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MEASUREMENT OF HEART RATE TO DETERMINE CAR DRIVERS' PERFORMANCE IMPAIRMENT IN SIMULATED DRIVING: AN OVERVIEW

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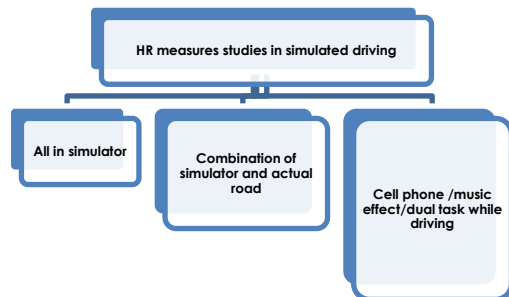[b]Department of Mechanical and Process Engineering, Faculty of Engineeering, University Duisburg-Essen, Lotharstraesse 1, 47057 Duisburg, Germany

Graphical abstract

Abstract

Fatigue is a gradual process related with an effort to keep awake, eventually resulting in declination of human performance. It is one of the well-known risk factors for traffic accidents. The objective of this study is to understand the psychophysiological aspects of driver fatigue by using driving simulator. This study had focused on heart rate (HR) measures to determine drivers' performance as this method can be measured in a less intrusive manner. Hence, in this study, 17 relevant studies were discussed, chosen from electronic databases. This study encompasses a range of subject areas, including concepts and theories of fatigue, driver fatigue, and psychophysiological indicators and countermeasures of driver fatigue. A variety of psychophysiological measures and parameters have been used in past research as indicators of fatigue. Based on this review, HR can assists researchers to determine performance according to a task demand, condition and its complexity. The review highlighted gaps in the literature and opportunities for future studies.

Keywords: Heart rate, driver, simulator, road, fatigue, discomfort

Abstrak

Kelesuan adalah proses beransur-ansur yang berkaitan dengan usaha untuk memastikan diri terjaga, yang menyebabkan prestasi merosot. Kelesuan dikenalpasti antara salah satu faktor yang menyebabkan kemalangan jalan raya. Objektif kajian ini adalah untuk memahami aspek-aspek psikofisiologikal kelesuan pemandu dengan menggunakan simulator memandu. Kajian ini tertumpu kepada pengukuran kadar degupan jantung dalam menentukan prestasi pemandu kerana kaedah ini kurang gangguan daripada faktor-faktor lain. Oleh itu, dalam kajian ini, 17 kajian yang relevan telah dibincangkan, yang dipilih daripada pangkalan data elektronik. Kajian ini meliputi pelbagai bidang, termasuk konsep dan teori kelesuan, kelesuan pemandu, dan penunjuk psikofisiologikal dan cara mengatasi kelesuan di kalangan pemandu. Pelbagai langkah psikofisiologikal dan parameter telah digunakan dalam penyelidikan masa lalu sebagai penunjuk kepada kelesuan. Berdasarkan kajian ini, kadar degupan jantung boleh membantu penyelidik untuk menentukan prestasi mengikut permintaan tugas, keadaan dan kerumitan. Kajian ini menekankan jurang dalam kajian yang lepas dan peluang untuk kajian akan datang.

1.0 INTRODUCTION

The development of fatigue interacts with other factors which influence the general drivers' state[1]. In addition, according to Brookhuis & De Waard and Heinze et al. , human performance can measured by monitoring the condition of the human while reacting and responding to the task demand [2-3]. In general, fatigue level will changed according to specific state and can be reflected with performance impairment and declination. Performance can be impaired during fatigue when an individual continues to perform the current activity as normal [4]. As for example, fatigue is increasing with the time spent when [5-6]. In fact, there is the link between fatigue, human performance impairment and safety [7].

Direct measures of fatigue and performance are simply impossible to achieve. Thus, past studies have used measurable indicators to determine fatigue level and monitor performance state while driving [8]. Psychophysiological methods are one of the main measurable indicators to quantify fatigue level. Another approach proposed by the researchers is performance test such as lane keeping ability and speed control. Normally, this approach is combined together with psychophysiological methods to obtain reliable findings related to fatigue.

Kramer and Wierwille & Eggemeier had reported variety of psychophysiological measures in the past studies to detect fatigue level such as electrocardiogram (ECG), electromyogram (EMG), electroencephalogram (EEG) and electrooculogram (EOG), respiratory measures, and electro dermal measures [9-10]. Among all these physiological parameters, ECG can be measured in a less intrusive manner [11].

ECG has been used as a physiological measure of workload particularly during driving. Based on past studies, there was significant and large decrease in HR during driver fatigue [12]. Roscoe had reviewed considerable amounts of literatures regarding HR responses, Heart Rate Variability (HRV) and respiration among pilots [13]. It is obvious that HR was affected by, excitement, anxiety, anger and other emotions. In addition, HR can be influenced by environmental factors such as vibration, noise, and heat and also stimulant factors such as caffeine, pain and discomfort and diurnal variations.

Generally, based on all these reviews, HR change is one of a sign for individual alertness and performance impairment. However, this issue needs further investigation before any firm conclusion can be drawn about its potential to indicate fatigue. Therefore, research related to HR measures, including its setting, analysis and findings has been reported and discussed in this paper.

2.0 METHODOLOGY

A list of English language articles dating as far back as 1991 were compiled from Science Direct, Springer and Google Scholar websites. Heart rate; fatigue; discomfort; driver; road; simulator were the keyword search terms for this paper. In addition, a secondary search was performed by using bibliography of retrieved articles in order to support the first retrieved paper. The aim of this paper is to first, identify from the existing literature the potential of using psychophysiological factors, particularly heart rate as an indicator of fatigue, and second, to assess the possibility of a countermeasure based on detecting physiological changes during fatigue. This review will provide a discussion on the study design and setting and analysis. In addition, discussion and concerns on the findings in the light of directions for future studies are also provided in this review.

3.0 RESULTS AND DISCUSSION

Driving simulators offer a safe and controlled environment to apprehend driver behaviour for research purposes [14]. In fact, Son et al. had validated the simulator can be used to identify the physiological reactivity patterns in response to cognitives workloads [15]. Figure 1 demonstrates the category of the 17 past studies that had been reviewed in this paper.
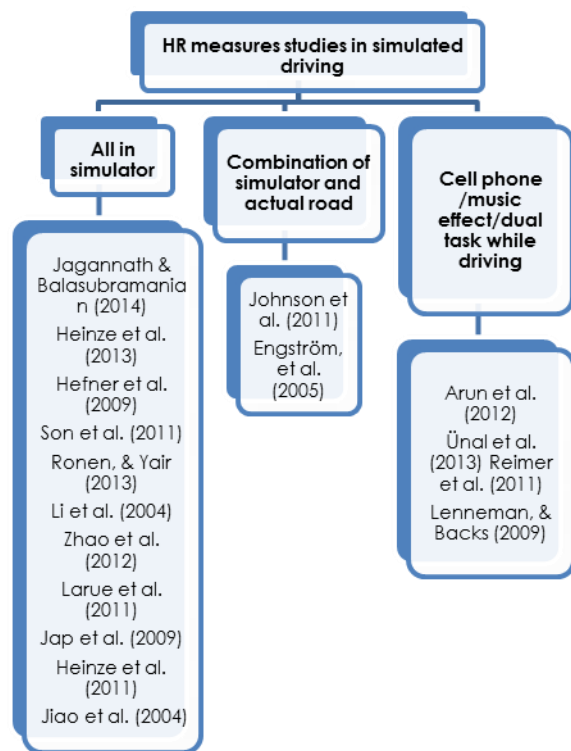
Figure 1 Category for past studies in this paper

3.1 Application of Car Simulator to Determine Drivers' Vigilance and Alertness

Table 1 shows a summary of fatigue evaluation studies from 17 past studies. This literature is organised in terms of the study design, HR setting as well as findings and suggestions for future study.

For example, Jagannath & Balasubramanian [16] evaluated driver fatigue by means of EMG, EEG, seat interface pressure, BP, HR, and oxygen saturation level using static simulator. The static driving simulator comprises of a steering wheel with force feedback, gear shift lever, foot pedals and a projection of the driving environment for visual feedback. This study showed that the significant change in HR at the end of the driving session indicated that variation in cardiovascular parameters could be used as merely a predictor for a close examination of other parameters.

Heinze et al. [17] had found the correlation between heart rate measures from the frequency domain and driver performance as well as driver sleepiness state, using data from five subjects. This study indicated there is strong correlation between HR, KSS and VLD. In addition, Hefner et al. [18] were able to find relationship between HRV and multiple fatigue measures, including KSS, VLD, eye blink, HR and performance test. This study was performed during night time by using simulator.

Ronen & Yair [19] had examined the relationship between subjects' subjective sensation of acclimation and objective driving performance measures by using simulator. At first, subjects need to sit in the car for 7

min and rest while reading a magazine in order to record their physiological baseline. Based on this study, curved road induced longer need for adaptation compared to the other road types. In addition, deterioration of performance was observed toward the end of the drive.

Li et al. [20] had evaluated the effects of reducing driver fatigue using HR, RT testing and subjective evaluation. Forty healthy subjects were recruited and randomly divided into two groups, study and control groups. The subjects were required to drive at constant vehicle velocity of 80 km/h continuously for 3 hours. Ünal et al. [21] had explored a music effect on driving performance, excitement and mental in a monotonous car-following task with a low complexity of traffic setting. Results indicated that listening to music does not deteriorate performance in a monotonous, and have an ability to improve some aspects of performance due to feel of excitement.

Zhao et al. [22] had evaluated mental fatigue among 13 drivers by using EEG and ECG. All subjects were required to perform the simulated driving task on monotonous and repetitive highway scene lasted nearly 120 minutes. Larue et al. [23] had investigated an impact of two monotony dimension under four different scenarios of road design and road side variability towards drivers' alertness and driving performance. In each experiment, the subject was required to drive and obey to road rules for approximately 40 min. Each subject was asked to drive according to the specific lane, at constant speed (60 kilometres per hour), without having to stop the car (no red traffic lights, stops) or to brake a lot (no T inter-sections or perpendicular turns), no manual gear changes, no need to change lane or indicate (turn signals) and low traffic.

Jap et al. [24]] had evaluated the performance of different algorithms, which had the potential to function as a fatigue indicator. The subject was completed two driving sessions, namely initial and monotonous driving sessions. In the first session, the subject was required to drive for 10 to 15 minutes which would serve as a baseline measure to check for alert driving condition. During this session, participants were provided a track involving many cars and stimuli on the road. In the second session, the subject was required to drive continuously between 60 and 80 km/h for approximately 1 hour. This session involved the participants driving with very few road stimuli.

Heinze et al. [25] had assessed the suitability of HR recordings for establishing a reliable connection to well-defined fatigue and performance measures. In this study, all subjects were required to hold the lane on a road without intersections, crossroads or any other cars present through a landscape at dark night at high speed. There were eight experiment sessions in one trial, each lasting one hour, thus the last session finished at 8:30 am. Volunteers had a 1-hour break at 3:30 am. Each session included a 40-minute driving task, a 10-minute Compensatory Tracking Task (CTT), and a 5-minute Psychomotoric Vigilance Test (PVT). Lenneman & Backs [26] were required the subject to

concurrently perform a simulated driving task and a verbal working memory task under two different driving conditions, while driving only and while dual-task driving. Compared to driving only, dual-task driving elicited a significant response in measures of cardiovascular reactivity, but no change in driving performance. Jiao et al. [27] had examined the different vibration frequencies effect on HRV and driving fatigue in simulated driving. Sixty subjects were recruited and divided into three groups, A, B and C, and the subjects of each group participated in the simulated driving for 90 min with vertical sinusoidal vibration (acceleration 0.05 g) of 1.8 Hz (group A), 6 Hz (group B) and no vibration (group C), respectively. This study exhibited that different effects on autonomic nerve activities were induced by different vibration frequencies. Arun et al. [11] were able to develop a system that can detect hypovigilance, which includes both drowsiness and lack of focus, using ECG signals.

3.2 Combination of Simulator and Actual Road Setting to Evaluate Drivers' Performance

Johnson et al. [14] had performed two separated studies to evaluate physiological responses to simulated and on-road driving. In a first study, three events were set into a simulated road circuit. The first event involved of an unexpected car join the road from the road shoulder, while the remaining two events comprised of a green traffic light changing to amber as the driver approached the intersection. In a second study, comparison on HR, oxygen consumption (VO2), and mean ventilation (MVE) responses to similar simulated and on-road drives had been performed. Another study conducted by Engström et al. [28] had investigated the effects of visual and cognitive demand on driving performance and driver condition under three experimental settings, static simulator, moving base simulator and actual road study. The results demonstrated that visual demand led to reduced speed and increased lane keeping variation. On the other hand, cognitive load did not affect speed and resulted in reduced lane keeping variation. Moreover, the cognitive load resulted in increased gaze concentration towards the road centre.

Table 1 Summary of recent studies by using HR as one of physiological measures

Common symbols: S=Simulator, NR=Not reported
Abbreviations: BPM=Beat per minutes, FD=Frequency domain, FFT=Fast Fourier Transform, HF=High frequency, LF=Low frequency, MD=Mean distance, MF=Mid frequency, MRT=Mean Response Time, MSE=Micro sleep power, MV=Mean velocity, PSD=Power spectral density, RR=Rhythm to rhythm, RT=Reaction time, SD=Standard deviation, TD=Time domain, VLD=Variation lane deviation, VLF=Very low frequency

No	References	Study design	HR setting & analysis	HR findings & suggestions
1	Jagannath & Balasubramanian [16]	Subject: 20 drivers Country: India Condition: S (static), 60 minutes	Monitored using Model 900 Pulse Oximeter during driving.	HR decreased significantly from 76.6 to 69.2 bpm.
2	Heinze et al. [17]	Subject: 5 subjects Country: Germany Condition: S (night), 55 minutes (40 min driving task, 10 min compensatory tracking task and 5min psychometric vigilance test.	HR derived from the ECG by detecting the position of R-peaks. HR and HRF used here were calculated using a 5 minute moving window with time steps of one minute. In the FD, the PSD of the RR time series was calculated using the FFT. Based on the PSD result, the power values for different frequency bands were derived. The commonly used standard frequency bands are VLF, 0-0.04 Hz, LF, 0.04-0.15 Hz and HF 0.15-0.40 Hz.	Correlation between HR and KSS is stronger than the correlation between HR and VLD.
3	Hefner et al. [18]	Subject: 1 subject (pilot study) Country: Germany Condition: S (3 tests), 40 minutes monotonous driving	TD of HR measures calculated directly from the ECG are the Mean and SD of the RR intervals which denoted as "MRR" and "SDRR". Or also the Zero Crossings. FD in VLF, LF and HF. FD parameters include the mean relative powers of VLF, LF, and HF bands, and SD VLF.	There is strong correlations between heart rate variability (HRV) measures and multiple fatigue measures, but to confirm these results, and to generalize our findings will require data collection and analysis of additional subjects.
4	Son et al. [15]	Subject: 30 males Country: Korea/USA Condition: S (highway) 2 groups, aged 25-35 and 60-69, engaged in 3 levels of a delayed auditory recall task	Mean and SD for HR (comparison between baseline, during driving, and recovery for two age groups)	HR and skin conductance increased with each level of demand, demonstrating that these indices can correctly rank order cognitive workload.
5	Ronen, & Yair [19]	Subject: 45 drivers Country: Israel Condition: S, 30-40 minutes	ECG signals were recorded from 2 electrodes at 500 samples/s Hz using Atlas Researches LTD polygraph connected to a PC computer by an optic fibre. Analysis: Average % changes (relative to the baseline of 100% before the drive) in HRV and standard error during each road type. Divided it into 3 periods.	HR decreased during all sessions in all three road types but with different patterns. HR decrease between the 1st period and 3rd period was relatively large for straight road (decrease of 8.5 bpm, and minor on the curved road (decrease of less than 2 bpm) and urban road (decrease of less than 4 bpm).
6	Li et al. [20]	Subject: 40 subjects (study and control groups) Country: China Condition: S, 3 hours, velocity 80 km/h at an expressway	Differences between 2 continuous variables were compared with 2-tailed T-test. Mann–Whitney rank sum test was used to compare non-continuous parameters. Two-way analysis of variance was used to analyse the interaction of group (treatment and control) and time-of-test (before and after). Results are given as mean value.	Average HR tend to decrease over the time, and in the tired state after 3 hrs driving. Limitation: Not measured HRV due to limitation of equipment.
7	Ünal et al. [21]	Subject: 47 subjects	ECG signal was recorded at 250 Hz. For resting and	Arousal was higher in the presence than absence of music

		Country: Netherlands Condition: S, with music and without music	experimental sections, mean HR and HRV in the MF band were computed. Similar to the procedure with the car-following performance indicators, mean HR and HRV scores were recorded based on 5-min intervals of the 30-min driving task.	irrespective of the volume level. Mental effort, which was inferred from the physiological measurement of heart-rate variability, did not differ in conditions with and without music.
8	Zhao et al. [22]	Subject: 13 subjects Country: China Condition: S, 90 minutes, simple highway scene with very light curvature	ECG sampled at 500 Hz with a 0.05–70 Hz band-pass filter and 50 Hz notched	There was significant differences before and after long term driving. In future studies, the sample size should be increased in order to preferably reduce inter-subject differences. At the same time, a control group for some other task should be considered in the design of the experiment in order to find more reliable physiological measurements for driving mental fatigue.
9	Johnson et al. [14]	Subject: 24 drivers Country: Canada Condition: S, 3 unexpected events.	HR was recorded at 100 Hz by ECG. Mean HR was calculated for 15-second periods surrounding each unexpected event, resulting in a pre-event HR and a post-event HR Two-way ANOVA and Tukey's Significant Difference post-hoc analysis were used to assess the effects of event (Car, Light 1, and Light 2) and time (Pre and Post) on Mean HR. A one-way ANOVA was used to assess differences between relative change values between the three events.	HR is a sensitive marker for both driving related and general changes in cognitive workload even though no abnormal driving behaviour occurred. Further studies are needed to improve simulator test, to understand interaction between individuals (gender, age, experience, etc.), driving outcomes (accidents, lane changes, decision making, etc.), and behavioural elements (attention, vigilance, visual search).
10	Larue et al. [23]	Subject: 25 subjects Country: Australia Condition: S, 1 hour, 4 different scenarios	ECG (one channel) Testing times were 9 am (7 participants), 11 am (5 participants), 1 pm (9 participants) and 3 pm (4 participants).	HR decreased from 0.101 to 0.00 in the case of alertness decrement. No difference with the reference was observed in the case of MS for HR and inter-beat-intervals. HRV increased only when MS occurred, from 0.07 to 0.16, while no trend was observed for the T-wave amplitude. Limitation of this study is that participants were not asked to avoid drinking caffeine beverages before the study.
11	Jap et al. [24]	Subject: 52 drivers Country: Australia Condition: S	HR was collected before and after the driving task. Conducted around noon ±1.5 h in a temperature-controlled laboratory. Analysis: T-test	Average pre-study HR was 72 ± 10 beats/min and 65 ± 9 beats/min for the post-study HR.
12	Reimer et al. [30]	Subject: 37 subjects Country: USA Condition: S, data recorded in 3 periods (P1, P2, P3)	A model SRC-2 pulse oximeter photoelectric plethysmograph sensor (Nellcor Puritan Bennett, Inc., Pleasanton, CA) was placed on each subject's left middle finger and connected to an Angilent A1 Patient Monitor to record heart rate every 20 s. Analysis: T-test	At baseline, late middle age (M) HR appeared marginally higher than young age (Y), although this difference was not statistically significant ($F_{(1, 35)} = 3.19$, $p = .083$). Follow-up with a larger sample is indicated to further investigate the patterns that may appear in response to this task
13	Heinze et al. [25]	Subject: 5 subjects Country: Germany Condition: S (overnight), 1 hour (40 min driving)	HR was recorded over the entire experiment; HR-measures were derived and correlated against measures that were established from driving and vigilance task performance.	Lateral lane deviation exhibits good correlations to HR measures. The strong coherence between long-term HRV properties and specific fatigue measures suggests the possibility to predict driver and operator fatigue in the middle-term (around 30 minutes) solely from HR. Larger study samples in the future.
14	Engström, et al.	Subject: 48 (fixed	Electrocardiogram (ECG, for measuring heart rate) was	HRV were significantly reduced both in the simulator

	[28]	simulator), 48 (moving base simulator, 24 (actual) Country: Sweden Condition: S & A (different conditions)	sampled at 1024 Hz. The measures only recorded in the moving base simulator and actual road.	$F_{(3,50)} = 1.025$, $p < .05$) and in the field ($F_{(3,66)} = 3.73$, $p < .05$). No significant effect was found in HRV, although there was a tendency for a decrease (indicating increased workload). Future study tried to use similar road condition in simulator and actual road to compare.
15	Lenneman, & Backs [26]	Subject: 32 subjects Country: USA Condition: S (2 driving tasks-driving task, and *n-back* task)	ECG-Impedance cardiogram data for 2 participants were collected using a Minnesota Impedance Cardiograph Model304b, and data for the other 30 participants were collected using a Mindware Impedance Cardiograph Model 2000.	HR increased significantly and HRV (HF) decreased significantly.
16	Jiao et al. [27]	Subject: 60 subjects Country: China Condition: S, 90 minutes	LF and HF components of HRV, and the LF:HF ratio were measured throughout all periods. All HRV indices were calculated in the pre, mid and end of experiment period, and analysed by repeated measures analysis of variance.	Significant differences in all indices of HRV were observed between different experiment periods and between any two groups.
17	Arun et al. [11]	Subject: 15 subjects Country: Malaysia Condition: S, 2 hours	Electrodes were placed in the arms and legs to measure ECG data. Power Lab Data Acquisition System was used to collect the ECG data at a sampling frequency of 1000 Hz.	Energy feature of ECG is efficient to detect hypo vigilance with a maximum accuracy of 98%.

3.3 Cell Phone Effect while Driving in the Simulator

Driver inattention includes concentrating on secondary tasks such as using cell phone and music player while driving. In the US, damages of $43 billion per year has been estimated due to cell phone related crashes [29]). In this review, there is one paper conducted a study on cell phone as secondary task while driving.

Reimer et al. had compared middle age and younger adult performance when dealing with hand free phone demands under three periods segments [30]. The analysis of heart rate during the three segments (P1–P3) shows a significant main effect of period $F(2, 68) = 10.578$, $p < .01$, and a significant interaction between immediately prior to the phone task (P1) (paired t-test $T(37) = ?0.439$, $p > .05$). The analysis of heart rate during the three segments (P1–P3) shows a significant main effect of period $F (2, 68) = 10.578$, $p < .01$, and a significant interaction between age and period $F(2, 68) = 6.079$, $p < .01$.

Based on these past studies, using mobile phone while driving had a slight effect on the driver performance. Therefore, some advice and guidelines can be provided to authorities, manufacturers, and drivers when handling with mobile phone while driving. It is suggested that drivers use hands free mobile telephone sets. Or else, the drivers do not have it, they must keep sufficient distance from the other traffic users and drive at moderate speed in the slower traffic lanes [31].

3.4 Main Discussion from 17 studies

Overall, all these reviewed studies had discussed on a few main points as listed below:

i. HR value will be decreased after driving.
ii. Past study combines HR measures with other measures tools, either in subjective or objective way.
iii. There is strong correlation between HR and KSS (Sleepiness Scale).
iv. There is strong correlation between HR and lane deviation (driving performance with regards to steering wheel control).
v. There is strong correlation between HR and multiple fatigue measures.
vi. There is significant difference between HR and different setting parameters, such as simulator setting (static/moving base), vibration frequencies, and different task while driving.

Table 2 depicted the point based on the above-mentioned lists according to the past studies.

Table 2 Points taken based on past studies

Authors	i	ii	iii	iv	v	vi
[16]	✓	✓				
[17]		✓	✓	✓		
[18]		✓			✓	
[15]		✓			✓	
[19]	✓	✓			✓	
[20]	✓	✓				
[22]	✓	✓				
[23]	✓					
[24]	✓					
[25]		✓		✓		
[27]						✓
[14]		✓				
[28])						✓
[30]						✓
[21]						✓
[11]						✓
[26]	✓					

4.0 CONCLUSIONS

This review indicates that drivers' fatigue is important issues need to be deal to reduce road traffic accidents. Therefore, fatigue countermeasures are needed which provide a better solution to detect drivers' fatigue and determine driving performance. Normally, experiments involving driving over long distance of highway on the normal roads took some efforts due to time consuming to setup the equipment, high cost, hard to control and also potentially high risk. With the development of better display, computing power and motion technologies, driving simulators are becoming more realistic because the researcher can control the experiment parameter and less risky.

Based on past studies, there is evidence that HR can determine the individual physiological level of workload. HR generally increases with arousal and workload. Nevertheless, the HR may fluctuate either increase or decrease based on how attention is directed or allocated. In addition, as noted previously, most studies show that HRV decreases during high demand task. It has also been shown that HR decreases significantly during a monotonous driving task.

Overall, even though there is numerous research conducted on HR measures, however, there is still limitation in the past studies. In addition, it is very important to investigate the drivers' performance impairment and implement intervention programs to reduce traffic accident. A detailed review on these measures will provide insight for future studies and enhancements can be performed to find the best parameters to determine the driver performance.

Acknowledgement

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