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ORIGINAL ARTICLE

Regression Analysis of Heart Rate for Driving Fatigue Using Box-Behnken Design.

Muhammad Shafiq Ibrahim[1], Seri Rahayu Kamat[1], Syamimi Shamsuddin[2]

Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka,

Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia[1]

Department of Community Health, Advanced Medical and Dental Institute, Universiti Sains

Malaysia, 13200 Kepala Batas, Pulau Pinang, Malaysia[2]

seri@utem.edu.my [1]

Abstract: There are few road accident studies that use heart rate as an indicator of driving fatigue. This study offers a mathematical regression analysis to discover which independent variables (driving speed, driving duration, body mass index (BMI), gender and types of roads) are significant in influencing the heart rate and the way these parameters interact to indicate driver fatigue. The regression analysis was conducted using a Box-Behnken design by Design Expert software. The results revealed that the values of Prob>F for all variables were less than 0.01%, indicating that all variables influenced heart rate significantly. The heart rate increased when driving speed, driving duration and BMI increased. The similar pattern was observed as the driving path shifted from urban to a moderately difficult uphill/downhill road. However, the pulse rate reduced when a female driver was replaced by a male driver. The model's accuracy was evaluated by comparing the output data obtained from actual road driving with software prediction. First, the prediction interval of both techniques' output data was within 95%, meeting the minimum quantitative criteria of 90% predictive interval. Subsequently, the residual errors were less than 10%. The application of regression analysis to investigate the driver's physiological system as a factor in driving fatigue is becoming less common. The majority of current research focuses on perceptual, psychological and electrophysiological methods to detect driving fatigue. As a result, a future study will assess the effect of cognitive skills impairment, such as decision-making, on driving fatigue using the same methodology. The regression model will be useful to shed light on traffic safety measures for preventing fatigue-related road accidents.

Keywords: driving fatigue, heart rate, regression analysis, road accident, mathematical regression analysis.

1.0 INTRODUCTION

Fatalities and injuries on the world's roadways have become a worrying public health issue, particularly in low-and middle-income nations like Malaysia. The number of traffic collision cases in Malaysia has climbed from 462,426 cases in 2012 to 567,516 cases in 2019, according to a recently released figure by the Malaysian Institute of Road Safety Research (MIROS). Due to the adoption of the movement control order (MCO) during the COVID-19 epidemic, the trend was reduced significantly to 418,245 cases by 2020 [1].

Fatigue-related loss of awareness, a sluggish decision-making process and an inability to recognise incoming dangers are the leading causes of traffic accidents [2]. Driving fatigue is the extreme tiredness caused by physical or mental exertion while operating a motor vehicle. In this situation, it is very important to find out what causes drivers to get fatigue so that they can be kept from getting into accidents.

A review of the existing literature revealed that very few studies have investigated on the potential of human physiological systems, such as heart rate in indicating driver fatigue. According to studies, heart rate is a reliable indicator of fatigue because it reflects both a mental and physical state under a variety of task demands. A study found that the heart rate declines as driving time increases [3]. A decrease in heart rate causes low blood pressure, which in turn causes chest pain due to an inadequate supply of oxygen-rich blood to the heart muscle, resulting in fatigue [4]. Therefore, it is reasonable to assume heart rate as an indicator to driving fatigue.

Hence, the purpose of this study was to determine which independent variables, namely (i) driving speed, (ii) driving duration, (iii) body mass index (BMI), (iv) gender and (v) types of roads, are significant in influencing the heart rate and how these factors influence each other in indicating driving fatigue using mathematical regression analysis with a Box-Behnken design using Design Expert software.

2.0 METHODOLOGY

The whole experiment was conducted in real-world driving conditions. The independent variables and their levels were set first before designing an experimental design layout. The experiment was then conducted after a series of preliminary fatigue evaluations.

Independent Variable Selection and Level Setting

<u>*Driving Speed*</u>

Driving speed has been demonstrated to have a significant impact on physiological behaviour. According to one study, when driving aggressively (at high speeds), the heart rate increased by about 3% [5]. A study discovered a considerable increase in heart rate while driving at 100km/h [6].

Driving Duration

The longer the driving duration, the more stressful events, such as maintaining a constant pace or merely sitting in traffic may trigger an acute stress response, impacting important physiological systems. A study discovered that 15 to 30 minutes of driving is adequate to generate fatigue and influenced the average heart rate [7].

Body Mass Index (BMI)

High BMI individuals' blood volume and cardiac output increase due to increased mass and baseline oxygen demand. A study discovered that very obese adults (BMI: 53 kg/m^2) needed 60% more oxygen at rest than normal-weight patients [8]. A study found that obese drivers suffer from reduced oxygen saturation compared to healthy drivers during 30 minutes of driving [9]. Obese people may have enhanced neural respiratory drive to compensate for increased ventilatory burden. When these compensatory systems fail, the risk of cardiovascular disorders such as hypertension (high blood pressure), coronary artery disease (CAD), stroke and heart failure increases [10].

Types of Roads

Road geometry, such as uphill/downhill and urban roads, has an impact on road accidents. A study discovered that when driving on an uphill/downhill route at a higher speed than on a monotonous road, drivers gradually grew drowsier and thus made more driving errors [11]. The presence of street lighting and in most but not all situations, the presence of curbs and channels adjacent to the roadside distinguishes urban roadways. Driving fatigue may result from having to brake hard to prevent an accident, as well as braking and pulling away at traffic lights [12].

Gender

Because of anatomical and physiological differences, physiological system performance limits may differ by gender. Men have more muscle mass, bone mass and a lower body fat percentage than women. These variations affect many organ systems in adult males and females, potentially affecting physiological function [13]. Even after accounting for height, men have larger lungs, wider airways and greater lung diffusion capacity than women.

Table I: Design summary of experimental design (independent variable)

	Minimum	Maximum	Unit
Numeric Variable			
Driving Speed	80.00	100.00	km/h
Driving Duration	15.00	30.00	minute
BMI	18.50	35.00	kg/m²
Categorical Variable			
Types of Roads	Uphill/downhill	Urban	-
Gender	Female	Male	-

Experimental Design Layout

The experimental design layout is a collection of input parameter (independent variable) combinations at their corresponding levels. The Design Expert software generated 68 experimental runs based on the five independent variables and their levels. The Box-Behnken design was employed as this statistical technique is deemed effective to determine the regression model and optimize an output response which is affected by several independent variables. The heart rate data (output response) was then entered into the layout for next analysis.

Table II: Sample of experimental design layout

Run	A: Driving Speed, km/h	B: Driving Duration, min	C: BMI, kg/m²	D: Gender	E: Types of Roads
1	80	15.0	18.50	Male	Urban
2	80	22.5	26.75	Male	Uphill/Downhill
	…	…	…		…
68	100	22.5	26.75	Female	Urban

Demographic Data

15 female and 15 male volunteers participated to perform all 68 experimental runs. All participants were between the ages of 20 and 25, as young drivers within this range have higher fatal and non-fatal crash rates than drivers in the middle-age ranges [14]. All volunteers were free of both short-and long-term diseases and required no daily medication.

Experimental Procedure

Preliminary fatigue evaluation

The data are not accurate if the volunteers are already fatigued prior to data collection. To ensure that the volunteers were competent and that the level of fatigue was comparable, the experiment began by ordering the volunteers to go through two steps of preliminary fatigue evaluations.

Step 1: Complete the volunteer’s readiness checklist

A question checklist was distributed before the experiment to verify the volunteers' readiness. Questions such as "Did you receive at least eight to nine hours of adequate sleep last night?" "Did you consume alcohol- or caffeine-containing beverages in the last seven hours?" "Did you take any medication in the last 3 days?" and "Did you have breakfast this morning?" were asked. If any of these criteria hadn't been fulfilled, the volunteers would have refused to take part.

Step 2: Conduct the blood pressure measurements

Insufficient nighttime sleep may contribute to high blood pressure (hypertension), which may have negative effects on the heart, eyes and lungs. Before the driving test, volunteers' blood pressure was measured with an Omron Evolv to ensure they had normal blood pressure below 120 mm Hg for systolic and below 80 mm Hg for diastolic.

Experimental Details

An automatic transmission Perodua Bezza GA T was used. The driving test was performed between 9:00 a.m. and 10:00 a.m., when there were fewer reported fatigue-related traffic accidents [15] and fewer traffic. All experiments were conducted during sunny days, and cell phone and radio use while driving was prohibited. The uphill/downhill road driving tests were conducted out from Simpang Masjid Tanah, Alor Gajah (2.409561830410841, 102.15719833139521) to Ayer Limau, Alor Gajah (2.3738230511734275,102.11318864589161). Meanwhile, the urban road driving tests were conducted out from Mydin MITC Ayer Keroh (2.271108717375982, 102.29262414154466) to Universiti Teknikal Malaysia Melaka - Kampus Teknologi (2.279860517578614, 102.27356448764729). The participant's heart rate was measured by placing a wireless pulse oximeter on their fingertip. The heart rate measurements for each experimental run were taken both prior to and just after the driving task.

3.0 RESULTS AND DISCUSSION

Heart Rate Before and After the Driving Experiment

Figure 1 shows an increment in heart rate after the driving experiment, showing that driving activity had a significant impact on the human physiological system.

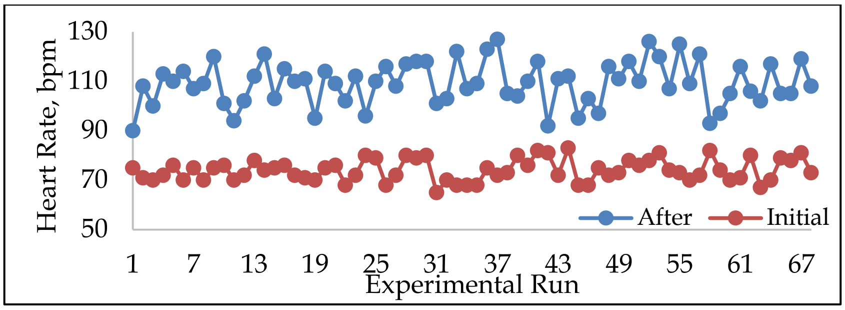

Figure 1: Heart rate initial and after driving experiment

Analysis of Variance (ANOVA

The ANOVA by Design Expert software was conducted using the heart rate data acquired after the driving experiment to determine which independent variable had a significant impact on the dependent variable and how the dependent variable responded when confronted with multiple independent variables in signalling driver fatigue.

Table III: ANOVA analysis

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	4941.28	5	988.26	278.57	< 0.0001
A	1104.50	1	1104.50	311.34	< 0.0001
B	1339.03	1	1339.03	377.45	< 0.0001
C	1188.28	1	1188.28	334.95	< 0.0001
D	648.53	1	648.53	182.81	< 0.0001
E	660.94	1	660.94	186.31	< 0.0001
Residual	219.95	62	3.55		
Lack of Fit	150.35	46	3.27	0.75	0.7799
Pure Error	69.60	16	4.35		
Cor Total	5161.24				

The Prob>F values for A = Driving Speed, B = Driving Duration, C = BMI, D = Gender and E = Types of Roads were less than 0.01%, indicating that the independent variables significantly influenced the dependent variable (heart rate). The following section discusses the interaction between the independent variables and heart rate in indicating driver fatigue by comparing the data obtained by software prediction (using equations in Table IV) and actual driving experiments.

Driving speed

Figure 2(a) depicts the changes in heart rate for data obtained by software prediction and actual driving, which increased as the driving speed increased from 80 km/h to 100 km/h. The results may be attributable to the adrenaline produced by stressful driving situations. There is a strong relationship between the driver's cognitive workload and the choice of vehicle speed. When confronting stressful and complex situations, a driver tended to alter the vehicle's speed and increase his or her level of attention in order to effectively manage task difficulty. The consequence of how the human brain adapts to stressful events will have a negative impact on the ensuing behavioural and psychological response [16]. A study examining the relationship between emotional state and driving speed among taxi drivers on the job found that intense emotions such as anger and sadness have significant effects on increasing driving speed [17]. According to a study [18], the heart rate's reaction to stressful situations is significantly greater than its reaction to non-stressful situations. The human body releases adrenaline, a hormone that temporarily increases the heart rate and blood flow to the brain and muscles, in response to such a dangerous and threatening situation. So, the stressful driving events that caused the driver to speed up had an immediate effect on the heart rate.

Driving duration

Figure 2(b) demonstrates that as the duration of driving increased from 15 to 30 minutes, the heart rate increased. The trend may be caused by the adrenaline produced by stressful driving situations. Driving a vehicle is a stressful activity involving a series of hazardous and unpredictable occurrences. According to a study [18], the heart rate responds to stress. A study provided moderate evidence to conclude that long hours of driving induce a prolonged stress response [19]. According to a study, extremely long driving duration and irregular working hours are the causes of stress among long-distance truck drivers [20]. In response to stress, as depicted in Figure 2a, the human body temporarily releases adrenaline, a hormone that causes the heart rate to increase in order to increase the force of the heart's contraction. Therefore, the stress caused by long periods of driving significantly increased the heart rate.

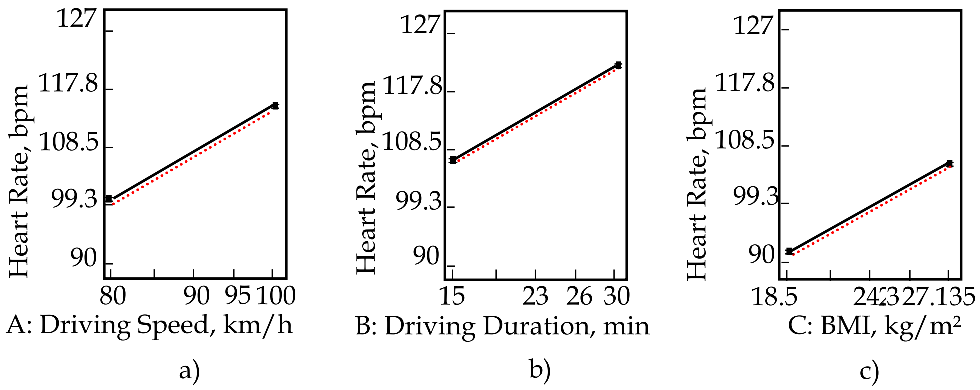

Figure 2: Interaction between heart rate and (a) driving speed; (b) driving duration; (c) BMI
—: Actual driving experiment; ······· : Software prediction

BMI

Figure 2(c) depicts the increase in heart rate as BMI increased from 18.50 kg/m² (healthy) to 35.00 kg/m² (obese). The trend may be linked to an obesity-related illness. A person with a BMI of 30 kg/m² or higher is more likely to suffer from atrial fibrillation, which is characterised by an irregular and frequently abnormally rapid heart rate (AF). A study revealed that obese people have a nearly 40% higher risk of developing atrial fibrillation than non-obese people [21]. This finding is consistent with previous research, as obese individuals have a more rapid heart rate than adults with a normal BMI [22]. The accumulation of excessive fatty substances in the arteries of obese individuals causes the heart to pump more forcefully in order to continuously supply blood to the organs, resulting in a faster heart rate. Due to stimulation from the nervous system, the increasing heart rate causes hypertension by increasing the blood pressure on the inner walls of the arteries. A study found that drivers of long-distance trucks with a BMI of 30 kg/m² or higher are more likely to suffer from hypertension [23].

Gender

Figure 3(a) displays the decrease in heart rate acquired by software prediction and actual driving experiments when female drivers were replaced with male drivers. The distinction in sex hormones may account for the decrease in heart rate. Driving is stressful because it involves a variety of intense events that men and women respond differently. Additionally, driving necessitates a high level of multiple cognitive functions, such as attention, visuospatial skills, and memory, which may induce stress. According to a study, stressful life activities can cause an abnormally rapid heart rate [18]. A study revealed that women are twice as likely as men to experience severe anxiety and stress

[24]. In accordance with a previous study, women experience a greater susceptibility to stress behind the wheel than men, as their hormonal systems cause them to react more emotionally [25]. Moreover, the hormonal changes that occur during puberty and perimenopause may cause dysregulation of biological stress, making women more sensitive to their surroundings [26]. Therefore, a woman's hormonal system has a big effect on how she feels, which in turn affects her heart rate.

Types of Roads

Figure 3(b) depicts the pattern of heart rate for both methods inclining as the road geometry changes from urban to uphill/ downhill. The results demonstrated that the design of the road geometry had a significant effect on driving performance by altering heart rate. The heart rate decreased while driving on a less demanding urban road compared to a relatively demanding uphill/downhill road. The uphill/downhill road provided a greater variety of geometry and demanded maximum task effort to negotiate numerous steep slopes and corners. Compared to the latter, this type of road requires greater alertness and vigilance to prevent collisions. A study revealed that a driver's alertness decreased significantly when driving in a less demanding environment and route design [27]. A different study confirmed that the driver becomes fatigued quickly while driving on the expressway and that the fatigue level is significantly higher than when driving on a road with varying geometry for the same duration [28]. Under such conditions, drivers tend to experience more passive fatigue symptoms, which can lead to fatigue driving. A study compared the heart rate fluctuations of normal and sleepy driving, the heart rate decreases significantly from 85+-5.6 bpm to 81.5+-bpm during fatigue driving [29]. Thus, a less challenging urban road led to a low heart rate because it had a different effect on the body.

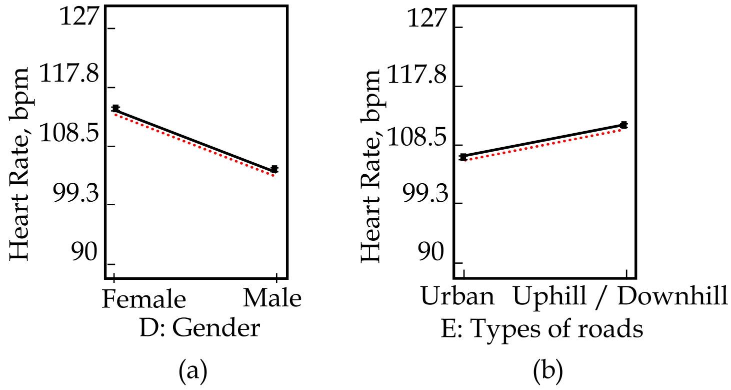

Figure 3: Interaction between heart rate and (a) gender; (b) types of roads
—: Actual driving experiment; ······ : Software prediction

Regression Model Validation

The mathematical regression model was validated to assess its accuracy in predicting which independent variable significantly influenced the dependent variable (heart rate) and how the dependent variable responded when confronted with multiple independent variables signalling driver fatigue. The validation was done by comparing the heart rate value from the software's prediction with the heart rate value from the actual driving experiment:

1) The predictive interval for the dependent value calculated using software prediction and actual driving experimentation must be within 90% of the true value. The polynomial equations as summarized in Table IV were utilized to forecast the heart rate value. In order to predict the heart rate, the actual unit of each independent variable was put into the equations. This was done by referring to the experimental design layout.
2) The accuracy of the regression model is high if the residual error is less than 10%.

Table IV: Polynomial regression equation to predict an output response

	Gender: Female	**Road: Urban**
1	Heart Rate = + 11.25432 + (0.58750 * Driving Speed) + (0.86250 * Driving Duration) + (1.05978 * BMI)	
	Gender: Male	**Road: Urban**
2	Heart Rate = + 5.07785 + (0.58750 * Driving Speed) + (0.86250 * Driving Duration) + (1.05978 * BMI)	
	Gender: Female	**Road: Uphill/Downhill**
3	Heart Rate = + 17.48961 + (0.58750 * Driving Speed) + (0.86250 * Driving Duration) + (1.05978 * BMI)	
	Gender: Male	**Road: Uphill/Downhill**
4	Heart Rate = + 11.31314 + (0.58750 * Driving Speed) + (0.86250 * Driving Duration) + (1.05978 * BMI)	

As shown in Table V, the validation outcomes for all three samples (3 out of 68 runs) satisfy the quantitative requirements for a precise output prediction. First, the dependent value predictive interval obtained through software prediction and actual driving experiment was within 95%, meeting the minimum quantitative requirements for a 90% predictive interval. The residual errors are also less than 10%.

Table V: Data validation (A= Driving Speed, B= Driving Duration, C= BMI, D= Gender and E= Types of Roads)

Run	Input Parameter	Prediction (bpm)	Actual (bpm)	95% PI low (bpm)	95% PI high (bpm)	Error (%)
23	A= 100 km/h B= 15 min C= 24.25 kg/m² D= Female E= Urban	108.64	112	104.68	112.60	3.36
49	A= 80 km/h B= 24.25 min C= 30.00 kg/m² D= Female E= Urban	109.45	111	105.49	113.41	1.55
58	A= 80 km/h B= 24.25 min C= 18.50 kg/m² D= Male E= Urban	91.09	93	87.13	95.05	1.91

4.0 CONCLUSION

The Analysis of Variance (ANOVA) shows that the Prob>F values for A=Driving Speed, B=Driving Duration, C=BMI, D=Gender, and E=Types of Roads are less than 0.01%. This means that the independent variables have a large effect on the dependent variable. Due to the release of adrenaline hormones when driving is stressful, the heart rate increases with driving speed and driving duration. The same trend is seen as BMI increased and driving roads changed from urban to having more uphill and downhill turns due to diseases linked to obesity and sensory simulations of the road environment, respectively. In addition, contrasting trends in heart rates were also observed between drivers of different genders. The male drivers showcased a lower heart rate trends as opposed to the female drivers. This is most notably due to biological differences such as sex hormones. The regression model was validated to see how accurate it is by comparing the output data from software predictions and real-world driving experiments. First, the model was very good at predicting data within a 95% predictive interval, which meets the minimum quantitative requirement of a 90% predictive interval. Second, the model's predictions of the heart rate were accurate because the model's errors were less than 10%. The use of regression analysis to look into the health of the driver as a factor in driving fatigue is less prevalent. The majority of current research focuses on perceptual, psychological and electrophysiological methods to detect driving fatigue. As a result, using the same methods, a future study will evaluate the role of cognitive skills impairment, such as decision-making to indicate driving fatigue. The study's findings will assist researchers and policymakers in the field of road safety in taking appropriate measures to prevent road accidents.

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