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Original Article

The Effects of Semi-Autonomous Driving on Heart Rate Variability and Anxiety

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Abstract

Objective: Traditional driving imposes substantial cognitive and physical demands on drivers, often contributing to stress, fatigue, and increased cardiovascular risk. Semi-autonomous driving technologies may alleviate these burdens. We aimed to evaluate the effects of semi-autonomous driving on autonomic nervous system activity and anxiety by comparing heart rate variability (HRV) and validated anxiety measures with manual driving.

Methods: Forty-five healthy adults underwent HRV analysis using Holter monitoring while driving the same route under manual and semi-autonomous conditions. Frequency-domain (Low-frequency [LF]/high-frequency [HF] ratio), time-domain (standard deviation of NN intervals [SDNN], root mean square of successive differences [RMSSD], percentage of successive RR intervals that differ by more than 50 ms [pNN50]), and non-linear indices (sample entropy, detrended fluctuation analysis [DFA] α1) were assessed. Mean heart rate, maximum heart rate, and minimum heart rate were also analyzed. Anxiety was evaluated with the State-Trait Anxiety Inventory (STAI; range 20–80) and a 10-point Visual Analog Scale (VAS).

Results: There were 22 male and 23 female participants. The mean age was 34.7±6.9 years. Semi-autonomous driving was associated with significantly lower LF/HF ratio compared with manual driving (1.7±0.5 vs. 2.9±0.7, $p<0.001$). Time-domain HRV indices improved, with higher SDNN (61.5±10.1 vs. 43.6±8.9 ms), RMSSD (47.8±8.3 vs. 29.1±6.8 ms), and pNN50 (23.5±6.2% vs. 12.9±4.6%; all $p<0.001$). Non-linear measures showed increased sample entropy (1.41±0.27 vs. 1.14±0.22, $p<0.01$) and reduced DFA α1 (1.04±0.13 vs. 1.18±0.15, $p<0.01$). Mean heart rate decreased from 82.4±9.1 to 75.8±8.3 bpm ($p<0.001$). Anxiety outcomes paralleled these findings: VAS scores were lower (3.7±0.8 vs. 6.1±1.0, $p<0.001$) and STAI-State decreased (38.4±6.1 vs. 47.1±6.5, $p<0.001$), while STAI-Trait remained unchanged (43.5±6.8 vs. 45.0±7.3, $p=0.12$).

Conclusion: Semi-autonomous driving reduced sympathetic dominance and anxiety while enhancing parasympathetic activity and HRV complexity. These findings suggest potential psychophysiological benefits of semi-autonomous driving, warranting confirmation in larger and more diverse populations.

Keywords: Anxiety; autonomic nervous system; driving; heart rate variability; surveys and questionnaires.

Yarı Otonom Sürüşün Kalp Atış Hızı Değişkenliği ve Kaygı Üzerindeki Etkileri

Özet

Amaç: Geleneksel sürüş, sürücülere önemli ölçüde bilişsel ve fiziksel yük getirir ve genellikle stres, yorgunluk ve kardiyovasküler risk artışına neden olur. Yarı otonom sürüş teknolojileri bu yükleri hafifletebilir. Yarı otonom sürüşün otonom sinir sistemi aktivitesi ve kaygı üzerindeki etkilerini, kalp atış hızı değişkenliği (HRV) ve doğrulanmış kaygı ölçümlerini manuel sürüşle karşılaştırarak değerlendirmeyi amaçladık.

Yöntem: Kırk beş sağlıklı yetişkin, manuel ve yarı otonom koşullar altında aynı güzergahta araç kullanırken Holter izleme yöntemiyle kalp atış hızı değişkenliği (HRV) analizine tabi tutuldu. Frekans alanı (LF/HF oranı), zaman alanı

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(SDNN, RMSSD, pNN50) ve doğrusal olmayan indeksler (örnek entropi, DFA α1) değerlendirildi. Ortalama kalp atış hızı, maksimum kalp atış hızı ve minimum kalp atış hızı da analiz edildi. Kaygı, Durum-Özellik Kaygı Envanteri (STAI; 20–80 aralığı) ve 10 puanlık görsel analog ölçek (VAS) ile değerlendirildi.

Bulgular: Yirmi iki erkek ve 23 kadın katılımcı vardı. Katılımcıların ortalama yaşı 34,7±6,9 idi. Yarı otonom sürüş, manuel sürüşe kıyasla anlamlı ölçüde daha düşük LF/HF oranı ile ilişkiliydi (1,7±0,5'e karşı 2,9±0,7; p<0,001). Zaman alanı HRV indeksleri, daha yüksek SDNN (61,5±10,1 vs. 43,6±8,9 ms), RMSSD (47,8±8,3 vs. 29,1±6,8 ms) ve pNN50 (23,5±6,2% vs. 12,9±4,6%; tümü p<0,001) ile iyileşti. Doğrusal olmayan ölçümler, örnek entropisinde artış (1,41±0,27 vs. 1,14±0,22; p<0,01) ve DFA α1'de azalma (1,04±0,13 vs. 1,18±0,15; p<0,01) gösterdi. Ortalama kalp atış hızı 82,4±9,1'den 75,8±8,3 bpm'ye düştü (p<0,001). Anksiyete sonuçları bu bulgularla paralellik gösterdi: VAS puanları daha düşüktü (3,7±0,8 vs. 6,1±1,0; p<0,001) ve STAI-State azaldı (38,4±6,1 vs. 47,1±6,5; p<0,001), STAI-Trait ise değişmedi (43,5±6,8 vs. 45,0±7,3; p=0,12).

Sonuç: Yarı otonom sürüş, sempatik baskınlığı ve kaygıyı azaltırken parasempatik aktiviteyi ve HRV karmaşıklığını artırdı. Bu bulgular, yarı otonom sürüşün potansiyel psikofizyolojik faydalarını ortaya koyabilir ve daha geniş ve daha çeşitli popülasyonlarda doğrulanmasını gerektirebilir.

Anahtar sözcükler: Anksiyete; otonom sinir sistemi; sürüş; kalp atış hızı değişkenliği; anketler ve soru formları.

Introduction

Driving is a cognitively and physically demanding activity that taxes vigilance, visuomotor coordination, and executive control. Prolonged exposure to driving stressors – dense traffic, unpredictable maneuvers, time pressure – has been linked with sympathetic overactivation, elevated anxiety, and downstream cardiovascular risk.[1–3] Within the society of automotive engineer (SAE) J3016 framework, Level 2 (L2) driver assistance systems, such as adaptive cruise control (ACC) and lane-keeping assist (LKA), partially automate longitudinal and lateral control while requiring continuous driver supervision.[4,5] By reducing moment-to-moment control effort and stabilizing speed/lane trajectories, semi-autonomous support may attenuate allostatic load during routine driving.

Heart rate variability (HRV) provides a non-invasive window into autonomic nervous system balance.[6,7] Frequency-domain indices (e.g., Low-frequency [LF]/high-frequency [HF]) are often interpreted as sympathetic–parasympathetic interplay, while time-domain (standard deviation of NN intervals [SDNN], root mean square of successive differences [RMSSD], percentage of successive RR intervals that differ by more than 50 ms [pNN50]) and non-linear metrics (sample entropy, detrended fluctuation analysis [DFA] α1) capture complementary aspects of vagal modulation, signal complexity, and fractal scaling.[8–10] Although LF/HF alone has limitations as a stand-in for "sympathovagal balance,"[11] convergent improvements across multiple HRV domains and concurrent reductions in state anxiety strengthen physiological inference. Prior simulator and field studies suggest that driver-assist features can reduce perceived workload and stress;[1–5] however, real-world, within-subject evaluations that integrate frequency + time-domain + non-linear HRV with validated anxiety measures remain scarce.

We hypothesized that semi-autonomous driving would lower LF/HF, increase vagal/complexity indices (SDNN, RMSSD, pNN50, sample entropy), and reduce DFA α1, and reduce state – but not necessarily trait – anxiety.

Materials and Methods

This prospective, within-subject, two-condition field study was conducted in accordance with the Declaration of Helsinki and approved by the Liv Ankara Hospital Ethical Committee (no: LAH 06/2024/007, date: 22.06.2024). Written informed consent was obtained from all participants.

A total of 45 healthy adults (23 female, 22 male) with valid Turkish driver's licenses and regular driving activity were enrolled. Exclusion criteria included cardiovascular, neurological, or psychiatric disorders; psychotropic or substance use; arrhythmias that could compromise HRV validity; and pregnancy. All participants had normal resting echocardiography and treadmill exercise testing.

In addition to preserved left ventricular ejection fraction (>55%), all participants had normal diastolic parameters within age-adjusted limits, including E/A ratio (1.2±0.3), septal e' velocity (10.1±1.8 cm/s), average E/e' ratio (7.1±1.4), left atrial diameter (33.4±3.7 mm), and deceleration time (188±24 ms). No participant had evidence of grade I–III diastolic dysfunction, left ventricular hypertrophy, valvular disease, or regional wall motion abnormality. Baseline characteristics are presented in Table 1.

Table 1. Demographic and baseline characteristics of participants

Variable	Value
Number of participants (n)	45
Age, years (mean±SD)	34.7±6.9
Sex (n)	
Female	23
Male	22
Handedness (n)	
Right	43
Left	2
Driving experience, years (Mean±SD)	11.8±5.2
Primary driving habit, (n)	
Automatic	31
Manual transmission	14
History of cardiovascular, neurological, or psychiatric disease	None
Cardiovascular medication	None
Resting LVEF (%)	61.8±3.7
E/A ratio	1.2±0.3
Septal e' velocity (cm/s)	10.1±1.8
Average E/e' ratio	7.1±1.4
Left atrial diameter (mm)	33.4±3.7
Psychiatric medication	None

SD: Standard deviation; LVEF: Left ventricular ejection fraction.

Participants' previous driving habits were recorded before the study. Thirty-one participants routinely used automatic-transmission vehicles, whereas 14 regularly used manual-transmission vehicles. Because the study vehicle (Tesla Model Y) is fully automatic, all participants first completed a 15-min familiarization drive with the same vehicle and route environment before any HRV recording. In addition, participants underwent a 10-min supervised familiarization period with the Level 2 functions (ACC and LKA) before the semi-autonomous session. Thus, HRV measurements were performed only after the participant had become accustomed to both the vehicle and the automation system.

The study vehicle was a Tesla Model Y (2024) equipped with Level 2 features, including ACC and LKA. The same vehicle was used for all participants, with constant tires and firmware throughout the study. The driving route consisted of a 30-km suburban loop in Konya, Türkiye, with mixed single- and dual-carriageway segments and roundabouts.

The Konya suburban route was selected because it provides a reproducible and relatively homogeneous driving environment with moderate traffic density, limited signalized intersections, and stable speed conditions, thereby minimizing environmental variability between sessions. The 30-km route and 32–45-min session duration were chosen according to prior HRV field studies indicating that recordings of at least 20–30 min are sufficient for reliable frequency-domain, time-domain, and non-linear HRV analysis.[6,8]

Sessions were conducted on weekday afternoons at approximately 15:00 during dry and sunny August conditions. Fridays were excluded to avoid atypical traffic surges. A trained safety operator was present in the passenger seat for all runs.

Each participant completed two contiguous sessions on the identical route: manual driving (Level 0) followed by semi-autonomous driving (Level 2). The fixed order preserved identical traffic windows and ecological validity. Although randomization was not applied, this design was intentionally selected to preserve nearly identical environmental and traffic conditions. To reduce possible sequence or habituation effects, a 10-min seated rest period was inserted between sessions, and participants completed the familiarization phase before HRV recording. Moreover, the large and internally consistent changes across multiple HRV and anxiety measures make a pure learning or adaptation effect unlikely.

A 10-min seated rest was provided between sessions to minimize carryover effects while preserving the same environmental conditions.

HRV was recorded using a TLC-5000 Holter monitor (Contec, PRC) with 3-lead placement and 250 Hz sampling. Electrode placement was standardized, with skin prepared using alcohol to ensure impedance <5 kΩ. R-peaks were detected automatically and verified manually; ectopic beats and artifacts were removed.

Participants were instructed to avoid caffeine, nicotine, alcohol, and vigorous exercise for at least 12 h before the study. Mean habitual daily caffeine consumption was 1.6±0.8 cups/day, and nine participants were active smokers. Smokers refrained from smoking for at least 12 h before both sessions. Compliance was confirmed verbally immediately before testing. A post hoc analysis showed no significant difference in HRV response patterns between smokers and non-smokers (interaction $p>0.30$ for all HRV indices).

RR intervals were linearly interpolated for missing segments of <5%. Participants with more than 10% unusable data per session were to be excluded, though none met this criterion.

In addition to the predefined HRV indices, mean heart rate, minimum heart rate, maximum heart rate, and heart rate at the beginning and end of each session were analyzed. Continuous RR intervals were analyzed across the entire session, including lane changes and merging, to reflect real-world driving demands.

Frequency-domain analysis was performed by resampling RR intervals at 4 Hz and applying the Welch periodogram. LF power was defined as 0.04–0.15 Hz, HF power as 0.15–0.40 Hz, and the LF/HF ratio was calculated. Time-domain parameters included SDNN, RMSSD, and pNN50 derived from artifact-corrected NN intervals.

Non-linear analyses included sample entropy ($m=2$, $r=0.2 \times$ standard deviation) and DFA $\alpha 1$ (short-term scaling, 4–16 beats).

Anxiety was assessed using the state-trait anxiety inventory (STAI), with the STAI-State administered immediately after each driving condition and the STAI-Trait administered once at baseline. Both scales range from 20 to 80, with higher scores indicating greater anxiety. In addition, a 10-point Visual Analog Scale (VAS) was used to measure perceived anxiety during the just-completed drive.

HRV processing was performed independently by two analysts blinded to the driving condition. Inter-rater reliability was evaluated using the intraclass correlation coefficient (ICC) (two-way mixed, absolute agreement), with a pre-specified acceptability threshold of ≥0.85. Reliability was excellent, with ICC values of 0.92 for SDNN and 0.90 for RMSSD.

Statistical Analysis

The primary endpoint was the within-subject change in LF/HF ratio between manual and Level 2 driving. Secondary endpoints included SDNN, RMSSD, pNN50, sample entropy, DFA $\alpha 1$, STAI-State, and VAS scores. A post hoc power analysis demonstrated that the inclusion of 45 participants provided >90% statistical power to detect a moderate within-subject effect size ($dz=0.60$) for the primary LF/HF endpoint at $\alpha=0.05$.

Normality of within-subject differences was assessed using the Shapiro–Wilk test. Paired t-tests were used for normally distributed variables and Wilcoxon signed-rank tests otherwise. All analyses were two-tailed with a significance level of $p<0.05$. For multiple HRV comparisons, both unadjusted and Holm-Bonferroni adjusted p-values were calculated. Effect sizes were reported as Cohen's dz with 95% confidence intervals. Sensitivity analyses were performed using a linear mixed model with condition as a fixed effect and subject as a random intercept. Statistical analyses were performed using Statistical Package for the Social Sciences version 26 (IBM Corp., Armonk, NY, USA). No missing data were observed.

Table 2. Driving protocol and experimental conditions

Component	Description
Vehicle	Tesla model Y, 2024 (commercial EV)
Automation level	Society of automotive engineer level 2 (adaptive cruise control+lane keeping assist)
Route	30 km suburban loop, Konya, Türkiye
Timing	Weekdays, ~3:00 pm (Fridays excluded)
Weather	Dry and sunny (August 2024)
Sessions	Manual (Level 0); Semi-autonomous (Level 2)
Familiarization	15-min vehicle familiarization+10-min level 2 familiarization before recording
Smoking/Caffeine restriction	No nicotine, caffeine, alcohol, or vigorous exercise within 12 h before testing
Randomization	Not applied to preserve identical traffic and environmental conditions; acknowledged as a limitation

Table 3. Heart rate variability results: Frequency-, time-domain, and non-linear parameters (n=45)

Parameter	Manual (mean±SD)	Semi-autonomous (mean±SD)	p	Effect size (dz, 95% CI)
LF/HF ratio	2.9±0.7	1.7±0.5	<0.001	1.05 (0.72–1.36)
SDNN (ms)	43.6±8.9	61.5±10.1	<0.001	1.68 (1.30–2.05)
RMSSD (ms)	29.1±6.8	47.8±8.3	<0.001	1.80 (1.42–2.18)
pNN50 (%)	12.9±4.6	23.5±6.2	<0.001	1.65 (1.28–2.02)
Sample entropy	1.14±0.22	1.41±0.27	<0.01	0.55 (0.24–0.86)
DFA α1	1.18±0.15	1.04±0.13	<0.01	0.61 (0.30–0.92)
Mean heart rate (bpm)	82.4±9.1	75.8±8.3	<0.001	0.88 (0.56–1.18)
Maximum heart rate (bpm)	109.7±13.4	98.6±11.9	<0.001	0.76 (0.45–1.05)
Minimum heart rate (bpm)	58.2±6.7	57.1±6.2	0.18	0.12 (-0.17–0.41)

All statistically significant differences remained significant after Holm-Bonferroni correction for multiple comparisons. Positive effect sizes indicate greater parasympathetic activity and lower stress during semi-autonomous driving. LF: Low-frequency; HF: High-frequency; DFA α1: Detrended fluctuation analysis α1; SDNN: Standard deviation of NN intervals; RMSSD: Root mean square of successive differences; pNN50: Percentage of successive RR intervals that differ by more than 50 ms; SD: Standard deviation; CI: Confidence interval.

Results

Of 45 participants, 23 were female and 22 male. The mean age of the participants was 34.7±6.9 years. The mean driving experience was 11.8±5.2 years. Thirty-one participants were regular users of automatic-transmission vehicles, and 14 mainly drove manual-transmission vehicles. No significant differences in baseline LF/HF ratio, RMSSD, or STAI-State score were observed between these two subgroups before the experiment (all p>0.10). Furthermore, the magnitude of HRV improvement during semi-autonomous driving did not differ significantly according to previous transmission habit (interaction p=0.27).

All 45 enrolled participants completed the study protocol without adverse events. Demographic and baseline characteristics are summarized in Table 1. Sessions were performed under standardized vehicle/route/timing/weather conditions (Table 2). Semi-autonomous (Level 2) driving was well tolerated. Manual interventions during Level 2 sessions occurred in 12 of 45 participants, with a mean of 0.4±0.6 interventions per session, primarily related to hands-on compliance acknowledgments. No disengagement-related incidents or safety concerns were observed.

Additional Holter-Derived Heart Rate Findings

Mean heart rate decreased from 82.4±9.1 bpm during manual driving to 75.8±8.3 bpm during semi-autonomous driving (p<0.001). Maximum heart rate decreased from 109.7±13.4 bpm to 98.6±11.9 bpm (p<0.001), whereas minimum heart rate did not differ significantly (58.2±6.7 bpm vs. 57.1±6.2 bpm, p=0.18). Heart rate during the first 5 min of each session was higher than during the final 5 min in both conditions; however, this decline was significantly greater during manual driving, suggesting greater early sympathetic activation.

HRV Outcomes

Physiological outcomes consistently favored the semi-autonomous condition. LF/HF ratio decreased markedly from 2.9±0.7 during manual driving to 1.7±0.5 with Level 2 assistance (p<0.001). Time-domain parameters demonstrated significant increases: SDNN rose from 43.6±8.9 ms to 61.5±10.1 ms (p<0.001), RMSSD from 29.1±6.8 ms to 47.8±8.3 ms (p<0.001), and pNN50 from 12.9±4.6% to 23.5±6.2% (p<0.001). Non-linear metrics reflected enhanced signal complexity and vagal modulation. Sample entropy increased from 1.14±0.22 to 1.41±0.27 (p<0.01), while DFA α1 decreased from 1.18±0.15 to 1.04±0.13 (p<0.01). These results are summarized in Table 3. All statistically significant HRV differences remained significant after Holm-Bonferroni correction. Positive effect sizes consistently indicated greater parasympathetic activity and lower physiological stress during semi-autonomous driving.

Table 4. Anxiety outcomes (n=45)

Measure	Manual (mean±SD)	Semi-autonomous (mean±SD)	p*
VAS anxiety (0–10)	6.1±1.0	3.7±0.8	<0.001
STAI-state (20–80)	47.1±6.5	38.4±6.1	<0.001
STAI-trait (20–80)	45.0±7.3	43.5±6.8	0.12

*: VAS and STAI-State differences remained significant after Holm-Bonferroni correction. STAI-trait was assessed only once at baseline; the comparison shown is between the single baseline measurement and the post-manual value (no within-subject condition comparison was performed). VAS: Visual Analog Scale; STAI: State-trait anxiety inventory; SD: Standard deviation.

Anxiety Outcomes

Psychological outcomes also favored Level 2 assistance. VAS anxiety scores decreased significantly from 6.1±1.0 to 3.7±0.8 (p<0.001). STAI-State scores improved from 47.1±6.5 during manual driving to 38.4±6.1 after Level 2 driving (p<0.001). In contrast, STAI-Trait scores remained unchanged (45.0±7.3 vs. 43.5±6.8, p=0.12), consistent with the stability of trait anxiety over short-term interventions. VAS and STAI-State differences remained significant after Holm-Bonferroni correction. Anxiety outcomes are presented in Table 4.

Sensitivity Analyses

Sensitivity analyses using a linear mixed model, with condition as a fixed effect and subject as a random intercept, confirmed the significant main effect of driving condition on LF/HF ratio (F[1,44]=61.7, p<0.001). Similar robust effects were observed for SDNN, RMSSD, pNN50, and STAI-State (all p<0.001), supporting the reliability of the within-subject findings.

Discussion

In this real-world, within-subject study involving 45 drivers, semi-autonomous (Level 2) driving was associated with reduced LF/HF ratio and state anxiety, alongside increases in SDNN, RMSSD, pNN50, and sample entropy, and a decrease in DFA α1 compared with manual driving. These convergent improvements across multiple HRV domains, accompanied by psychological relief, indicate a coherent physiological de-stress response under Level 2 assistance.

Several mechanisms may explain these findings. First, reduced cognitive load likely plays a central role. ACC and LKA stabilize speed and lateral positioning, minimizing micro-corrections and continuous sensorimotor effort. This reduced tonic demand is reflected in higher RMSSD and pNN50 values, markers of vagal modulation, and in lower LF/HF ratios.[6,8–10] Second, semi-autonomy enhances predictability and distributes control, dampening unpredictability in car-following and lane deviations. This effect improves signal regularity while preserving adaptive complexity, as evidenced by higher sample entropy and lower DFA α1. Third, affective spillover contributes, with perceived ease and safety leading to reduced state – but not trait – anxiety. The parallel reduction in STAI-State scores and HRV improvements supports a psychophysiological coupling consistent with neurovisceral integration models.[12–16]

An important concern is whether the observed differences merely reflect unfamiliarity with either manual driving or the Level 2 system. To address this issue, all participants underwent a standardized familiarization period before recording, and prior transmission habits were documented. Moreover, HRV changes did not differ according to whether participants routinely drove automatic- or manual-transmission vehicles. Although sequence and learning effects cannot be completely excluded because the study was not randomized, the magnitude and consistency of the changes across multiple physiological and psychological variables make a pure habituation explanation unlikely.

These results extend prior research. Simulator-based studies have shown reduced workload with driver-assist technologies, but field data remain scarce and typically focus on single HRV measures.[1–5] By integrating frequency, time-domain, and non-linear HRV indices with validated anxiety scales, this study enhances mechanistic inference beyond LF/HF alone – a measure whose standalone interpretation can be problematic.[10] The magnitude of change, such as a ~58% increase in RMSSD and an ~82% increase in pNN50, is notable and potentially clinically meaningful, particularly for stress-sensitive populations.

The findings have several clinical and translational implications. Everyday commuters may experience lower acute stress when using Level 2 features, potentially contributing to long-term reductions in allostatic load. For patients with hypertension, arrhythmia susceptibility, or anxiety disorders, attenuating sympathetic drive during frequent driving could complement lifestyle and pharmacological interventions, though dedicated trials are needed. HRV metrics themselves may serve as digital biomarkers in automotive human-factors research and as endpoints in clinical studies evaluating different automation levels or human–machine interface designs.

This study has important methodological strengths. The within-subject design controlled for inter-individual variability, while the combination of multi-domain HRV measures with validated psychological scales enhanced construct validity. Standardization of vehicle, route, time window, and weather reduced environmental noise, and blinded dual-analyst HRV processing with excellent inter-rater reliability further supported measurement robustness.

Nevertheless, several limitations should be acknowledged. The non-randomized order of conditions leaves the possibility of sequence or habituation effects, although sensitivity analyses mirrored the primary results. As noted in the methods, the fixed order was a deliberate choice to preserve identical traffic conditions, and we attempted to mitigate carryover effects with familiarization and a rest period; however, randomized crossover designs in future studies would strengthen causal inference. The sample consisted of healthy adults from a single region, limiting generalizability to patient populations or other demographics. Exposure was short-term, without assessment of long-term adaptation, trust dynamics, or learning curves.

While the multi-metric approach reduces reliance on LF/HF, interpretive caveats remain. Finally, the study was restricted to one vehicle platform and a single driving environment under fair weather and daytime conditions, excluding scenarios such as nighttime driving, adverse weather, heavy congestion, or highway-exclusive routes.

Future research should address these limitations with counterbalanced, multicenter crossover randomized trials involving diverse drivers and platforms across automation levels.

Conclusion

In 45 healthy drivers, semi-autonomous (SAE Level 2) driving was associated with lower sympathetic dominance (reduced LF/HF), higher vagal/complexity indices (SDNN, RMSSD, pNN50, sample entropy; lower DFA $\alpha 1$), and reduced state anxiety compared with manual driving on the same route. The multi-domain HRV improvements alongside psychological benefits suggest that L2 assistance confers a measurable physiological “de-stress” effect during everyday driving. While promising for mental and cardiovascular health, these findings warrant confirmation in counterbalanced, multicenter, and longer-term studies across broader populations and driving contexts.

Disclosures

Ethics Committee Approval: The study was approved by the Liv Ankara Hospital Ethics Committee (no: 06/2024/007, date: 22/06/2024).

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