A Study of Psychophysical Factor for Driver Fatigue Using Mathematical Model

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ABSTRACT

The purpose behind the study is to develop the mathematical modeling of a psychophysical factors for drivers' fatigue, which can predict the relationship between the process input parameters and output response. Ten subjects participated in this study. The electromyography (EMG) responses were taken and evaluated using an Electromyography (EMG) device. The psychophysical factor such as muscle fatigue is one of the contributors to the drivers' fatigue problem, which led to road accidents among Malaysian. To efficiently formulate and develop the mathematical modeling of a psychophysical factors, the process modeling using Response Surface Methodology (RSM) was proposed. Design Expert 8.0.6 software was used in the RSM analysis. The mathematical model was successfully developed and validated. The modeling validation runs were within the 90% prediction interval of the developed model, and the residual errors compared to the predicted values were less than 10%. The significant parameters that influenced the muscle fatigue were also identified. Muscle fatigue was influenced by the time exposure, type of road, gender, interaction between time exposure and type of road, and interaction between type of road and gender. Throughout this study, the authors believe there is a new contribution to the body of knowledge.

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Introduction

In the modern civilization, transportation becomes an important medium in development of the country. As a developing country, Malaysia nowadays had improvized its transportation, road and highway systems. This improvization had encouraged infrastructures, facilities and comfort ability among Malaysian users. Obviously, the used of road and highway were Malaysian preferred as this system getting better, cheap and affordable nowadays. As this medium offered huge benefit to human life, it also brings the negative effect on a nation is the loss of life whereby the human factor life is considered priceless. As road accidents in Malaysia always highest compared to other countries in the world, the statistic being disaster as new killer of the population. Traffic accidents, which involve cars, motorcycles and public transport, become a major problem in Malaysia. Since 1997 until 2014, the statistics shows an increasing number of accidents. According to the Malaysian Institute of Road Safety (MIROS), the rate of road accidents in Malaysia is one of the highest compared to other countries in the world. The road traffic statistic from 1997 to 2014 shows that the total number of accidents had risen from 215,632 cases (1997) to 476,196 cases in 2014.

Besides, MIROS has made the prediction on number of fatalities in 2015 and 2020. They have predicted that there will be 8,760 fatalities in 2015, while 10,716 fatalities in 2020 [1]. The U.S. National Highway Traffic Safety Administration (NHTSA) reported that every year, around 100,000 traffic accidents and 71,000 injuries related to driver drowsiness, out of which more than 1,300 are fatal. NHTSA estimates that between 2% and 23% of all vehicle crashes can be attributed to driver fatigue [2]. Besides, the National Police Administration of France concludes that 20.6% of accidents causing death are fatigue related [3]. Fatigue, sleepiness or drowsiness can be defined as the transitory period between being awake and sleep [4]-[6].

Psychophysical factors have been identified as contributing factors to road accidents. Psychophysical originally is from the word psychophysics which describes as one method that can be used to estimate acceptable load under variety of force, repetition, posture and duration conditions. This paper focused on the muscle fatigue for psychophysical factor. From the experiments, this factor had been proven effected to fatigue level of the drivers. Muscle Fatigue occurs when the muscle experiences a reduction in its ability to produce force and accomplish the desired movement. The blood flow to the muscle become less because the muscles intensely contracting thus can reduce blood flow and thus oxygen availability, or the muscle is simply working so intensely that there literally is not enough oxygen to meet demand (a sprint at top speed). In order to measure the muscle fatigue, the Surface Electromyography (SEMG) can be used. SEMG is a tool that deals with the detection analysis and use of electrical signal that display from contracting muscles [7].

Mathematical modeling is used to describe and explain real-world phenomena, investigate important questions about the observed world, test ideas and make predictions about the real world. The objective of this research is to formulate and validate the mathematical models of psychophysical factor (muscle fatigue) using ergonomic approach in solving the driver fatigue. The modeling work is based on the response surface methodology (RSM). Application of RSM in modeling and optimization has been proven in various fields, from food products to electronic technology as it is being practicality, economy and relative ease of use [8]-[10]. Published work of RSM modeling on driver fatigue and ergonomics study is lacking. A wide range of factors affecting fatigue are still not modeled [11] and psychophysical and biomechanical factors are one of them. Besides, Voznesensky in 1974 stated that RSM is the best methods for an empirical study of the relationships between one or more measured responses [12]. In developing the model using the RSM statistical analysis, the Design Expert 8.0.6 software was used as this software is widely used for analysis in various research areas [13]-[16].

Experimental Setup

Subjects and Population

In this study, ten subjects or drivers (five males and five females) which, at least two years driving experiences involved in this study. This ten subjects represented three populations of each gender; big, average, and small. However, only average population of each gender is been discussed in this paper. All the subjects are normal, have healthy bodies and has been told that they are refrained from taking or drinking coffee, tea or alcohol, smoking and free taking any medication. Before the experiment, the health evaluation has been done 24 hours as to ensure they have enough habitual amount of sleep at night in order to avoid sleep deprivation [17].

Questionnaire Respond Analysis

The questionnaires were distributed to the subjects as to investigate the driving experience while undertaken the experiment. The subjects needs to answer the questionnaire before and after the driving session. This questionnaire consists of three parts. The first part is focus on personal information, while the second part is more on driver’s comfort experience throughout the type of road condition; straight, winding, uphill, and downhill.

The final part is more on driver physical comfort, which examines the comfort of the whole body of the subjects such as head, neck, arm, and etc.

Test Apparatus and Protocol

Proton Saga FLX 1.3L engine with automatic transmission was used as the test vehicle. Proton Saga is a national car, also known as national symbol of Malaysia and majority of Malaysian population used it as it is an affordable cars or an economic cars. In monitoring and measuring the muscle activity and overall performance of muscle, the electromyography (EMG) was used in this study. EMG is used to ensure the muscle responsiveness with the electrodes for about 30 minutes. There are four types of muscle where the EMG has been placed as shown in Figure 1; left upper trapezius, right upper trapezius [18] right biceps and left biceps [19].

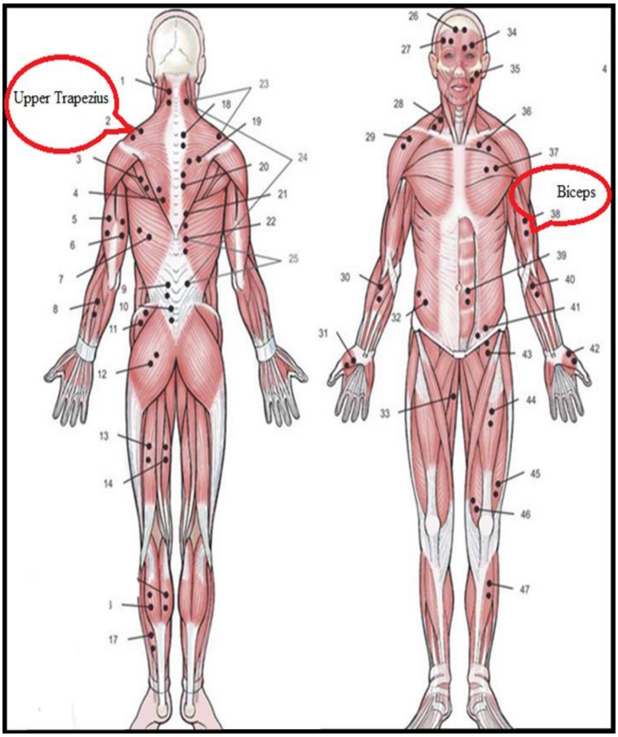

Figure 1: Type of muscles for EMG test.

This EMG tool was set up at the subject body as shown in Figure 2. The electrodes were placed on the surface of the skin based on the type of muscles.

Figure 2: The EMG was set up at the subject's body

RSM Data Analysis

In developing and formulating mathematical modeling, RSM data analysis was carried out through this study. As discussed in early section, RSM is suitable and the application of RSM in modeling and optimization has been proven in various fields. According to Montgomery (2008) RSM includes a collection of mathematical and statistical techniques that can be used for modeling and optimizing of processes [20]. RSM also interpret the relationships between one or more output responses with the significant input factors. The RSM data analysis is carried out using Design Expert 8.0.6 software. Several steps has been followed in order to analyze the data collected [20]. Figure 3 summarized the steps taken in RSM data analysis.

The output responses data for each experimental run were entered into the respective run number matrix. The software recognizes which model chooses for further analysis. The identification and selection is based on the sequential sum of square. This analysis compares the models by showing the statistical significance of adding model terms to those already in the model. The highest degree model that has a p-value less than 0.10 should be chosen as the model to represent the model. Then, the selected model was analyzed using ANOVA where the significant of the model, significant parameters, and interaction factors were determined. The Prob>F value is small or less than 0.1 indicates that the model or factors has a significant effect on the output response. Finally, the final equation of the model was generated through the analysis.

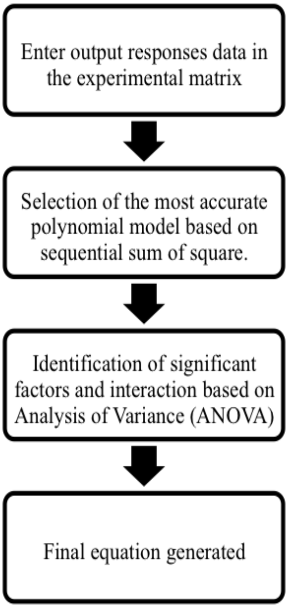

Figure 3: Summary of RSM data analysis flow

This final equation of the model then been validated by using quantitative validations to analyzed the results. This validation runs should meet the following two conditions:

1. To determine if the model can predict the validation run outcome based on specific output parameters within 90% of its predictive interval.
2. The accuracy of a process model can be assessed using residual error method with respect to the validation run [21]. The residual error was calculated based on the percentage difference between the validation run value and predicted value over the predicted value. This percentage value should be less than 10% to represent the accuracy of the model.

Results And Discussion

EMG functions as measurement of muscle activation in workspace related tasks during the driving session. Through this study, psychophysical factor (muscle fatigue), has been proven as a lead factor to the driver fatigue among Malaysian. Hence, this study will developed the mathematical model based on this factor as to solve the driver fatigue problems. This section will discussed the development, formulating and validation of the mathematical modeling through RSM data analysis.

Data for Muscle Fatigue

All the data of the measurement of muscle fatigue was recorded in table. Table 1 shows the data for the muscle fatigue. This data was used in developing and formulating the mathematical modeling.

RSM Modeling of Muscle Fatigue (voltage), µV

Thirty-two (32) experimental runs were carried out as reflected in Table 1. The muscle fatigue or the sEMG signal amplitude (voltage) of the subjects while driving for each experimental run was analyzed using an EMG tool. In this experiment, three factors and one response were studied; time exposure, type of road, and gender; whilst muscle fatigue as the response in this experiment. This study used the historical data as the design type because this study focused on finding the main effect and developed the model relationship between all the factors. Two muscles fatigue measurement were collected per sample and the average muscle fatigue were calculated and used as the output response of the process as tabulated in Table 1.

Table 1: Experimental run and results of muscle fatigue (µV)

		Factor 1	**Factor 2**	**Factor 3**	**Response 1**
Std	**Run**	**A: Time Exposure, min**	**B: Type of Road**	**C: Gender**	**Muscle Fatigue, µV**
14	1	15.00	Straight	Female	54.100
2	2	30.00	Straight	Female	129.500
11	3	15.00	Uphill	Female	108.550
10	4	30.00	Uphill	Female	322.100
26	5	15.00	Winding	Female	330.600
12	6	30.00	Winding	Female	566.300
18	7	15.00	Downhill	Female	285.600
6	8	30.00	Downhill	Female	353.600
24	9	15.00	Straight	Female	52.950
16	10	30.00	Straight	Female	116.900
1	11	15.00	Uphill	Female	103.500
5	12	30.00	Uphill	Female	310.300
19	13	15.00	Winding	Female	322.900
3	14	30.00	Winding	Female	535.400
25	15	15.00	Downhill	Female	283.850
21	16	30.00	Downhill	Female	358.600
15	17	15.00	Straight	Male	96.700
28	18	30.00	Straight	Male	241.500
20	19	15.00	Downhill	Male	574.100
27	20	30.00	Downhill	Male	634.200

29	21	15.00	Winding	Male	936.300
30	22	30.00	Winding	Male	1036.200
17	23	15.00	Uphill	Male	316.000
4	24	30.00	Uphill	Male	607.900
31	25	15.00	Straight	Male	99.850
7	26	30.00	Straight	Male	233.600
23	27	15.00	Uphill	Male	315.475
22	28	30.00	Uphill	Male	606.600
9	29	15.00	Winding	Male	955.250
8	30	30.00	Winding	Male	1055.200
32	31	15.00	Downhill	Male	593.925
13	32	30.00	Downhill	Male	635.700

Determination of Appropriate Polynomial Equation to Represent RSM Model

Sum of squares sequential model (SMSS) and lack of fit test were carried out to determine the appropriate polynomial equation to show the relationships between the input parameters (factors) and output response (muscle fatigue). Table 2 represents the SMSS analysis. While Table 3 shows the lack of fit test for the model. These two analyses suggested the relationship between factors and response can be modeled by using 2FI (factor of interaction).

Table 2: Sequential model sum of squares (SMSS) analysis for muscle fatigue model

Sequential Model Sum of Squares						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Mean vs Total	5.423E+006	1	5.423E+006			
Linear vs Mean	2.317E+006	5	4.634E+005	41.64	< 0.0001	
2FI vs Linear	2.744E+005	7	39205.18	49.92	< 0.0001	Suggested
Quadratic vs 2FI	0.000	0				Aliased
Residual	14921.87	19	785.36			
Total	8.029E+006	32	2.509E+005			

Table 3: Lack of fit test for the muscle fatigue model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Linear	2.881E+005	10	28807.98	360.57	< 0.0001	
2FI	13643.53	3	4547.84	56.92	< 0.0001	Suggested
Quadratic	13643.53	3	4547.84	56.92	< 0.0001	Aliased
Pure Error	1278.33	16	79.90			

ANOVA for Response Surface 2FI Model

Table 4 shows the ANOVA analysis for the 2FI model. The "Model F-value" of 274.99 implies that the model is significant. There is only a 0.01% chance that a "Model F-value" this large could occur due to the noise. This implies that the model represent the data within the required 90% confidence interval.

Table 4: ANOVA analysis of the 2FI model for muscle fatigue

ANOVA for Response Surface 2FI Model						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	2.592E+006	12	2.160E+005	274.99	< 0.0001	significant
A-Time Exposure	1.673E+005	1	1.673E+005	213.05	< 0.0001	
B-Type of Road	1.458E+006	3	4.861E+005	618.99	< 0.0001	
C-Gender	6.914E+005	1	6.914E+005	880.38	< 0.0001	
AB	40327.61	3	13442.54	17.12	< 0.0001	
AC	5.00	1	5.00	6.367E-003	0.9372	
BC	2.341E+005	3	78034.56	99.36	< 0.0001	
Residual	14921.87	19	785.36			
Lack of Fit	13643.53	3	4547.84	56.92	< 0.0001	significant
Pure Error	1278.33	16	79.90			
Cor Total	2.606E+006	31				

A cubic term ABC is added to the model in order to improve the model. Table 5 represents the ANOVA analysis of the Reduced Cubic Model. The "Model F-value" of 2173.84 implies the model is significant and the "Prob > F" value indicated that there is only a 0.01% chance that a "Model F-value" this large could occur due to noise.

Table 5: ANOVA analysis of the Reduced Cubic Model for muscle fatigue

ANOVA for Response Surface Reduced Cubic Model						
Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**	
Model	2.605E+006	15	1.737E+005	2173.84	< 0.0001	significant
A-Time Exposure	1.673E+005	1	1.673E+005	2094.27	< 0.0001	
B-Type of Road	1.458E+006	3	4.861E+005	6084.58	< 0.0001	
C-Gender	6.914E+005	1	6.914E+005	8653.94	< 0.0001	
AB	40327.61	3	13442.54	168.25	< 0.0001	
AC	5.00	1	5.00	0.063	0.8056	
BC	2.341E+005	3	78034.56	976.70	< 0.0001	
ABC	13643.53	3	4547.84	56.92	< 0.0001	
Pure Error	1278.33	16	79.90			
Cor Total	2.606E+006	31				

Determination of Significant Model Terms Influencing Muscle Fatigue

Values of "Prob > F" less than 0.1000 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant. In this case time exposure, type of road, gender, interaction between time exposure and type of road, and interaction between type of road and gender are the significant influencing factors of the resultant muscle fatigue. While the interaction between type of road and gender is not a significant model term. The interaction among the three input parameter "ABC" p-value is also below 0.1, however this interaction cannot be ascertained due to alias nature of cubic term for this particular experimental setup. This determination was done by carrying out ANOVA on response surface reduced cubic model as shown in Table 5.

Polynomial Equation

From the surface response modeling, the 2FI polynomial equation was developed to relate the input parameters to the muscle fatigue is shown in Table 6.

Table 6: Polynomial equation for the muscle fatigue model in terms of actual factors

Type of Road	Straight
Gender	Female
Muscle Fatigue = -16.15000+4.64500* Time Exposure	
Type of Road	Straight
Gender	Male

Muscle Fatigue = -41.00000+9.28500* Time Exposure	
Type of Road	Winding
Gender	Female
Muscle Fatigue = +102.65000+14.94000* Time Exposure	
Type of Road	Winding
Gender	Male
Muscle Fatigue = +845.85000+6.66167* Time Exposure	
Type of Road	Uphill
Gender	Female
Muscle Fatigue = -104.15000 +14.01167* Time Exposure	
Type of Road	Uphill
Gender	Male
Muscle Fatigue = +24.22500+19.43417* Time Exposure	
Type of Road	Downhill
Gender	Female
Muscle Fatigue = +213.35000+4.75833* Time Exposure	
Type of Road	Downhill
Gender	Male
Muscle Fatigue = +533.07500+3.39583* Time Exposure	

The equation in terms of actual factors can be used to make predictions about the response for the given levels of each factor. Here, the levels should be specified in the original units for each factor.

Mathematical Model Validation

At the final stage of the analysis, the mathematical model validation activity is carried out to quantify the accuracy of the model through comparisons of experimental data with the prediction of the model (final equation) [22]. This activity will determine the degree of accuracy of the model as representation of the real world. It is accomplished through the comparison of predictions from a model to experimental results. Three set of process parameters were chosen as validation runs through the point prediction capability of the software. The software, based on the algorithm developed, calculates the predicted muscle fatigue values together with their 90% prediction interval values. Besides, the residual error was also calculated to determine the accuracy of the model. If the residual errors is less than 10%, the model is considered validated and accurate [21, 23]. Table 7 shows the validation results of the three sets of parameter settings. The residual error calculation is done by calculating the percentage error between the actual data with the model prediction. The formula of percent error is shown in Equation (1).

$$\%Error = \frac{Predicted - Actual}{Predicted} x\,100\% \quad (1)$$

Table 7: Validation data of muscle fatigue model

Input Parameters			Prediction (μV)	90% PI low (μV)	90% PI Hi (μV)	Actual (μV)	Error (%)
Time Exposure	Type of Road	Gender					
15.00	Straight	Female	53.525	34.412	72.638	54.100	1.074
22.50	Straight	Female	88.363	70.915	105.810	88.750	0.438
30.00	Downhill	Male	634.950	615.837	654.063	634.20	0.118

The results showed that the validation data fall within the 90% prediction interval. Besides, the residual errors of these three validation runs are ranging from 0.438% to 1.074%. Hence, this model is accurate enough to predict the resultant muscle fatigue as the residual error values is less than 10%.

Conclusion

Throughout this study, the RSM can be used to developed mathematical model of psychophysical factor in order to solve fatigue's problems among Malaysian. The mathematical model in the form of polynomial equation was successfully developed to relate the relationship between muscle fatigue input process parameters (time exposure, type of road, and gender) and one output response (muscle fatigue). The model validation founds that the muscle fatigue output of the modeling validation run was within the 90% prediction intervals of the developed model and the residual error which compared to the predicted values, was less than 10%. The research identified the significant parameters that affected the muscle fatigue through ANOVA analysis during the development of the model. Muscle fatigue was influenced by the time exposure, type of road, gender, the interaction between time exposure and type or road, and the interaction between the type of road and gender.

Based on this research, the authors believed that there is a new contribution to the body of knowledge in the development of mathematical model of psychophysical factor (muscle fatigue) for the driver fatigue problem using Response Surface Methodology (RSM). The authors have also suggested that the RSM can be used to develop mathematical model for others factor such as biomechanical factors and ergonomic factors in order to solve the fatigue problem among Malaysian. Indirectly, it can reduce the number of accidents in Malaysia.

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