A Study to Predict the Effects of Tyres Vibration to Sound Quality in Passenger Car Cabin

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Abstract

Vehicle acoustical comfort and vibration in passenger car cabin are the factors which attract the buyers to a vehicle in order to have a comfortable driving environment. The amount of discomfort depends on the magnitude, frequency, direction and also the duration of exposed vibration in the cabin. Generally the vibration is caused by two main sources, which are engine transmission and interaction between tyres and the road surface. The comfort of the driving will affect the drivers by influencing their performance by bothering vision, and at the same time giving stress to the driver due to generated noise. In this study an approach has been carried out to find the amount of noise which influenced by the vibration due to interaction between tyres and road surface. The sound quality study has focused on the estimation of the noise changes through the generated sound quality depending on engine speeds. From the results, the amount of sound quality followed the increase and decrease of the engine speeds. Through the study, a technical method is provided to show the correlation between generated noise sound quality and the exposed vibration caused by the interaction between tyres and road surface.

Keywords: Vibration, Sound Quality, Vibration Dos Value

1. INTRODUCTION

Generally noise which is generated by the vehicle system vibration will affect driver's emotions and decrease the level of driving focus. Vibration exposure may cause relative movement between the viewed object and the retina, resulting in a blurred image. This will decrease the visual performance and at the same time affect the driving comfort and will alter the driving focus, which could potentially cause an accident. This noise may also be described as a source of annoyance for humans where unwanted noise may interfere with speech communication between passengers, affect driving concentration and also can cause sleep disturbance during the night. In this study both the noise (sound quality) and vibration trends against engine speeds will be compared in order to determine the correlation between exposed vibration and produced noise level in passenger car cabin.

1.1 Evaluation of Vibration

Basically, vibration or noise is directly related to engine speed due to changes in direct proportion to engine rpm [1-6]. A vibration that comes from engine surface will generate noise where the sources of the vibration are combustion vibration and mechanical vibration. Based on previous research, generally the main sources of vehicle interior vibrations in vehicle systems can be influenced by two sources: engine transmission during acceleration or deceleration of the car and tyre interaction with the road surface.

At certain speeds, the vibration is mainly caused by the interaction between rolling tyres and road surface [7,8]. The generated vibration is not only caused by the rolling tyres, but also radiated by structure-borne vibration which spread to the rim and other parts of the vehicle body.

The vibration is dependent on the roughness of the road surface where the tyres are rolling on, with the rougher the surface of the road causing more vibration to be generated. Here, the vibration sources that act at the tyres caused by the up–and-down of the road surface. In this case, Kindt et al [9] has conducted study to do measurement and do analysis to the vibration of rolling tyres. Their findings show that for the velocity more than 40 km/h the main source of the noise to passenger cars is the interaction between tyre and road surface. The results also show the important fact about the tyre resonance frequencies at the onset of rolling. Here, the excitation amplitude dependency showed to be restricted to the tyre sidewall stiffness. Basically the stiffness vibration is determined by mass, stiffness and dumping forces which are contained in their component parts. Meanwhile the vibration source to the vehicle body due to change of the engine speeds. The generated vibration depends on vehicle speed and may be felt in the steering wheel, seats or floor board.

In this study, BS6841 (British Standards Institution 1997) refers to the use of the vibration magnitude evaluation method using r.m.s acceleration *a(t)*. The reason why BS6841 is used is the standard is simple, less ambiguous, internally consistent and quite familiar with assessment of whole body vibration. Due to car motion by shocks or impulsive velocity changes, the use of the time integrated fourth power of an acceleration, known as vibration dose value (*VDV*) is considered more suitable for vibration assessment. Here, the value of *VDV* shows the total amount vibration received by the human over a period of time. Generally, *VDV* ($ms^{-1.75}$) is the measure of total exposure to vibration which considers the magnitude, frequency and exposure duration and can be defined as

$$VDV = \left(\int_0^T a(t)^4 \, dt \right)^{1/4} \tag{1}$$

Where VDV : Vibration dose value ($ms^{-1.75}$)
$a(t)$: Frequency- weighted acceleration
T : Total period in seconds that the vibration occurred

1.2 Evaluation of Noise

A lot of researches have been done by automotive researchers to determine and predict the generated noise and exposed vibration in internal vehicle at moving conditions [10, 11]. Generally, noise transmission into vehicle can be divided to sources: airborne noise and vehicle structure borne. For the vehicle manufacturing company, they may take the results into account to optimize or improve the structure of the parts which are believed may reduce the generated vibration and at the same time may decrease the noise in passenger car cabin [12-15]. D.J. O'Boy et al (2008) in their study have investigated the effect of vibration of tyre belt (tread rubber) to the interior noise in passenger car cabin. The results show that the characteristics of the tread rubber will produce different level of sound.

By using a Proton Perdana V6 as a tested vehicle, the generated sound quality is measured at two conditions which are stationary and moving condition, where the types of road are highway and pavement road (Table 1, Figure 1). In order to evaluate the noise level, sound quality metrics are measured depending on engine speeds (rpm). The parameters of sound quality which considered are four types which are Zwicker loudness [sone], sharpness [acum], roughness [asper] and fluctuation strength [vacil]. The measurement results will be summarized and correlation between generated sound quality parameters and engine speeds will be obtained in order to look the trends of noise over the generated vibration in passenger car cabin. Then, formulas will be formed to let the future automotive researchers be able to predict the effects of the vibration due to the noise which caused by interaction between tyres and road surface.

Road Type	Location	Characteristic
Highway	Kajang – Bangi Highway	Two lanes each side highway with smooth road surface
Pavement	Putrajaya	Broad pavement road surface

TABLE 1: Locations of Tested Road

FIGURE 1: Two different roughness of road surface (a) Highway and (b) Pavement road

2. METHODOLOGY

The sound quality measured at two condition which are stationary condition and moving condition.

Measured sound quality will be analyzed to obtain sound quality parameters which are loudness, sharpness, roughness and fluctuation strength [17]. Sound quality is measured by the binaural Head and Torso (HAT) equipment based on its frequencies and amplitudes.

Vibration is normally evaluated by measuring the level of vibration at certain parts that are identified as dominant source of vibration for the driver in the car interior. Here, the car floor next to the drive side was chosen as the location for vibration measurement.

The noise and vibration are measured by depending on engine speeds [rpm]. The reasons why this study choose to measure the noise and vibration by depending on engine speeds is, vehicle speed measurement (velocity [km/h]) only can be done while the car is moving and not at the stationary condition. However, in this case, the study assumes that:-

i. both of the noise that produced due to the engine transmission during at stationary and moving condition are equal.
ii. the noise that produced due to interaction between tyre and road surface at stationary condition is ‘0’.

Thus, the reason why both of the condition (stationary and moving) dependent to engine speeds is the engine transmission noise are considered only will give minor effect to the measurements of noise and the major contributor of the noise is assumed came from the effect of vibration caused by the interaction between tyres and road surface.

2.1 Test Method

In this test, a Proton Perdana V6 Automatic car was used as the vehicle in measurements of sound quality. The sound quality will be conducted using Bruel & Kjaer portable and multi-channel PULSE type 3560D. B&K Head & Torso (HAT) type 4100 (Figure 2) was placed at the front seat next to the driver side area. Measured noise from only the right channel is recorded due to HAT being a binaural device (choose either right or left channel to standardize the measurement). In this study four metrics are analyzed and considered to find the correlation between the sound quality and engine speeds. They are Zwicker loudness (L), sharpness(S), roughness (R) and fluctuation strength (F) (Table 2). B&K type 7698 sound quality software is used to analyze and find the metrics for sound quality.

FIGURE 2: The B&K head and torso used to measure the sound quality during the test

Metric	Right	Left	Unit
Inst .	10.5	10.4	sone
Sharpness	1.21	1.17	acum
Roughness	1.89	1.46	asper
Fluctuation	1.03	1.21	Vacil

TABLE 2: Example of Measured Sound Quality

The vibration level measured only at moving condition since we assuming that no vibration occur due to the interaction between tyre and the road surface. Vibration detector was B&K isotron accelerometer model 751-100 installed at the front floor next to the driver side (Figure 3). The measurement software is B&K Pulse Labshop. By using formula (1), vibration dose value was obtained in order to evaluate the level of exposed vibration at the car floor.

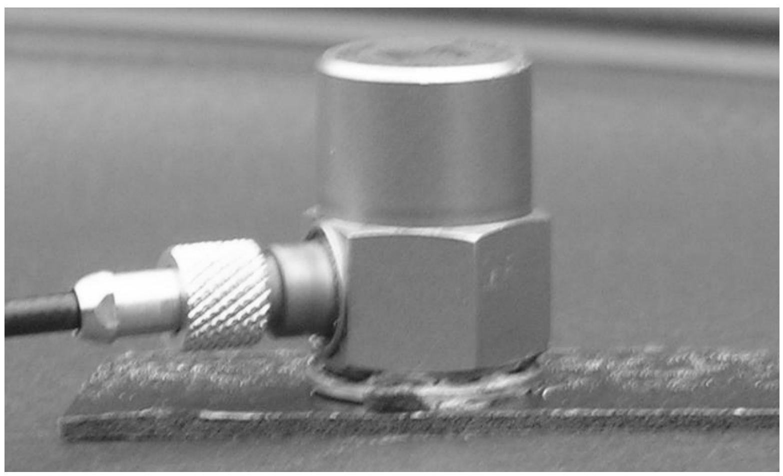

FIGURE 3. B&K Accelerometermodel 751-100 and installed location

The sound quality measurement will be carried out at two conditions, stationary and moving condition. At stationary condition, sound quality is measured five times depending on the engine speeds. That engine speeds are 1500rpm, 2000 rpm, 2500 rpm, 3000 rpm and 3500 rpm. Since the type of road influences the generated noise in passenger car cabin at moving condition, the sound quality was measured on two types of road which are highway road and pavement road. Since different tyre surface pattern (tread) will produce different level of noise, Figure 4 and Table 3 shows the tyre tread pattern and specification of the tested tyres on the Perdana V6.

The duration for each measurement is 10 seconds, with the test being conducted by two members, including the driver. The driver's task is to drive the car while maintaining specific engine speeds (rpm) according to the testing plan. One test assistant is compulsory to handle the laptop computer and at the same time record the sound quality of noise and vibration measurements. For highway road the measurements are taken for 4 times only due to velocity constraints. However, for pavement road and at stationary condition, the sound quality and vibration measurement will be taken for 5 times depending on the engine speeds. That engine speeds are shown in Table 4. To get reliable data, the measurement for each engine speed is repeated for 4 times. The details about

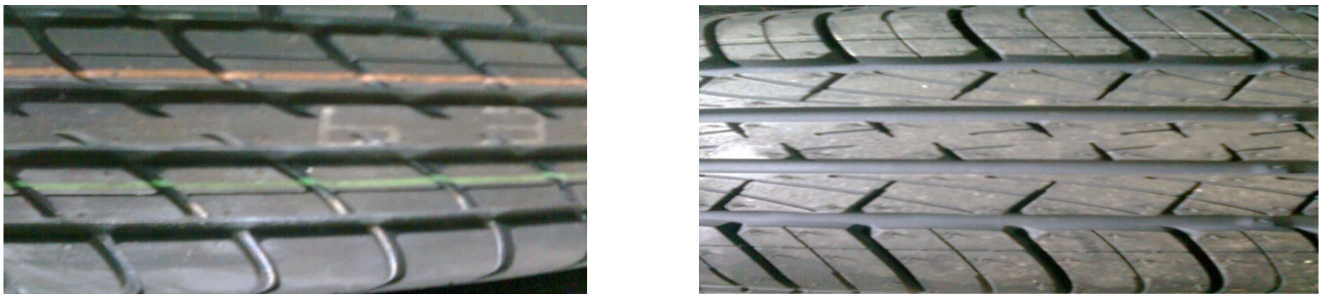

FIGURE 4: Two different tyre surface patterns (treads)(a) Tyre A and (b) Tyre B

Specification	**Front portion**	**Back portion**
Type	A	B
Model	P205/55R	P205/55R
Nominal section width	205 [mm]	205 [mm]
Aspect ratio	55%	55%
Radius	16 " (inch)	16 " (inch)
Load index	91V (615kg)	89V (580kg)

TABLE 3 : Specifications of tested tyres

the research procedure can be referred in Figure 5.

Stationary	Moving	
	Highway	**Pavement**
1500	1600 rpm	1200 rpm
2000	1900 rpm	1500 rpm
2500	2500 rpm	1600 rpm
3000	2800 rpm	1800 rpm
3500	-	1900 rpm

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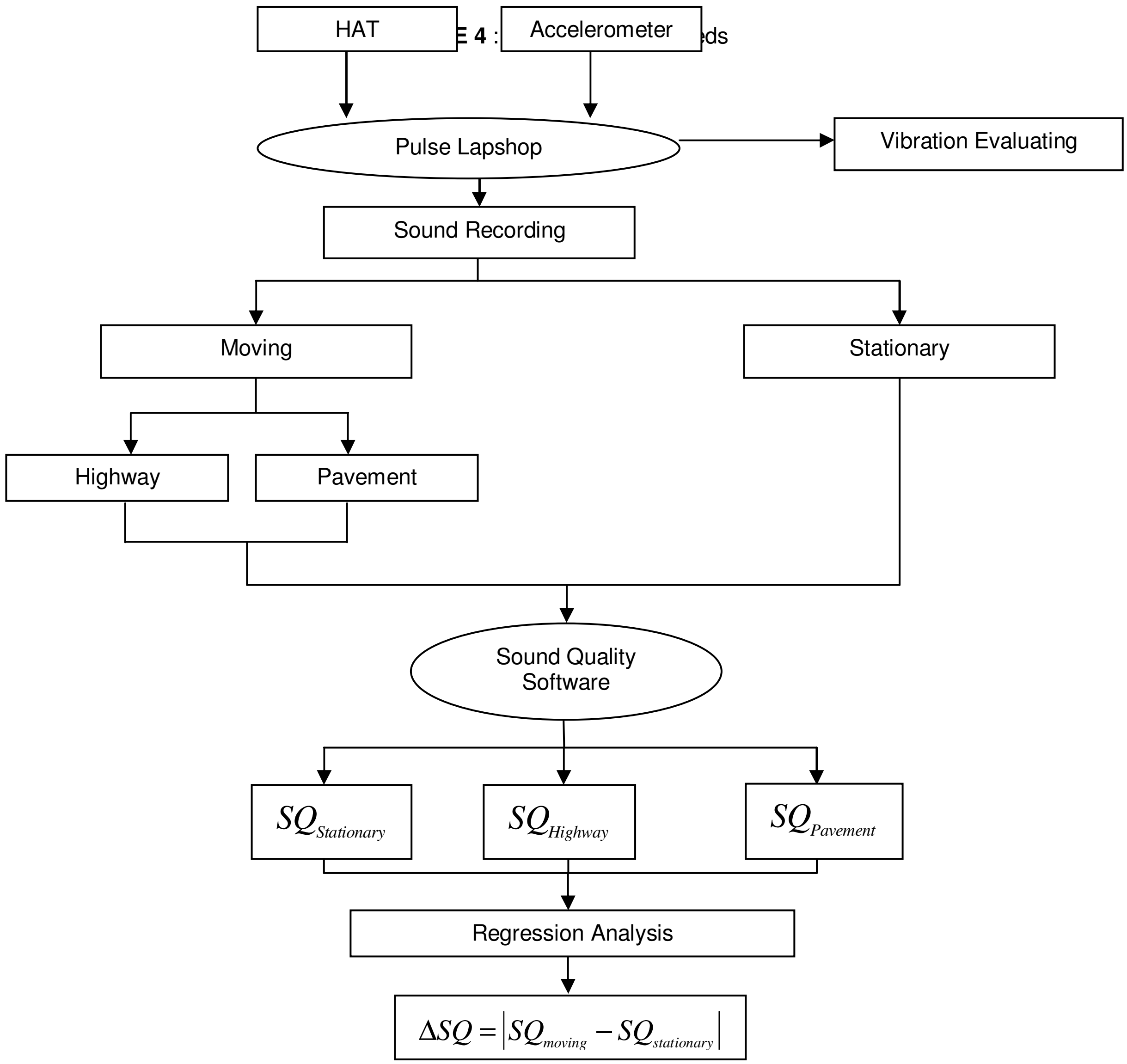


FIGURE 5: Research procedures process flow

3. RESULTS AND DISCUSSION

Figure 6 and Table 5 illustrates the results for measurement of the sound quality metrics for Zwicker loudness, sharpness, roughness and fluctuation strength. For both of the highway and pavement road, the parameter of loudness increase with the increase of engine speed. Meanwhile, for sharpness metrics, the values decrease with the increase of engine speeds. However there is no particular trend for fluctuation strength metric values with the increase of engine speeds.Table 6 shows the vibration level in VDV unit that exposed at the car floor depending on engine speeds and to show the correlation ship between the vibration level and generated noise, Table 7 is formed to illustrate the measured sound quality depending on the vibration level exposed at the car floor. Figure 7-9 are plotted look the changes trend of sound quality corresponding to engine speeds for both condition either stationary or moving condition,

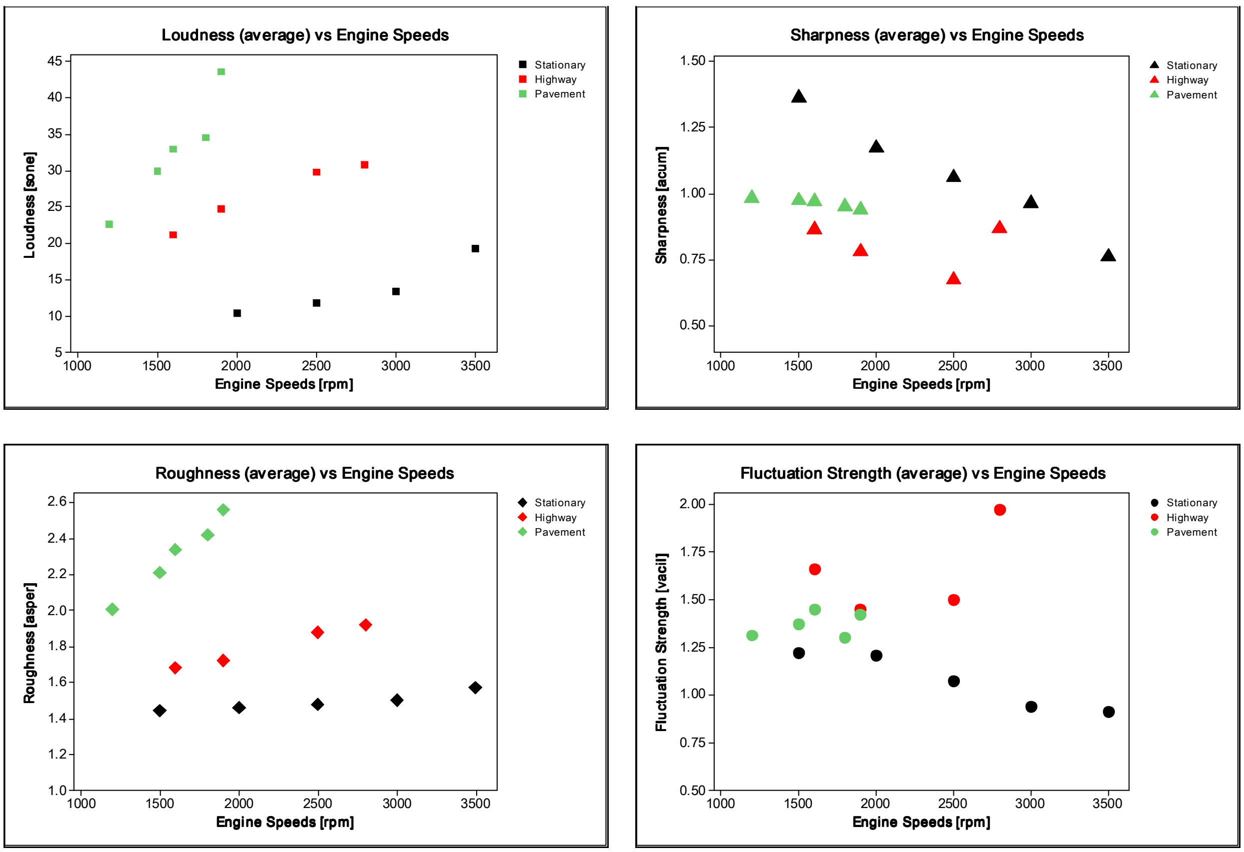


FIGURE 6 : Measured sound quality (average)

Engine Speed (rpm)	Stationary				Moving							
					Highway				Pavement Road			
			R	*F*			*R*				*R*	
200									2.6	0.981	2.01	.31
500	.8	1.362	.44	.22					9.9	0.973	2.21	.37
500					**1.1**	**0.861**	**1.68**	**.66**	3.0	0.969	2.34	.45
300									4.5	0.948	2.42	.30
900					**4.8**	**0.781**	**1.72**	**.45**	3.6	0.937	2.56	.42
000	0.4	1.173	1.46	.21						-	-	
500	1.8	1.061	1.48	.07	**9.8**	**0.674**	**1.88**	**.50**		-	-	
300			-		**0.8**	**0.867**	**1.92**	**.97**		-	-	
000	3.4	0.9	1.50	.94						-	-	

500	9.3	640.762	1.57	.91	-	-

L: Loudness[Sone] , S: Sharpness [Acum] , Roughness [Asper] and F: Fluctuation Strength [Vacil]

TABLE 5: The values of sound quality metrics (average)

Condition	**Engine Speed [rpm]**	**Read 1**	**2**	**3**	**4**	**Average [ms$^{-1.75}$]**
Stationary	1600	0.	0	0.	0.	0.01
	2000	0.	0	0.	0.	0.02
	2500	0.	0	0.	0.	0.03
	3000	0.	0	0.	0.	0.02
	3500	0.	0	0.	0.	0.02
Highway	**1600**	**0.**	**0**	**0.**	**0.**	**0.36**
	1900	**0.**	**0**	**0.**	**0.**	**0.41**
	2500	**0.**	**0**	**0.**	**0.**	**0.44**
	2800	**0.**	**0**	**0.**	**0.**	**0.43**
Pavement	1200	0.	0	0.	0.	0.69
	1500	0.	0	0.	0.	0.83
	1600	0.	0	0.	0.	0.90
	1800	1.	1	1.	0.	0.91
	1900	1.	1	1.	1.	1.16

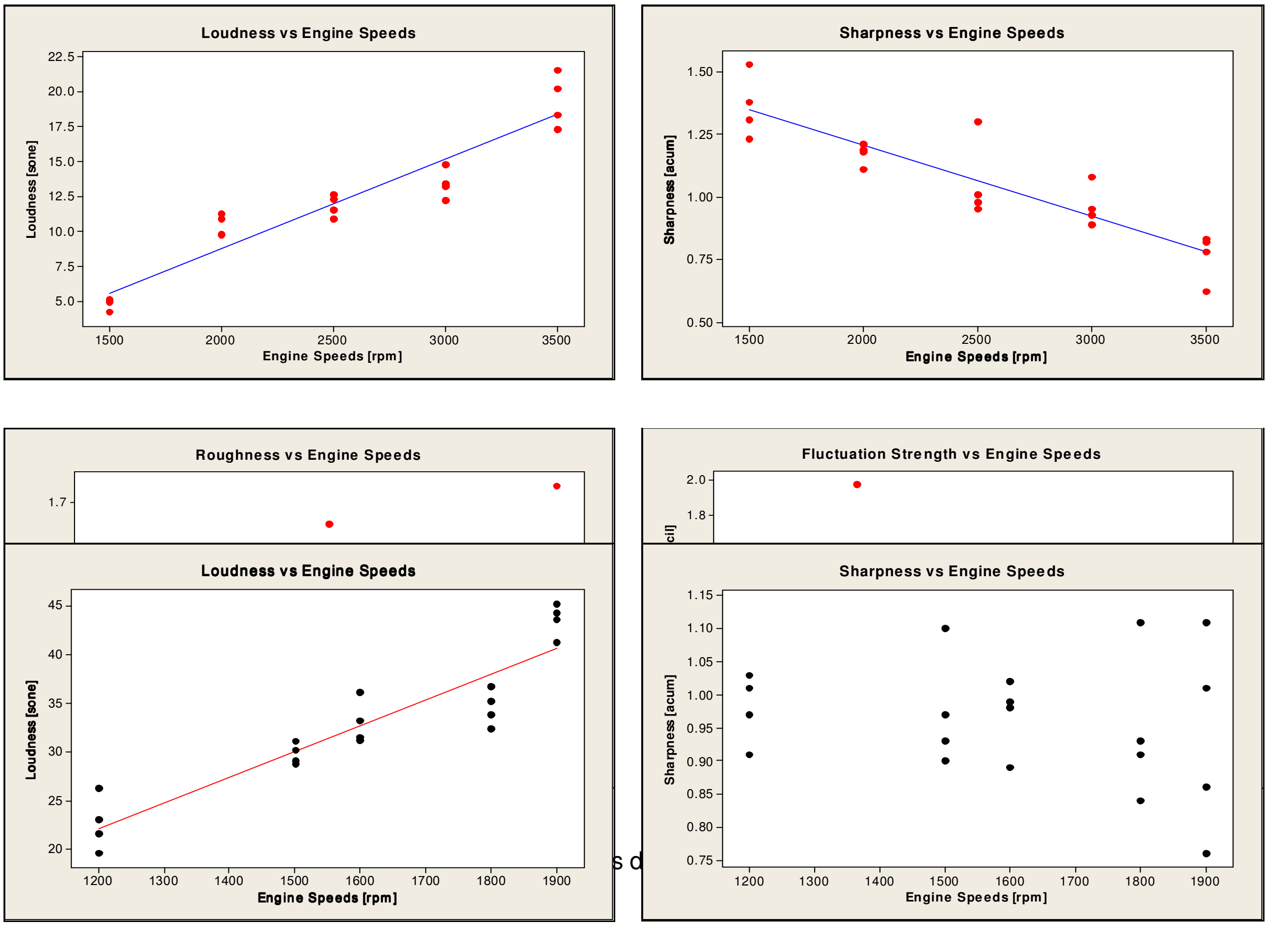
TABLE 6: The average values of vibration dos value [ms$^{-1.75}$] versus engine speed

Condition	**VDV [ms$^{-1.75}$]**	**Average Loudness**	**Sharpness**	**Roughness**	**Fluct. Str.**
Stationary	0.0	4.8	1.362	1.44	1.22
	0.0	10.4	1.173	1.46	1.21
	0.0	11.8	1.061	1.48	1.07
	0.0	13.4	0.964	1.50	0.94
	0.0	19.3	0.762	1.57	0.91
Highway	**0.3**	**21.1**	**0.861**	**1.68**	**1.66**
	0.4	**24.8**	**0.781**	**1.72**	**1.45**
	0.4	**29.8**	**0.674**	**1.88**	**1.50**
	0.4	**30.8**	**0.867**	**1.92**	**1.97**
Pavement	0.6	22.6	0.981	2.01	1.31
	0.8	29.8	0.973	2.21	1.37

0.9	33.0	0.969	2.34	1.45
0.9	34.5	0.948	2.42	1.30
1.1	43.6	0.937	2.56	1.42

Loudness[Sone] , S: Sharpness [Acum] , Roughness [Asper] and F: Fluctuation Strength [Vacil]

TABLE 7: The average values of vibration dos value versus engine speed



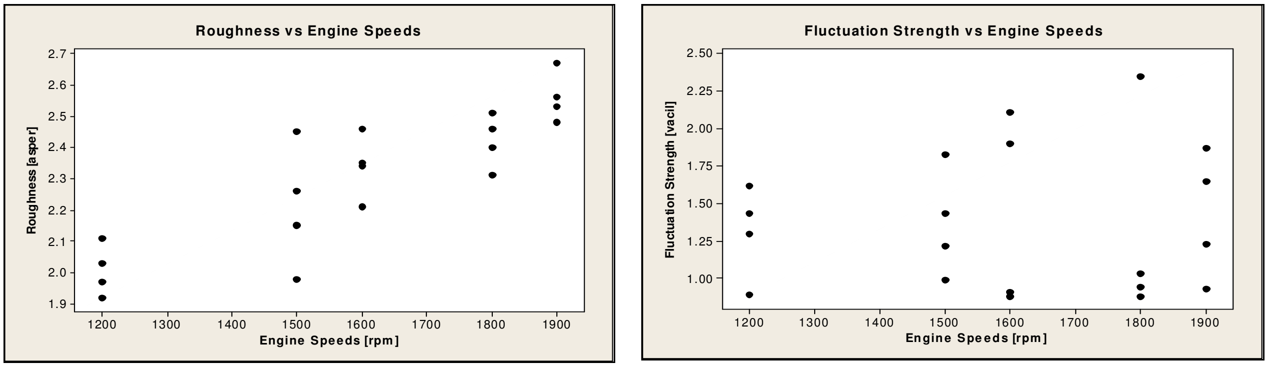


FIGURE 9 : Sound quality trends at moving condition on the pavement road

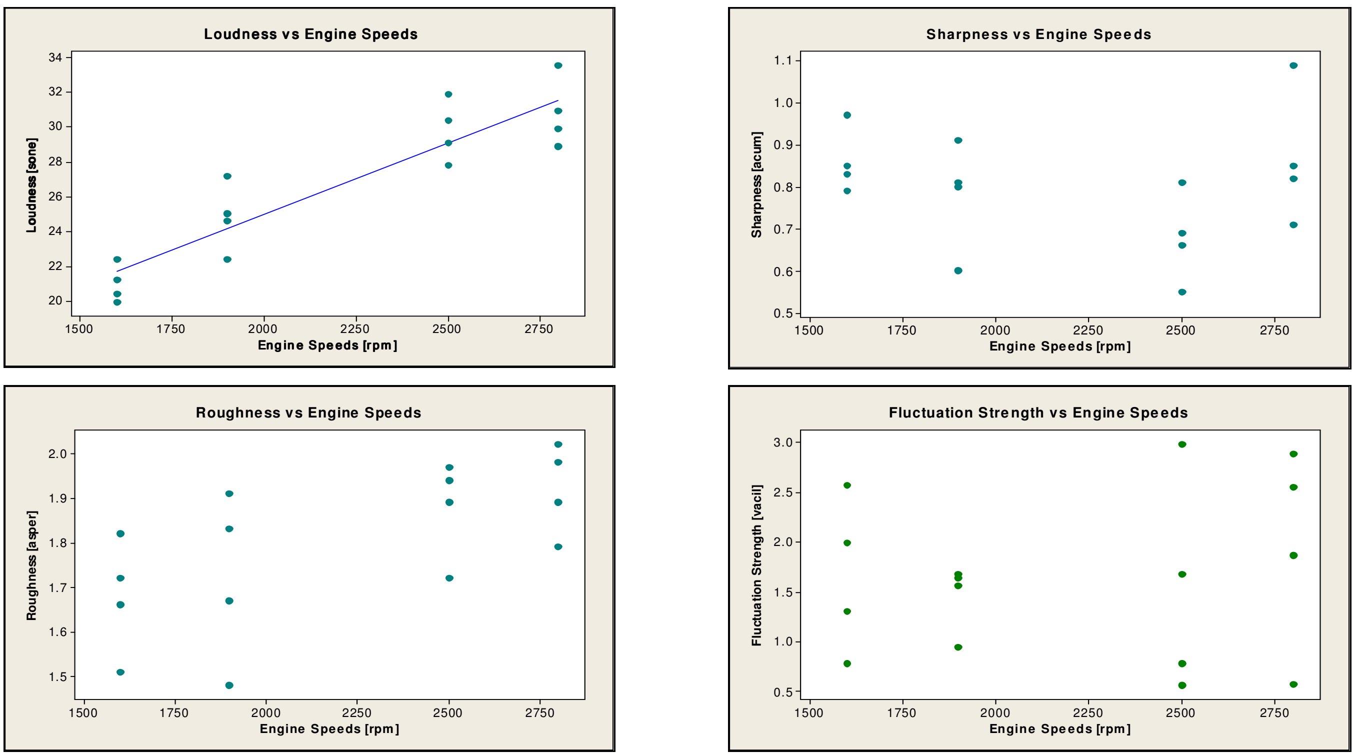


FIGURE 8 : Sound quality trends during moving condition on the highway road

Each parameter must fulfill 2 criteria below in order to be chose which metric of sound quality is significant and truly corresponds with the engine speeds

(i) Regression value R^2 for correlation between each sound quality parameter and engine speeds must be greater than 50%

(ii) p-value must be smaller than 0.05

After regression analysis is performed, each sound quality trend is observed and we only chose which sound quality that fulfilled above criteria for both condition stationary and moving condition. In this case we successfully found that only loudness parameter is significant and linearly corresponds with engine speeds for both of condition. The regression equations are obtained in order to predict the generated sound quality depending on engine speeds in the future (Table 8). The obtained equations for loudness parameters are shown below.

Stationary	**Highway**	**Pavement**
$L = 0.00641 \times V_{engine} - 4.07$	$L = 0.00821 \times V_{engine} + 8.54$	$L = 0.0265 \times V_{engine} - 9.77$

Condition	Metrics	Regression (R^2)	Multiple R	p-value
Stationary	Loudness	0.897	0.947	0.00678
	Sharpness	0.803	0.896	5.5E-14
	Roughness	0.178	0.422	1.6E-12
	Fluctuation Strength	0.423	0.179	4.4E-06
Highway	***Loudness***	***0.846***	***0.920***	***0.00117***
	Sharpness	***0.011***	***0.106***	***0.00013***
	Roughness	***0.647***	***0.418***	***4.8E-07***
	Fluctuation Strength	***0.018***	***0.136***	***0.25484***
Pavement	Loudness	0.854	0.924	5.7E-05
	Sharpness	0.032	0.178	3.6E-07
	Roughness	0.755	0.869	3.3E-06
	Fluctuation Strength	0.002	0.046	0.093

TABLE 8 : Results of Regression Analysis

By assuming more vibration will produce more noise, thus we look the changes trend of the loudness parameter with the increase of vibration level. The objective is to verify that the loudness parameter is exactly parameter that we supposed to consider. Figure 10 is plotted to recognize the trend pattern of the loudness parameters corresponding with the exposed vibration dose value at the car floor. The regression analysis result shows that loudness parameter linearly corresponds with the increase value of vibration dose value where regression (R^2) is 84.7% and adjusted R is 84.4% (Figure 11).

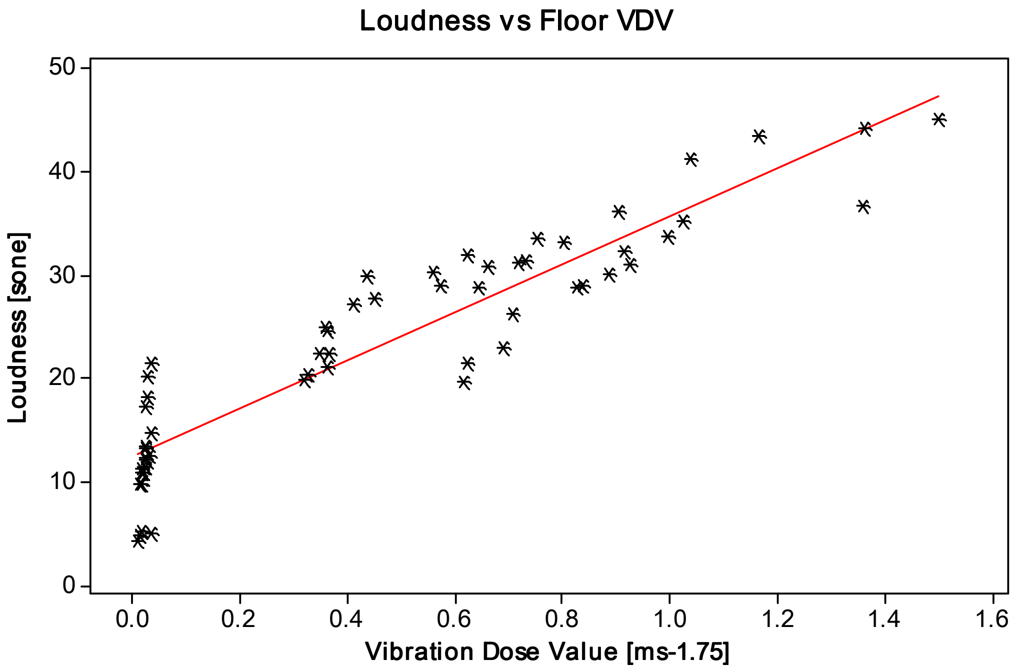


FIGURE 10 : Changes trend of loudness parameter with increase of vibration dose value

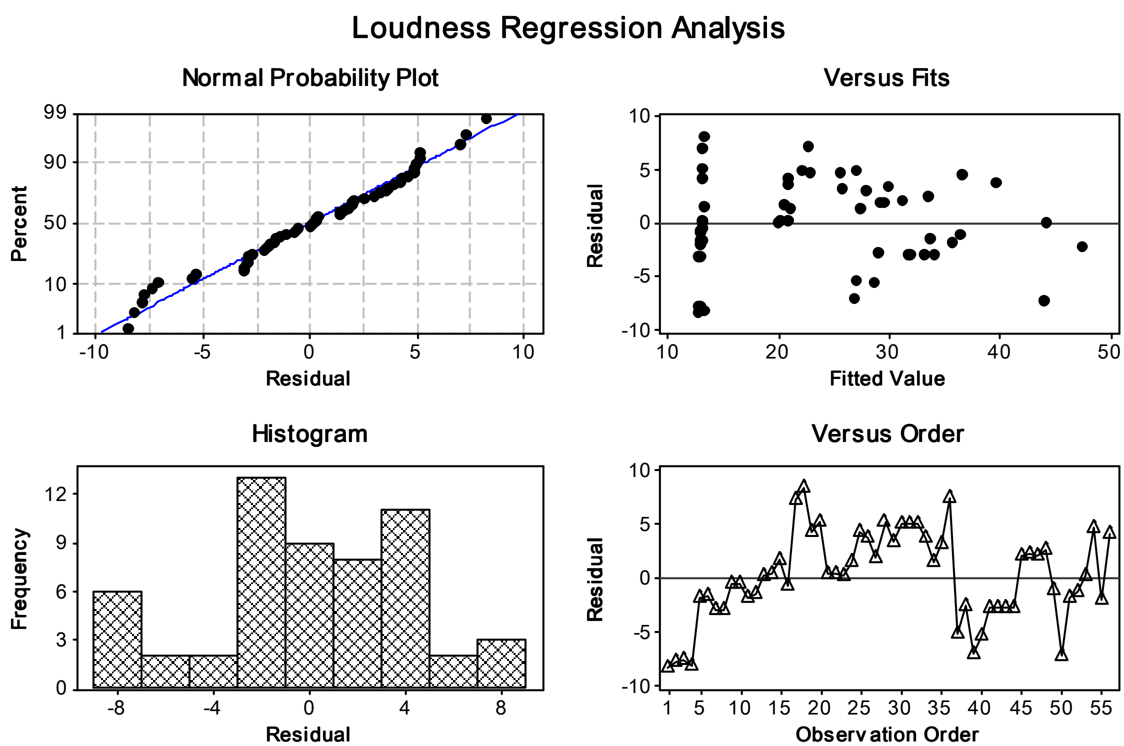


FIGURE 11 : Regreesion analysis for loudness vs vibration dose value

Table 9 shows the noise which is considered the noise contributed by interaction between tyres and road surfaces. From Table 9, there are two sources of noise that can be separated by dividing the values of annoyance levels to SQ and ΔSQ. In this case we assume that ΔSQ is the annoyance of noise produced by tyres, With this technical method, we belive that to reduce the noise in passenger car cabin, we can cluster the source of the noise into two types. These two noises are the noise produced by the engine and the noise produced by the vibration due to interaction between tyres and road surface. By using this technical method, automotive researchers able to predict the noise produced by the tyres (ΔSQ) by using the proposed equation (9).

$$\Delta SQ = \left| SQ_{moving} - SQ_{stationary} \right| \tag{2}$$

Engine Speeds [rpm]	Stationary	Highway		Pavement	
	L	*L*	Δ*L*	*L*	Δ*L*
1200	3.62	18.39	**14.77**	22.03	**18.41**
1300	4.26	19.21	**14.95**	24.68	**20.42**
1400	4.90	20.03	**15.13**	27.33	**22.43**
1500	5.55	20.86	**15.31**	29.98	**24.44**
1600	6.19	21.68	**15.49**	32.63	**26.44**
1700	6.83	22.50	**15.67**	35.28	**28.45**
1800	7.47	23.32	**15.85**	37.93	**30.46**
1900	8.11	24.14	**16.03**	40.58	**32.47**
2000	8.75	24.96	**16.21**	43.23	**34.48**
2100	9.39	25.78	**16.39**	45.88	**36.49**
2200	10.03	26.60	**16.57**	48.53	**38.50**
2300	10.67	27.42	**16.75**	51.18	**40.51**
2400	11.31	28.24	**16.93**	53.83	**42.52**
2500	11.96	29.07	**17.11**	56.48	**44.53**
2600	12.60	29.89	**17.29**	59.13	**46.53**
2700	13.24	30.71	**17.47**	61.78	**48.54**
2800	13.88	31.53	**17.65**	64.43	**50.55**
2900	14.52	32.35	**17.83**	67.08	**52.56**
3000	15.16	33.17	**18.01**	69.73	**54.57**

TABLE 8 : Amount of noise contributed by the vibration due to interaction between tyres and road surface

4. CONCLUSION

From the results, the studies successfully clustering the noise into two sources: Noise due to engine transmission and noise due to interaction between tyres and road surface. The results also show that main contributor of the noise in passenger car cabin is the noise which produced due to the vibration that generated by the interaction between tyres and the road surface.

The results of the study are displayed in Table 8. The results show that the increase in the engine speed values corresponds to an increase in the level of vibration. The table shows that the value of loudness parameter increases with the increase of the engine speed values. From the observation of the results also we understood that with the increase of the engine speeds will increase level of exposed vibration to the car body either at stationary or moving condition. Thus, we may conclude that the higher the vibration, the higher the annoyance factor of the noise. From Table 6-7, it can be concluded that the increase of engine speed can influence the noise level by increasing the value of the loudness parameter; in other words, with the increase of engine speeds it may cause more noise due to the vibration from the engine combustion and vibration due to interaction between tyre and the road surface.

The purpose of this study is to obtain the amount of noise level which produced by the interactions between tyres and road surface. Thus, the equations that proposed in this study cannot be applied or used directly by the researcher. In order to obtain the noise produced by the tyre vibration, researcher has to conduct the testing on the vehicle started from the first until the last step in order to predict the amount of noise. Since the type of road influences the generated noise in passenger car cabin, it is important to the automotive researchers to ensure that during the testing, the road surface must having similar characteristics and specifications in order to obtain the read of measurements for noise and vibration more precise and accurate. Furthermore, different tyre surface pattern (tread) will produce different level of noise.

REFERENCES

[1] Ih, J.-G., Kim, H.-J., Lee, S.-H., & Shinoda, K. (2009). Prediction of Intake noise of an automotive engine in run-up condition. *Applied Acoustics, 70*(2), 347-355.

[2] Leopoldo P.R. de Oliveira, K. J., Peter Gajdatsy, Herman Van der Auweraer, Paulo S. Varoto, Paul Sas, Wim Desmet. (2009). Active sound quality control of engine induced cavity noise. *Mechanical Systems and Signal Processing, 23*(2), 476-488.

[3] M. Ferrer, A. G., M. de Diego, G. Piñero, J. J. Garcia-Bonito. (2003). Sound quality of low-frequency and car engine noises after active noise control *Journal of Sound and Vibration, 265*(3), 663-679.

[4] Shin, S.-H., Ih, J.-G., Hashimoto, T., & Hatano, S. (2009). Sound quality evaluation of the booming sensation for passenger cars *Applied Acoustics, 70*(2), 309-320.

[5] Daruis, D. D. I., Nor, M. J. M., Deros, B. M., & Fouladi, M. H. (2008). *Whole –body Vibration and Sound Quality of Malayisan Cars*. Paper presented at the 9th Asia Pacific Industrial Engineering & Management Systems Conference.

[6] H. Nahvi, M. H. F., M.J. Mohd Nor. (2009). Evaluation of Whole-Body Vibration and Ride Comfort in a Passenger Car. *International Journal of Acoustics and Vibration, 14*(3), 143-149.

[7] D.J. O'Boy, A. P. D. (2009). Tyre/road interaction noise—A 3D viscoelastic multilayer model of a tyre belt. *Journal of Sound and Vibration, 322*(4-5), 829-850.

[8] D.J. O'Boy, A. P. D. (2009). Tyre/road interaction noise—Numerical noise prediction of a patterned tyre on a rough road surface. *Journal of Sound and Vibration, 323*(1-2), 270-291.

[9] P.Kindt, P.Sas, & W.Desmet. (2009). Measurement and analysis of rolling tire vibrations. *Optics and Lasers in Engineering, 47*, 443-453.

[10] Wang, Y. S., Lee, C.-M., Kim, D.-G., & Xu, Y. (2007). Sound-quality prediction for nonstationary vehicle interior noise based on wavelet pre-processing neural network model.

[11] Wang, Y. S. (2009). Sound quality estimation for nonstationary vehicle noises based on discrete wavelet transform. *Journal of Sound and Vibration, 324*(3-5), 1124-1140.

[12] Maria B. Dühring, J. S. J., Ole Sigmund. (2008). Acoustic design by topology optimization. *Journal of Sound and Vibration, 317*(3-5), 557-575.

[13] Ricardo Penna Leite, S. P., Samir N.Y. Gerges. A sound quality-based investigation of the HVAC system noise of an automobile model. *Applied Acoustics, 70*(4), 636-645.

[14] Şahin Yıldırım, İ. E. (2008). Sound quality analysis of cars using hybrid neural networks. *Simulation Modelling Practice and Theory, 16*(4), 410-418.

[15] Shin, S.-H., Ih, J.-G., Hashimoto, T., & Hatano, S. (2009). Sound quality evaluation of the booming sensation for passenger cars *Applied Acoustics, 70*(2), 309-320.

[16] Genuit, K. (2004). The sound quality of vehicle interior noise: a challenge for the NVH-engineers. *International Journal of Vehicle Noise and Vibration, 1*(1/2), 158-168.

[17] Nor, M. J. M., Fouladi, M. H., Nahvi, H., & Ariffin, A. K. (2008). Index for vehicle acoustical comfort inside a passenger car. *Applied Acoustics, 69*, 343-353.