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Driving Under Pressure: Quantifying the Impact of Escalating Cognitive Stressors on Professional Driver Behavior †

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Abstract

Public transport and professional drivers operate under substantial cognitive load arising from multiple sources. During real-time traffic participation, schedule pressure and passenger interactions may adversely affect driving behavior. The present study examines whether increased cognitive load and schedule pressure induce risk-averse drivers to engage in risk-taking and commit traffic violations. In the experiment, participants complete a predefined route in a bus simulator in both directions. Initially, they drive under baseline conditions without schedule constraints. On the return route, cognitive load is gradually increased through the introduction of escalating stressors. Results indicate that high-pressure conditions did not consistently deteriorate driving style or simulator performance. Instead, eye-tracking metrics revealed that schedule pressure effects were highly participant-specific. While these findings validate a multidimensional framework—combining telemetry, questionnaires, behavioral tasks, and eye-tracking—the small sample size and pilot nature require cautious interpretation.

Keywords: bus driver; eye-tracking; driver behavior; cognitive load

1. Introduction

Professional driving is widely recognized as a high-risk occupation characterized by extreme levels of occupational stress and mental workload [1]. The primary sources of this stress include a heightened awareness of responsibility for passengers and cargo, irregular work schedules, and the cognitive demands of continuous information processing [2]. For long-distance truck drivers, these stressors are further compounded by social isolation, job insecurity, and chronic fatigue, which cumulatively increase the risk of developing depressive symptoms [1]. Time pressure and rigid delivery schedules are critical determinants of driver risk [2,3]. High job demands often lead drivers to withdraw attentional resources from the primary driving task to focus on internal worries regarding the repercussions of being late [3]. This psychological strain frequently results in maladaptive behaviors, such as exceeding speed limits or violating traffic regulations in an attempt to maintain schedules [2]. Furthermore, the complexity of the road environment significantly impacts mental workload; while urban settings impose high cognitive and physical demands due to traffic density, rural roads often present monotonous conditions that increase drowsiness and reduce driver arousal [4].

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The long-term health implications for professional drivers are severe, with the group consistently identified as one of the unhealthiest occupational populations [2]. Key health risks include cardiovascular diseases, gastrointestinal disorders, and musculoskeletal problems, the latter of which are often linked to static postures and whole-body vibration [2]. Fatigue remains a predominant factor in traffic accidents, typically resulting from sleep deprivation, irregular shifts, and the disruption of circadian rhythms [2,5,6].

To address these challenges, research has shifted toward multifaceted technological and organizational countermeasures [7]. Physiological monitoring systems utilizing Heart Rate Variability (HRV) analysis have shown promise in automatically diagnosing stress and fatigue in real-time to alert drivers before accidents occur [6]. Additionally, Advanced Driver Assistance Systems (ADAS), such as collision and drowsiness warning systems, are regarded as effective in mitigating risks caused by driver inattention [7]. Beyond technology, organizational interventions like workload reductions and improved communication are essential for improving driver coping strategies and overall road safety [1].

2. Literature Review

Professional bus driving is a complex perceptual-motor activity that requires the simultaneous coordination of vehicle control, urban navigation, and passenger safety [8]. Among the operational constraints faced by bus drivers, schedule adherence is a major source of workload and stress. Increased time pressure may impair information processing and increase the likelihood of missing critical traffic events [9]. This elevated cognitive load is closely associated with fatigue, which can more than double accident risk during typical extended shifts [10]. The effects of operational pressure are often shaped by individual differences. According to the transactional theory of driver stress, personality-related factors influence how drivers appraise and respond to environmental challenges [11]. Although calm or risk-averse drivers may generally prioritize safety, acute schedule pressure may still lead to performance deterioration and riskier coping strategies, such as increased speed or reduced compliance with traffic rules. This study applies a multimodal research framework in a high-fidelity bus simulator to examine whether naturally calm and risk-averse drivers become more prone to safety infractions under cumulative stress [12]. By integrating Pupil Labs Neon eye-tracking data with psychometric profiling, specifically the Iowa Gambling Task (IGT) for risk-related decision-making and a shortened Cognitrone (COG) task of the Vienna Test System (VTS) for attention and concentration, the study aims to identify the point at which environmental pressure may override otherwise safe driving predispositions [13]. Recent advances in eye-tracking and pupillometry have made these technologies valuable tools for the objective, real-time assessment of driver states. Pupil dilation is widely regarded as a robust indicator of mental effort, with diameter increases of approximately 20% observed during high-stress driving scenarios. Under acute pressure, drivers may also exhibit "visual tunneling," in which gaze distribution narrows toward the road center and attention to peripheral hazards may decrease. Blink duration is another important marker, as average values above 150 ms may indicate fatigue-related vigilance decline [8]. To obtain a more comprehensive understanding of the driver's internal state, recent research increasingly combines objective visual metrics with neurocognitive profiling. The Iowa Gambling Task (IGT) can assess decision-making and risk-taking tendencies [14], while the Cognitrone (COG) of the Vienna Test System (VTS) assesses attention and concentration performance [15]. The integration of synchronized eye-tracking data with vehicle dynamics and physiological signals has been reported to achieve 91.4% stress classification accuracy, outperforming unimodal approaches [13]. This multimodal approach is therefore well-suited to examining how cumulative stressors, such as schedule delay alerts and mandatory dispatcher communication, influence professional bus driver performance.

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The study addressed the following research questions:

RQ1. *How does schedule pressure influence cognitive workload and visual attention?*

RQ2. *How do risk-taking tendency and monotony tolerance relate to infractions under time pressure?*

RQ3. *How do operational stressors affect fatigue, situational awareness, and driving behaviour?*

3. Materials and Methods

At the beginning of the study, participants completed a questionnaire to provide basic demographic information and details on their previous driving and simulator experience. They also provided a self-reported estimate of their approximate cumulative driving distance in public passenger transport service. Participants were selected based on predefined inclusion criteria, with the main requirements being possession of a valid Category D driving entitlement and prior experience in bus driving in an urban traffic environment. Familiarity with the selected driving route was not required as an inclusion criterion. Three participants took part in the study, all of whom were male, with a mean age of 35 years. In addition to meeting the license-related criterion, all participants possessed the professional qualifications and official authorizations required under the current Hungarian regulations to operate buses in public passenger transport service. Each participant had held the required entitlement for at least one year. Within the sample, two participants had previous experience with simulator-based driving, whereas one participant had no prior simulator experience. None of the participants reported discomfort, nausea, or symptoms related to simulator sickness during the completion of the simulator-based driving tasks. The main characteristics of the participants' driving and simulator experience are summarised in Table 1.

Table 1. Main characteristics of participants' driving and simulator experience.

Participant	Age	Licence Year	Driving Experience	Driving Experience Rating
P01	38	2018	≈550,000 km [1]	Very high
P02	27	2023	≈23,000 km [1]	Low
P03	40	2025	≈80,000 km [1]	Moderate

[1] Based on self-reported approximate cumulative driving distance.

The simulator environment was based on OMSI 2, a bus simulation software selected for its detailed representation of bus operation, including vehicle dynamics, timetable-based service, traffic interactions, signalised intersections, and passenger transport processes. The software also allowed the selected route and traffic environment to be modified, enabling the creation of controlled urban driving situations relevant to the research scenario. The hardware setup included a MOZA (Shenzhen Gudsen Technology Co., Ltd., Shenzhen, China) TSW steering wheel, a MOZA R5 force-feedback wheelbase, a MOZA Multi-Function Stalk, a genuine bus driver's seat (ISRINGHAUSEN GmbH & Co. KG, Lemgo, Germany), three curved monitors (Samsung Electronics Co., Ltd., Suwon, Republic of Korea), a right-hand control panel (Shenzhen AJAZZ Tongchuang Electronic Technology Co., Ltd., Shenzhen, China), and a tablet (Xiaomi Inc., Beijing, China) placed on the left-hand side of the driver. The steering wheel and adjustable force-feedback settings were used to approximate the steering characteristics of a power-assisted bus steering system, while the tablet displayed real-time timetable deviations and served as an interactive interface during the experimental task.

Data were collected using multiple measurement instruments and data sources. Simulator-based vehicle data were recorded from OMSI 2 via a custom dynamic-link library

(DLL), enabling extraction of telemetry variables during the driving task. The recorded variables included vehicle speed, time information, timetable deviation, stop events, door states, and other operational parameters relevant to the analysis of driving behaviour. Visual attention and selected physiological indicators were recorded using Neon eye-tracking glasses (Pupil Labs GmbH, Berlin, Germany). The recorded eye-tracking videos were used for post hoc inspection of driving events and traffic rule violations, while the eye-tracking data were used to extract indicators of cognitive load, stress, and attentional state, including blink count and duration, pupil diameter changes, and fixation count and duration. Questionnaire data were collected at the beginning of the study to obtain basic demographic information and self-reported data on participants' driving and simulator experience. The questionnaire also included two short computer-based tasks: a shortened 40-trial Iowa Gambling Task, used as a supplementary indicator of risk-taking tendency and decision-making under uncertainty, and a shortened 3 min task based on the Cognitrone (COG) of the Vienna Test System (VTS) [14]. These tasks were not intended to replace full standardised psychological assessments, but served as brief supplementary measures within the experimental protocol. Due to the characteristics of the data acquisition process, the simulator-based time-series data were pre-processed before analysis. Linear interpolation was applied to obtain a smoother and more consistent temporal representation of the recorded variables, and values above the 95th percentile were excluded for selected dynamic variables to reduce the influence of logging artefacts and unrealistic outliers. Longitudinal acceleration was then calculated from consecutive speed and time values.

$$a_i = \frac{v_i - v_{i-1}}{t_i - t_{i-1}} \quad (1)$$

where a_i denotes longitudinal acceleration, v_i and v_{i-1} denote consecutive speed values, and t_i and t_{i-1} denote the corresponding timestamps. Positive values represented acceleration, while negative values represented deceleration.

A composite driving score was calculated to support descriptive comparison between participants and driving runs. The score ranged from 0 to 100, with higher values indicating smoother and more stable vehicle handling. It consisted of four weighted components: dynamic safety, smoothness, consistency, and stop/service handling:

$$S = 0.35 \cdot \mathrm{DYN} + 0.30 \cdot \mathrm{SMO} + 0.25 \cdot \mathrm{CON} + 0.10 \cdot \mathrm{SER} \quad (2)$$

where S denotes the overall driving score, DYN the dynamic safety component, SMO the smoothness component, CON the consistency component, and SER the stop/service handling component. Timetable deviation was not included in the composite driving score, as it was treated as a separate outcome variable. Due to the small sample size, the analysis was primarily descriptive.

The experimental driving task was conducted on a simulated version of Budapest bus route 183, a suburban, relatively low-traffic public transport line. The official scheduled running times were 12 min outbound and 11 min inbound. The route included several infrastructure and traffic elements relevant to urban bus driving, such as signalised and priority-controlled intersections, limited-visibility road sections, a roundabout, tram-road crossings, and a level crossing. These elements were present in both directions, allowing the two experimental conditions to be compared under similar route and infrastructure characteristics. The outbound drive served as the low-pressure condition, in which participants were instructed to focus only on the driving task and were not exposed to additional task-related stressors. The return drive represented the high-pressure schedule recovery condition. In this phase, participants were instructed to adhere to the timetable as closely as possible, compensate for delays where feasible, and use the tablet-based real-time timetable-deviation information to inform their schedule-keeping decisions. When the simulated

delay reached 3 min, an auditory alert and a pop-up message were presented on the tablet and had to be acknowledged. At 5 min of delay, participants received dispatcher-like verbal information about the delay and related operational issues, which they also had to acknowledge and respond to. Upon arrival, participants received a brief explanation of the study procedure, the simulator task, and the types of data collected during the session. Written informed consent was obtained before data collection. Each session followed the same sequence: participants first completed the questionnaire and the two short behavioural tasks, followed by an unstructured familiarisation drive to test the simulator controls, experience the vehicle handling characteristics, and learn the selected route. Prior route knowledge was therefore not required. When participants indicated that they were ready to begin, the Pupil Labs Neon eye-tracking glasses were fitted and prepared for recording. Participants then completed the low-pressure outbound drive followed by the high-pressure return drive. Throughout both drives, simulator telemetry, eye-tracking data, and task-related interactions were recorded. After the return drive, participants secured the vehicle, the eye-tracking glasses were removed, and a short debriefing was conducted.

4. Results

Due to the small sample size, the results are reported descriptively, with the main focus on within-participant comparisons between the low-pressure outbound drive and the high-pressure return drive. Aggregated summaries are also provided to show overall patterns across participants. Simulator telemetry data were processed using a custom analysis tool, while selected traffic events and rule violations were verified through manual review of the recorded eye-tracking videos. The questionnaire and short behavioural tasks were used to describe participants' baseline characteristics and selected individual factors relevant to driving behaviour. The questionnaire contained 62 items rated on a 1–4 scale and covered self-reported driving-related behaviour, including reactions to traffic situations, passenger-related irritation, acceptance of traffic rule violations, and general driving style. Participants also completed a shortened 40-trial Iowa Gambling Task and a shortened monotony tolerance task. The Iowa Gambling Task was used as a supplementary indicator of decision-making under uncertainty and risk-related choice tendencies. In the present study, the VoRP index was calculated as [16]:

$$\text{VoRP} = [(C + D) - (A + B)] \quad (3)$$

where A, B, C, and D refer to the number of choices from the respective decks. Negative VoRP values indicated a tendency towards disadvantageous deck choices, while values closer to zero indicated a more balanced decision pattern [16]. The learning index reflected changes in decision strategy during the task, with positive values indicating more adaptive choices in the later trials. The monotony tolerance task was used as a brief measure of performance under repetitive task conditions and was classified as passed if the participant made no more than four errors and met the 700 ms response-time criterion [9]. These behavioural task indicators were interpreted descriptively and were not used as diagnostic psychological measures. The questionnaire and behavioural task results are summarised in Table 2.

Higher irritation scores indicate greater self-reported sensitivity to traffic- or passenger-related situations. VoRP was used as a descriptive Iowa Gambling Task index, with negative values indicating a tendency towards disadvantageous deck choices, while the learning index reflected changes in decision strategy [14,16]. The COG-based task was classified using a maximum of four allowed errors and a 700 ms response-time criterion [9]. These behavioural task results were interpreted as supplementary, non-diagnostic indicators. The results suggest distinct baseline profiles across participants. P02 showed higher irritation scores, a negative VoRP value, a negative learning index, and failed the monotony tolerance task, suggesting

a more distraction-sensitive attentional profile. P03 also showed elevated irritation scores and a negative VoRP value, but the positive learning index and successful monotony task performance indicate a more adaptive profile. P01 showed the lowest irritation scores, a balanced IGT result, and successful monotony task performance, suggesting a low-reactivity and relatively stable baseline profile. Timetable deviation was not analysed in detail, but participants were consistently running behind schedule during the high-pressure return drive, indicating that the schedule recovery condition was maintained throughout the task. Simulator-based driving performance was evaluated using OMSI telemetry data and the composite driving score described in the Methods section. Threshold-based events were analysed for speed and deceleration. Speeding events were defined as speed values exceeding 53 km/h, while strong deceleration events were defined as deceleration values exceeding 2.2 m/s^2 [10]. Repeated threshold exceedances within a 3 s window were merged and treated as a single event. The main simulator-based indicators are summarised in Table 3.

Table 2. Summary of questionnaire and behavioural task results.

Participant	Traffic Irritation [1]	Passenger Irritation [1]	Rule Violation Acceptance [1]	IGT VoRP	Learning Index	Monotony Task	Median RT	Target-Hit Rate
P01	1.57	1.31	1.33	0	0	Passed	443 ms	100%
P02	3.21	3.46	1.67	−10	−2	Failed	528 ms	89.13%
P03	3.07	3.85	2.00	−6	+10	Passed	515 ms	98.44%

[1] Questionnaire items were rated on a 1–4 scale. Higher values indicate stronger agreement or higher intensity.

Table 3. Summary of simulator-based driving performance indicators.

Participant	Condition [1]	Max Speed (km/h)	Speeding Events	Max Acceleration (m/s^2)	Max Deceleration (m/s^2)	Strong Decelerations	Verified Violations [2]	Driving Score
P01	LP-Out.	49.81	0	1.37	2.81	20	1	49/100
	HP-Ret.	53.37	3		2.43	23	5	48/100
P02	LP-Out.	58.44	8	1.42	2.99	27	6	47/100
	HP-Ret.	58.15	8	1.41	2.92	22	7	46/100
P03	LP-Out.	55.30	4	1.37	3.17	35	1	48/100
	HP-Ret.	56.70	6	1.39	2.99	28	7	47/100

[1] LP-Out. = low-pressure outbound drive; HP-Ret. = high-pressure return drive. [2] Manually verified violations were identified through post hoc review of the recorded eye-tracking videos.

Eye-tracking indicators were compared within participants between the low-pressure outbound drive and the high-pressure return drive. As analysed durations differed between conditions, count-based measures were interpreted using duration-normalised values. The main indicators are summarised in Table 4.

The eye-tracking indicators were interpreted as indirect markers of visual attention and task demand. Previous pilot work on multidimensional bus driver behaviour highlights that bus driving involves several parallel task components, including vehicle control, route and schedule-related tasks, passenger-related interactions, and communication demands [15]. These factors may increase cognitive and attentional load during service operation. In this study, shorter fixations combined with longer or larger saccades were interpreted as signs of more active visual scanning, while blink measures were treated as supplementary indicators of attentional or physiological state [15,17]. P02 showed the clearest change under high-pressure driving, with increased blink rate, shorter fixations, and longer saccades, suggesting higher attentional demand. P01 and P03 showed more stable patterns, with smaller changes between conditions.

Table 4. Summary of eye-tracking indicators by participant and condition.

Participant	Condition [1]	Fixations/min	Mean Fixation Duration (ms)	Blinks/min	Mean Blink Duration (ms)	Saccades/min	Mean Saccade Duration (ms)	Mean Saccade Amplitude (°)
P01	LP-Out.	119.65	448.42	9.38	217.69	119.58	51.59	9.41
	HP-Ret.	120.56	441.50	10.07	219.14	120.56	55.43	11.45
P02	LP-Out.	112.21	455.33	20.84	206.00	112.21	78.00	9.90
	HP-Ret.	114.98	432.57	27.38	212.19	114.98	89.26	10.75
P03	LP-Out.	193.57	175.88	10.29	209.25	193.57	134.05	5.91
	HP-Ret.	191.94	184.03	8.79	221.76	191.87	128.70	6.53

[1] LP-Out. = low-pressure outbound drive; HP-Ret. = high-pressure return drive.

5. Conclusions

This study was conducted as a pilot measurement to test the applicability of a multidimensional assessment approach in a simulator-based public transport environment. Therefore, the results should be interpreted as preliminary observations rather than generalisable conclusions about professional bus driver behaviour. The study examined how schedule pressure and task-related stressors may affect driving behaviour, visual attention, and selected behavioural indicators. The results suggest that the high-pressure condition did not cause a clear or consistent deterioration in driving style or simulator-based performance. Composite driving scores changed only slightly between the low-pressure and high-pressure drives, while speed- and deceleration-related indicators showed limited differences. Some participants displayed minor changes in speeding events or visual scanning behaviour, but these patterns were not uniform across the sample. Eye-tracking indicators suggest that the effects of schedule pressure were mainly participant-specific. In some cases, the high-pressure condition was associated with more active visual scanning or altered attentional behaviour, but this was not consistent for all drivers. This indicates that individual factors, such as previous experience, baseline behaviour, attentional strategy, and stress tolerance, may influence drivers' responses to operational pressure.

Overall, the findings support the use of a multidimensional approach combining simulator telemetry, questionnaire data, behavioural tasks, and eye-tracking indicators. However, due to the small sample size and the study's pilot nature, the results must be interpreted with caution. Further research should involve more participants, longer and repeated driving tasks, more varied operational scenarios, and, where possible, real-world or naturalistic driving data.

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