A Comparative Study on Whole Body Vibration (WBV) Comfort towards Compact Car Model through Data Mining Approach

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***Abstract*—Nowadays people of Malaysian spend a significant amount of time traveling by the vehicle to travel from one location to another location, and this could be the main reason to decrease minimal vibration for the comfort level in transportation. The vibration that generated while driving can influence pressure and eliminate the focus to the driver and passenger, and this is one of the main causes that can lead accidents on the roads. In this study, we investigate the effect of the vibration caused by the tire interaction with the road surface. The methodology focuses on the trends which occur on the vibration exposure that has been generated throughout the engine operating rpm range in both stationary and non-stationary conditions. An equation will be approached through the analysis to find the significant data that can be used in the process which is K-Means algorithm. Based on the trends of the experienced and exposed vibration, the model is able to differentiate the level of comfort between the clusters by grouping the level of vibration into five categories. To review the accuracy of classification data cluster, the K-Nearest Neighbor method and Analysis Linear Discriminant is used for shows the percentage accuracy of classification data have been a cluster. Later, the vibration for the three cars in this study which has analyzed, compared using the approach of analysis of variations (ANOVA).**

***Index Terms*—Analysis Linear Discriminant; Analysis of Variations; K-Nearest Neighbors.**

I. INTRODUCTION

Minimal whole-body vibration comfort is an important criterion for buyers in determining the quality or ratings in the purchase of a car. Nowadays people spend a significant amount of time travelling by the vehicle from one location to another location, and this could be the main reason to decrease minimal vibration for the comfort level in transportation. In the recent years, the researchers and engineers from automotive industry have conducted a lot of study and experiment for assessment and evaluation of the interior car cabin vibration [1-5]. However, the effects of vibration in a car will produce noise that causes focus or concentration of driver distracted and can lead to an accident. As a result of this situation, the generated vibration causes tense for the driver and passengers while driving the vehicle. Nevertheless, blurred visual images are produced through the visual performance of the drivers because of the direct exposure to vibration in interior cabin car, and this can be the main cause of an accident. The engine transmission; exhaust exit, and the noise caused by the tier-road contact are the main sources that generated vibration velocities [6]. Normally, vibration in the interior car cabin correspond generated due to directly to the increase of engine speed because the engine speed and vibration velocity are in direct proportion. Thus, higher engine speed (rpm) the vibration generate more as well. In the recent years, automotive companies face a tough task in producing cars that have benchmarks and criteria for the better of design to fulfill customers' requirements and encourage sophisticated competitive benefit in terms of acoustic comfort, cost, safety, the weight of vehicle, waste reduction and environmentally friendly. The assessment and evaluation of the interior acoustical comfort have received significant consideration from the automotive engineers and researchers. Besides that, the increase of the level of comfort in terms of acoustical comfort in transportation has become an important foundation. Improvements are needed in the riding comfort of the automotive industry with varying reasons, including the vehicle performance will be better if there is less vibration. Meanwhile, in terms of safety, driver fatigue while operating a vehicle, the vibration must be less. Current assessment methods towards the experienced vibration comfort by human are classified as a subjective valuation, which are based on physical variables such as temperature, acceleration, and vibration velocity. Alternatively, physiological variables for the occurrences of feelings could be one of the factors that contribute to the judgment of human's valuation and feelings toward the comfort level. Nowadays, most of the automotive industry employed jury test to evaluate the whole-body vibration comfort level, however, jury test is usually known for its biasness.

A. Definition of Vibration

Vibration is a mechanical movement that vacillates about a fixed point, and it is a form of a mechanical wave that transfers energy through the wave. This transfer needs mechanical structure to enable the travel of vibration. Some examples of mechanical structures are machine, tool, vehicle, and even the human body. Vibration is generated by friction between the tire and the road surface and also a vibration resulting from the structure components [7,8]. The causes of vibration in the car interior cabin are caused by the engine during acceleration and also transmition of deceleration of the vehicle. Vibration associated with the velocity where it can be hypothesized rougher road surface the higher vibration velocities will increase and the speed also affect the vibration velocities at which the higher speed rpm will increase more vibration.

B. The Effect of Vibration in the Vehicle Cabin

Whole body vibration produced when the driver is exposed to the surface of the vibrating, and it will transfer energy from mechanical structure vibration to the body of the driver. When the driver's body is exposed to vibration, the vibration wave will transfer its energy from the body to the head. One of the energy transfer mechanisms that connect the vibration is the seat surface in the car cabin where it transfer vibration to the body of the driver on the nervous system; the skeleton, including the spine where an injury might occur; and ultimately the skull, which might have its own dynamic responses to the transmitted vibration.

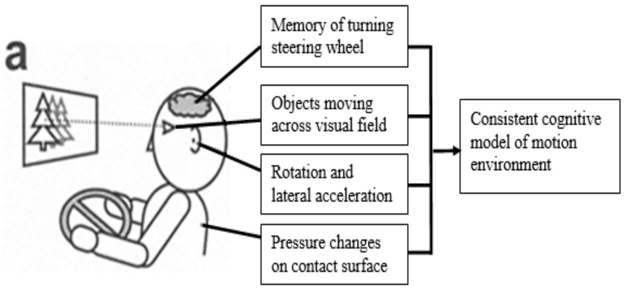

Figure 1: Effects of vibration in the interior car cabin

The noise that produced by the generated vibration in car cabin will affect the focus and emotion of the driver which can be led to road accidents. In other words, vibration can also disturb the concentration of the driver when driving due to the movements the retina of the eye with the object being viewed while driving (Figure 1).

C. Evaluation of Vibration

Factors that contribute to affect the comfort of the drive is the correlation between vibration and speed where the increasing value in rotational speed per minute (rpm) is influenced increasing the value of the resulting vibration. Central interface for the human body is a measure as adjusted in order to obtain an accurate and precision measurement of vibration. British Standard 6841 (BS6841) and International Standard 2631 (ISO2631) is a method used to evaluate the whole-body vibration where British Standard 6841 (BS6841) are used as the equation to evaluate the vibration magnitude for acceleration the root mean square (rms). In this study, the vertical direction is assumed in order to perform the measurement of the vibration.

The frequency, magnitude, and duration of exposure is one of the influences which affect the equation of Root Mean Square (rms) to measure the amount of the exposure towards vibration and also can show the amount of vibration experienced by humans while in interior vehicles. The weighted root-mean-square (rms) acceleration can be calculated by using this following Equation (1).

$$r.m.s = \left(\int_0^T a(t)^2 \, dt \right)^{\frac{1}{2}} \tag{1}$$

where: r.m.s = Weighted root-mean-square

a(t) = Weighted acceleration (translational or rotational) as a function of time (time history), in metres per second squared (m/s^2) or radians per second squared (rad/s^2) respectively

T = Total period in seconds during which the vibration occurs

D. Clustering and Classification

In this study, the authors developed algorithms to cluster and classify the levels of sound vibration into a few categories in order to recognize the level of comfort based on the sound vibration experienced more accurately in the vehicle cabin. This assessment is essential especially due to the fact that we need to identify the comfort level which is experienced by the driver or passenger(s) while they are in the car as we believe that to improve the current structure or part in the cabin we must initially identify the level of vibration that has been exposed. Therefore clustering and classification will be the main tools that can be used for that purpose. Basically, there have been attempts to categorize a group of data based on their trends following a required number of categories in this study approach.

E. K-Means Algorithm

K-means clustering contains data analysis methods or data mining process which are unsupervised where it aims to develop a system to collect data partitioning into several clusters specific commonly known as k [9]. In this study data that had been obtained are cluster to five sections that feed data into some classes is needed where the characteristics of the same within one another in merged of form a class and also shows the difference of the characteristic from any other data from other classes to represent the finest data to the lowest of hierarchical data.

F. K-Nearest Neighbors (KNN)

K-Nearest Neighbors (KNN) classifiers function by dividing data into a test set and or each row of the test set; the KNN training set vectors are found for each row of the data set which is the clustering class for the level of comfort [10]. Thus, the data clustering with the majority of ties broken at random is determined by the KNN classifier. Therefore, the result of the boundary of classifier exceedingly non-linear because of the KNN classifier approach the shape of the decision boundary is no assumptions, and this classifier is totally non-parametric. In this study, KNN classification was used to obtain the classification accuracy of the data.

G. Linear Discriminant Analysis (LDA)

In this study, linear discriminant analysis (LDA) is used as a function of the classifier and find the finest vector in differentiating between classes in the space base. Through this method, this feature is given a connection with certain data that has been clustering by K-means and will form a combination of linear data where it produces a maximum mean difference between the compulsory classes. The frequency of the classes generated by K-Means clustering is not identical and performance evaluation tested on data provided is random [11,12]. In order to solve this problem, one algorithm is generated and be used where some values or characteristics that are related to clustering data will be changed to another by forming a linear combination between data to produce the mean maximum for the value of the difference between the classes of K-Means clustering.

II. METHODOLOGY

In this research, data collection for vibration was taken in two situations, namely the stationary state and non-stationary state for each Perodua compact cars and the value that had been measured was taken one at a time. For accelerometers sensor, six sensors are used to collect the data, and the sensor is mounted in the car cabin interior. The sensors mounted or placed on a surface that is determined, namely, two sensors attached to the surface of the dashboard, two sensors on front of the rear floor of the car floor, two sensors attached to the surface of the car’s door and another one is attached to the rear surface of the dashboard of the car. Consuming data acquisition will be conducted in the state of stationary and non-stationary. Vibration measurements were carried out at the same time, depending on the engine speeds revolutions per minute (rpm). The measurement based on velocity is only practically done while the car is in the driving mode since the measurement is based on distance. However, at a stationary position, the measurement cannot be based on velocity since the car is parked. As another option, the measurement based on engine speed (rpm) is used. Thus, to standardize the measurements of the sound and vibration under both stationary and non-stationary conditions, the measurements are performed over the changes of the rpm engine.

Figure 2: Subjective car (Axia,Myvi and Viva)

A. *Test Method*

The vehicle that was used to measure the vibration was the Perodua compact cars which namely Axia, Myvi and Viva (Figure 2). For this research, portable and multi-channel NI cDAQ-9174 (Figure 3) is used as a transducer to convert the data of accelerometers that been measured by the sensor into the waveform. NI cDAQ-9174 sensor was placed on the floor and dashboard (Table 3). In our study, Laboratory Virtual Instrument Engineering Workbench (LabVIEW) was used to measure the level of vibration. For data collection vibration in the car interior cabin for the stationary state, all Perodua’s compact cars are taken at the exact same place. Vibration data collection will be recorded during the 10-seconds starting with the engine speed at 1000 rpm and 250 rpm increments until the engine speed reaches 3000 rpm. All of this data collection will be saved in Microsoft Excel. The test was conducted by two members. In this case the driver has to drive at the same time focusing on the specific engine speed following the testing plan. Meanwhile, one assistant is needed to handle the laptop computer in order to record the level vibration using the measurement software.

Figure 3: NI cDAQ-9174 and acceleration sensors

Figure 4: Pavement road, highway road and urban road

Table 1
Location of Tested Road

Road Type	Location	Characteristic
Highway	Changlun-Kuala Perlis Highway	Two lanes of each side of the highway with the smooth road surface
Urban	Kampus Pauh Putra, UNIMAP	One lane of each side of the highway with the smooth road surface
Pavement	Kampus Pauh Putra, UNIMAP	Broad pavement road surface

Table 2
Tested Engine Speed

Stationary	Pavement	Highway	Urban
1000 rpm	1000 rpm	1000 rpm	1000 rpm
1250 rpm	1250 rpm	1250 rpm	1250 rpm
1500 rpm	1500 rpm	1500 rpm	1500 rpm
1750 rpm	1750 rpm	1750 rpm	1750 rpm
2000 rpm	2000 rpm	2000 rpm	2000 rpm
2250 rpm	2250 rpm	2250 rpm	2250 rpm
2500 rpm	-	2500 rpm	-
2750 rpm	-	2750 rpm	-
3000 rpm	-	3000 rpm	-

For data collection vibration in the car interior cabin for the non-stationary state, all Perodua compact cars are taken at the exact same place but this time data collection vibration needs to be conducted while the car is driven. Vibration data collection for non-stationary will be measured and recorded into three types of road which is pavement, highway and urban (Figure 4 & Table 1) For highway road, vibration data collection will be recorded during the 10-seconds starting with the engine speeds at 1000 rpm with 250 rpm increments until the engine speed reaches 3000 rpm. Meanwhile, for pavement and urban road, vibration data collection will be recorded during the 10-seconds starting with the engine speed at 1000 rpm with 250 rpm increments until the engine speed reaches 2250 rpm (Table 2). All of these data records will be recorded and saved in Microsoft Excel.

Table 3
Sensor Location Attachment and References

Back dashboard	In front dashboard	Front floor Passenger floor Right back floor Left-back floor figure
		

III. DATA ANALYSIS

From the observation, it was found that the value of vibration parameters corresponds with the increase in engine speeds. In this study, linear regression analysis method is used to get an accurate relationship since this process involves two variables. Relationships between variables which are dependent and independent variables were obtained through a single regression analysis. Usually, the regression analysis can be estimated with the dependent variable independent variable where the average value depending upon the variables are fixed. In order to determine the significance for each of the vibration parameters, there are two criteria must be obtained that correspond with the changes in the engine speed:

i. The R-square value which is the regression indicator between each parameter of vibration and the rpm must be higher than 80%.
ii. P-value must be less than 0.05.

In addition, the correlation between vibrations with engine speed matches as theory increase engine speed will produce more vibration as well as the values of P where the hypothesis is synonyms. Selected data is based on a specific point of for the next calculation to be assessed and taken into account through the site or parts that produce a lot of vibration. Here, we are looking for the equation that represents the total value of the whole-body vibration (WBV) as compared to engine speed resulting from the regression analysis. Thus, the equation to represent the amount of whole body vibration (WBV) values over the engine speeds is shown in Equation (2) below.

$$WBV = \alpha\left(RPM\right) + \beta \qquad (2)$$

where WBV = Whole body vibration
α = Coefficient for RPM value
RPM = Parameter value (engine speed or revolution per minute)
β = Constant variable

IV. MODELLING

In order to cluster the level of comfort, both components of sound and vibration are combined through the data set so that the data can be clustered based on their trends into a few classes that are required. In this case, it is aimed to cluster the level of comfort into five categories following the level of comfort from the vibration. The next fragment of data mining is the Monte Carlo simulation [13,14] which is a numerical mathematical technique to represent quantitative analysis and decision making which can be used to generate random data based on the amount that researcher want to generate. The normal distribution method is used to generate the number of random data that required to proceed to the next process which is 1000 random data for each of the cluster meaning that it will produce 5000 random data since there are five clusters generated from the K-Means clustering. Multivariate Normal (MVN) distribution is used to generalizing the unvaried normal distribution since the data in this study contain multi-variables. The definition of MVN is explained as follows:

Let $x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} \in \mathbb{R}^N$. The expected of *x*, $E(x) = \begin{bmatrix} E(x_1) \\ E(x_2) \\ \vdots \\ E(x_N) \end{bmatrix} \in \mathbb{R}^N$, and the $\sum(x)$ is the covariance, where $\sum = E\left((x-\mu)(x-\mu)^T\right) \in \mathbb{R}^{N\times N}$ and μ is the average variable, where $\mu = E(x) \in \mathbb{R}^N$. The generation the random data from *x* until *N* can be expressed as

$$f\left(x \mid \hat{\mu}, \sum(x)\right) = \frac{1}{(2\pi)^{N/2}|\Sigma|^{1/2}}.e^{\left\{-\frac{(x-\hat{\mu})^T\Sigma^{-1}(x-\hat{\mu})}{2}\right\}} \qquad (3)$$

Based on previous clustered data, it can be classified by the neural network approach which namely K-Nearest Neighbors (KNN) since this algorithm is very recommendable when it comes to solving pattern recognition problems. In this case, the back-propagation algorithm will be applied, as the neural network involves the learning or teaching algorithm in order to estimate the parameter of each variable in the modeled data. Later, in order to verify the results that have been obtained from a previous neural network model, the authors use the Linear Discriminant Analysis (LDA) as their second classification method.

V. RESULTS

In this classes, the cluster the level of vibration comfort in weighted root-mean-square (rms) acceleration are divided into five classes following the level of comfort from the experienced vibration which class one represents the most pleasant in other word extremely comfortable by the driver or passenger follow by hierarchical classes until the last class 5 which represent the most annoying level of comfort which can distract the focus of the driver. Thus, the parameters of the vibration data for the front floor, passenger floor, left and right back floor and back dashboard were used in the data that are to be clustered using the K-means algorithm.

Axia is the car that produces the lowest noise inside the car cabin among the three cars that were tested during in all condition. It is shown in Table 4 where Axia had the highest total count in cluster 1, which is grade class for lowest generation of vibration. The results obtained also shows that in all tested experiment, Axia and Viva with similar level only producing vibration up to level 3 compared to Myvi which is until level 5. While the car that produces the highest generation of vibration in the car cabin during all the tested experiment is Myvi. This can be seen in Table 4 which, in the cluster class 5, which is the highest grade vibration level which is the most annoying condition while Viva and Axia only until level 4.

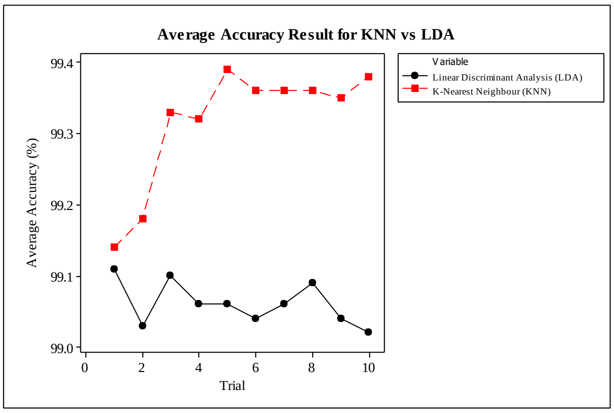

Figure 5: The accuracy result LDA vs KNN

In terms of the performance of the network, it is also understood that with this combination the accuracy rate is higher compared to other combinations. The average accuracy rate for KNN is 84.9%, higher than LDA where the range of average accuracy of KNN is 99.14% to 99.39% while for LDA the average accuracy is 99.02% to 99.11% (Figure 5). For the hypothesis it can be expected KNN classifier approach is more precise than LDA classifier when the result of boundary is highly non-linear because of the KNN approach where the shape of the decision boundary is no assumptions and this classifier is totally non parametric so as a result, the KNN classifiers is statistically better than the LDA classifiers through statistical analysis.Therefore, KNN classifiers are more reliable than LDA classifiers in term of classifying the cluster class of driving comfort level.

Table 4
The Level of Correlation of Exposed Vibration for Axia, Myvi, and Viva

	Location	Regression Analysis	Sensor Location (Refer to Table 3) 1	2	3	4	5	6
Axia	Highway	R-square (%)	88.70%	84.50%	91.70%	88.10%	92.20%	93.60%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Pavement	R-square (%)	90.70%	96.20%	95.70%	96.80%	95.80%	93.40%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Urban	R-square (%)	33.50%	81.70%	84.90%	89.00%	89.60%	89.50%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Stationary	R-square (%)	32.40%	28.10%	6.20%	0.80%	36.90%	39.40%
		P-value	<0.05	<0.05	0.098	0.557	<0.05	<0.05
Myvi	Highway	R-square (%)	88.50%	87.60%	80.60%	92.50%	87.40%	87.60%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Pavement	R-square (%)	78.30%	85.20%	85.20%	80.70%	79.80%	78.50%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Urban	R-square (%)	9.60%	86.40%	92.70%	95.70%	86.70%	90.90%
		P-value	0.096	<0.05	<0.05	<0.05	<0.05	<0.05
	Stationary	R-square (%)	81.60%	80.90%	30.60%	58.40%	6.30%	23.50%
		P-value	<0.05	<0.05	<0.05	<0.05	0.097	<0.05
Viva	Highway	R-square (%)	89.00%	70.00%	85.30%	70.40%	76.10%	77.00%
		P-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Pavement	R-square (%)	9.40%	98.10%	95.90%	97.70%	96.50%	96.80%
		P-value	0.1	<0.05	<0.05	<0.05	<0.05	<0.05
	Urban	R-square (%)	0.36%	96.10%	93.00%	91.90%	93.70%	92.70%
		P-value	0.789	<0.05	<0.05	<0.05	<0.05	<0.05
	Stationary	R-square (%)	45.90%	6.90%	17.50%	57.00%	17.20%	14.00%
		P-value	<0.05	0.081	<0.05	<0.05	<0.05	0.011

Table 5
Result of ANOVA on Type of Car

Road Type	Cars	Number (N)	Mean	Standard Deviation
Highway	**Axia**	9	0.005633	0.002328
	Myvi	9	0.010628	0.003834
	Viva	9	0.005962	0.001369
Pavement	**Axia**	6	0.008233	0.004022
	Myvi	6	0.008672	0.004688
	Viva	6	0.008411	0.003835
Urban	**Axia**	6	0.005499	0.002713
	Myvi	6	0.006538	0.003742
	Viva	6	0.006062	0.002245

According to the result of ANOVA in Table 5, Myvi is the highest generation of vibration comforts in the interior car cabin among these three cars. While for Viva become the second most generation of vibration comfort and Axia is the best interior vibration comfort among these three cars because Axia produces the lowest vibration between the other 2 cars, in every state through the stationary, highway, urban and pavement road tested in this study. The highest generation of vibration comforts in the interior car cabin among these three cars is Myvi through the exposure to a vibrating seat or a floor in interior cabin, and direct contact with vibration steering wheel or handling the handle.

From the result shown in Table 6, it can be concluded that pavement that contributes to the highest generation of vibration comforts for the interior car cabin among these three type of road. While urban become the second most generation of vibration comforts and the highway is the lowest generation of vibration comforts among these three type of road. The category or type of road and the friction between the tire and the road surface could be the main factors as well that contribute to the generated vibration. The road type encourages the generation produce of vibration's occurrence to the rougher of the surface road effects more of the production of vibration in interior car cabin where the rougher road surfaces, the higher increase vibration levels, however the smoother the surface, the less generated vibration. As for the differences issue of pavement surface produce more generation of vibration than another type of road which is highway and urban. Therefore this due to the pavement surface is rougher and undulating their arrangement compared to the asphalt where derived from tar, which is a sticky substance that been made by natural composite as a by-product of oil production. Table 7 shows the characteristics of the comfort levels[15].

Table 6
The result of ANOVA on Type of Road

Cars	Road Type	Number (N)	Mean	Standard Deviation
Axia	**Highway**	6	0.004358	0.001590
	Pavement	6	0.008233	0.004022
	Urban	6	0.005499	0.002713
Myvi	**Highway**	6	0.008525	0.002619
	Pavement	6	0.008672	0.004688
	Urban	6	0.006538	0.003742
Viva	**Highway**	6	0.005212	0.000935
	Pavement	6	0.008411	0.003835
	Urban	6	0.006062	0.002245

Table 7
The Characteristics of the Comfort Levels

Class	Category's Name	Level of Comfort
5	Most pleasant	Extremely comfortable
4	Medium pleasant	Quite comfortable
3	Marginal	Moderate disturbance
2	Medium annoying	Intrusive and slightly disturbance
1	Most annoying	Extremely intrusive and emotionally disturbance

VI. CONCLUSION

The first objective of the study is to evaluate the impact of the sources that contribute for vibration that generated in the vehicle cabin where the major of the amount of vibration generated is caused by the tire interaction with the road surface. In order to generate data of vibration, the experiment has been conducted to perform the data analysis from the first to the last stage, based on the procedures explained in the previous section. As seen in the data analysis, the roughness of the road and engine speeds serves as a major contributor to the vibration which exists in the cabin. Since different road surfaces and rpm affect the noise level that is generated, it is very important for us to consider and take note of the specifications and patterns of the tires surfaces. Hence, the equations proposed through this study cannot be applied directly by other researchers since different models of vehicle, different types of tires, and different types of roads contribute to the different vibration levels in the cabin. The results also prove that the main contributor of the vibration in the cabin is produced from the interaction between the tires and the road surface. Through the observation of the results, we can conclude that the changes in the rpm affect the vibration experienced in the cabin. The vibration might be transmitted to the car body through the mechanical vibration due to the transmission of the engine and through the tire-road contact. Thus, we can also conclude that higher rpm can produce more vibration in the car cabin. Besides that, we have also proven that by considering the vibration comfort parameter, a comparison between both of the conditions would be a correct measure, since the results show that this parameter can represent human perceptions more accurately.

For the second objective is to measure the level of vibration in the cabin based on experimental analysis through the clustering & classification methods. Through the results, the level of vibration can be recognized based on the classes that represent the states of annoyance and degree of annoyance by ignoring both the negative and extreme value. From the results, it may be concluded that the developed model is able to cluster and classify the level of vibration in the vehicle cabin successfully. The proposed LDA algorithm is able to cluster and classify the vibration level from the provided database efficiently. Based on the trends of the experienced and exposed vibration, the model is able to differentiate the level of comfort between the clusters by grouping the level of sound vibration into five categories which are most pleasant, medium pleasant, marginal, medium annoying and most annoying. These two LDA and KNN classifiers are efficient as they can be applied in order to evaluate the level of vibration comfort towards the vibration experienced and exposed vibration in the vehicle cabin by excluding the subjective test. Referring to the vibration's degree of annoyance will assist the researchers in predicting or estimating the strength level of the vibration comfort without performing the jury test which always involves the biased perception.

ACKNOWLEDGMENT

Special appreciations to Universiti Malaysia Perlis for the financial support and encouragement in conducting this research.

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