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

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ABSTRACT

There are few road accident studies that use heart rate as an indicator of driver fatigue. This study offers a mathematical regression analysis to discover which independent variables (driving speed, driving duration, body mass index, gender , and types of roads) are significant in influencing the heart rate and how these parameters interact to indicate driver fatigue. The analysis is 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 influence heart rate significantly. The heart rate increased when driving speed, driving duration and body mass index (BMI) increased. A similar pattern was observed as the driving path shifted from urban to a moderately difficult uphill/downhill road. However, the pulse rate was 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 a 90% predictive interval. Subsequently, the residual errors were less than 10%. The regression model will be useful to shed light on traffic safety measures for preventing fatigue-related road accidents.

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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 climbed from 462,426 in 2012 to 567,516 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 fatigued so that they can be kept from getting into accidents.

A review of the existing literature revealed that very few studies have investigated 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 of driving fatigue.

Hence, the purpose of this study is 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.

Methodology

Independent variable selection and its level setting

Driving speed

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 100 km/h [6].

Driving duration

The longer the driving duration, the more stressful events, like maintaining a constant pace or merely sitting in traffic may trigger an acute stress response, impacting physiological systems [7]. Studies found that 15 to 30 minutes of driving is adequate to cause fatigue [8] and influence the average heart rate [9].

Body Mass Index (BMI)

High BMI individuals' blood volume and cardiac output increase due to increased mass and baseline oxygen demand [9]. A study discovered that very obese adults (BMI: 53 kg/m²) needed 60% more oxygen at rest than normal-weight patients [10]. A study found that obese drivers suffer from reduced oxygen saturation compared to healthy drivers during 30 minutes of driving [11]. 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 [12].

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 [13]. 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 [14].

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 [15]. Even after accounting for height, men have larger lungs, wider airways, and greater lung diffusion capacity than women. Table 1 summarizes the details of the independent variables.

Table 1: 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 heart rate data (output response) was then entered into the layout. Table 2 shows the sample of experimental design layout.

Table 2: 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	Heart rate bpm (after)
1	80	15.0	18.50	Male	Urban	90
2	80	22.5	26.75	Male	Uphill/downhill	108
…	…	…	…		…	…
68	100	22.5	26.75	Female	Urban	107

Demographic data

Six female and six 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 [16]. All volunteers were free of both short-and long-term diseases and required no daily medication.

Experimental procedure

First, anthropometric measurements and a health assessment were performed. The participants were instructed to get between seven and nine hours of sleep the night before the driving test in order to ensure that baseline fatigue levels were comparable among the subjects. 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. The participants were also told not to drink anything with caffeine or alcohol for seven to eight hours before the experiment. 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 [17] and less 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. Figure 1 illustrates the experimental flow.

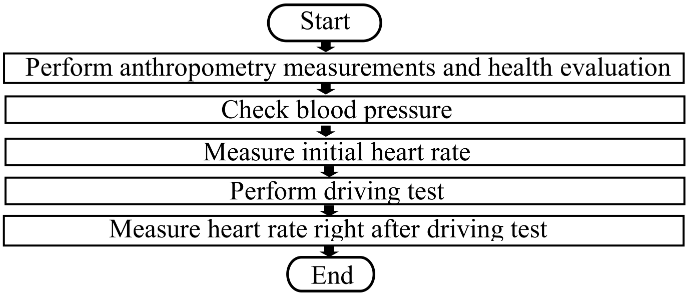


Figure 1: Experimental flow

Results and Discussion

Heart rate before and after the driving experiment

Figure 2 shows an increment in heart rate after the driving experiment, showing that driving activity had a significant impact on the human physiological system.

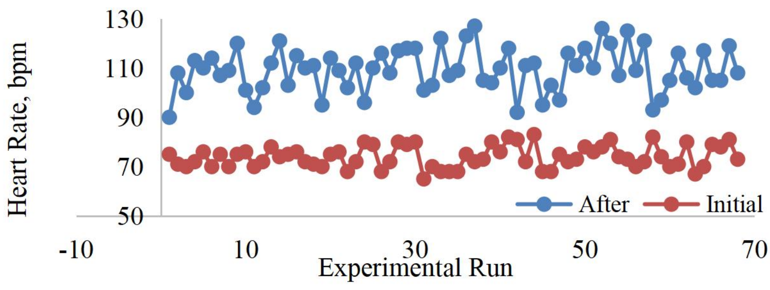


Figure 2: Heart rate initial and after driving experiment

Analysis of Variance (ANOVA)

The Analysis of Variance (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 3 shows the results of the ANOVA analysis.

Table 3: 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	67			

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 4) and actual driving experiments.

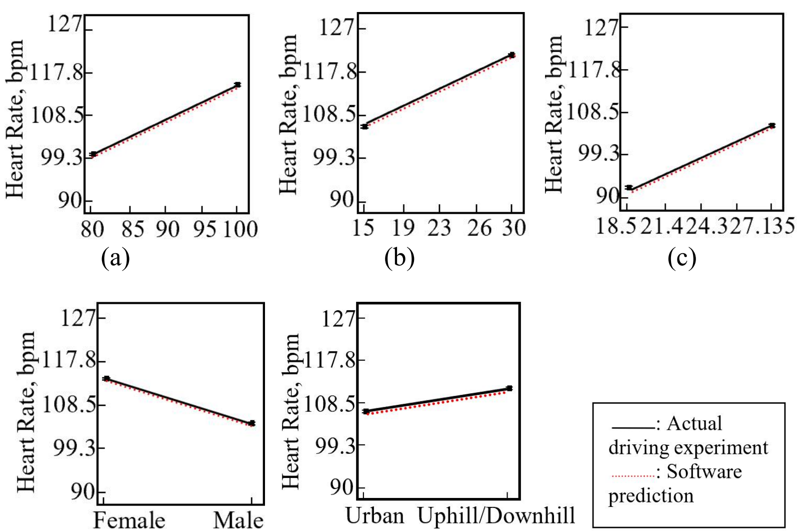
Driving speed: Figure 3(a) depicts the changes in heart rate for data obtained by software prediction and actual driving, which increased as the driving speed increased from 80 km/h to 100 km/h. The results may be attributable to the adrenaline produced by stressful driving situations. There is a strong relationship between the driver's cognitive workload and the choice of vehicle speed. When confronting stressful and complex situations, a driver tends 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 [18]. 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 [19]. According to studies [20]-[21], 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 3(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 studies [20]-[21], the heart rate responds to stress. A study provided moderate evidence to conclude that long hours of driving induce a prolonged stress response [22]. According to a study, extremely long driving duration and irregular working hours are the causes of stress among long-distance truck drivers [23]. In response to stress, 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 increases the heart rate.

BMI: Figure 3(c) depicts the increase in heart rate as BMI increased from 18.50 kg/m^2 (healthy) to 35.00 kg/m^2 (obese). The trend may be linked to an obesity-related illness. A person with a BMI of 30 kg/m^2 or higher is more likely to suffer from atrial fibrillation, which is characterised by an irregular and frequently abnormally rapid heart rate. A study revealed that obese people have a nearly 40% higher risk of developing atrial fibrillation than non-obese people [24]. This finding is consistent with previous research, as obese individuals have a more rapid heart rate than adults with a normal BMI [25]. 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/m^2 or higher are more likely to suffer from hypertension [26].

Gender: Figure 3(d) 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 [21]. A study revealed that women are twice as likely as men to experience severe anxiety and stress [27]. 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 [28]. Moreover, the hormonal changes that occur during puberty and perimenopause may cause dysregulation of biological stress, making women more sensitive to their surroundings [29]. 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(e 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 [30]. 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 [31]. Under such conditions, drivers tend to experience more passive fatigue symptoms, which can lead to fatigued driving. A study compared the heart rate fluctuations of normal and sleepy driving, the heart rate decreased significantly from 85+-5.6 beat per minute (bpm) to 81.5+-bpm during fatigue driving [32]. Thus, a less challenging urban road led to a low heart rate because it had a different effect on the body.



(d) (e)

Figure 3: Interaction between independent variables and heart rate (a) driving speed (km/h), (b) driving duration (min), (c) BMI (kg/m²), (d) gender, and (e) types of roads

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 4 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 4: Polynomial regression equation to predict an output response

1	Gender: female	Road: urban
	Heart rate = + 11.25432 + (0.58750 * driving speed) + (0.86250 * driving duration) + (1.05978 * BMI)	
2	Gender: male	Road: urban
	Heart rate = + 5.07785 + (0.58750 * driving speed) + (0.86250 * driving duration) + (1.05978 * BMI)	
3	Gender: female	Road: uphill/downhill
	Heart rate = + 17.48961 + (0.58750 * driving speed) + (0.86250 * driving duration) + (1.05978 * BMI)	
4	Gender: male	Road: uphill/downhill
	Heart rate = + 11.31314 + (0.58750 * driving speed) + (0.86250 * driving duration) + (1.05978 * BMI)	

As shown in Table 5, the validation outcomes for all three samples satisfy the quantitative requirements for a precise output prediction. First, the dependent value predictive interval obtained through software prediction and the 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 5: 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

Conclusion

The 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 goes up with driving speed and driving duration. The same trend is seen as BMI goes up and driving roads go from being urban to having more uphill and downhill turns due to diseases linked to obesity and sensory simulations of the road environment respectively. However, as a driver changes from female to male, their heart rate slows down because their sex hormones are different. The regression model is tested to see how accurate it is by comparing the output data from software predictions and real-world driving experiments. First, the model is 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 are very accurate because the model's errors are less than 10%.

Contributions of Authors

M.S. Ibrahim: Conceptualization, Methodology, Software, Writing- Original Draft Preparation, S.R. Kamat: Data Curation, Validation, Supervision; Software, Validation, Writing Reviewing and M. Fukumi: Writing-Reviewing and Editing.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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