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Effects of Prolonged Monotonous Driving on Lane Change Performance, Visual Attention, and Highway Control

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Abstract

Prolonged monotonous driving is associated with hypovigilance and reduced alertness, yet its influence on subsequent visual attention and driving behavior remains insufficiently understood. This study investigated how prolonged monotonous driving influences highway control, subsequent lane change performance, visual attention to lane change signs, and the relationship between subjective state and objective driving control. Sixteen licensed drivers completed a simulated drive consisting of a pre-highway lane change task, a prolonged monotonous highway segment, and a post-highway lane change task. Driving performance and eye-tracking metrics were assessed. The findings suggest that prolonged low-demand driving weakens lateral control, while visual attention to lane-change signs became faster and more extensive in the post-highway session. This pattern is consistent with compensatory visual reallocation following underload when task demands become visually explicit and behaviorally structured. These results highlight the importance of multimodal assessment for road safety, as subtle changes in control stability and visual attention may not be captured by vehicle dynamics alone, despite their relevance for driver readiness in attention-critical situations.

Keywords: visual attention; lane change task; eye-tracking; monotonous driving; highway driving performance; driver vigilance

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1. Introduction

1.1. Monotonous Driving and Hypovigilance

Road traffic crashes are a major global safety concern [1], with fatigue and inattention substantially contributing to crash risk [2]. A significant proportion of crashes has been associated with fatigue, particularly during long highway driving, where visual and cognitive stimulation is limited [3], highlighting the need to better understand how monotonous driving conditions affect driving behavior. Driving tasks that involve prolonged exposure to constant and predictable stimuli influence cognitive load and driver attention, such as monotonous driving conditions where the task primarily involves lane keeping. In these cases, drivers may stay physically engaged in controlling the vehicle while their alertness and attention gradually decline. This gradual reduction in vigilance is commonly referred to as hypovigilance, typically develops slowly, allowing drivers to keep stable vehicle paths while their ability to notice, process, and respond to rare or sudden events weakens [4]. This separation between seemingly stable driving and actual attention levels makes it hard to evaluate driver safety during long and low-demand driving periods.

Monotonous driving has been linked to problems in information processing and reduced reaction to unexpected events, even when the driver does not feel overtly drowsy [5]. From a physiological and cognitive perspective, monotonous driving is associated with reduced central nervous system activation and the development of hypovigilance, manifesting as lower alertness, reduced attentional engagement, and decreased processing of task-relevant information [6]. The work reported in [7] has shown that vigilance can decline rapidly during uneventful driving, even when the driver does not feel particularly sleepy. Prolonged monotony might lead to brief lapses in attention or microsleeps, in which drivers momentarily lose focus on the driving task without realizing it, while maintaining vehicle control. However, their ability to notice and respond to unexpected events worsens [8]. Therefore, extended monotonous driving becomes a concern for traffic safety when drivers become hypovigilant and underestimate their level of inattentiveness.

1.2. Road Geometry and Vigilance Decline

A road environment with limited geometric variation and low levels of stimulation leads to underload fatigue of the central nervous system. It usually happens during extended highway driving on straight roads with low traffic density, low curvature, flat geometry, and repetitive scenery. In this situation, driving primarily involves lane keeping, and the low event rate combined with reduced cognitive demand increases the risk of hypovigilance. This phenomenon is also referred to as 'highway hypnosis', which means driving without complete awareness of the surroundings [9–12]. Driving performance impairment due to road geometry and vigilance decline has been studied across different conditions. A study reported in [13] showed that vigilance can decline under monotonous conditions due to both road design and monotony of the road scenery. The vigilance degradation in EEG is also correlated with observable measurements from the vehicle and environment, such as affected lane positioning, heart rate variability, blink frequency, and electrodermal response rates [13]. This evidence suggests that underload fatigue manifests as reduced vigilance and alertness rather than physical tiredness.

A review by Khotimah and Sjafruddin (2024) emphasizes that road geometric design, such as straight and monotonous roads, is the main cause of highway hypnosis, which impairs a driver's situational awareness, responsiveness to hazards, and memory for the drive, while maintaining vehicle control [11]. This is consistent with simulator studies on road geometry showing that the geometric variety of roads, for example, curvature and alignment, affects workload, lane keeping, and speed control. A 45-min simulator study in [9] compared three rural highways with low, moderate, and high geometric variety. The results showed that lane positioning improved by 11–12% on more varied alignments. Another study showed that a significant effect of time on task was observed, while the deterioration rate was lower with higher geometric variety [14]. The work reported in [15] defines landscape intervention as an alertness-maintaining tool to counter monotony, thereby reducing deficiencies in visual reference. The results indicated significant alertness maintenance in the semi-open chevron landscape compared with other spatial patterns used in this simulator study [15]. These studies are relevant to the present work because they support the use of a straight highway as a monotonous driving segment. However, they do not examine how prior exposure to monotonous driving affects performance when transitioning to a subsequent structured driving task.

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1.3. Re-Engagement of Attention After Low-Demand Driving

After prolonged monotonous driving, the ability to re-engage attention becomes critical when drivers are required to respond to increased task demands, such as lane changes or sudden hazards. Existing research indicates that low cognitive load is inherently associated with monotonous driving and the use of partially automated vehicles on highways. Low cognitive load can lead to vigilance decrements that impair the ability to respond to on-road threats [16]. Research on cognitive load and driving performance further shows that when task demands increase, drivers may maintain performance by reallocating mental resources and modifying gaze behavior [17]. This is particularly relevant to our study, where the post-highway lane change task provides a structured and attention-sensitive context for examining the re-engagement of attention after prolonged monotonous driving.

Findings in [18] indicate that increased mental demand can impair attentional responsiveness in drivers without necessarily deteriorating basic vehicle control. The experiments were conducted using the ISO-standardized Detection Response Task (DRT) to assess attentional load, resulting in increased cognitive load and prolonged response times, whereas the standard deviation of lane position remained unchanged or decreased. Findings from a study on in-vehicle warning systems demonstrate that visually-rich warnings lead to increased braking reaction times, especially among drivers with low working memory capacity under high cognitive load [19]. Another work reported in [20], focusing on hypovigilance and speed variability during monotonous daytime driving, found that speed variability was negatively correlated with sleepiness and hypovigilance. It is also highlighted by these findings that greater variability of speed within the speed limit also keeps drivers more alert and less fatigued [20].

Existing research indicates that dynamic re-engagement is possible during monotonous driving or under increased cognitive load. The work reported in [21] introduces an inverted-U relationship between load and performance, meaning that the transition from very low to moderate load improves performance by restoring optimal arousal. The empirical findings in [22] support the idea that moderate cognitive demand can help drivers stay alert during monotonous and semi-automated driving. Recent work on visual attention tasks and eye tracking investigated the effects of pre-takeover resource engagement on attention restoration. The results showed that attention reactivates as task demands increase, with cognitively engaging tasks producing greater pupil dilation and longer response times, followed by improved post-takeover attentional performance. This indicates that attentional resources can be dynamically re-engaged rather than continuously reduced [23]. Neurophysiological evidence indicates both correlation and dissociation between passive fatigue arising from monotonous underload conditions and active fatigue arising from sustained high cognitive demand. This evidence highlights the distinct physiological mechanisms underlying these states, despite producing some overlapping behavioral outcomes [5]. While vigilance degradation can emerge under both monotonous low-demand conditions and sustained high cognitive workload, these two fatigue states are characterized by distinct physiological signatures, reflecting different mechanisms of fatigue development and effort regulation [5]. Despite this growing understanding of attentional re-engagement, few studies have directly examined how the transition from prolonged monotonous driving to a subsequent structured task affects both behavioral performance and visual attention simultaneously.

1.4. Attention-Sensitive Assessment

Collectively, the studies discussed above show that behavioral, visual, and physiological measurements provide strong means for exploring how drivers change their behavior as task demands shift. These measures reveal both the loss of vigilance during extended periods of low cognitive demand and the adjustment of resources when cognitive demands rise [5,24,25]. However, much of the current research focuses on either monotonous driving or high-demand tasks in isolation, or interprets stable performance during monotony as proof of a maintained driver state. Consequently, less is known about how hidden hypovigilance due to prolonged monotony affects drivers' visual attention and performance when task demands subsequently increase.

Conventional speed metrics alone, such as speed and lane position variability, may be insufficient on their own to characterize driving safety fully. Recent work reported in [26] has further demonstrated that multi-dimensional trajectory features provide a more comprehensive characterization of driving behavior than single-dimensional metrics alone. Therefore, an additional measure is needed that is sensitive not only to vehicle control but also that probes attention-related performance more directly. The Lane Change Task (LCT) is an ISO-standardized driving simulation paradigm used to quantitatively measure human performance degradation on a primary driving-like task while a secondary task is being performed [27]. A study reported in [13] used the LCT to examine performance degradation due to increased cognitive load. In addition, eye-tracking measures such as TTFF indicate shifts in visual readiness and cognitive processing speed [17]. However, the combined application of LCT performance metrics and sign-directed eye-tracking indicators within a pre–post monotonous driving design remains underexplored.

1.5. Research Gap and Study Objectives

Building on the reviewed literature, an important gap remains despite growing evidence on monotonous driving, vigilance decline, and attentional re-engagement. Previous studies primarily focused on prolonged highway driving or high-demand tasks in isolation. However, less attention has been given to how driving performance and attention allocation change when drivers transition from prolonged monotony to a subsequent structured task.

This study addresses this gap by applying a pre–post LCT design to probe performance changes following monotonous driving. Specifically, this study assesses the influence of monotonous driving on lane-keeping performance by comparing lane task execution before and after the highway segment. To evaluate attentional engagement and readiness, time to first fixation, dwell time, and fixation count were used to capture visual scanning behavior before and after a monotonous drive.

By integrating behavioral performance measures with visual attention indicators, the study provides a deeper understanding of driver state and readiness that could not be obtained from vehicle dynamics alone. Our study extends the literature by applying the LCT framework to post-monotony performance assessment.

The present study tested three predefined hypotheses derived from the literature review. (H1) SDLP would increase progressively across the highway segment, reflecting degraded lateral control as a consequence of prolonged low-demand driving and vigilance decline. (H2) The post-highway LCT performance would deteriorate broadly in response accuracy relative to the pre-highway baseline. (H3) Given the deterioration anticipated in H2, prolonged low-demand driving would slow visual orienting to the lane change signs, reflected in longer TTFF and accompanied by changes in dwell time and fixation count.

The remainder of this paper is organized as follows. Section 2 covers the experimental design, participants, and apparatus. Section 3 defines the performance measures across the four assessment domains. Section 4 outlines the data analysis procedures. Section 5 presents the results, followed by the discussion in Section 6. Practical recommendations, limitations, and conclusions are presented in Sections 7, 8, and 9, respectively.

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2. Materials and Methods

2.1. Participants and Recruitment

For this study, sixteen licensed drivers were recruited on a voluntary basis using convenience sampling from students, staff, and personal contacts in Belgium, consisting of 5 females and 11 males. Participation was limited to healthy adults aged 18 to 60 years (M = 34, SD = 8). Participants were required to have normal or corrected-to-normal vision. They were instructed to refrain from consuming alcohol, caffeine, or tea for at least two hours prior to participation, and to obtain adequate sleep the night before the experiment. Exclusion criteria included the presence of diagnosed neurological or physiological conditions, sleep disorders, or current use of medications or substances known to affect focus or sleep. Participants were instructed to inform the researcher immediately if they experienced any discomfort, nausea, or disorientation during the drive, and were reminded that withdrawal was possible at any point without consequences. No participant reported experiencing simulator sickness or requested to stop the session.

2.2. Apparatus and Driving Scenario

For this study, we used a cockpit driving simulator, which consisted of a cabin equipped with a steering wheel, pedals, gearbox, speedometer, tachometer, indicators, and horn, replicating a real car. The virtual driving scenario was projected onto three screens (total resolution of 5760 × 1080 pixels with a constant refresh rate of 60 Hz) positioned in front of the cockpit. The multiscreen setup improved ecological validity while allowing participants to perceive both forward roadway and side information. The system operated using STISIM Drive version 3 software from Systems Technology Inc. (Hawthorne, CA, USA), which allows programmable driving scenarios and event control.

A structured driving scenario was designed by adapting the original LCT from [13,27] and combining it with a prolonged monotonous highway segment. The full scenario included a 3 km pre-highway LCT-1, an approximately 107.3 km prolonged monotonous highway segment, and a 3 km post-highway LCT-2. Prior to the main experimental session, participants completed a familiarization drive consisting of an 18-event lane change task followed by a brief monotonous highway segment.

The experiment was conducted under controlled conditions, with dry and sunny weather, constant room temperature (20 °C), and no environmental noise. The scenario was deliberately designed to minimize known triggers of simulator sickness. Because sickness in driving simulators is driven primarily by high speed, sharp curves, and provocative motion rather than by distance traveled [28], the use of a straight road at moderate constant speed, with no sharp curves, elevation changes, or surrounding traffic, together with a temperature-controlled room and a short familiarization drive, represents a low-provocation configuration associated with minimal sickness in prior work [29,30]. The highway segment consisted of a straight, two-lane road with minimal geometric variation. It had uniform green verges and rows of identical trees that repeated throughout the segment. The scenery provided consistently low visual stimulation, no intersections, no roadside structures, no oncoming traffic, and no meaningful variation in the visual environment. This road design matches known patterns of monotonous driving that can cause hypovigilance [9,10]. The driver's views of the monotonous highway segment and the LCT track are shown in Figures 1a and 1b, respectively. The three-lane LCT track, with lane-change signs appearing on both sides of the road, is illustrated in Figure 2. The posted speed limit was 60 km/h during the lane change tasks, and 120 km/h during the highway segment (vehicle mechanical limit: 130 km/h).

To monitor visual scanning behavior during the task, eye-tracking data were concurrently collected with the driving simulator. A wearable eye-tracking system, Tobii Pro

Glasses 2 (Tobii, Stockholm, Sweden), continuously recorded eye movements during the driving tasks, including pupil size, fixations, blinks, and saccades. The driving simulator and the wearable eye tracker are shown in Figure 3a,b.

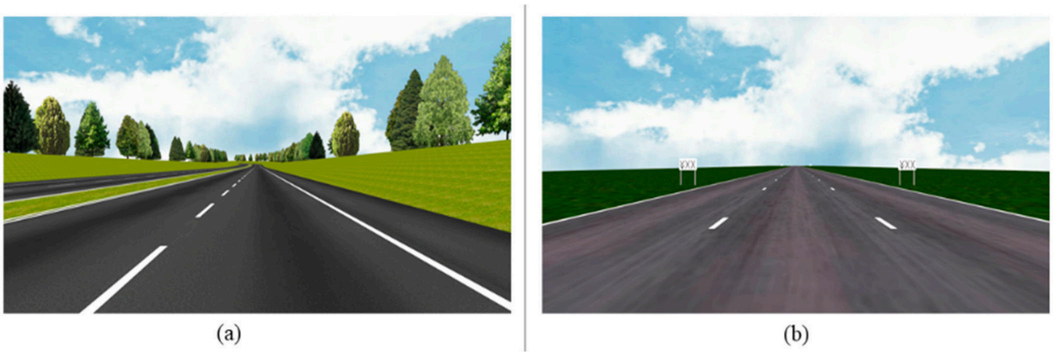

Figure 1. Driver's view of the two simulated driving scenarios. (**a**) The monotonous highway segment: a straight, two-lane road with uniform green verges and rows of identical, regularly spaced trees repeating throughout, with no intersections or other roadside variation, providing consistently low visual stimulation. (**b**) The lane change task (LCT) track: a straight roadway on which lane change signs appear on both sides of the road, instructing the driver to move to the indicated lane.

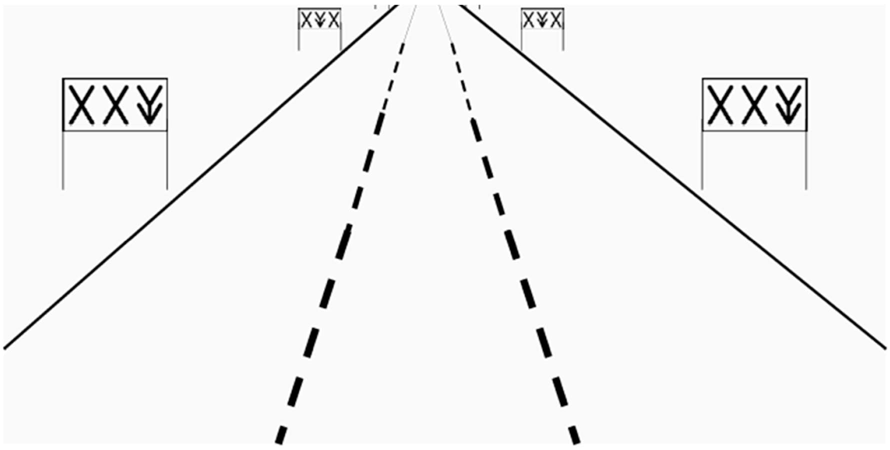

Figure 2. The LCT track, a three-lane, straight, simulated roadway, with lane change signs appearing on the left and right sides of the road at regular intervals, was administered twice before (LCT-1) and after (LCT-2) [27].

Figure 3. Experimental equipment (**a**) Simulator (**b**) Eye tracker [31].

3. Performance Measures

This study integrates lane change tasks, a monotonous highway driving segment, eye-tracking recordings, and subjective assessments into a single protocol. The complete dataset is organized into four measurement domains, which are described in this section.

3.1. Lane Change Task Measures

The normative model represents the idealized lateral trajectory a driver is expected to follow when responding correctly to a lane change sign. A graphical illustration of the normative trajectory is shown in Figure 4. It defines the timing of sign appearance, the preview distance before maneuver initiation, and the length and shape of the lateral transition. This predefined trajectory served as the reference for calculating deviations of the actual driven path.

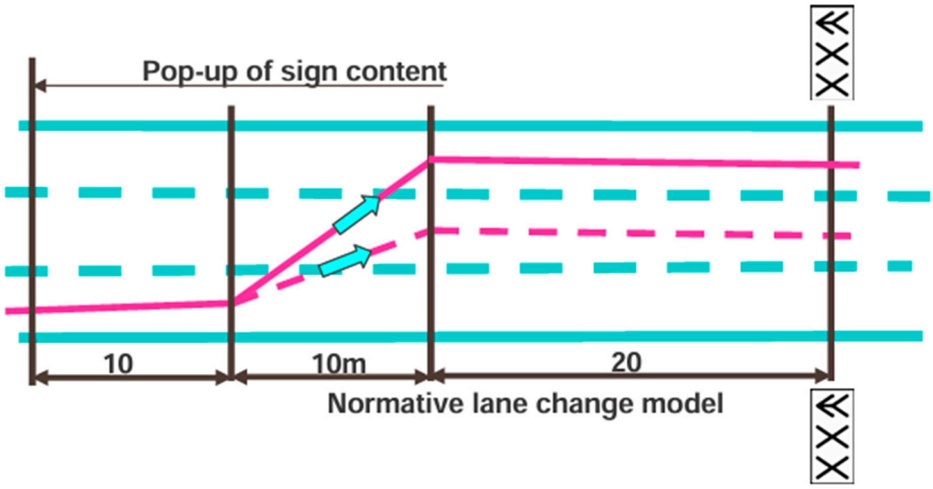

Figure 4. Graphical representation of the distances for sign content pop-up, normative lane change model, and sign position (adapted from ISO 26022:2010) [27].

Both LCT-1 and LCT-2 sessions were implemented in accordance with ISO 26022:2010 [27], which defines the standardized lane change trajectory and associated performance metrics. The normative model was implemented using the 1030 configuration, assuming a 10 m reaction distance (i.e., the distance between sign onset and maneuver initiation) and a 30 m lane change maneuver length. This configuration was applied consistently across both LCT sessions. Although ISO 26022 primarily describes the 1010 configuration, it also provides a trajectory-based procedure for identifying lane change initiation from longitudinal position data. Specifically, ISO 26022 (p. 30) identifies the longitudinal position y30 as the point at which the derivative of the lateral trajectory first reaches 30% of its maximum value, as a first approximation of the lane change initiation point. The 1030 configuration adopted in the present study applies this criterion directly. The absence of steering wheel angle data in the present simulator setup necessitated this approach. Because both LCT-1 and LCT-2 used the same 1030 configuration, within-study comparisons remain valid. Trajectory-based identification of lane change initiation is an accepted procedure within ISO 26022 and has been applied in prior LCT research where steering-angle data were unavailable [13].

The performance measures defined below are derived from previous studies [32,33], which applied the ISO 26022 framework to simulator-based lane change studies.

3.2. Mean Deviation (MDEV)

MDEV is calculated as the mean of the absolute lateral deviations between the vehicle's actual position and the normative lane change trajectory across track segments. A symbolic example of the normative model and driving data taken from (ISO 26022:2010, p. 11) is shown in Figure 4.

$$\underline{x}_{deviation} = \frac{1}{S}\Sigma\left(x_{deviation}, i\left(\frac{y_{i+1} - y_{i-1}}{2}\right)\right) \quad (1)$$

As defined in [27], in Equation (1) S represents the length of the analyzed segment and $X_{deviation,i}$ denotes the absolute lateral distance between the actual vehicle position and the corresponding point on the ISO normative trajectory. Prior studies have treated increased lateral deviation and lateral position variability as markers of degraded steering quality, poor lane keeping, and less precise execution of maneuvers [34,35].

3.3. Percentage of Correct Lane Changes (PCL)

PCL is used for the assessment of participants' accuracy in responding to lane change signs, which involves lane change sign detection, decision making, preparation, and execution [32]. We calculated the percentage of correctly executed lane changes within 40 m of the sign onset, relative to the total number of required lane changes. Equation (2) was used to calculate PCL, where $N_{correct}$ represents the number of correctly executed lane changes and N_{total} represents the total number of required lane changes. PCL values were computed to examine potential changes in sign response accuracy following prolonged highway driving for both LCT-1 and LCT-2. Missed and incorrect lane changes were not counted as correct responses.

$$PCL(\%) = \frac{N_{correct}}{N_{total}} \times 100 \quad (2)$$

3.4. Lane Change Initiation (LCI)

LCI estimates the response latency to lane change signs, defined as the time interval between sign onset and the initiation of a systematic trajectory change toward the correct lane. According to ISO 26022 [27], LCI computation typically involves detection of (i) trajectory change, (ii) steering wheel action, and (iii) calculation of the mean delay. However, steering wheel angle data were not available in the present dataset. Therefore, LCI was derived solely from vehicle trajectory data, following the procedure described in (ISO 26022:2010, p. 11) [27]. For each correctly executed lane change, initiation latency was calculated as the difference between the time of trajectory change and the time of sign onset, and the participant's overall LCI was obtained as the mean of these latencies across 18 events. The mathematical computation is given in Equation (3).

$$LCI = \frac{1}{n}\sum_{i=1}^{n}\left(t_{initiation,i} - t_{sign,i}\right) \quad (3)$$

The absence of steering wheel angle data introduces some imprecision in LCI estimation. Steering-based detection captures lane change initiation at the moment the driver acts. In contrast, trajectory-based detection using the y30 criterion identifies initiation slightly after the vehicle has begun to move physically. This delay may be larger for participants with gradual or hesitant steering inputs than for those with decisive, sharp maneuvers, potentially introducing individual variability in LCI estimates beyond true differences in response latency. However, because both LCT-1 and LCT-2 used the same trajectory-based procedure, this source of imprecision affects both sessions equally and does not systematically bias the pre–post comparison.

3.5. Highway Driving Measures

The monotonous highway driving segment was located between LCT-1 and LCT-2. To investigate highway driving performance, we extracted data from a stable 100 km highway segment after excluding the transition zone. The resulting 100 km stable segment was selected because it provided a clean equal-interval structure suitable for time-on-task analysis, consistent with prior simulator studies on monotonous driving [9,10]. For time-on-task analysis, the segment was divided into 100 consecutive, non-overlapping zones, each 1 km in length. These zones were further grouped into three broader phases for descriptive and inferential analysis: Early (Zones 1–33), Mid (Zones 34–66), and Late (Zones 67–100). All measures were computed separately for each participant. The following three driving measures were examined across the highway segment.

3.5.1. Longitudinal Control

Mean speed was used to characterize longitudinal control [36] and was computed from speed values spatially interpolated [37] at a resolution of 0.5 m within the stable highway segment.

3.5.2. Overspeeding

Overspeeding was defined as the proportion of distance driven above the posted speed limit [36] of 120 km/h, which remained constant throughout the highway segment. This proportion of overspeeding was calculated relative to the total distance within the segment.

3.5.3. Standard Deviation of Lateral Position (SDLP)

SDLP was used as the main indicator of lateral control and lane-keeping variability [36]. Lateral position values were spatially interpolated [37] at a resolution of 0.5 m and expressed relative to the lane center.

3.6. Eye Tracking Measures

For this study, time to first fixation (TTFF) on the lane change sign was extracted as an eye movement metric related to visual attention. It represents the time interval between the moment a lane change sign becomes clearly visible and the first fixation within the corresponding area of interest (AOI). Each LCT session contained 18 lane change events, and signs appeared on both sides of the road. TTFF was calculated separately for both sides, and the minimum value was used to represent the earliest visual detection of the sign. Additionally, we extracted total fixation duration (dwell time) and the number of fixations (fixation count) within AOIs to further evaluate visual engagement with the lane change signs. TTFF, dwell time, and fixation count are relevant to our investigation because they capture the speed of visual orientation, the extent of visual engagement, and the allocation of visual resources [17,23,25]. These metrics are well established in driving and attention research and provide a direct and sufficient characterization of sign-directed visual attention for the present pre–post comparison.

3.7. Subjective Measures

Subjective data were collected using structured questionnaires administered after the experimental session. A socio-demographic questionnaire was used to obtain information on age, gender, driving license, education level, occupation, driving experience, and habitual sleep patterns. The recruitment questionnaire also verified eligibility criteria related to sleep schedule and sedative medications or other drugs that may affect sleep. In addition, widely used validated subjective rating scales, including NASA Task Load Index (TLX) and Karolinska Sleepiness Scale (KSS), were used to assess subjective outcomes. These subjective measures were used to complement behavioral driving performance metrics [38].

NASA–TLX evaluates perceived workload by means of six dimensions [38]: (i) mental demand, (ii) physical demand, (iii) temporal demand, (iv) performance, (v) effort, and

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(vi) frustration. After the driving task, participants rated each dimension on a 10-point scale.

Whereas KSS indicates subjective sleepiness on a nine-point self-report scale [38] comprising (i) extremely alert, (ii) very alert, (iii) alert, (iv) rather alert, (v) neither alert nor sleepy, (vi) some signs of sleepiness, (vii) sleepy but no difficulty staying awake, (viii) sleepy and making effort to stay awake, and (ix) extremely sleepy, fighting sleep.

4. Data Analysis

The simulator log files were preprocessed in MATLAB (R2024b), and the resulting datasets were imported into IBM SPSS Statistics (version 30.0) for statistical analysis. The LCT variables were extracted in accordance with the ISO 26022. Event-level values corresponding to non-executed or invalid lane changes were excluded prior to session-level aggregation. Only the mean of valid event-level observations was used to calculate performance metrics. Normality of continuous variables was assessed using the Shapiro–Wilk test. Differences between LCT-1 and LCT-2 performance measures were examined using paired-samples *t*-tests, and effect sizes were reported as Cohen's d. Statistical significance was evaluated at $\alpha = 0.05$ (two-tailed) for all analyses. Results with *p*-values between 0.05 and 0.10 were interpreted as weak or suggestive evidence rather than as statistically significant effects, in line with recommendations to avoid strict dichotomization around a single threshold [39–41].

The monotonous highway segment located between LCT-1 and LCT-2 was extracted for analysis. The stable 100 km section was divided into 100 consecutive, non-overlapping 1 km zones. To examine time-on-task effects, zone-wise metrics were aggregated into three phases. Highway driving performance was evaluated using mean speed, SDLP, and overspeeding proportion. Mean speed characterized longitudinal control, SDLP indexed lane-keeping variability, and overspeeding was defined as the proportion of distance driven above the posted speed limit of 120 km/h. Phase-wise means were compared using repeated measures ANOVA. Polynomial contrasts were examined to characterize linear and quadratic trends, and pairwise comparisons were performed using the LSD adjustment. Sphericity was assessed using Mauchly's test, and the Greenhouse–Geisser correction was applied where necessary. Effect sizes were reported as partial eta squared ($\eta^2 p$).

The eye-tracking data were preprocessed using Tobii Pro Lab software; the hardware head unit operated on firmware version 1.25.6. The pair of identical lane change signs presented on the left and right sides of the road was treated as the primary analytic unit because identical lane change signs were presented on both sides of the road, as shown in Figure 2. A sign pair was considered detected if either the left or right sign showed fixation evidence. The eye-tracking measures were aggregated at the participant level. For each participant, TTFF was calculated as the minimum of the left and right values, while dwell time and fixation count were calculated as the sum of the left and right values. Mean values for LCT-1 and LCT-2 were then computed across all valid sign pairs, and paired comparisons were performed using the Wilcoxon signed rank test.

To evaluate the adequacy of the sample size, post-hoc power analyses were conducted using G*Power (3.1.9.7) [42]. For the repeated measures ANOVA examining SDLP across driving phases ($\eta^2 p = 0.19$, f = 0.485, $\alpha = 0.05$, $n = 16$, three measurements), the achieved power was 0.987, indicating excellent statistical power for the primary highway analysis. For the LCI paired comparison (d = 0.62, $\alpha = 0.05$, $n = 16$), the achieved power was 0.640, which falls below the conventional 0.80 threshold; this result should therefore be interpreted with caution and warrants replication in larger samples. For the eye-tracking subsample ($n = 13$), a sensitivity analysis indicated that effects of $d \geq 0.85$ could be detected at 80% power. The observed effect sizes for dwell time (r = 0.86) and fixation count (r = 0.88) exceeded this threshold, while TTFF showed a large effect size (r = 0.71), which fell only marginally below the threshold.

5. Results

This section presents results across four distinct assessment domains: LCT performance, highway driving performance, eye-tracking metrics, and subjective measures. Statistical analyses were conducted separately within each domain, as the measures within each domain reflect distinct aspects of driving and attention. Within-domain correlations among performance measures are reported in Section 5.5.

5.1. Pre- and Post-Highway Comparison of LCT Performance

The changes in performance between LCT-1 and LCT-2 sessions were assessed using paired samples *t*-tests. Descriptive statistics and test results are presented in Table 1.

Table 1. Comparison of LCT Performance. The asterisk (*) indicates a statistically significant difference ($p < 0.05$).

Measure	LCT-1	LCT-2	t(15)	*p*	Cohen's d
MDEV (m)	0.582 (0.224)	0.497 (0.193)	1.98	0.066	0.53
LCI (s)	0.907 (0.128)	0.881 (0.119)	2.48	0.026 *	0.62
PCL (%)	98.61 (3.21)	99.31 (2.78)	−1.46	0.164	0.38
Error Rate (%)	1.39 (3.21)	0.69 (2.78)	1.46	0.164	0.38

The results indicate that mean deviation from the normative trajectory decreased from LCT-1 (M = 0.582 m, SD = 0.224) to LCT-2 (M = 0.497 m, SD = 0.193). This reduction did not reach statistical significance ($p = 0.066$), and a moderate effect size was observed (d = 0.53). However, this indicates a tendency toward improved trajectory control in the post-highway session.

In addition, LCI was significantly lower in LCT-2 than in LCT-1, decreasing from 0.907 s (SD = 0.128) to 0.881 s (SD = 0.119), t(15) = 2.48, $p = 0.026$, d = 0.62. This result indicates faster initiation of lane change maneuvers after the monotonous drive. This corresponds to an absolute difference of approximately 26 ms, which is modest in magnitude, equivalent to less than half a meter of travel at 60 km/h. The effect was nonetheless statistically reliable and consistent in direction, indicating a genuine post-highway change in initiation timing.

Despite these timing-related differences, response accuracy remained highly stable. PCL was 98.61% (SD = 3.21) in LCT-1 and 99.31% (SD = 2.78) in LCT-2, with no significant difference between sessions, t(15) = −1.46, $p = 0.164$. Error rate also remained low and did not differ significantly between LCT-1 (M = 1.39%, SD = 3.21) and LCT-2 (M = 0.69%, SD = 2.78), t(15) = 1.46, $p = 0.164$. However, given the near-ceiling accuracy in both sessions, the null result should be interpreted cautiously, as it may reflect the limited sensitivity of the measure.

Taken together, the LCT findings do not indicate post-highway deterioration. Rather, they suggest preserved accuracy and slightly faster maneuver initiation following the monotonous driving segment.

5.2. Eye-Tracking Performance During LCT

This section outlines the eye-tracking measures analyzed to examine the allocation of visual attention to lane change signs during LCT-1 and LCT-2. For paired eye-tracking comparisons, analyses were conducted on 13 participants due to incomplete eye-tracking data for some cases. Across both LCT-1 and LCT-2, the detection performance remained consistently high, at 99.6%, with only one true miss for one participant in LCT-1.

At the participant level, mean TTFF to the sign pairs decreased from 1.28 ± 0.32 s in LCT-1 to 0.99 ± 0.31 s in LCT-2, indicating faster visual orientation to the lane change signs in LCT-2 (Wilcoxon $p = 0.008$). The directional change across participants is illustrated in Figure 5. Mean dwell time per sign pair increased from 3.21 ± 0.70 s to 3.83 ± 0.60 s (Wilcoxon $p < 0.001$), and mean fixation count increased from 4.48 ± 1.03 to 5.94 ± 0.97 (Wilcoxon $p < 0.001$). Notably, this pattern was consistent, with TTFF decreasing in 11 of 13 participants, dwell time increasing in 12 of 13 participants, and fixation count increasing in all 13 participants. Together, these findings indicate that sign detection performance remained high in both LCT-1 and LCT-2. However, LCT-2 showed a distinct visual scanning pattern, with faster fixation, greater dwell time, and a higher fixation count.

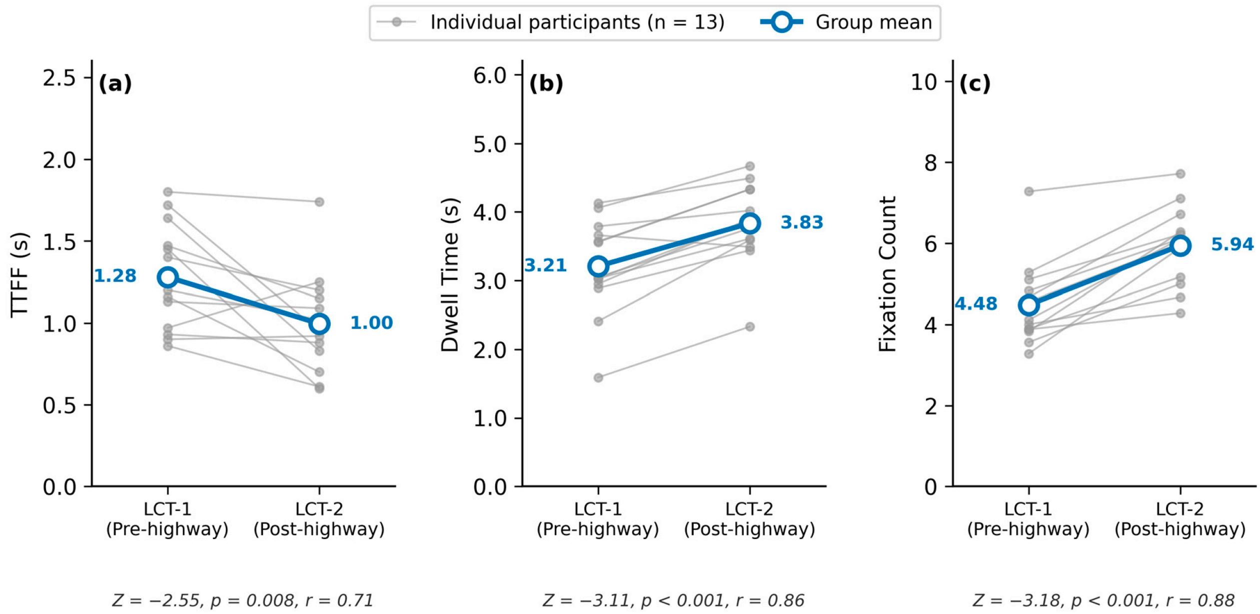

Figure 5. Participant-level changes in eye tracking metrics between LCT-1 (pre-highway) and LCT-2 (post-highway) for (**a**) TTFF, (**b**) dwell time, and (**c**) fixation count.

5.3. Association Between Subjective Measures and LCT Performance

Correlation analyses indicated that sleep duration and subjective sleepiness were not significantly associated with LCT performance. Similarly, no significant differences in LCT outcomes were found between participants with regular and irregular sleep schedules. Although most NASA-TLX dimensions were not related to LCT performance, two significant associations emerged in the post-highway session. Specifically, mental demand was positively correlated with MDEV during LCT-2 ($r = 0.52$, $p = 0.037$), and temporal demand also showed a positive correlation with MDEV ($r = 0.59$, $p = 0.017$). These associations were not evident in LCT-1, suggesting that perceived task demand was more strongly linked to objective lane change performance after the monotonous drive.

5.4. Performance Across the Highway Segment

The 100 km highway segment was divided into three phases: early, mid, and late. Descriptive statistics and repeated measures ANOVA results for the highway driving metrics are presented in Table 2.

The proportion of distance driven above the posted speed limit increased from 33.18% (SD = 30.46) in the early phase to 37.43% (SD = 31.28) in the Mid phase and remained similar in the late phase at 37.12% (SD = 30.85). The overall effect of phase did not reach statistical significance, F(2,14) = 3.16, $p = 0.074$, partial $\eta^2 = 0.31$. However, exploratory pairwise comparisons indicated significantly higher overspeeding in the mid phase than in the early phase ($p = 0.020$). No other pairwise differences were significant.

Table 2. Highway driving performance across phases. The asterisk (*) indicates a statistically significant difference ($p < 0.05$).

Measure	Early	Mid	Late	F	*p*	η^2p
Mean Speed (m/s)	32.89 (1.00)	33.10 (1.05)	33.07 (1.02)	F(2,14) = 6.32	0.011	0.47
SDLP (m)	0.271 (0.071)	0.299 (0.097)	0.301 (0.069)	F(2,30) = 3.46	0.045 *	0.19
Overspeeding (%)	33.18 (30.46)	37.43 (31.28)	37.12 (30.85)	F(2,14) = 3.16	0.074	0.31

Mean speed increased from the early phase to the mid phase and remained nearly unchanged in the late phase. A repeated measures ANOVA revealed a main effect of phase, F(2,14) = 6.32, $p = 0.011$, partial $\eta^2 = 0.47$. Mauchly's test indicated a violation of sphericity ($p = 0.018$), and the Greenhouse–Geisser correction attenuated the effect ($p = 0.059$), although the multivariate test remained significant. Accordingly, the mean speed effect is not marked as significant in Table 2 and is treated as a trend. Polynomial contrasts showed a significant quadratic trend ($p = 0.016$), indicating non-linear modulation of speed across the drive. Pairwise comparisons revealed significantly higher speed in the mid phase than in the early phase ($p = 0.003$), whereas the mid–late and early–late comparisons were not significant.

SDLP increased progressively across phases, from 0.271 m (SD = 0.071) in the early phase to 0.299 m (SD = 0.097) in the mid phase and 0.301 m (SD = 0.069) in the late phase. The repeated measures analysis showed a significant effect of phase, F(2,30) = 3.46, $p = 0.045$, partial $\eta^2 = 0.19$ (see Figure 6). A significant linear contrast was observed ($p = 0.015$), indicating a systematic increase in lateral variability across the drive. Pairwise comparisons showed that SDLP was significantly higher in the late phase than in the early phase ($p = 0.015$), whereas the mid phase did not differ significantly from either the early or late phase.

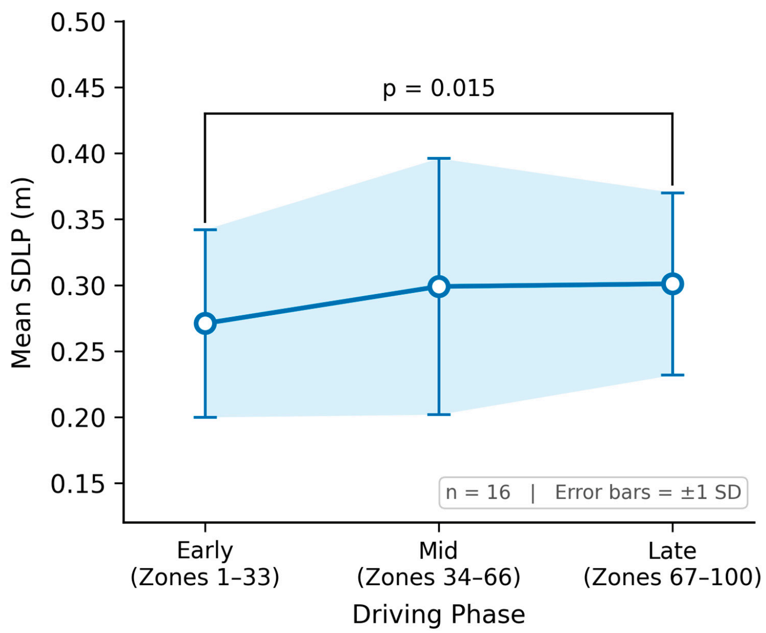

Figure 6. Mean Standard Deviation of Lateral Position (SDLP) across the three driving phases of the monotonous highway segment.

5.5. Relationships Among Performance Measures

Correlation analyses among LCT performance metrics revealed expected internal relationships. MDEV was positively correlated with error rate (r = 0.608, $p = 0.012$) and LCI (r = 0.588, $p = 0.017$) and negatively correlated with PCL (r = −0.608, $p = 0.012$). These associations indicate that greater deviation from the normative trajectory was associated with higher error rates, slower lane change initiation, and lower response accuracy. Strong associations were also observed between error rate and LCI (r = 0.943, $p < 0.001$) and between LCI and PCL (r = −0.943, $p < 0.001$), further supporting the interdependence of timing, deviation, and accuracy in lane change performance.

No significant correlations were found between highway driving metrics (mean speed, SDLP, and overspeeding proportion) and LCT performance metrics (all $p > 0.17$), suggesting that lane change task performance was largely independent of within-drive variations in lateral control and speed.

Overall, the results indicate that prolonged monotonous driving was associated with degraded lateral stability during the highway segment, while post-highway lane change task performance remained preserved. Eye-tracking findings further showed a different visual scanning pattern in LCT-2 with faster fixation but greater visual sampling during sign processing.

6. Discussion

This study investigated the effects of prolonged monotonous highway driving on performance progression during the highway segment, subsequent lane change task, visual attention to lane change signs, and the relationship between objective driving performance and reported subjective state. The findings indicate that during monotonous driving, lateral control worsened over time, as reflected by the increase in SDLP from early to late. Contrary to this, LCT-2 (post-highway LCT) did not show broad impairment. MDEV showed a non-significant reduction, LCI became significantly shorter, and response accuracy remained high. Eye-tracking findings showed faster sign-oriented gaze, longer dwell time, and more fixations in LCT-2. The results suggest that a low-demand monotonous driving segment degraded sustained lateral control, whereas this pattern is consistent with compensatory visual scanning [36] during the subsequent lane-change task. These findings indicate that the changed driver's state was not fully reflected in driving performance but became evident in the way drivers allocated visual attention when transitioning to a higher-demand, visually explicit task. These findings align with existing simulator research showing that time-on-task effects under monotonous conditions are often strongest in lateral-control measures [43–45] rather than in all aspects of later task performance.

A key finding from the monotonous highway driving segment is the progressive increase in SDLP. This observation is consistent with previous research indicating that prolonged low-demand driving primarily affects sustained control and vigilance. Recent research has emphasized SDLP as a sensitive indicator of early vigilance degradation [43]. The present results align with this interpretation, as participants continued to drive, but their lateral stability declined from the mid to late phases. This has important implications for traffic safety, as it highlights that monotonous driving may compromise underlying control stability without immediate awareness [46].

Following the monotonous highway segment, the slight reduction in MDEV in LCT-2 points to a change in driving behavior. The transition from a long, uneventful highway section to a structured lane change task likely increased alertness and task engagement. The onset of LCT-2 also introduced higher task demands compared with the preceding low-demand condition. Previous research [17] suggests that an increase in cognitive load can reduce lateral deviation and is often accompanied by more focused gaze behavior.

Similarly, other work reported in [18] has shown that under higher cognitive load, drivers adopt a more centralized and less dispersed gaze pattern while maintaining overall driving performance. In line with these findings, the present study observed reduced MDEV, shorter LCI, and stronger sign-oriented gaze in LCT-2. Although LCI reached statistical significance, the absolute difference of approximately 26 ms corresponds to less than half a meter of travel at 60 km/h. In addition, the LCI comparison was statistically underpowered (achieved power = 0.640), so this faster post-highway initiation should be confirmed in larger samples and interpreted with caution as part of the broader pattern of post-highway attentional reorientation. In this study, this pattern supports the interpretation that the transition from low-demand driving facilitated attentional re-engagement, rather than reflecting a generalized improvement in driving skill.

Contrary to H3, TTFF did not lengthen but shortened, while dwell time and fixation count increased, which is the opposite of the slowed orienting expected under reduced alertness. Sign detection, meanwhile, remained almost perfect in both LCT-1 and LCT-2. However, the near-ceiling PCL values limit the sensitivity of the accuracy-based assessment, and this null result should be interpreted with caution. As the LCT is an ISO-standardized task, future work could instead increase sensitivity to subtle performance differences through larger samples and the addition of a concurrent secondary task. The post-highway LCT performance did not deteriorate despite the monotony-related change observed during the highway segment itself. More importantly, the eye-tracking pattern indicates that visual engagement with lane change signs was greater in LCT-2. This pattern of shorter TTFF with increased dwell time and fixation count is consistent with compensatory visual reallocation, although alternative accounts such as task novelty effects and strategic adaptation deserve consideration. First, the abrupt return to the structured LCT after a monotonous highway may have independently increased visual orientation to signs, irrespective of the driver's vigilance state [23]. Second, drivers may have deliberately allocated more visual attention to the signs as task demands increased, reflecting strategic adaptation [17]. Third, perceptual uncertainty may have produced more extensive gaze behavior as a form of perceptual checking rather than compensatory effort [47]. Distinguishing between these accounts would require a control condition in which participants completed LCT-2 without prior highway exposure, such as in our previous study [13].

This supports existing work showing that eye-tracking measures provide a more sensitive and direct assessment of visual attention and situation awareness [47]. Recent studies [48,49] have demonstrated that observable driving behavior does not always reliably reflect the underlying attentional state, whereas eye-tracking metrics capture variations in attention, workload, and situational awareness more effectively. In line with this, increased visual engagement in LCT-2 reflects a reallocation of attentional resources following prolonged low-demand driving, which would not have been fully captured using vehicle dynamics alone.

The subjective findings indicate that higher perceived mental and temporal demand was associated with greater post-highway MDEV. This supports the interpretation that the transition from prolonged underload to a more structured maneuvering task may require compensatory effort, as reflected in the eye-tracking data. It is consistent with recent work [50] showing that drivers adjust control behavior under increased workload to maintain performance. Together, these findings indicate that prolonged low-demand driving may weaken continuous control stability, while still allowing attentional resources to be re-engaged when task demands become more structured and visually explicit. This highlights the value of combining vehicle-based, eye tracking, and subjective measures to better understand driver state transitions that may not be evident from driving performance alone.

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7. Practical Recommendations

The findings of this study have practical relevance for driver monitoring system design, highway infrastructure planning, the development of automated driving interfaces, and road safety assessment. Highway driving performance showed that prolonged low-demand driving can gradually weaken lateral control before a clear loss of vehicle control occurs. It supports the need to consider road geometry, visual repetitiveness, and traffic density in road safety design. On long highway sections, scenery variation, geometric variety, and alertness-supporting roadside design may help reduce highway hypnosis and vigilance decline. The SDLP progression observed in this study suggests that lateral instability develops within the first third of the monotonous drive segment. It indicates that alertness-supporting interventions should be placed proactively along monotonous highway roads.

The preserved lane change accuracy after the monotonous highway segment is of interest, but it cannot be interpreted as full recovery of the driver's state. The increased dwell time and greater fixation count indicate greater visual sampling during decision making. This highlights the importance of eye tracking and other physiological measures in driver monitoring systems because vehicle-based measures alone may not fully capture changes in driver state. Combining vehicle control indicators with visual scanning and physiological measures may help identify early signs of compensatory effort before overt driving errors occur. Furthermore, the present study design closely mirrors the attentional challenge in Level 3 automated driving, where drivers must resume manual control after extended automated periods. Therefore, modern driver monitoring systems should incorporate eye-tracking-based measures for the classification of vigilance states, as these metrics reflect visual attention before the deterioration of driving performance. Given the modest sample size, these should be regarded as candidate practical applications that require confirmation in larger studies before implementation.

8. Limitations and Future Research

Although the multimodal and within-subject design enabled detailed assessment of driving performance and visual scanning behavior, several limitations of our study should be considered when interpreting the findings. First, the sample size was relatively small. However, the post hoc power analyses confirmed adequate power for the primary highway and eye-tracking effects. Nonetheless, larger and more diverse samples remain desirable. Second, despite efforts to ensure ecological validity, the experiments were conducted in a controlled simulator environment, whereas longer real-world highway exposure may affect vigilance states differently. Third, the transition from the highway segment to LCT-2 may have produced an alerting effect because LCT-2 was more structured and visually explicit. Fourth, LCI was derived using the y30 trajectory criterion from ISO 26022, which restricts the precision of absolute LCI values and reduces direct comparability with steering-based studies. Fifth, the study did not systematically examine the full range of individual differences known to influence driver fatigue, which remains a direction for future investigation. Beyond these limitations, future studies should consider different post-monotony tasks, including hazard response, overtaking, and other related tasks, to examine similar patterns in more naturalistic situations.

9. Conclusions

In conclusion, we examined the influence of prolonged monotonous highway driving on task progression, subsequent lane change task, visual attention to lane change signs, and the relationship between objective driving control and subjective state. The findings did not show a broad post-highway task impairment, but instead selective effects across performance domains. During the highway segment, SDLP increased over time, indicating reduced stability. The post-highway performance remained largely preserved and accurate. The eye-tracking results showed faster TTFF, longer dwell time, and more fixations during LCT-2, suggesting that preserved performance was accompanied by increased visual sampling. Altogether, these findings suggest that prolonged monotony weakened continuous lateral control, as reflected by the progressive increase in SDLP across the highway segment. In the subsequent lane change task, visual attention to signs became faster and more extensive. This pattern is consistent with compensatory visual scanning, although task novelty effects and strategic reorientation cannot be excluded. This work shows that vehicle-based measures alone may not fully reflect the driver's underlying attentional state. However, the multimodal assessment combining behavioral, visual, and subjective measures offers a more complete understanding of post-monotony driver readiness. Overall, this study highlights that the safety risk of prolonged monotony lies not only in overt performance decline but also in subtle shifts in control stability and compensatory visual allocation.

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Data Availability Statement: The data presented in this study are not publicly available due to privacy and ethical restrictions, as they contain individual driving and eye-tracking records collected under participant consent and GDPR provisions.

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Conflicts of Interest: The authors declare no conflicts of interest. Author Veerle Ross is affiliated with Faresa; however, this organization had no role in the design, conduct, analysis, or interpretation of the study.

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