and age group. The experimental design incorporated two between-subjects independent variables: truck type (wing box truck, tanker truck, and dump truck) and age group (<40 years old, ≥40 years old). The dependent variables

Table 1: Mean (SD) Values of Driving Performance

Driving Performance	Truck Type			Age Group	
	Wing box truck (N=10)	**Tanker truck (N=10)**	**Dump truck (N=10)**	**< 40 y.o. (N=14)**	**≥ 40 y.o. (N=16)**
Response Time (ms)	1495 (245.1)	1419 (273.12)	1809 (268.73)	1460 (295.29)	1674 (287.79)
Number of Misses and Errors (n)	51.8 (24.34)	24.8 (6.68)	79.2 (29.67)	41.57 (20.33)	61 (36.75)

Table 2: Mean (SD) Values of Mental Workload

Mental Workload	Truck Type			Age Group	
	Wing box truck (N=10)	**Tanker truck (N=10)**	**Dump truck (N=10)**	**< 40 y.o. (N=14)**	**≥ 40 y.o (N=16)**
Absolute LF Power (ms^2)	937 (673.47)	457 (311.11)	381 (354.49)	797 (603.9)	412 (369.45)
Absolute HF Power (ms^2)	670 (634.71)	244 (267.92)	119 (95.34)	542 (544.6)	172 (275.34)
LF/HF Ratio	3.27 (2.92)	3.88 (4.46)	3.71 (1.33)	2.43 (1.55)	4.67 (3.69)
RMSSD	40.29 (24.21)	28.26 (23.88)	16.83 (8.27)	39.1 (26.04)	19.15 (11.52)

comprised two categories: driving performance measures (response time and total number of misses and errors) and mental workload indicators (absolute LF power, absolute HF power, LF/HF ratio and RMSSD). In addition, bivariate correlation analyses were conducted to examine the associations between driving performance metrics and physiological indicators of mental workload.

Statistical significance was established at $\alpha = 0.05$, and partial eta squared (η2) was calculated to determine effect sizes across all analyses. The descriptive statistics, including means and standard deviations (SDs) for all dependent variables, are presented in Table 1 and Table 2.

3.1. Multivariate Analysis of Variance (MANOVA)

3.1.1. Response time

1) Truck Type

A significant main effect was observed for truck type on response time, F(2,24) = 5.812, p = 0.009, η2 = 0.326. A Bonferroni post-hoc test showed that there was a significant difference for mean response time between wing box truck and dump truck (p = 0.05), tanker truck and dump truck (p = 0.11). The data indicated that tanker truck drivers exhibited the shortest response time, followed by wing box truck drivers, and dump truck drivers (see Figure 4). This finding suggests that type of truck significantly influences driver response to stimuli.

2) Age Groups

The Figure 4 shows that the ≥ 40 years old group exhibited a longer mean response time compared to the < 40 years old group. While the statistical analysis indicated that the effect of age on response time was not significant (p = 0.055), the trend suggests that older drivers tend to respond more slowly to stimuli. This aligns with existing research on age-related cognitive and motor decline, where older individuals often experience reduced processing speed and slower neuromuscular responses. The error bars in the figure represent standard deviations, indicating the variability within each group. The higher variability in the older group suggests that response time differences among older drivers may be influenced by individual factors such as driving experience, cognitive ability, and fatigue levels.

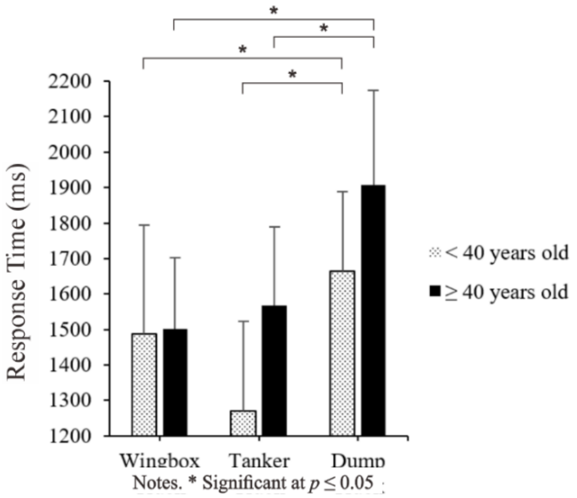


Fig. 4: Truck drivers' response time based on truck types and age groups

3.1.2. Total Errors

1) Truck Type

A significant main effect of truck type on response time was identified, F(2,24) = 14.692, p < .001, η^2 = 0.550. A Bonferroni post-hoc test showed that there was a significant difference for mean response time between wing box truck and tanker truck (p = 0.026), wing box truck and dump truck (p = 0.049), and tanker truck and dump truck (p = <.001). The analysis revealed that tanker truck drivers demonstrated the shortest mean response time, followed by wing box truck drivers and dump truck drivers (refer to Figure 5).

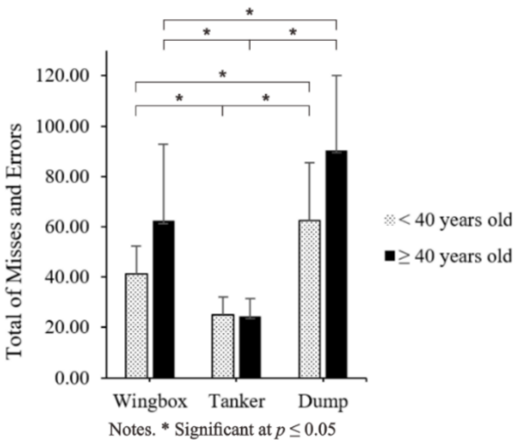
2) Age Groups

A significant main effect was observed for age groups on Total Errors, F(1,24) = 4.299, p = 0.049, η2 = 0.152. The data indicated that group < 40 years significantly has shorter Total Errors than group ≥ 40 years (see Figure 5).

3.1.3. LF and HF Power

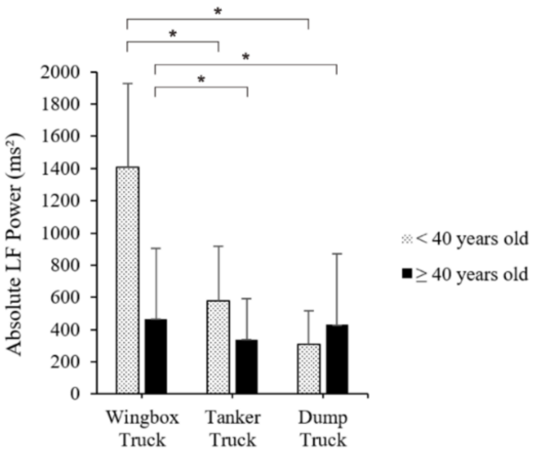
1) Truck Type

A significant main effect of truck type was found on Absolute LF Power, F(2, 24) = 6.052, p = 0.007, η^2 = 0.335. Post-hoc comparisons using the Bonferroni correction revealed significant differences in mean response time



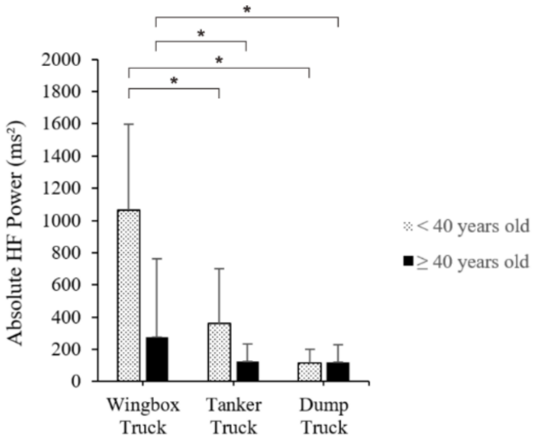
Notes. * Significant at $p \leq 0.05$

Fig. 5: Comparison of truck drivers' total miss and error based on truck types and age groups



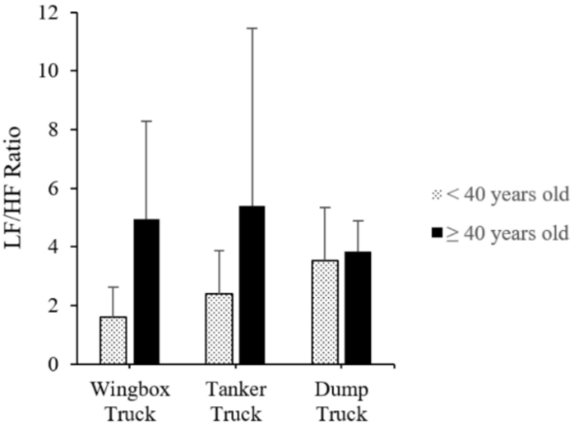
Notes. * Significant at $p \leq 0.05$

Fig. 6: Comparison of truck drivers' absolute LF power based on truck types and age groups



Notes. * Significant at $p \leq 0.05$

Fig. 7: Comparison of truck drivers' absolute HF power based on truck types and age groups



Notes. * Significant at $p \leq 0.05$

Fig. 8: Comparison of truck drivers' LF/HF ratio based on age groups

between wing box and tanker truck drivers (p = 0.034), as well as between wing box and dump truck drivers (p = 0.011). The results demonstrated that dump truck drivers had the lowest levels of Absolute LF Power, followed by those driving tanker trucks, with wing box truck drivers showing the highest values (see Figure 6).

Similarly, truck type had a significant effect on Absolute HF Power, F(2, 24) = 7.410, p = 0.003, η^2 = 0.382. Bonferroni-adjusted pairwise comparisons showed significant differences in mean response time between wing box and tanker truck drivers (p = 0.026), and between wing box and dump truck drivers (p = 0.004). As with LF Power, dump truck drivers displayed the lowest Absolute HF Power values, followed by tanker truck drivers, while wing box drivers exhibited the highest (see Figure 7).

2) Age Groups

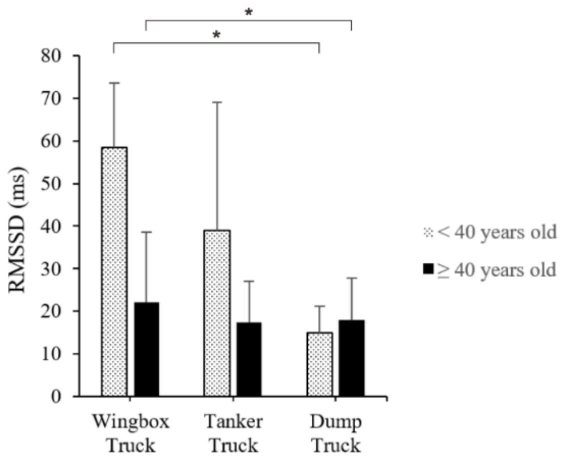
A significant main effect of age group was found for Absolute LF Power, F(1, 24) = 6.078, p = 0.021, η^2 = 0.202. Bonferroni-adjusted post-hoc comparisons revealed a significant difference in mean Absolute LF Power between participants under 40 years of age and those aged 40 and above (p = 0.021). The results indicated that younger participants (< 40 years) exhibited significantly higher Absolute LF Power than their older counterparts (≥ 40 years) (see Figure 6).

Similarly, a significant main effect of age group was observed for Absolute HF Power, F(1, 24) = 7.647, p = 0.011, η^2 = 0.242. Post-hoc analysis confirmed a significant difference between the two age groups (p = 0.011), with younger participants displaying higher Absolute HF Power than older participants (see Figure 7).

3.1.4. LF/HF Ratio

1) Truck Type

No significant differences were observed in the LF/HF ratio across the different vehicle types. However, the data did reveal notable trends: the wing box truck exhibited the lowest LF/HF ratio, followed by the dump truck, and the tanker truck. These findings suggest a relative variation in the LF/HF ratios between the truck types, although the



Notes. * Significant at $p \leq 0.05$

Fig. 9: Comparison of truck drivers' RMSSD based on age groups

Table 3: Pearson Correlations Between Driving Performance Measures and HRV Parameters

Var	1	2	3	4	5	6
1	-					
2	.62**	-				
3	-.324	-.327	-			
4	-.241	-.267	.817**	-		
5	.303	.199	-.367*	-.468	-	
6	-.342	-.372*	.750**	.904**	-.537**	-

***. Significant at* $p \leq 0.01$
**. Significant at* $p \leq 0.05$
1: Response Time (ms)
2: Number of Misses and Errors (n)
3: Absolute LF Power (ms^2)
4: Absolute HF Power (ms^2)
5: LF/HF Ratio
6: RMSSD (ms)

differences were not statistically significant, as shown in Figure 8.

2) Age Groups

Despite of no significant main effect found in LF/HF ratio. Figure 9 shows that the LF/HF ratio is higher for drivers aged ≥40 years compared to drivers under 40 years old. This suggests that older drivers experience increased physiological stress or reduced parasympathetic activity during driving tasks. The error bars represent standard deviations, indicating some variability in individual responses within both age groups.

The findings emphasize the potential impact of age on autonomic regulation and stress management during driving. Older drivers may be more prone to experiencing stress-related impairments, which could influence their mental workload and driving performance.

3.1.5. RMSSD

1) Truck Type

A significant main effect was observed for truck type on RMSSD, F(2,24) = 5.057, p = 0.015, η2 = 0.296. A Bonferroni post-hoc test showed that there was a significant difference for mean response time between wing box truck and dump truck (p = 0.012). The data indicated that dump truck drivers exhibited the lowest RMSSD, followed by tanker truck drivers, and wing box drivers (see Figure 9).

2) Age Groups

A significant main effect was observed for age groups on RMSSD, F(1,24) = 9.030, p = 0.006, η2 = 0.273. A Bonferroni post-hoc test showed that there was a significant difference for mean RMSSD between age groups < 40 years and ≥ 40 years (p = 0.006). The data indicated that group < 40 years significantly has higher value of RMSSD than group ≥ 40 years (see Figure 9).

3.2. Bivariate Correlation Analysis

The strength and direction of associations among the key variables were examined using Pearson correlation, as summarized in Table 3. The correlation analysis revealed that higher error rates were significantly associated with longer response times (r = .620, p < .001), indicating that drivers who took more time to detect and respond to hazards were also more prone to missing or incorrectly responding to stimuli. Furthermore, number of misses and errors were negatively correlated with RMSSD (r = –.372, p = .043), a time-domain HRV metric that reflects parasympathetic nervous system activity and short-term heart rate variability. These findings suggest that increased mental workload impairs driving performance and reduces physiological recovery, underscoring the cognitive and physiological demands placed on drivers under high workload conditions.

Additionally, strong positive correlations between HRV indicators (e.g., RMSSD and Absolute HF power, r = .904, p < .001) and their negative relationships with LF/HF ratio (r = –.537, p = .002) confirm that reduced parasympathetic activity is a reliable marker of elevated mental workload.

4. Discussion

The results of this study confirm that truck type significantly influences response time, misses, and errors, which are critical indicators of driving performance. Among the three vehicle categories studied, dump truck drivers exhibited the slowest response times and the highest number of missed and incorrect responses, indicating that operating this vehicle type imposes a higher cognitive and physical workload. In contrast, tanker truck drivers consistently showed superior performance, with shorter response times and lower error frequencies, suggesting that both the vehicle's operational demands and its organizational context contribute to performance outcomes.

Age was another significant factor affecting driving performance. Although the difference in response time between drivers under 40 and those aged 40 and above was not statistically significant, the trend suggests that older drivers take longer to respond to hazards[31)]. This is consistent with cognitive aging research, which indicates that processing speed and motor responses decline with age[15)]. More notably, older drivers exhibited a significantly higher number of total errors and misses, reinforcing concerns about age-related deterioration in attentional capacity and decision-making accuracy[32)]. These findings suggest that truck driving safety strategies should include adaptive interventions for older drivers, such as training programs focusing on situational awareness, hazard perception, and response improvement techniques.

Heart rate variability (HRV) metrics provided objective confirmation of the cognitive demands imposed by different truck types and age groups. Dump truck drivers exhibited the lowest absolute LF and HF power. In the context of Mental workload (MWL), MWL typically leads to a decrease in time domain measures and a reduction in both Low Frequency (LF) and High Frequency (HF) powers of Heart Rate Variability (HRV), suggesting an increased sympathetic response and reduced parasympathetic activity, which is often associated with heightened stress and fatigue[33)]. In contrast, wing box truck and tanker truck drivers displayed higher HRV values, indicative of better autonomic regulation and lower stress levels.

Similarly, RMSSD values, which reflect short-term HRV fluctuations, were significantly lower for dump truck drivers and older participants, reinforcing the link between cognitive workload, stress, and age-related decline in physiological resilience. These findings align with prior studies that suggest that HRV suppression is associated with increased cognitive strain and impaired decision-making ability under high-workload conditions[34,35)]. In addition, sustained mental load driven by lifestyle-related stress has been shown to trigger drowsiness and inattentive driving behaviors, both of which critically undermine driver safety[36)].

Furthermore, Pearson correlation analysis provided additional support for the link between workload and performance. A significant positive correlation was found between response time and total errors ($r = .620$, $p < .001$), indicating that drivers who took longer to respond were also more likely to make mistakes. Additionally, total errors were negatively correlated with RMSSD ($r = –.372$, $p = .043$), suggesting that drivers with lower short-term HRV—a marker of reduced parasympathetic activity—were more prone to performance lapses. Although not all correlations reached statistical significance, negative trends between performance measures and both LF and HF power further suggest that diminished autonomic flexibility is associated with poorer driving outcomes. This aligns with previous research showing that HRV suppression corresponds to increased cognitive strain and reduced capacity for recovery under sustained workload conditions.

The observed performance disparities among truck drivers can be plausibly attributed to divergent organizational management practices. Wing box and tanker truck drivers, typically employed by larger-scale corporations, benefit from comprehensive safety driving training programs and regular skill enhancement initiatives prioritized as part of their employers' operational strategies. These companies are generally characterized by higher safety awareness, as evidenced by their membership in the Indonesian Security and Safety Association, possession of the Safety Management System certificate issued by the Directorate General of Land Transportation, and certification in the Quality Management System ISO 9001:2015. In contrast, dump truck drivers, employed by smaller-scale enterprises, may experience less consistent implementation of structured management approaches to driving skill improvement. To further validate these classifications, we conducted interviews with drivers regarding their safety practices. Drivers from high-safety-awareness companies reported participation in safety briefings or driving training, whereas approximately 60% of drivers from low-safety-awareness companies indicated that they had never received safety driving training.

This discrepancy in organizational size and resource allocation likely contributes to varying levels of driver preparedness and skill proficiency across different truck categories. Larger companies' systematic focus on safety protocols and continuous professional development potentially results in enhanced performance and heightened safety awareness among their drivers, while smaller enterprises may face challenges in providing equally robust training opportunities due to resource limitations. Prior studies also highlight that when professional drivers perceive their work environment as cost-conscious, with clear time schedules and strong work orientation, they report lower frequencies of driving errors and violations[11)]. Furthermore, evidence indicates that a stronger safety culture helps drivers manage job demands, remain focused, avoid fatigue, and maintain good reaction time while on duty[12)] In addition, the implementation of safety culture has been shown to enhance drivers' own perceptions of safety, although such perceptions are still largely shaped by the organization's overall commitment to managing safety culture and providing training programs aimed at reducing fatigue[13)].

In addition to organizational differences, the nature of the task demands inherent to each truck type plays a critical role in shaping driver performance and cognitive workload. Wing box truck drivers are responsible for delivering logistics over long distances while ensuring the quality and integrity of high-value goods, which requires sustained vigilance, careful handling, and time-sensitive operations.

Tanker truck drivers face even greater cognitive and procedural demands due to the hazardous nature of their cargo—fuel that is highly flammable and environmentally sensitive. As a result, these drivers may develop a higher level of situational awareness, risk perception, and cognitive preparedness. These attributes likely contributed to the superior driving performance and lower mental workload observed among wing box and tanker truck drivers in this study. In contrast, dump truck drivers typically transport bulk construction materials over shorter distances, often on less regulated routes, with fewer cargo quality constraints. The relatively lower operational demands may result in reduced cognitive engagement and situational preparedness, which could explain their poorer performance and higher physiological indicators of mental strain during the simulation task.

The results of this study emphasize the need for targeted interventions to enhance truck driver safety and performance. Consistent with prior work on human safety in traffic environments37), our findings reinforce the need to integrate human-centered safety strategies that address mental workload in commercial freight operations. Given that dump truck drivers exhibited higher mental workload and poorer driving performance, training programs should focus on improving hazard anticipation skills, strengthening situational awareness, and enhancing reaction efficiency38). Additionally, vehicle manufacturers should consider ergonomic adjustments in truck design39), such as enhance comfort, improving visibility40), reducing physical effort for steering41), and integrating technologies such as advanced driver assistance systems (ADAS), lane departure warning, adaptive cruise control, and fatigue sensors to help drivers reduce errors and support drivers under high workload conditions42).

For older truck drivers, particularly those aged 40 and above, implementing comprehensive age-specific interventions is crucial to maintain safety and performance standards. These strategies should include tailored training programs utilizing driving simulators to enhance preparedness for high-risk scenarios, especially for dump truck operators who may face unique challenges. Additionally, adaptive safety measures such as regular cognitive and physiological assessments should be instituted to proactively address age-related declines in response time and workload tolerance. To mitigate the effects of aging and sustain long-term performance, companies should encourage frequent rest breaks, implement workload monitoring systems, and provide cognitive training programs. These multifaceted approaches can help older drivers adapt to the evolving demands of their profession while simultaneously ensuring road safety for all stakeholders in the transportation industry.

Furthermore, implementing biofeedback-based interventions, where drivers receive real-time HRV feedback to regulate their stress levels, could enhance workload management and decision-making efficiency in high-demand driving conditions.

5. Conclusion

This study provides empirical evidence on how truck type and driver age influence driving performance and mental workload. The results highlight that Drivers operating dump trucks exhibited the poorest performance and lowest HRV, suggesting a higher cognitive and physiological burden, while tanker truck drivers consistently showed superior performance and lower workload indicators, likely due to both operational demands and better organizational management practices.

Age-related differences were also observed, with drivers aged 40 and above showing longer response times and increased cognitive workload, as evidenced by both performance metrics and HRV indicators. The physiological data support the claim that older drivers and those operating heavier trucks experience higher cognitive strain, necessitating interventions to improve safety and reduce workload. The correlation analysis further confirmed that slower response times and increased errors were significantly associated with reduced RMSSD values, reinforcing the link between elevated mental workload and impaired driving performance.

The results underscore the need for context-sensitive interventions, including enhanced training for high-demand vehicle operators, ergonomic improvements in truck design, and age-adaptive safety programs supported by real-time workload monitoring. By addressing these human-centered factors, stakeholders can foster safer, more sustainable trucking operations and reduce risk across the freight transport system.

Future research should explore the use of EEG and eye-tracking technologies to capture more detailed neurophysiological and visual attention indicators of mental workload. In addition, combining objective metrics with subjective workload assessments such as the NASA Task Load Index (NASA-TLX) could provide a more holistic understanding of drivers' perceived workload under varying conditions. Conducting studies using driving simulators or naturalistic driving settings is also recommended to improve ecological validity and reflect real-world complexities that may not be fully captured in controlled experimental environments. These directions would contribute to developing more robust, multi-method approaches for assessing and managing workload in commercial transportation systems.

Acknowledgements

We extend our gratitude to the Safety and Security Transportation Organization for their invaluable assistance in supplying participants for this investigation. This study inquiry received financial support from the Indonesian Ministry of Finance's LPDP and the National Research and Innovation Agency via the Research and Innovation for Advanced Indonesia Program, grant number B-839/II.7.5/FR.06/5/2023.

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