

The Effects of 30% Oxygen Concentration Inhalation on Driving Fatigue and Heart Rate Variability

Byung Chan Min*, Kazuyuki Mito, Sang Kon Lee, Seoung Chul Kim, Jeong Han Kim, Seung Hee Hong*

Abstract: This study aimed to evaluate the correlation between heart rate variability and driving fatigue through a physiological approach, examining the effects of oxygen concentrations ranging from normal to high. Driver fatigue, a factor in fatal accidents, has complex causes and varied symptoms. The ambiguity in reporting physiological changes due to mixed terminology such as fatigue and drowsiness prompted this study, which is based on the premise that physiological fatigue originates from the same mechanisms as stress. A driving scenario that induces fatigue was simulated, involving fifteen university student drivers. Experiments were conducted at oxygen concentrations of 21%, 30%, and 40%. Data were collected via an electrocardiogram system and analyzed statistically. Our findings reveal that at a 30% oxygen concentration, drivers showed a significant increase in SDNN and a decrease in LF/HF ratio, indicating enhanced autonomic nervous system stability and reduced sympathetic dominance. This intervention was found to effectively reduce and delay driving fatigue, demonstrating that oxygen supplementation at 30% concentration could notably improve traffic safety by mitigating driver fatigue.

Keywords: driver fatigue; driving stress; Electrocardiogram (ECG); Heart Rate Variation (HRV); 30% Oxygen stimulation

1 INTRODUCTION

Driver fatigue is a principal cause of traffic accidents which, in turn, have a major effect on driver behavior, driving conditions, and driving time in general [1]. Driver fatigue has been reported to cause drowsiness, poor judgment, delayed reaction time, tunnel vision, and occurrences of microsleep. Fatigue while driving is expressed in multiple terms, including drowsiness, distraction, and negligence. Because of the ramifications of the adopted operational definition of driver fatigue, it is necessary to examine the clinical definition and mechanism of fatigue.

Prior to the present study, fatigue had been considered from the perspective of drowsiness; consequently, the reported experimental results encapsulate the incidence of drowsiness rather than the physiological responses to fatigue. Therefore, in this study, the emphasis was to investigate the physiological responses associated with driver fatigue. In addition, we examined the viability of a method for reducing fatigue through oxygen injection.

2 LITERATURE REVIEW

2.1 Definition of Biofatigue

Fatigue may be defined as a form of physical and mental exhaustion resulting on strenuous activity [2], associated with difficulty in initiating and sustaining voluntary activity [3]. Clinically, the manifestation of fatigue is divided into three groups expressed as mental/physical/neural fatigue, central/peripheral fatigue, and acute/chronic fatigue. Mental fatigue occurs because of neurological fatigue caused by psychological factors, whereas physical fatigue occurs because of the accumulation of waste products and insufficient energy supply resulting from continuous muscle use. Neural fatigue occurs because of the processing of large volumes of information collected by sensory organs. An accumulation of fatigue leads to decreasing information processing ability [4]. Peripheral fatigue is a form of muscle fatigue involving neuromuscular junctions, whereas central fatigue is a subjective form of fatigue perceived in the central

nervous system [5] which is closely related to socio-psychological factors [6, 7].

2.2 Fatigue and Physiological Indicators

Silverman's research provides a nuanced perspective on fatigue, grounding its physiological basis in mechanisms traditionally associated with maintaining homeostasis under challenging conditions. This framework suggests that fatigue can be understood through the lens of the body's intricate system interactions, involving the nervous, endocrine, and immune systems. Such a perspective implicitly parallels the physiological responses observed in stress-related processes, yet it emphasizes a clear focus on fatigue as a distinct phenomenon.

In exploring the physiological underpinnings of fatigue, Silverman introduces noninvasive evaluation methods aimed at understanding how the body copes with this condition. These methods include the measurement of salivary cortisol, salivary alpha-amylase, and heart rate variability, each offering insights into different aspects of the body's response to fatigue [8]:

- 1) Salivary Cortisol: This method focuses on measuring the free cortisol present in saliva, which reflects the amount of cortisol circulating freely in the bloodstream. The approach, involving multiple continuous samplings and dynamic testing, is particularly sensitive to changes in the body's physiological state, providing a direct link to fatigue and its effects on the body.
- 2) Salivary Amylase: The analysis of salivary α -amylase (sAA) serves as a biomarker for the autonomic nervous system's (ANS) activity, particularly the sympathetic branch. Silverman's findings suggest that sAA levels increase in response to various types of stressors, pointing to its utility in understanding how the body's stress response mechanisms are engaged during physical exertion or psychological challenges [11].
- 3) Heart Rate Variability (HRV): By examining HRV, this approach assesses the balance between the sympathetic and parasympathetic branches of the ANS. The variability in

heart rate, especially as influenced by the slow transmission of sympathetic nerve signals, offers a window into the body's adaptive responses, marking a significant index for evaluating physiological states related to fatigue [12].

2.3 Driving Fatigue and Physiological Index

Driver fatigue can be studied in terms of a physiological approach, driver behavior evaluation, vehicle movement, and complex evaluation. According to a database survey spanning fifteen years from 2007 to 2021 [13], 129 studies of driver fatigue were conducted during that period. Forty-three of these studies considered a physiological approach, seventy a behavioral approach, four a vehicular approach, and twelve followed a mixed approach. These studies reflected social concerns and interests about the risk and impact of driver fatigue. Taguchi (1998) studied the relationship between vehicle vibration and driving fatigue, considering HR (Heart Rate), cardiac blood pressure fluctuations (in the form of MWSA: Mayer Wave Related Sinus Arrhythmia), cardiac respiration fluctuations (in the form of RSA: Respiratory Sinus Arrhythmia), and the incidence rate and selection reaction of adrenaline (Adr), Noradrenaline (Nor), salivary cortisol (Cor), and EEG (alpha) in urine. In that study, it was found that adrenaline responded most significantly to the driver's vibration fatigue. Persson et al [14] conducted a set of experiments consisting of driving sessions lasting either 90 min or 135 min, conducted on either motorways or rural roads, and performed at varying stages of alertness of the drivers. With respect to the relationship between HRV and driving fatigue, studies have revealed that HR decreased, whereas SDNN (the standard deviation of NN intervals), RMSSD (the root mean square of successive RR interval differences), pNN50 (the percentage of successive RR intervals that differ by more than 50 ms), LF (the rate of low-frequency oscillations), HF (the rate of high-frequency oscillations), and LF/HF (the ratio of low-frequency to high-frequency power) all increased. Zeng et al. [15] reported that the HR decreased, whereas SDNN, RMSSD, pNN50, LF, and HF all increased after driving for 60 min in a highway environment generated by a driving simulator. Buendia et al. [16] reported similar results. However, different HRV results were observed by Jung et al. [17] in their ECG-sensing device development and HRV threshold-setting experiment, which involved driving sessions lasting 2 h on an actual road). The HR, SDNN, RMSSD, and pNN50, as variables in the time domain, and the VLF, LF, HF, and LF/HF, as variables in the frequency domain, were measured and analyzed. The results indicated that a driver's HRV acted as a measure of fatigue in the form of a drowsiness transition (decrease in factors of HR, SDNN, RMSSD and pNN50; increase in factor of LF/HF).

The relationship between oxygen and fatigue has been a subject of numerous studies across various fields, revealing its complex interplay and significant implications for both physical performance and daily activities. Research in sports science and exercise physiology provides a foundational understanding of how oxygen uptake influences fatigue and

recovery during physical exertion. For instance, a study highlighted the importance of maximal oxygen uptake ($\dot{V}O_{2max}$) in determining fatigue and recovery during resistance exercise, underscoring aerobic capacity's role in physical performance [18]. Additionally, gender differences in oxygen saturation and muscle fatigue were explored, suggesting that variations in intramuscular pressures and skeletal muscle perfusion during exercise could lead to differing fatigue onset times between men and women [19].

In the context of team sports like futsal, another study investigated the relationship between heart rate, oxygen consumption, and energy expenditure, aiming to estimate the aerobic and anaerobic contributions to total energy expenditure during a simulated game. This research underscores the complexity of accurately predicting oxygen consumption and its effects on performance in activities characterized by intermittent, high-intensity efforts [20]

The relevance of these physiological insights extends beyond the realm of sports, touching upon everyday activities such as driving. Sung et al. noted the critical impact of stress and fatigue on driving, identifying them as leading causes of traffic accidents. They proposed oxygen injection as a potential solution to alleviate drivers' fatigue and stress, conducting an experiment where oxygen at concentrations of 18%, 21%, and 30% was administered to drivers. The study found that 30% oxygen concentration was the most effective in reducing fatigue and improving driving reaction times, based on subjective evaluations and kinematic measurements. However, this investigation highlighted a gap in research, as it did not assess the drivers' physiological responses to oxygen supplementation.

In light of evidence demonstrating the profound impact of oxygen concentration on physical and cognitive performance, the aim of this study is defined as the examination of how varying oxygen levels influence heart rate variability (HRV) in drivers. HRV, an indicator of autonomic nervous system function, is to be assessed to understand the physiological responses to oxygen variations in a simulated driving environment. Participants are to be exposed to oxygen concentrations of 18%, 21%, and 30%, with the hypothesis being that increased oxygen levels will correlate with improved HRV profiles, indicative of reduced stress and enhanced cognitive and physical resilience. This research is intended to contribute to the understanding of mechanisms by which oxygen can improve driving safety and performance, potentially informing strategies to mitigate driver fatigue-related accidents. The methodology involves a blend of subjective fatigue evaluations and objective physiological measures, aiming to offer insights into optimal driving conditions for safety enhancements.

3 EXPERIMENTAL METHOD

Fifteen male university students with driver's licenses were recruited openly, excluding those with health conditions affecting the experiment. Participants were briefed on precautions and compensated for their time. The study employed a controlled laboratory setup with a graphic

simulator, ECG measurement system, and oxygen injection system. Driving simulations induced mental fatigue on a highway scenario, with three 20-minute driving sessions per participant. HRV parameters were analyzed using electrodes attached via the chest induction method, focusing on time and frequency domains to assess autonomic nervous system balance and vagus nerve activity. Data analysis was conducted using MATLAB and SPSS.

3.1 Participants

In the pursuit of foundational research on Heart Rate Variability (HRV), the present study adopted a controlled sample demographic, limiting participants to male university students within a similar age range. This decision stems from the acknowledgment that HRV can significantly vary across different genders and age groups, necessitating a focused initial investigation to ensure clarity and reliability in the obtained results. Consequently, our experimental group comprised 15 male university students, all of whom possessed valid driver's licenses, symbolizing a homogeneous group in terms of both gender and age, as well as basic driving experience.

Participants were recruited through an open call within the university student community, ensuring that the selection process was transparent and inclusive. The final cohort was carefully chosen based on their health status, explicitly excluding individuals with cardiovascular or respiratory diseases, among other conditions, to minimize external variables that could potentially influence HRV. Additionally, potential participants were briefed about the importance of avoiding alcohol, tobacco, and drug use—factors known to affect the central and autonomic nervous systems—both on the eve of and on the day of the experiment, to further ensure the purity and accuracy of the study's findings.

Upon arrival at the laboratory, participants were thoroughly briefed by the experiment operator on the experiment's objectives, procedures, and safety precautions. It was emphasized that participation was entirely voluntary, with the freedom to withdraw from the study at any moment without any consequences. Following the acquisition of informed consent, physiological signal measuring electrodes were affixed to the participants, and a driving simulation exercise was conducted to standardize the experimental conditions across all subjects. To acknowledge their contribution and time, participants were compensated at a rate of approximately \$15 per hour.

3.2 Equipment

The GDS-300S graphic simulator, provided by Grid Space, plays a crucial role in replicating real-world visual stimuli within a controlled setting, allowing for precise manipulation and monitoring of visual inputs. Its sophisticated rendering capabilities and high fidelity make it an indispensable tool for experiments requiring accurate visual simulation, ensuring that the visual stimuli presented to participants are consistent and of the highest quality.

Simultaneously, the MP30 system from BIOPAC was employed for its unparalleled precision in capturing electrocardiogram (ECG) data. This system is designed to

facilitate the non-invasive monitoring of electrical activities of the heart, providing real-time insights into the cardiac health and stress responses of participants. Its reliability and accuracy in data acquisition make it an optimal choice for studies focusing on physiological responses to varying conditions.

These components were selected for their proven reliability, precision, and compatibility with the objectives of our study, ensuring that all data collected were of the highest fidelity and relevance. Data extraction and analysis were performed using MATLAB (MATLAB R2019a, MathWorks) for its robust data processing and visualization capabilities. For statistical analysis, SPSS ver.18 was utilized, offering comprehensive tools for in-depth statistical testing and interpretation, thus ensuring the integrity and validity of the experimental findings.

3.3 Environment

To guarantee the precision of our study results, we meticulously implemented control measures for external variables that could potentially influence HRV. These measures were designed to maintain a consistent ambient temperature within the simulation environment, rigorously kept at a constant 23 °C (± 1 °C), to negate the effects of temperature fluctuations on participant stress levels and HRV outcomes. Noise control was achieved through the use of sound-insulated headphones that delivered only simulation-related audio cues, thereby eliminating auditory distractions and ensuring that external sound variations did not affect the data.

Our study employed a double-blind design, ensuring that neither participants nor experimenters were privy to the allocation of oxygen conditions throughout the experiment. Participants were informed about exposure to varying oxygen levels in general terms, without specific details, while the sequence of conditions remained undisclosed to experimenters, overseen by an independent team member. This meticulous approach mitigated potential biases, safeguarding the impartiality of experimental implementation and participant response.

3.4 Scenarios

In our driving simulation, scenarios were set on a virtual highway with surrounding vehicles to impose mental fatigue, necessitating the overtaking of preceding vehicles as illustrated in Fig 2. Participants began their journey in the highway's lower lane, shifting to the second lane upon receiving specific instructions. If a preceding vehicle emerged randomly while the participant was in the second lane, they were directed to overtake by moving to the first lane. To moderate the graphic simulation's driving intensity, this procedure was conducted three times, with each driving session spanning 20 minutes. The comprehensive duration of the experiment, as shown in Fig. 1, totaled 150 minutes, including breaks before and after driving sessions, summing up to approximately 3 hours when factoring in preparation and simulator training time. The ordering of oxygen

concentration levels during these sessions was randomized and concealed from participants to prevent order effects. The primary objective of this experiment was to evaluate the influence of HRV and oxygen intake alterations on mental fatigue in conditions of induced driving fatigue. For a thorough assessment of central and acute fatigue, we recorded Electrocardiograms (ECGs) showcasing the activity of the parasympathetic nervous system, particularly the vagus nerve.

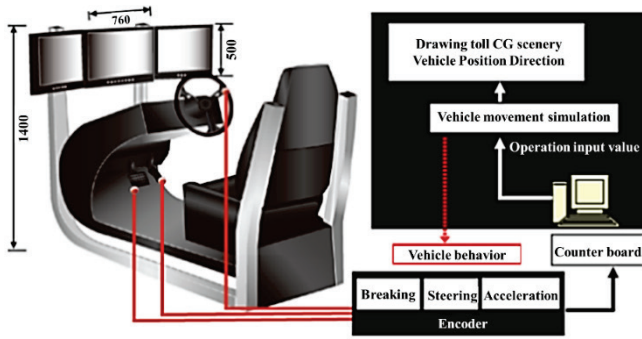


Figure 1 Graphic Simulator Configuration

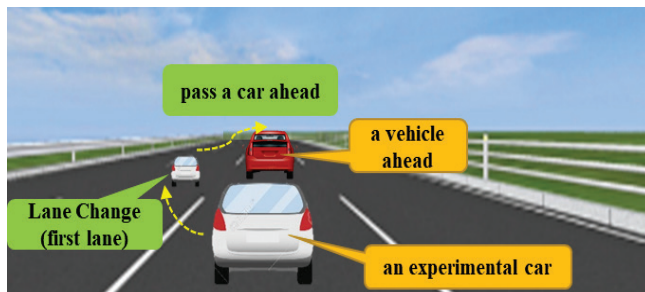


Figure 2 Experimental Driving Scenario

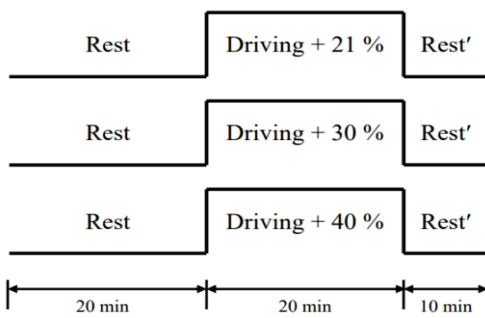


Figure 3 Experiment process and time required

Table 1 HRV Parameters

Parameters	Unit	Definition
		Analysis of 5 min (short-term) recordings
SDNN	ms	Standard deviation of NN intervals
RMSSD	ms	Square root of the mean squared differences between successive RR intervals
PNN50	%	NN50 divided by the total number of RR intervals
LF norm	nu	LF power in normalized units $LF/(total\ power - VLF) \times 100$ *LF Frequency range: 0.04–0.15 Hz
HF norm	nu	HF power in normalized units $HF/(total\ power - VLF) \times 100$ *HF Frequency range: 0.15–0.4 Hz
LF/HF	-	Ratio of LF power to HF power

The order of oxygen concentration released during driving was not notified to the participants in the experiment. In order to exclude order effects, the order of oxygen release was determined by randomization.

The experiment was conducted to evaluate the effect of a change in HRV and oxygen intake on mental fatigue in a situation where mental driving fatigue was imposed. In order to evaluate central and acute fatigue, ECGs reflecting the behavior of the parasympathetic nerve (vagus nerve) were recorded.

3.5 HRV Parameters

Electrocardiogram electrodes were attached using the chest induction (tripole) method depicted in Fig. 4. HRV measured from an electrocardiogram can be analyzed in the time domain and frequency domain. In this study, autonomic nervous system balance and vagus nerve evaluation variables among time and frequency domain parameters were utilized [19].

The variables used for evaluating fatigue were the normalized HF power (HFnorm) and normalized LF power (LFnorm), and those used for evaluating ANS balance were LF/HF and SDNN. Key time domain parameters were used for estimating changes in the vagus nerve. The RMSSD constitutes the HF of HRV. The proportion of NN50 among the entire beat interval (PNN50) was extracted and analyzed.

Continuously measured ECG data were analyzed after removing noise with a 60 Hz NF (Notch. Filter) and an IIR filter (Infinite Impulse Response Filter). HRV parameters were extracted in standard 5-minute units (short-term recordings) [20, 21]

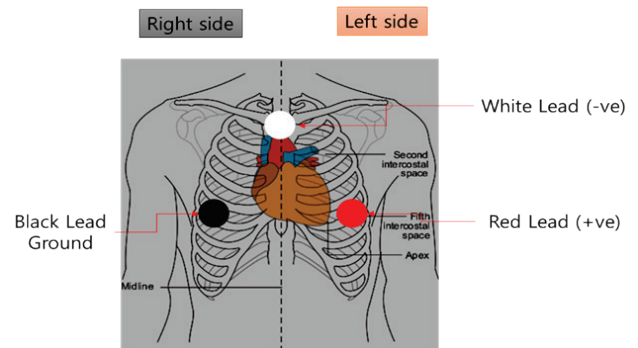


Figure 4 ECG Acquisition system and Configuration

4 EXPERIMENTAL RESULTS

Physiological fatigue responses were compared and evaluated in various ways based on the measurements of HRV in the form of time-lapse and oxygen concentration while resting and driving.

4.1 Changes in HRV over Time

First, we compared the change in heart rate variability with time for resting and driving conditions and the effect of driving on mental stress as a function of time.

In the resting condition, the SDNN maintained a higher value for the total time than in the driving condition, and the SDNN, RMSSD, PNN50, LFnorm, HFnorm, and LF/HF all showed an increase over time. However, in the driving condition, RMSSD, PNN50 and HF showed a decreasing trend over time, whereas LFnorm and LF/HF showed a slightly increase.

The multivariate analysis of HRV with respect to time generated a statistically significant difference between the values obtained for resting and driving conditions, respectively. The time-dependent differences of the SDNN were P5~10 min = 0.08, P10~15 min = 0.01, and P 15~20 min = 0.000, whereas that of PNN50 was P15~20 min = 0.021, and that of the RMSSD was P 15~20 min = 0.013, reflecting the activity of the parasympathetic and vagus nerves.

Table 2 HRV variation with time expressed as P-value

(min)	SDNN	RMSSD	PNN50	LFnorm.	HFnorm	LF/HF
0~5	.370	.243	.151	.308	.029	.382
5~10	.008	.091	.947	.744	.166	.392
10~15	.001	.061	.024	.183	.553	.462
15~20	.000	.013	.021	.620	.490	.073

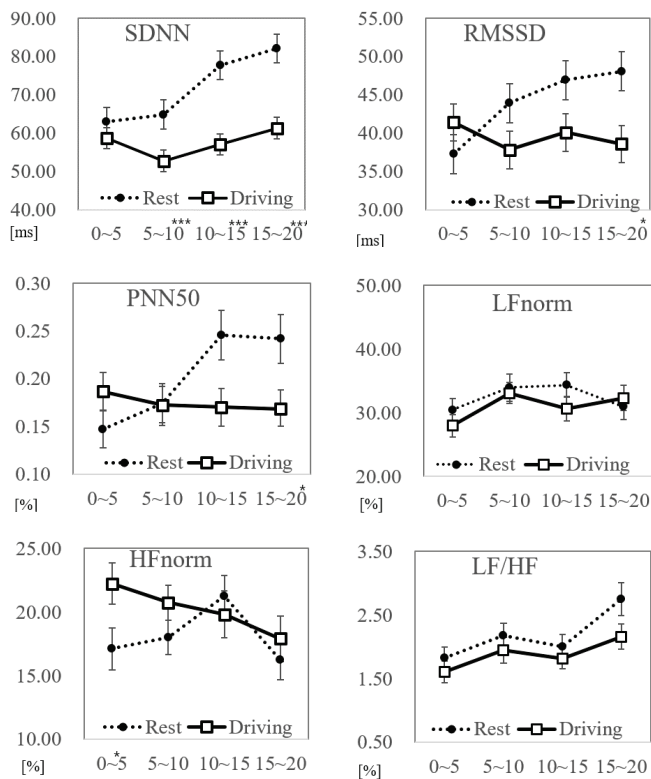


Figure 5 HRV over time while resting and driving

4.2 HRV According to Oxygen Concentration While Resting and Driving

In order to demonstrate the difference in heart rate variability measured by oxygen concentration before driving (that is, while in the resting condition) and after driving (that is, in the driving condition), the values of the parameters in the resting condition and in the driving condition are graphically displayed in Fig. 5. In addition, the statistically

significant differences were verified by performing a one-way ANOVA.

According to the results, the SDNN, RMSSD, and PNN50, which are time-dependent variables, all decreased after driving, relative to their values before driving. The SDNN exhibited a statistically significantly decrease (P21 % = 0.039, P30 % = 0.000, and P40 % = 0.001). The values of the LFnorm, HFnorm, and LF/HF, which are frequency-dependent, exhibited contrasting trends when measured in terms of oxygen concentration. Values of LFnorm decreased at both 21 % and 30 % oxygen concentrations and significantly decreased at 30 % (P30 % = 0.047), increasing only at 40 % concentration. Values of HFnorm exhibited a very small difference at 21 % and 40 %, whereas the value increased significantly at 30 % (P30 % = 0.000). For LF/HF, the difference in values was also small at 21 % and 40 %, whereas the value decreased significantly at 30 % (P30 % = 0.001).

Table 3 The methodology processes and their descriptions.

%	SDNN	RMSSD	PNN50	LFnorm	HFnorm	LF/HF
21	.039	.391	.272	.423	.842	.707
30	.000	.102	.272	.047	.000	.001
40	.001	.072	.338	.358	.987	.854

* Results with a P-value of 0.05 or less are indicated in bold.

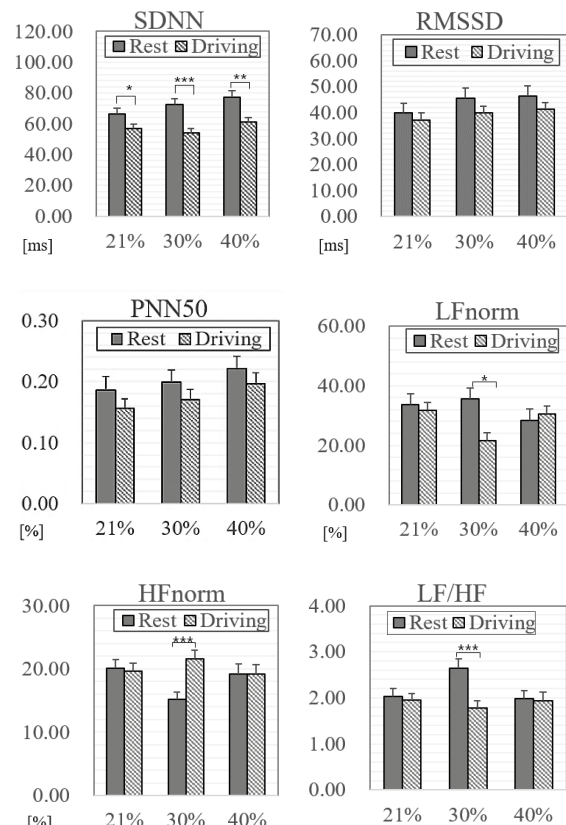


Figure 6 HRV according to oxygen concentration while resting and driving

4.3 HRV According to Oxygen Concentration and Time While Driving

This study was assessed the effect of oxygen on the fatigue and HRV of participants while driving after providing 21%, 30%, and 40% oxygen, respectively. The results were

displayed in Fig 6. At 21% oxygen concentration (the normal concentration in the atmosphere), the SDNN, RMSSD, PNN50, LFnorm, and LF/HF were observed a tendency to increase over time, whereas HFnorm was observed a tendency to decrease. When 30% oxygen was inhaled, the SDNN, RMSSD, PNN50, and HFnorm first decreased and then increased, whereas LFnorm and LF/HF showed a consistently increasing trend. At the highest oxygen concentration of 40%, the SDNN and PNN50 maintained constant levels from the start to the end of driving, whereas the RMSSD and HFnorm decreased sharply, and accordingly, LF/HF displayed an increasing trend. A multivariate analysis according to the time interval and oxygen concentration while driving indicated that there was no significant difference in any of the variables with respect to both oxygen concentration and elapsed time.

Table 4 HRV by time interval expressed as *P*-value

(min)	SDNN	RMSSD	PNN50	LFnorm.	HFnorm	LF/HF
0-5	.409	.100	.561	.285	.365	.107
5-10	.219	.518	.412	.935	.359	.445
10-15	.733	.733	.604	.580	.848	.528
15-20	.643	.810	.819	.102	.309	.795

4.4 Comparison of Variance in HRV by Oxygen Concentration

To verify whether the variance in HRV before driving and after driving differed with respect to the oxygen concentration, the variance of (HRV while driving - HRV while resting) was calculated using a one-way ANOVA. A significant difference in the variance by oxygen concentration was found in HFnorm ($P = 0.005$). Application of post hoc analysis (Scheffe's) indicated significant differences between O₂ 21% and O₂ 30% ($P = 0.011$) and between O₂ 30% and O₂ 40% ($P = 0.025$).

Table 5 Variance in HRV by Oxygen Concentration expressed as *P*-value

SDNN	RMSSD	PNN50	LFnorm.	HFnorm	LF/HF
.703	.733	.974	.128	.006	.152

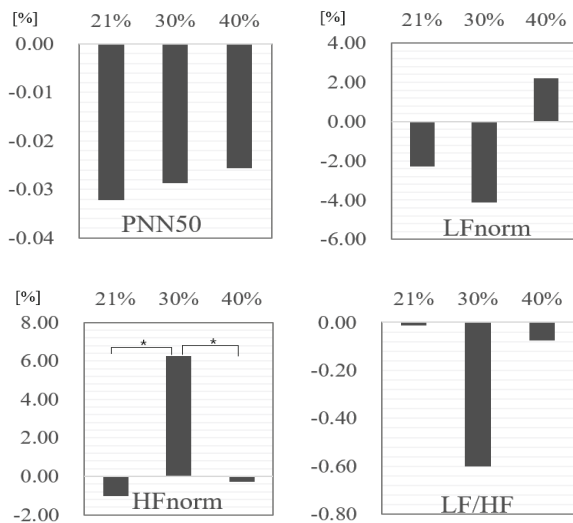


Figure 7 HRV according to oxygen concentration

4.5 A Pearson's Correlation Analysis of HRV

A Pearson's correlation analysis of HRV revealed that the SDNN exhibited a positive correlation with the RMSSD and PNN50 ($r = 0.66$ and $r = 0.56$, respectively) and a negative correlation with HFnorm ($r = -0.20$). Also, RMSSD exhibited a positive correlation with the SDNN, PNN50, and HFnorm ($r = 0.66$, $r = 0.78$, and $r = 0.21$, respectively), whereas PNN50 showed a positive correlation with the SDNN, PNN50, and HFnorm ($r = 0.56$, $r = 0.78$, and $r = 0.20$, respectively). However, it is also consistent with previous studies that LFnorm exhibited no correlation with other variables except LF/HF, HFnorm exhibited positive correlations with the RMSSD and PNN50 in the time domain ($r = 0.21$ and $r = 0.20$, respectively), and a negative correlation with the SDNN ($r = -0.20$), and the parameters of heart rate variability showed correlations with other variables. HF, which represents the activity of the parasympathetic nerve, exhibited a positive correlation with the RMSSD, which represents the vagus nerve activity of the parasympathetic nerve.

Table 6 The methodology processes and their descriptions

SDNN	RMSSD	PNN50	LFnorm.	HFnorm	LF/HF
.703	.733	.974	.128	.006	.152

		SDNN	RMSSD	PNN50	LFnorm	HFnorm	LF/HF
SDNN	Pearson	1	.656	.563	-.046	-.193	.186
	Correlation						
	Sig. (2-tailed)		.000	.000	.397	.000	.001
RMSSD	Pearson		1	.783	.065	.205	-.059
	Correlation						
	Sig. (2-tailed)			.000	.232	.000	.294
PNN50	Pearson			1	.075	.195	-.060
	Correlation						
	Sig. (2-tailed)				.156	.000	.273
LFnorm	Pearson				1	.059	.432
	Correlation						
	Sig. (2-tailed)					.267	.000
HFnorm	Pearson					1	-.699
	Correlation						
	Sig. (2-tailed)						.000

5 DISCUSSION AND CONCLUSION

This study contributes to the expanding research on the non-invasive assessment of driver fatigue through heart rate variability (HRV), aligning with the pioneering insights of Silverman (2010). Our findings underscore the utility of HRV as a reliable indicator of the autonomic nervous system's (ANS) regulatory dynamics, especially in relation to fatigue induced by driving activities. By analyzing both time-domain and frequency-domain parameters of HRV, we have demonstrated the sensitive interplay between physiological responses and environmental factors such as oxygen concentration.

Recent literature reaffirms the potential of HRV analysis in the context of driving fatigue. For instance, the systematic review by Lu et al. (2022) on driver fatigue detection systems using HRV highlights the promising yet variable performance of these systems, indicating a need for

standardization in future research to consolidate HRV's role as a fatigue marker [21]. Similarly, the study applied mutual information for feature selection in ECG-based fatigue detection, represents an advancement in the analytical methodologies, achieving significant accuracy in detecting fatigue states [22]. These studies not only validate the relevance of HRV in fatigue assessment but also illustrate the ongoing efforts to enhance the precision and applicability of HRV-based detection systems.

Our investigation into the effects of different oxygen concentrations on HRV parameters adds a novel dimension to understanding how environmental factors can modulate ANS activity, potentially influencing driver fatigue levels. This inquiry complements existing research, such as the work, which employed wavelet transform and ensemble logistic regression for driving fatigue detection, achieving an accuracy of 92.5% [23]. Moreover, the integration of vehicle data with ECG signals in the study by Halomoan et al. (2023) exemplifies the potential for multimodal approaches to enrich the detection framework.

Acknowledging the limitations inherent in our study, such as the confined sample size and specific driving conditions, we echo the call for broader research to solidify HRV's predictive utility across diverse scenarios. Future endeavors could benefit from exploring the synergy between HRV and other physiological or behavioral indicators of fatigue, offering a more comprehensive framework for real-time fatigue monitoring and intervention.

In sum, our research affirms the critical role of HRV in monitoring driver fatigue, paving the way for further exploration and technological development in this domain. As we move forward, the continued refinement of detection methodologies, bolstered by a deeper understanding of HRV's physiological underpinnings, will be key to realizing the full potential of HRV analysis in enhancing road safety and driver well-being.

Acknowledgement

This research was supported by the 3NF Co., LTD, Republic of Korea.

6 REFERENCES

- [1] Hong, S. H., Park, S. J., Min, B. C., Suzuki, K. & Doi, S. (2017). In-Vehicle System Design - Considering Cognitive Characteristics of Elderly Drivers. *International Conference on Platform Technology and Service (PlatCon2017)*, 1-4. <https://doi.org/10.1109/PlatCon.2017.7883713>
- [2] Evans, W. J. & Lambert, C. P. (2007). Physiological basis of fatigue. *Am J Phys Med Rehabil*, 86, 29-46. <https://doi.org/10.1097/PHM.0b013e31802ba53c>
- [3] Chaudhuri, A. & Behan, P. O. (2004). Multiple sclerosis is not an autoimmune disease. *Arch Neurol*, 61, 1610-1612. <https://doi.org/10.1001/archneur.61.10.1610>
- [4] Thayer, J. F. & Lane, R. D. (2009). Claude Bernard and the heart-brain connection: further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, 3(2), 81-88. <https://doi.org/10.1016/j.neubiorev.2008.08.004>
- [5] Davis, M. P. & Walsh, D. (2010). Mechanisms of fatigue. *J Support Oncol*, 8(4), 164-174.
- [6] Bower, J. E. (2008). Behavioral symptoms in patients with breast cancer and survivors. *J Clin Oncol*, 26, 768-777. <https://doi.org/10.1200/JCO.2007.14.3248>
- [7] Silverman, M. N., Heim, C. M., Nater, U. M., Marques, A. H. & Sternberg E. M. (2010). Neuroendocrine and immune contributors to fatigue. *PM&R*, 2(5), 338-346. <https://doi.org/10.1016/j.pmrj.2010.04.008>
- [8] Chrousos, G. P. (2009). Stress and disorders of the stress system. *Nat Rev Endocrinol*, 5, 374-381. <https://doi.org/10.1038/nrendo.2009.106>
- [9] Clow, A., Thorn, L., Evans, P. & Hucklebridge, F. (2004). The awakening cortisol response: methodological issues and significance. *Stress*, 7, 29-37. <https://doi.org/10.1080/10253890410001667205>
- [10] Kirschbaum, C. & Hellhammer, D. H. (2000). Salivary cortisol. In: Fink, G., editor. *Encyclopedia of Stress, Vol 3*. Academic Press, San Diego, CA, 379-383.
- [11] Nater, U. M. & Rohleder, N. (2009). Salivary alpha-amylase as a non-invasive biomarker for the sympathetic nervous system: current state of research. *Psychoneuroendocrinology*, 34, 486-496. <https://doi.org/10.1016/j.psyneuen.2009.01.014>
- [12] Thayer, J. F. & Sternberg, E. M. (2006). Beyond heart rate variability: Vagal regulation of allostatic systems. *Ann NY Acad Sci*, 1088, 361-372. <https://doi.org/10.1196/annals.1366.014>
- [13] Kamti, M. K. & Iqbal, R. (2022). Evolution of Driver Fatigue Detection Techniques—A Review from 2007 to 2021. *Transportation Research Record*, 2676(12), 485-507. <https://doi.org/10.1177/03611981221096118>
- [14] Persson, A., Jonasson, H., Fredriksson, I., Wiklund, U. & Ahlstrom, C. (2021). Heart Rate Variability for Classification of Alert versus Sleep Deprived Drivers in Real Road Driving Conditions. *IEEE Transactions on Intelligent Transportation Systems*, 22(6), 3316-3325. <https://doi.org/10.1109/TITS.2020.2981941>
- [15] Zeng, C., Wang, W., Chen, C., Zhang, C. & Cheng, B. (2020). Sex differences in time-domain and frequency-domain heart rate variability measures of fatigued drivers. *International Journal of Environmental Research and Public Health*, 17(22), 1-17. <https://doi.org/10.3390/ijerph17228499>
- [16] Buendia, R., Forcolin, F., Karlsson, J., Sjöqvist, B. A., Anund, A. & Candefjord, S. (2019). Deriving heart rate variability indices from cardiac monitoring—An indicator of driver sleepiness. *Traffic Injury Prevention*, 20(3), 249-254. <https://doi.org/10.1080/15389588.2018.1548766>
- [17] Jung, S., Shin, H. & Chung, W. (2014). Driver fatigue and drowsiness monitoring system with embedded electrocardiogram sensor on steering wheel. *IET Intelligent Transport Systems*, 8(1), 43-50. <https://doi.org/10.1049/iet-its.2012.0032>
- [18] Lundberg, T. R., Larsson, G., Alstermark, R. et al. (2024). Relationship between maximal oxygen uptake, within-set fatigue and between-set recovery during resistance exercise in resistance-trained men and women. *BMC Sports Sci Med Rehabil*, 16, 45. <https://doi.org/10.1186/s13102-024-00830-8>
- [19] Curiel, A. (2019). The Relationship between Oxygen Saturation and Muscle Fatigue in Men and Women. *PhD Theses*. University of Oklahoma. <https://shareok.org/handle/11244/321125>
- [20] Santos da Silva, H., Nakamura, F. Y., Papoti, M., Santos da Silva, A. & Dos-Santos, J. W. (2021). Relationship between Heart Rate, Oxygen Consumption, and Energy Expenditure in Futsal. *Frontiers in Psychology*, 12. <https://doi.org/10.3389/fpsyg.2021.698622>
- [21] Lu, K., Dahlman, A. S., Karlsson, J. & Candefjord, S. (2022). Detecting driver fatigue using heart rate variability: A

systematic review. *Accident Analysis & Prevention*, 178, 106830. <https://doi.org/10.1016/j.aap.2022.106830>

- [22] Sudiana, D., Gunawan, T. S. & Salman, M. (2023). ECG-Based Driving Fatigue Detection Using Heart Rate Variability Analysis with Mutual Information. *Information*, 14(10). <https://doi.org/10.3390/info14100539>
- [23] Halomoan, J., Ramli, K., Sudiana, D., Gunawan, T. S. & Salman, M. (2023). A New ECG Data Processing Approach to Developing an Accurate Driving Fatigue Detection Framework with Heart Rate Variability Analysis and Ensemble Learning. *Information*, 14, 210. <https://doi.org/10.3390/info14040210>

Authors' contacts:

Byung Chan Min

(Corresponding author)

Department of Industrial Management Engineering, Hanbat National University,
125, Dongseo-daero, Yuseong-gu, Daejeon, Republic of Korea
bcm@hanbat.ac.kr

Kazuyuki Mito

Department of Informatics, The University of Electro-Communications,
1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
k.mito@uec.ac.jp

Sang Kon Lee

NF Co., LTD,
24, Sinsajaesandan 1-ro, Jangan-eup, Gijang-gun, Busan, Republic of Korea
sklee@nfeco.co.kr

Seoung Chul Kim

Affiliated Research Institute, NF Co., LTD,
24, Sinsajaesandan 1-ro, Jangan-eup, Gijang-gun, Busan, Republic of Korea
sckim@nfeco.co.kr

Jeong Han Kim

Affiliated Research Institute, NF Co., LTD,
24, Sinsajaesandan 1-ro, Jangan-eup, Gijang-gun, Busan, Republic of Korea
jhkim3@nfeco.co.kr

Seung Hee Hong

(Corresponding author)

Corporate Support Team, Healthcare & Spa Industry Promotion Agency,
84, Yeomchisandan 1-gil, Eumbong-myeon, Asan-si, Chungcheongnam-do,
Republic of Korea
zeele82622@gmail.com