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Linear Programming: Optimization of Noise and Vibration Model in Passenger Car Cabin

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Abstract. **Car cabin interior acoustical is one of the factors which may influence the flexibility of the driving. Basically the amount of discomfort depends to magnitude, frequency, direction and also the duration of exposed vibration in the cabin. Generally the vibration is caused by two main sources: engine transmission and interaction between tyre and road surface. The noise which produced by the car system can cause hearing impairment, hypertension, annoyance and sometimes can decrease the driving focus which may cause an accident. There are studies have been carried out to measure the annoyance level of cabin interior acoustical by defining particular index [16]. In this study the effects of vibration to noise in passenger car cabin were investigated. Vehicle acoustical comfort index (VACI) was used to evaluate the noise annoyance level and vibration dose value (VDV) was used to evaluate the vibration level. By using the changes trend of noise and vibration level depending to engine speeds, optimization model was proposed to optimize the vibration level in the passenger car cabin.**

Keywords: *Vibration, Sound Quality, Vehicle Acoustical Comfort Index (VACI), Vibration Dose Value (VDV)*

1. Introduction

Since last a few decades, a lot of studies have been carried out by automotive researchers to find the solution of passenger car cabin interior noise. Thus, reduction of the noise level may improve the driving quality. Generally noise which is generated by the vehicle system vibration in the vehicle interior affects driver's emotions and decrease the level of driving focus. This noise may also be described as a source of annoyance for humans where unwanted noise may interfere with speech communication between passengers, and thus affecting driving concentration and sleep disturbance. The vibration in vehicle interior reduces driving comfort, which directly influence the focus of the driving and may lead to fatal accident. Vibration exposure may also cause relative movement between the viewed object and the retina, resulting in a blurred image. This condition decreases the visual performance and at the same time affects the driver's concentration. One of the main sources of the vibration in the car cabin is the vibration due to the interaction between tyre and road surface [1-2]. Basically the level of vibration is dependent on the velocities of the car, tyre pattern and the roughness of the road surface.

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8.1. Evaluation of Noise

Based on the previous research a number of the noise sources have been identified. The main source that familiar with the vehicle interior noise is engine transmission during acceleration or deceleration of the car. The vibration that caused by rolling tyres connected with road surface and the vibration of the parts in the vehicle such as the vibration of the dash box during the moving condition and the vibration from gear box system may be considered as second major contributor to the interior noise. However there are a few more noise sources that identified, even though given effects do not much as the effects that contributed by the engine system and the interior vibrations such as the driving unit which involving the combustion of the engine, noise resulting from streaming of air on the surface of the vehicle and in the channels and vehicle body and etc.

A number of studies were performed by automotive researchers to determine and predict the generated vibration in internal vehicle at moving condition [3-4].These results were used by the vehicle manufacturing company, they to optimize and improve the structure of the parts which in turn reduce the generated vibration and at the same time may decrease the noise in passenger car cabin [5-9].

For the acoustical engineers it is crucial to know the method or tools which may be applied to measure, to analyze and to describe the level of the noise and at the same time know how the way to improve the noise. To improve acoustics comfort in vehicle designs, researchers must understand the trends and characteristics of the noise and able to evaluate the noise. Thus, thru this study, to evaluate the noise level the measurement of the sound quality metric were used depending on engine speeds [rpm]. The parameters of sound quality referred to four types of sound quality metrics which are Zwicker loudness [sone], sharpness [acum], roughness [asper] and fluctuation strength [vacil]

8.2. Evaluation of vibration

Based on previous studies, in general the main source 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. Basically, vibration or noise is directly related to engine speed due to changes in direct proportion to engine rpm [10-13]. A vibration that comes from engine surface are combustion vibration and mechanical vibration.

Generally, vibration or noise is directly related to engine speed which is due to changes in direct proportion to engine rpm. A vibration that comes from engine surface will generate noise where the sources of the vibration can be divided into two main parts, which are combustion vibration and mechanical vibration. The combustion vibration is caused mostly by the rapid pressure rise created by ignition and mechanical vibration is caused by a number of mechanisms with perhaps piston slaps being one of the most important, especially in diesel engine. However, at certain speeds, the vibration is mainly caused by the interaction between rolling tyres and road surface. Basically, the generated vibration is not just caused by the rolling tyres, but is also radiated by structure-borne vibration which spread to the rim and other parts of the vehicle body. The generated vibration depends on vehicle speed and can be felt in the steering wheel, seats or floor board. The vibration is also dependent on the roughness of the road surface where the tyres are rolling on. Thus, rougher surface generates higher vibration level.

In this study, BS6841 (British Standards Institution 1997) refers to the use of the vibration magnitude evaluation method using r.m.s acceleration aw . Due car motion by shocks or impulsive velocity changes, the use of the time integrated fourth power of accelerations known as vibration dose value (VDV) is considered more suitable for vibration assessment [14-15]. VDV is more sensitive to peaks than the basic evaluation method by using the fourth power instead of the second power of the acceleration time history as the basis for averaging. Here, the measure of the total exposure to vibration which considers the magnitude, frequency and exposure duration. Thus VDV (ms-1.75) is defined as

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

where

$a_w(t)$: Frequency – weighted acceleration

T : Total period of the measurement

Vibration should be measured according to coordinate system centred at the interface of the body. In this study, where the driver is in sitting condition, the relevant orientation supposed to be determined by the axes of the body and the z-axis may not be vertical. The principal relevant basicentric systems are shown in Figure1.

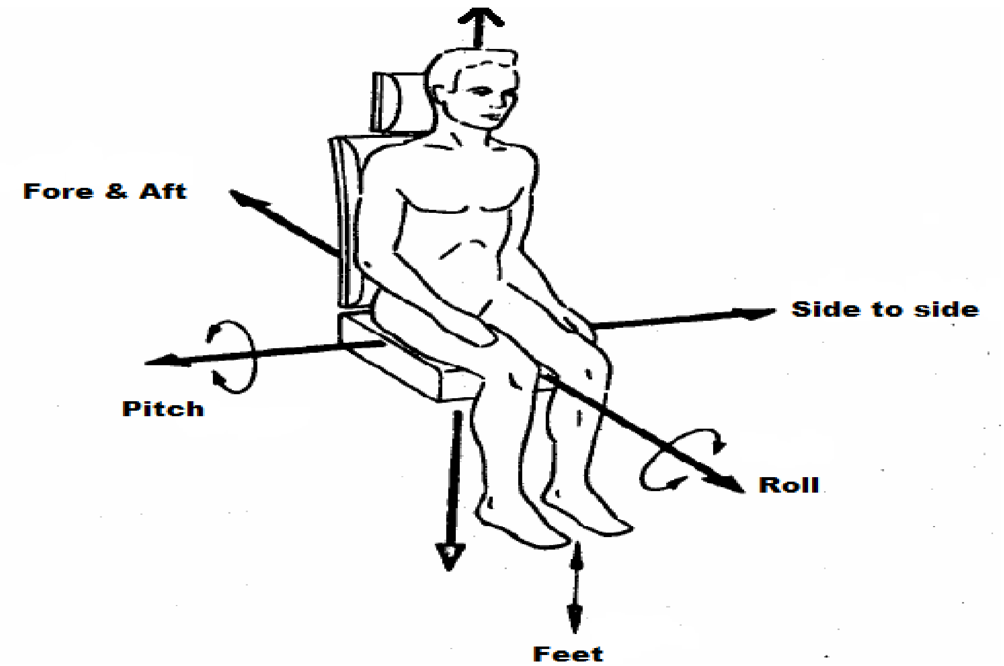

Figure 1. Principal basicentic axes for a seated person

2. Methodology

The sound quality was measured at stationary and moving conditions using binaural Head and Torso (HAT) equipment on its frequencies and amplitudes (Figure2). B&K type 7698 sound quality software is used to analyze and to find the metrics for sound quality. Measured noise from right channel was used only in VACI computation due to HAT being a binaural device. In order to obtain the level of annoyance of the noise while the car was in motion, the measured sound quality on the highway road were substituted in the equation (2) given by Nor et al [16] (Refer to Table 1).

Highway

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$$VACI = -0.3L - 4.1S + 14 \quad (2)$$

Figure 2. Head and Torso (HAT)

Table 1. Example of Measured Sound Quality

Metric	Right	Left	Unit
Inst . Loudness (Mean)	10.5	10.4	sone
Sharpness (Mean)	1.21	1.17	acum (Z)
Roughness	1.89	1.46	asper
Fluctuation Strength	1.03	1.21	Vacil

Since there was no equation describing for noise annoyance level at stationary condition, a new equation was formulated by using the equation (3) given by Nor *et al*. [16].

$$VACI = \sum c_j \cdot Q_{ij} + k \quad (3)$$

The obtained *VACI* values are not integer and thus to determine which annoyance level is the noise on the *VACI* scale, the obtained values must be rounded to integer form in the range from 1 to 5. The values of the *VACI* scale is stated in Table 2.

Table 2. The state of VACI Scale

VACI Scale	Annoyance State
1	Most annoying
2	Medium annoying
3	Marginal
4	Medium pleasant
5	Most pleasant

The vibration which is transmitted to the body shall be measured on the surface between the body and that surface and normally evaluated by taking the measurement level of vibration at certain parts that are identified as dominant sources of vibration for the driver in the car interior. In this study, the vibration detector was a B&K isotron accelerometer model 751-100 (Figure 3), installed at the front floor next to the driver side. The measurement software is B&K Pulse Labshop. By using the (1), the vibration dose value can be obtained in order to evaluate the level of exposed vibration at the car floor.

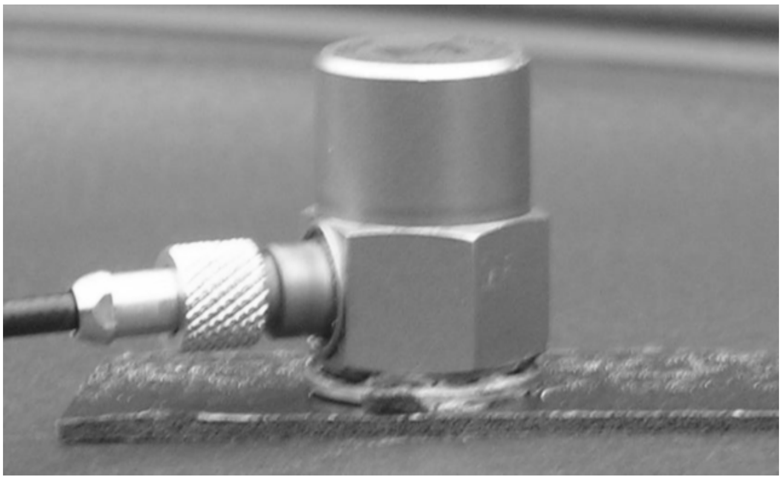

Figure 1. B&K Accelerometer model 751-100

The duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed. In this study, the duration for each measurement was 10 seconds. The test was conducted by two members; a driver and an assistant. The driver's task is to drive the car while maintaining specific speeds according to the testing plans. A test assistant is needed to handle the laptop computer and at the same time record the sound quality of noise measurement. The location of the tested highway was along the Kajang – Bangi Highway (Figure 4).

Figure 4. The roughness of the highway road surface

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3. Modelling

The measured sound quality of noise are divided for two categories, stationary and highway (when the car is in motion) due to interaction between tyres and road surface gives major effect to the generated noise in passenger car cabin. Table 3 and Figure 5 illustrate the examples of the results for measurement of the sound quality metrics for Zwicker Loudness, sharpness, roughness and fluctuation strength. For both of the stationary and highway, the parameters for loudness [sone] and roughness [asper] increase with the increase of engine speeds [rpm]. Meanwhile for sharpness [acum(Z)] and fluctuation strength [Mean] the parameter values decrease with the increase of engine speeds [rpm].

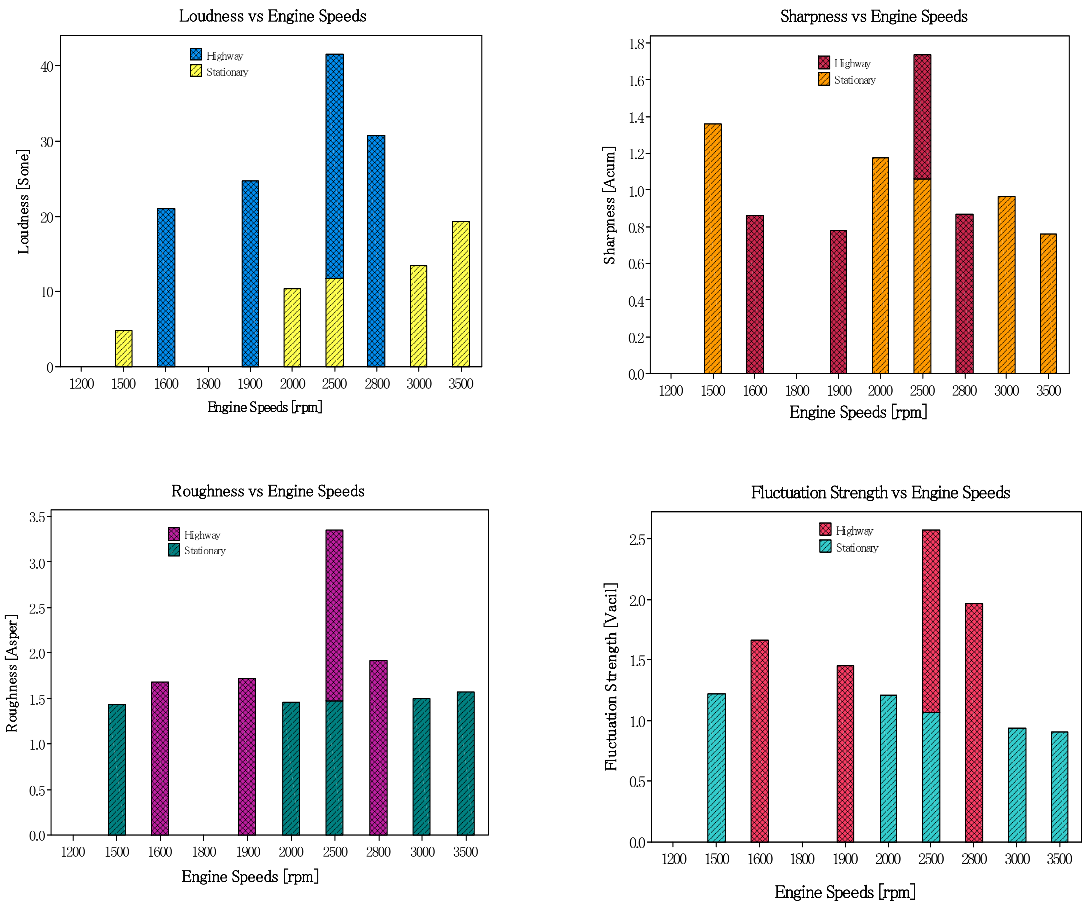

Figure 5. Measured Sound Quality

Table 3. The Data For Measured Sound Quality

Engine Speed (rpm)	Stationary				Moving (Highway)		
	L	*S*	*R*	*F*	*L*	*S*	*F*
1200	-	-	-	-	-	-	-

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1500	4.80	1.36	1.44	1.22	-	-	-
1600	-	-	-		21.1	0.861	1.66
1800	-	-	-	-	-	-	-
1900	-	-	-	-	24.8	0.781	1.45
2000	10.4	1.17	1.46	1.21	-	-	-
2500	11.8	1.06	1.48	1.07	29.8	0.674	1.50
2800	-	-	-	-	30.8	0.867	1.97
3000	13.4	0.96	1.50	0.94	-	-	-
3500	19.3	0.76	1.57	0.91	-	-	-

L: Loudness S: Sharpness R: Roughness F: Fluctuation Strength

At stationary condition, these 5 equations are formed depending on the five conditions of engine speeds [*rpm*] by using equation (3).

$$1500rpm$$
$$4.8L + 1.36S + 1.44R + 1.22F + k = 5$$
$$2000rpm$$
$$10.4L + 1.17S + 1.46R + 1.21F + k = 4$$
$$2500rpm$$
$$11.8L + 1.06S + 1.63R + 1.07F + k = 3$$
$$3000rpm$$
$$13.4L + 0.96S + 1.50R + 0.94F + k = 2$$
$$3500rpm$$
$$19.3L + 0.76S + 1.57R + 0.91F + k = 1$$

By solving the equations above simultaneously, new equation is formed in order to predict the noise annoyance level at stationary condition as shown below. From the Table 4, Figure 6 is plotted to observe the changing trends of *VACI* values depending to engine speeds [*rpm*].

$$VACI = -0.243L - 1.85S + 3.77R + 6.71F - 4.93 \quad (4)$$

Table 4. *VACI* values against engine speeds

Engine Speed [rpm]	Stationary	Highway
1200	-	-
1500	5.00	-
1600	-	4.14
1800	-	-
1900	-	3.36
2000	4.00	-
2500	3.00	2.30
2800	-	1.21
3000	2.00	-
3500	1.00	-

In order to study the changes trends, we plot the correlation between produced noise annoyance levels with the generated vibration follow to Table 5 (Figure 7 and Figure 8). From there we obtain linear trends for both of the situations (stationary and moving condition). Then we formulate two equations which can be used in optimization model.

Table 5. *VACI* values and vibration dose value against engine speeds

Engine Speeds (rpm)	*VACI* Stationary	*VACI* Moving (Highway)	Vibration Dose Value (*VDV*), $ms^{-1.75}$
1200	-	-	0.238
1500	5	-	0.287
1600	-	4.14	0.336
1800	-	-	0.380
1900	-	3.36	0.434
2000	4	-	-
2500	3	2.30	0.532
2800	-	1.2.1	0.630
3000	2	-	-
3500	1	-	-

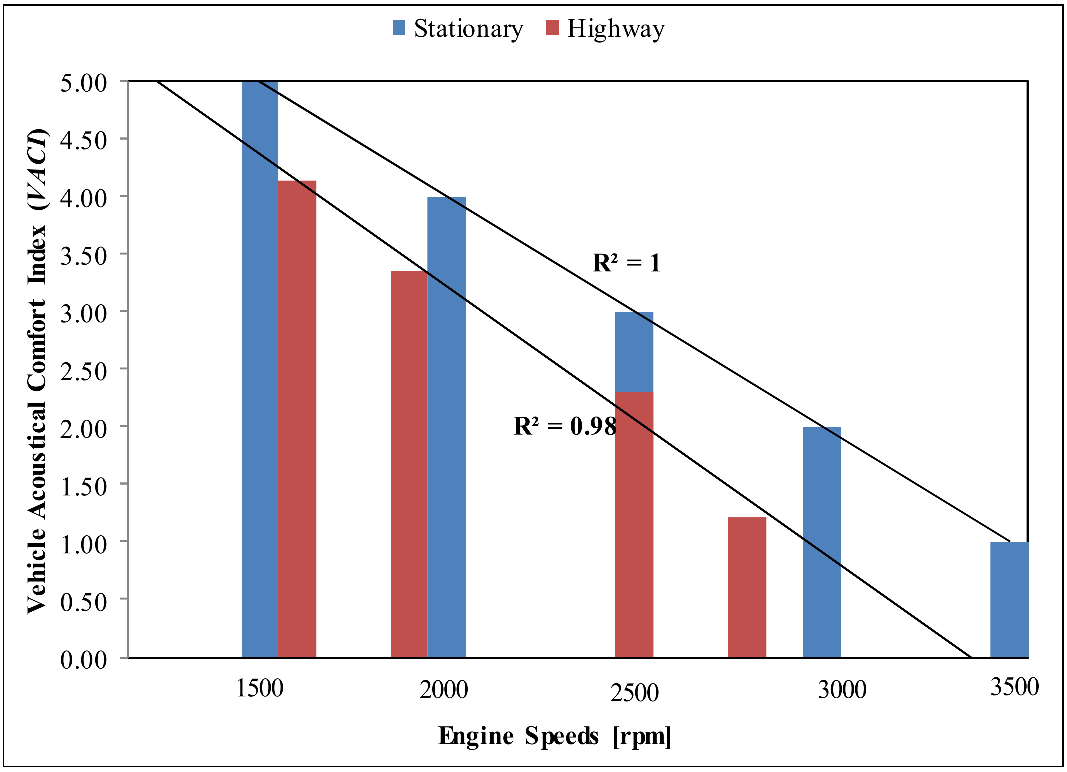

Figure 6. VACI values trends depending on engine speeds [rpm]

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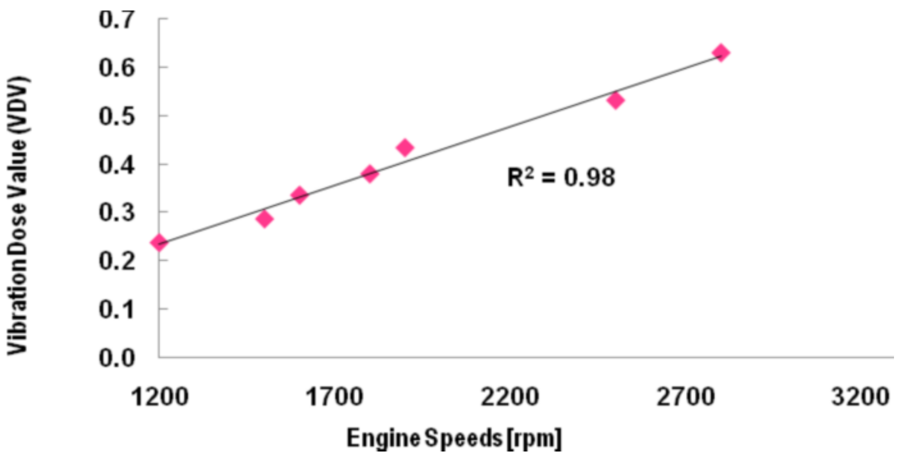

Figure 7. VDV values trend depending to engine speed

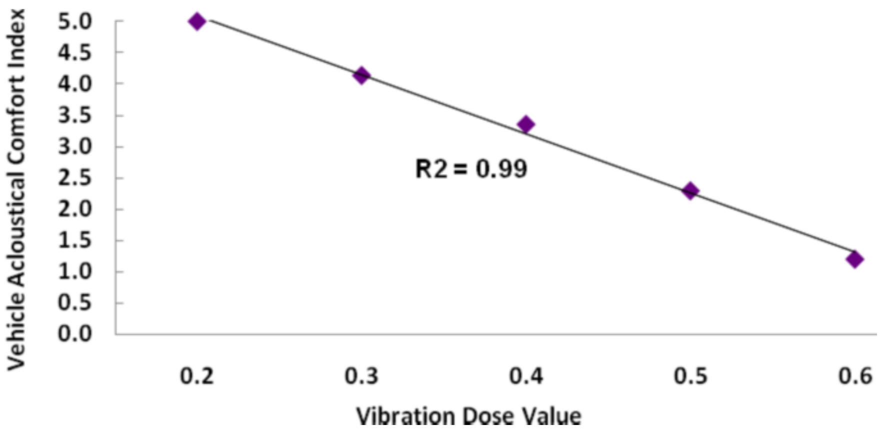

Figure 8. VACI values trend depending to VDV

From the Figure 6, the changing pattern of *VACI* values can be represented in equations (5) and (6).

Highway

$$VACI = -2.4 \times 10^{-3} V_{engine} + 7.9 \tag{5}$$

Stationary

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$$VACI = -2\times10^{-3}V_{engine} + 8 \quad (6)$$

For optimizing vibration level two linear programming models were set up. In the first model the range of required *VACI* was from 2.5 until to 4.4. These values were chosen because the acoustical comfort that required during moving condition was from scale 3 to scale 4. From model 2, engine speed was bounded from 1000 [*rpm*] to 2500 [*rpm*], since the maximum engine speed that normally achieved during moving condition is 2500 [*rpm*] and the engine speed after the car engine started normally more than 1000 [*rpm*].

Model 1

a) The objective of this model is to get max value of *VACI*.
b) To find the value of *VDV* value must be achieve in order to have required *VACI* value.

Constraints

1) Normally during normal condition, the range of the engine speeds is more than 1000[*rpm*] and not exceed to 2500[*rpm*]
2) The value of vehicle acoustical comfort index must be positive and cannot be more than scale 5.
3) The value of engine speed [*rpm*] must be positive.

The proposed model can be shown as below.

Max $VACI$

Subject to

$VACI = -2.4\times10^{-3}V_{engine} + 7.9$

$VACI = -8.83VDV + 7.2$

Constraints

Engine speed range

$V_{engine} \geq 1000$

$V_{engine} \leq 2500$

VACI values range

$VACI \leq 5$

Required VACI value

$VACI \geq k$

Additional constraint

$V_{engine} > 0$

End

Model 2

a) The objective of this model is to get max value of *VACI*.
b) To find the value of *VDV* value must be achieve in order to have required *VACI* value for any tested engine speed *k* [*rpm*].

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Constraints

1) Normally during normal condition, the range of the engine speeds is more than 1000[*rpm*] and not exceed to 2500[*rpm*]
2) The value of vehicle acoustical comfort index must be positive and cannot be more than scale 5.
3) The value of engine speed [*rpm*] must greater than *k* [*rpm*].

The proposed model can be shown as follows.

Max *VACI*

Subject to

$$VACI = -2.4\times10^{-3}V_{engine} + 7.9$$

$$VACI = -8.83VDV + 7.2$$

Constraints

VACI values range

$VACI \geq 0$

$VACI \leq 5$

Tested engine speed

$V_{engine} \geq k$

Engine speed range

$V_{engine} \leq 2500$

End

4. Results And Conclusion

The results of the LP models are displayed in Table 5 and Table 6. From Table 5, the results show that the increase of *VACI* values corresponds to the decrease the level of vibration. Table shows that value of *VDV* decrease with the increase of *VACI* values. From this observation it may be concluded that the more value of vibration can produce the more annoyance of the noise. From Table 6, it can be concluded that the increase of engine speed can influence the annoyance level by decreasing the value of vehicle acoustical comfort index, in other word it will contribute to more noise.

The main purpose of this study is to propose the way to minimize the noise in passenger car cabin by reducing the amount of vibration level. By using the provided models, automotive researchers were able to estimate the maximum level of vibration to be achieved in order to obtain better *VACI* values pleasant sound in car cabin interior. By modifying the particular structure of the car system to reduce the exposed vibration level, we are able to increase the *VACI* values and at the same time decrease the level of noise in passenger car cabin.

Table 5. Model 1 Results

Engine Speed [rpm]	Index		*VDV* Value [ms$^{-1.75}$]
	Index	Scale	
1000	5.00	5	0.249
1100	5.00	5	0.249
1200	5.00	5	0.249

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1300	4.78	5	0.274
1400	4.54	5	0.301
1500	4.30	4	0.328
1600	4.06	4	0.356
1700	3.82	4	0.383
1800	3.58	4	0.410
1900	3.34	3	0.437
2000	3.10	3	0.464
2100	2.86	3	0.492
2200	2.62	3	0.519
2300	2.38	2	0.546
2400	2.14	2	0.573
2500	1.90		0.600

Table 6. Model 2 Results

VACI		Engine Speed	*VDV* Value
Index	Scale	[rpm]	[$ms^{-1.75}$]
2.5	3	2250	0.532
2.6	3	2208	0.521
2.7	3	2167	0.510
2.8	3	2125	0.498
2.9	3	2083	0.487
3.0	3	2041	0.476
3.1	3	2000	0.464
3.2	3	1958	0.453
3.3	3	1916	0.442
3.4	3	1875	0.430
3.5	4	1833	0.419
3.6	4	1792	0.408
3.7	4	1750	0.396
3.8	4	1708	0.385
3.9	4	1625	0.362
4.1	4	1583	0.351
4.2	4	1542	0.340
4.3	4	1500	0.328
4.4	4	1458	0.317

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