Palestine Polytechnic University

Mechanical Engineering Departments

Graduation Project

Testing & Comparisons of Transmitted Vertical Vibration in Vehicles Due to Road Roughness

Project team

Anees M. Abufilat, Automotive Engineering

Yusuf R. Faqyat, Automotive Engineering

Supervisor

Eng. Jalal Salaymeh

Hebron-Palestine

January, 2014

Dedication

We would like to express our gratitude to our parents, our families and our friends, whom we admire very much and have brought love, warmth, patience, and understanding to our lives, without whom we would be unable to complete our project. All levels of success we have reached and will reach cannot be without your support and your real love and respect to us.

Acknowledgment

After thanking Allah; we want to thank Eng. Jalal Salaymeh, our supervisor, for his patience, help and guidance through the entire project who appreciated us for our work and motivated us, and we will never forget his support for us, he was as he always support, help and respect us with all readiness any time we need him. A special thanks for Prof. Dr. Karim Tahboub who helped us for finding the references and giving us his great experience. We cannot forget to thank Eng. Abdulkarim Almuhtasib, the generous person, who abbreviated days and hours of work by his help.

Abstract

Human comfort in passenger's cars is one of the major issues discussed continuously in automotive engineering. In this project; the comfortable of human body due to vertical vibration transmitted from road roughness done, & a comparison between the level of comfortable in three passenger cars also discussed , depending on the criteria of comfortable discussed in International Organization for Standardization (ISO). The results of testing explained that the chosen bump with a small height make passengers uncomforted. The comparison shows that the Volkswagen Polo is better than the other two vehicles tested.

الملخص

راحة الركاب في المركبات واحدة من أهم القضايا التي تناقش باستمرار في عالم هندسة المركبات. في هذا المشروع , تم مناقشة مدى تأثير خشونة الطريق على راحة الركاب داخل المركبة , وتم عمل مقارنة بين ثلاثة أنواع مختلفة من المركبات , بالاعتماد على المقاييس التي حددت من خلال منظمة المقاييس العالمية (ISO) . نتائج الفحص التي أجريت أظهرت أن المطب الذي تم اختياره مع أنه قليل الارتفاع كان يشكل تأثيرا على راحة الركاب وصحتهم . نتيجة المقارنة بين المركبات الثلاثة أظهرت أن السيارة التي من نوع فولكسفاجن (بولو) حققت المرتبة الأولى من حيث تخفيف التسارع المنتقل نحو الركاب.

List of Contents:

List of Figures

List of Tables

List of symbols

m	Proof mass
k	Spring stiffness in accelerometer
c	Damping coefficient of damper in accelerometer
F	Total force
x	Displacement in accelerometer
$\dot{x}$	First diff of displacement
$\ddot{x}$	Second diff of displacement
t	Time
Fa	Applied force
Fd	Damping force
Fs	Spring force
ω_n	Natural frequency in accelerometer
ζ	Damping ratio
a	Acceleration
h	Mass displacement
H	Displacement amplitude of mass
J	Base displacement
Kmph	Speed unit (Km/hour)
g	Acceleration level unit (1g=9.81m/s^2)

Chapter 1: Introduction

1.1 Introduction

The comfort in passenger's vehicles is very important issue in the world of automobile manufacture, and in automotive manufactures; a lot of additions and corrections done and will be done to improve the comfort for drivers & passengers.

1.2 The Project Importance

The project comes as graduation demand, where the steps to the title of engineer becomes under lights, so graduated students responsibilities as senior engineers put them face to face with engineering problems. It is believed that the passenger's safety and comfort are important field to concern with. Depending on the information discussed below; the importance of project will be clear for all.

1.3 Vibration Sources in Vehicle

Vibration in vehicle has two main sources. The first is internal, which occurs due to power plant, drive train, & exhaust system. The second source is external, which occurs due to road roughness & aerodynamic force. [8]

1.3.1 Vibration Due to Road Roughness

The road roughness, causes vertical acceleration of vehicle, which passengers get the proving and this adds to their discomfort, when a vehicle is being driven over the road, the oscillations of its spring have frequencies which has not only dependent on the frequency at which road impulses or bumps are encountered but also on the relation between the spring stiffness and the mass of the spring part of vehicle, the real description of road is random in nature. Therefore the statistical description of the track will be more appropriate. [4]

1.3.2 The Main Effects of Vibration Due to Road Roughness

The vibrations generated in vehicle produce Mechanical Damages, Physiological Response, & Subjective Responses to humans. [2] Human Engineering deals with various effects of vibrations on the different parts of human body.

The vehicle vibration produces physiological effect on humans. The evidence suggest that short time exposure to vibration causes small physiological effects such as increase in heart rate, increase in muscle tension, long term exposure to vibration causes effects such as disk to spine & effects on digestive system peripheral veins & the female reproductive organ. [3]

1.3.3 Effect of Vehicle Vibration on Human Body

While dealing with the effects of vehicle vibration on humans it is necessary to study the physical characteristics of body. The effect on body due to vibrations is mechanical, physiological & subjective responses. It also affects the performance of human. [2]

.

1.3.4 Mechanical Damage

Damage is produced when the accelerative forces are of sufficient magnitude and frequency. Chronic injuries may be produced by vibration exposure of long duration. In practice such effects are usually found after exposure to repeated blows or to random jolts shaking in vehicle on rough surface, give rise to irregular jolting motion, acute injuries from exposure to these situation are race but have resulted from repeated impact injuries to the spinal column, including fracture of vertebrae are reported due to vehicle vibration pathological changes have been observed in the spine of operators of cars & on the rood trucks & other occupations involving chronic exposure to whole body vibration such exposure to whole body vibration, such exposure is also accepted as a risk factor in the development of low back pain minor kidney injuries are occasionally suspected & rarely to act of blood may appear in urine due to the vehicle vibration. [4]

1.3.5 Physiological Responses

It is difficult to separate out effects due to vibration from effects due to sitting all-day or manual loading & unloading. The vibration of frequency range 4 to 10 Hz procures pain in the chest after backaches seem to occur very particularly, at 8 to 12 Hz headaches, eye strain & irritations in the intestines & bladder are usually associated with frequencies between 10 to 20 Hz.[1]

1.3.6 Subjective Responses

The subjective response most often assessed in the vibration studies is comfort; Comfort of course, is a state of feeling & so depends in part on a person experiencing the situation.

People are most sensitive for vertical vibrations between 5 & 16 Hz & to the lateral vibration between about 1 & 2 Hz. Women are more sensitive than men to vertical vibration above about 10 Hz. Most responses of seated subjects implicated the lower abdomen at 2 Hz moving up to body at 4 & 8 Hz, with most responses implicating head at 16 Hz. At 32 Hz the responses are divided between the head & lower abdomen. Table (1) shows the resonant frequencies of various body structures for a sitting person. [1]

Table 1.1: The resonant frequencies of various body structures for a sitting person [1]

3-4 Hz	Resonance in cervical vertebrae (neck).
4 Hz	Peak resonance in lumbar (upper torsos) vertebrae
5 Hz	Resonance in shoulder girdle
20.3 Hz	Resonance between head & shoulders
60 Hz	Resonance in eyeballs.

1.3.7 Effect of Acceleration Level of Vibration on Humans

It is observed form ISO 2631 (Human comfort chart) and Table (2) that the critical range-affecting humans is within 4 to 8 Hz. For analyzing the effects of acceleration levels of vibrations on humans, it is decided to take the acceleration levels at the frequencies 4 to 8 Hz. [1]

Table 1.2: Range for comfort [1]

Vibration	**Reaction**
Less than 0.315 m/s^2	Not uncomfortable
0.315 to 0.63 m/s^2	A little uncomfortable
0.5 to 1 m/s^2	Fairly uncomfortable
0.8 to 1.6 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

1.4 Project Scope

The project deals with passengers cars, and will study the discomfort for human body due to vertical vibration transmitted from road roughness.

Chapter one is an introduction. Literature survey is discussed in chapter two. Theoretical background with mathematical modeling is in chapter three.

Chapter four will discuss the model design, its criteria, properties, and justifications. The analysis and considerations will be extracted in chapter five. Finally chapter six will devote to the conclusions & recommendations.

Chapter 2: Literature Review

2.1 Introduction

Human discomfort in passengers cars is a continuous discussed issue, & a lot of researchers discussed the issues of discomfort, each of research focus on a partial problem, & still discomfort one of the most priority in automotive engineer.

Parsons, K. C. et. al. found that the worst vibration with respect to human discomfort is the vertical transmitted vibration , in their research "Method for Predicting Passenger Vibration Discomfort ". [3]

Graffin, M. H. found that the human response has a wide range , and to measure the response ; it needs a wide range of environments, in his research "Evaluation of Vibration with Respect to Human Response" . [2]

Katu U.S. et al. found that as speed increases acceleration level also increases up to certain limit, then the acceleration level decreases , in their research " Effect Of Vehicle Vibration On Human Body". [4]

Keiichi Hanada found that vehicle driving has a high effect for human body as a lower back pain , in his research "Comparison of Vibrational Ride Discomfort in Various Cars by New Quantitative Ride Discomfort Meter". [5]

American Ergonomics Corporation said that the vertical vibration has a ranges of frequencies affect on human body , and the measurement of vertical vibration can be obtained depending on a human body as one degree of freedom ,with a mass equal to a range of passenger's weight . [6]

Chapter 3: Theory

3.1 Introduction

The measurement in the project concentrates on the acceleration transmitted to the human body; since the criteria of decision of level of comfortability depends on the acceleration as it discussed in ISO of human comfortability.

Due to the proposed criteria from ISO to make a decision of discomfort in a passenger car, the effect will be taken on a quarter model of a car, and take the same decision for the other three quarters of the model.

The directions of translations and rotations in vehicle dynamics are described in fig (3.1), where yaw moment is taken about vertical direction, pitch moment is taken about lateral direction, & rolling is taken about longitudinal direction. And the direction of vibration will be studied in the project is the vertical direction (z). [8]

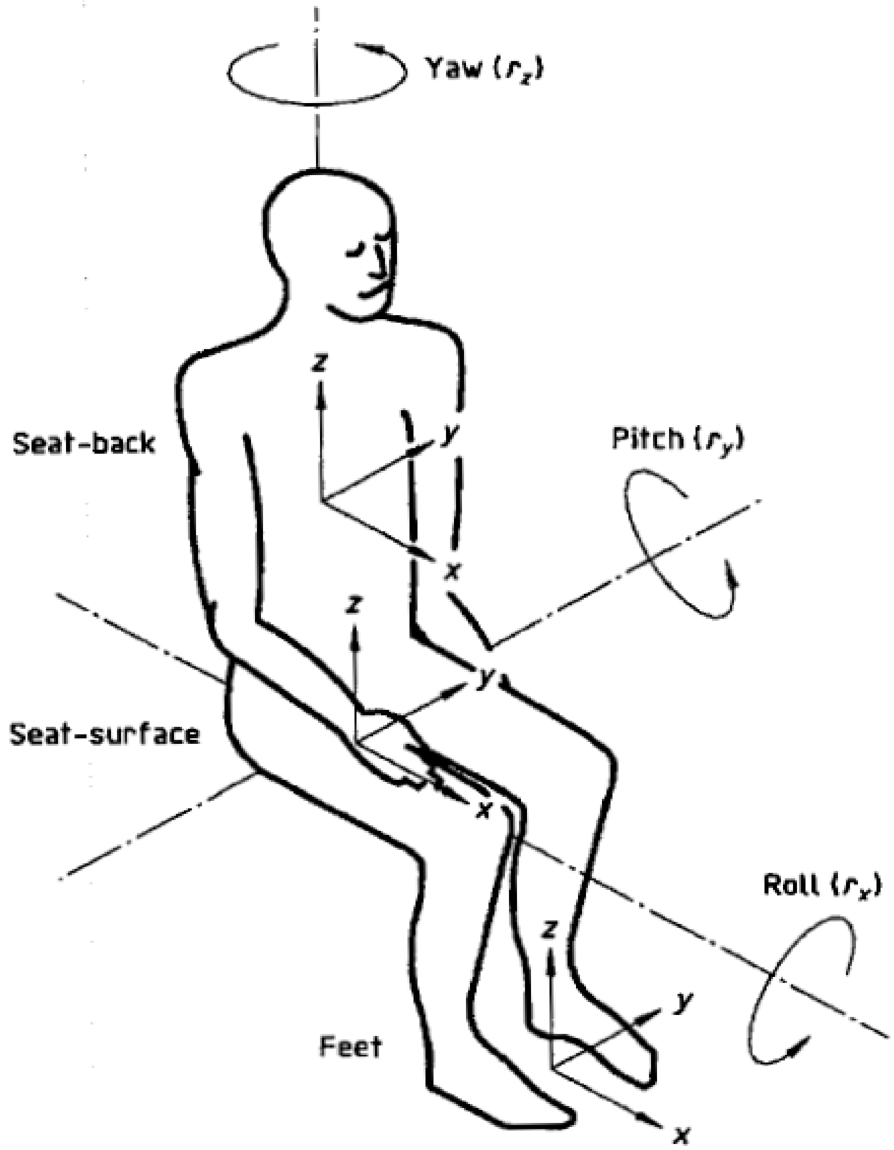

FIGURE 3.1 Basic enteric axes of the human body

3.2 Vibration Measurements

Measurements will be made to produce the data needed & the curves needed to analyze the behavior of suspension in the car, and to see the difference of response at same conditions, & also to decide the level of comfort by comparing results for two types of cars .

3.2.1 Accelerometer

The accelerometer is a sensor that measures the physical acceleration experienced by an object due to inertial forces or due to mechanical excitation. Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences acceleration, the mass is displaced and the displacement is then measured to give the acceleration. [9]

3.2.2 Working Principle of Accelerometer

The principle of working of an accelerometer can be explained by a simple mass (m) attached to a spring of stiffness (k) that in turn is attached to a casing, as illustrated in fig (3.2). The mass used in accelerometers is often called the seismic-mass or proof-mass. In most cases the system also includes a damper to provide a desirable damping effect. [9]

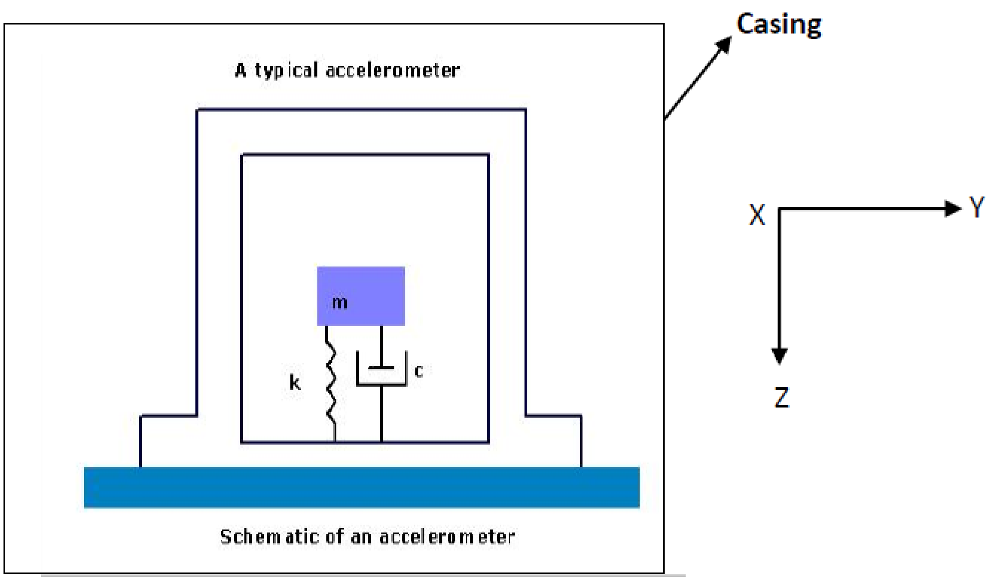

FIGURE 3.2 Schematic of an accelerometer [9]

The damper with damping coefficient (c) is normally attached to the mass in parallel with the spring. When the spring mass system is subjected to linear acceleration, a force equal to mass times acceleration acts on the proof-mass, causing it to deflect. This deflection is sensed by a suitable means and converted into an equivalent electrical signal. Some form of damping is required; otherwise the system would not stabilize quickly under applied acceleration.

To derive the motion equation of the system Newton's second law is used, where all real forces acting on the proof-mass are equal to the inertia force on the proof-mass. Accordingly a dynamic problem can be treated as a problem of static equilibrium and the equation of motion can be obtained by direct formulation of the equations of equilibrium. This damped mass-spring system with applied force constitutes a classical second order mechanical system.

From the stationary observer's point of view, the sum of all forces in the z direction is:

$Fa - Fd - Fs = m\ddot{x}$

$m\ddot{x} + Fd + Fs = F\text{a}$

$$m\ddot{x} + c\dot{x} + kx = F \quad (3.1)$$

The equation of motion is a second order linear differential equation with constant coefficients. The general solution x(t) is the sum of the complementary function $x_c(t)$ and the particular integral $x_p(t)$.

$$x(t) = x_c(t) + x_p(t) \quad (3.2)$$

The complementary function satisfies the homogeneous equation

$$m\ddot{x} + c\dot{x} + kx = 0 \quad (3.3)$$

The solution of $x_c(t)$ is

$$x_c(t) = Ce^{st} \quad (3.4)$$

Substituting (3.4) in (3.3)

$$(ms^2 + cs + k)Ce^{st} = 0 \quad (3.5)$$

As Ce^{st} cannot be zero for all values of t, then $(ms^2 + cs + k) = 0$ called as the auxiliary or characteristic equation of the system. The solution to this equation for values of S is

$$S_{1,2} = \frac{1}{2}m\left(-C \pm \sqrt{C^2 - 4mk}\,\right) \tag{3.6}$$

From the above equation (3.5), the following useful formulae are derived

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3.7 a}$$

$$c/m = 2\zeta\omega_n \tag{3.7 b}$$

$$\zeta = c/2\,\sqrt{km} \tag{3.7 c}$$

Where: ω_n is the natural frequency of the accelerometer

ζ is damping ratio of the damper in the accelerometer

c is damping coefficient of the damper in the accelerometer

3.2.3 Steady State Performance

In the steady state condition, that is, with excitation acceleration amplitude 'a' and frequency 'ω', the amplitude of the response is constant and is a function of excitation amplitude and frequency 'ω'. Thus for static response 'ω'=0, the deflection amplitude

$$X = X_0 = F/k \tag{3.8}$$

$$X = ma / k \tag{3.9}$$

Here the sensitivity S of an accelerometer is defined by,

$$S = X / a = m/k \tag{3.10}$$

3.2.4 Dynamic Performance

For the dynamic performance it is easier to consider the Laplace transform of eqn (3.1)

$$\frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{c}{m}s + \frac{k}{m}} \qquad (3.11)$$

It can be seen by comparing eqn (3.6) and (3.10) that the bandwidth of an accelerometer sensing element has to be traded off with its sensitivity since $S \, \alpha \, 1/{\omega_n}^2$ (this trade off can be partly overcome by applying feedback , i.e closed loop scheme).

The sensor response is determined by damping present in the system. A damping factor (ζ) between 0.6 to 1.2 results in high response time, fast settling time, good bandwidth and linearity.

3.2.5 Specifications of Accelerometer

Depending on the expected range of measurement, and unexpected range due to a high roughness road needed in the experiments; the accelerometer needed shall have a measuring range of ±15 'g' with a resolution which is not less than 10 mille 'g', to be sure that the accelerometer is able to measure the value of acceleration in a wide range with an acceptable accuracy, to get a reading of three digits in the right of the point.

3.3 Car Model Theory

In vehicle dynamics, the model of a car is taken in many visions, & this depends on the application needed.

As a quarter of a car model, it can be modeling as fig (3.3). , but as an overall system, and by assuming one degree of freedom, the model can be reformed as in fig 3.4).

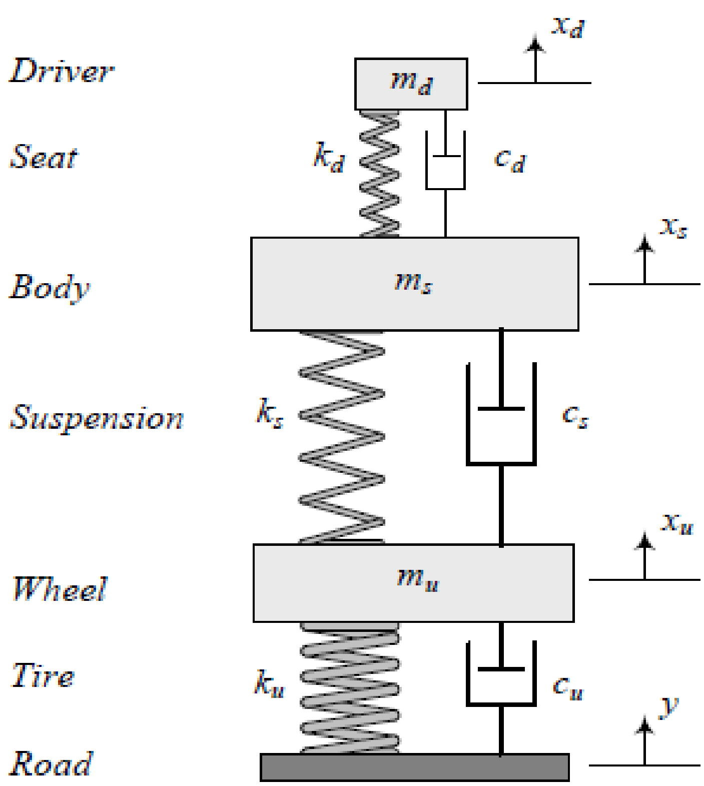

FIGURE 3.3 A quarter car model with driver [8]

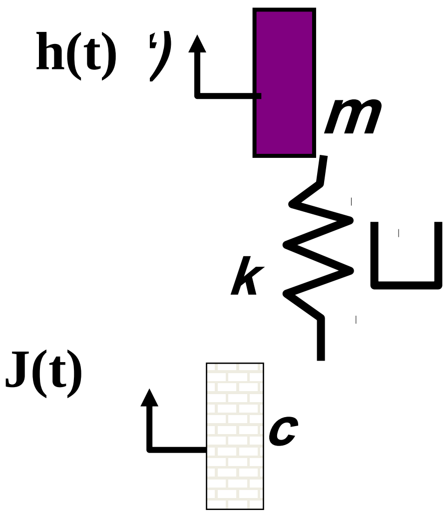

FIGURE 3.4 Base excitation model of one degree of freedom [7]

The following equation of motion describes the motion of the above model

$$\sum F = -k(h - J) - c(\dot{h} - \dot{J}) = m\ddot{h} \tag{3.12}$$

$$m\ddot{h} + c\dot{h} + kh = c\dot{J} + kJ \tag{3.13}$$

And the displacement transmissibility can be written as:

$$T_d = \frac{h}{J} = \sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}} \tag{3.14}$$

Fig. (3.5) show the relation between frequency ratio and displacement transmissibility, and the effect of increasing of damping ratio (ζ) on the displacement transmissibility.

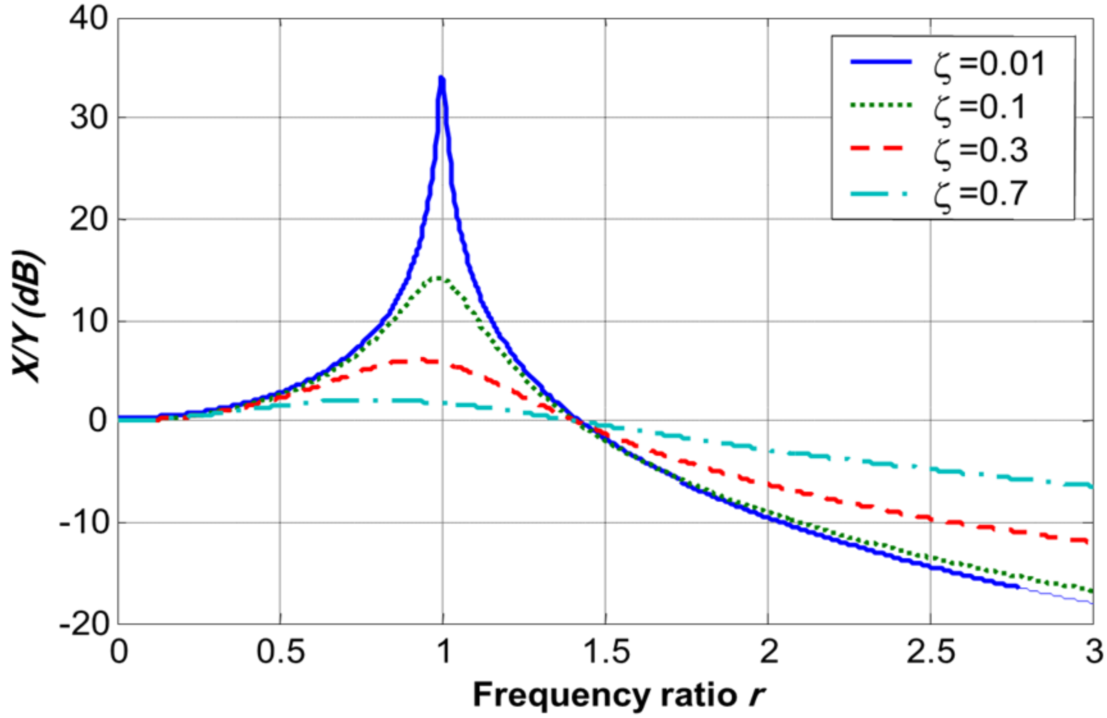

FIGURE 3.5 Relation between frequency ratio and displacement transmissibility [7]

But in measurement; and depending on ISO rules of vibration measurement; the decision of discomfort depends on the acceleration affected on human body, so from the general solution:

$$h(t) = Hcos(\omega t - \emptyset) \tag{3.15}$$

By differentiate the equation 3.15 two times

$$\ddot{h}(t) = -H\omega^2 \cos(\omega t - \emptyset) \tag{3.14}$$

So the accelerometer measures its value directly without need to measure the displacement transmissibility.

Chapter 4 : Design

4.1 Introduction

The project here depends on testing the amount of acceleration transmitted to the passengers, and the process of testing should be done by using testing equipment, in order to get the result of testing as a graphs, so the equipment's choice needs some dependencies, characteristics and identities.

4.2 Measurement system interview

The whole measuring system consists 'simply' of the main measuring subsystems, which are: input, output and process which explained by block diagram:

FIGURE 4.1: Simple block diagram of measurement system.

4.3 Measurement system components

4.3.1 Accelerometer

In this present project; an accelerometer is used to measure the acceleration change due to the roughness of road (bump). A signal of voltage is produced, and then this signal is displayed as acceleration–time curve.

Accelerometers in the world of electronics are classified depending on three identifications:

- Measured quantity: Analog & digital.
- Axis of measuring: Single axis, two axis & three axis.
- Range of measuring: 1g, 2g, 3g, 4g, 8g, 10g, 12g, 16g, 20g & 30g (the available for all).

In this project; one direction of vibration is tested, so that a single axis accelerometer is enough, the range of acceleration level is less than 2g, and the needed accelerometer is analog to get output as a signal directly and plotting the data after measuring. The least available accelerometer for sale is analog 3-axis 3g device. The characteristics of the chosen accelerometer are as following:

- Accelerometer purchase code; ADXL335.
- Small, low power, 3-Axis ±3 g accelerometer.
- Single-supply operation: 1.8 to 3.9V.
- Excellent temperature stability.

- Bandwidth adjustment with single capacitor axis.

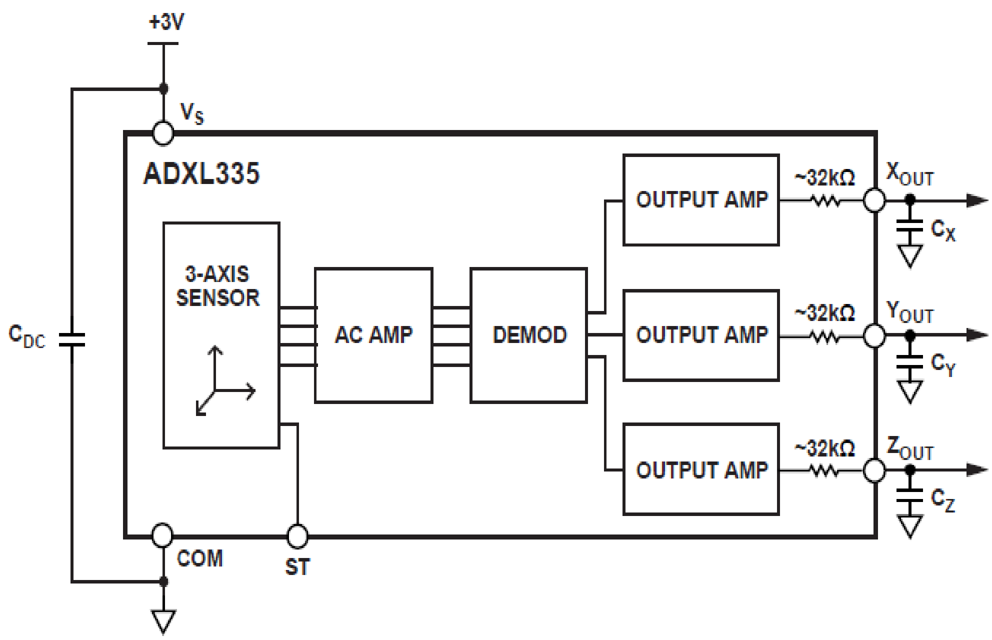

FIGURE 4.2: Inside circuit of the accelerometer.

As the manufacturer of accelerometer specified in the datasheet of ADXL335, the below table describes the main specifications.

Table 4.1: Specifications of the accelerometer.

Parameter	Conditions	Min	Typ	Max	Unit
Sensor Input	Each axis				
Measurement Range		±3	±3.6		g
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Interaxis Alignment Error			±0.1		Degrees
Cross-Axis Sensitivity			±1		%
Sensitivity (Ratiometric)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_s=3V	270	300	330	mV/g
Sensitivity Change Due to Temp[3]	V_s=3V		±0.01		%/C
Zero G Bias Level (Ratiometric)					
0 *g* Voltage at XOUT, YOUT	VS = 3 V	1.35	1.5	1.65	V
0 *g* Voltage at ZOUT	VS = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		Mg/C

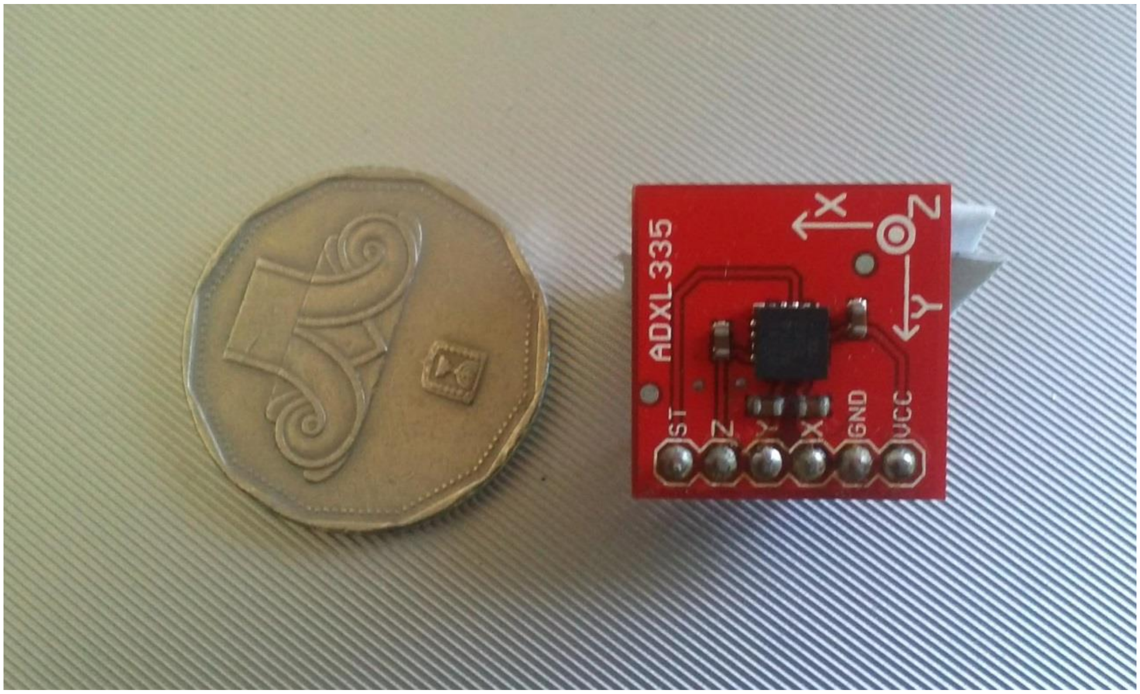

FIGURE 4.3: Accelerometer ADXL 335. Vs. 5NIS as a size

4.3.2 Data transmission

As it mentioned before; the signal comes from the accelerometer needs data travelling device, and the available methods to transform signal/wave to computer are Data Acquisition and Microcontroller. Table 4.2 describes a comparison between the two choices for the desired case.

Table 4.2: Comparison between Data Acquisition and Microcontroller.

Comparison field	Data Acquisition	Microcontroller
Connecting in the measuring system	Easier	Easy
Voltage supplying	Using computer's USB voltage	Using supply with exact needed voltage (with high accurate)
Ability to change connection	Easy	Needs special tools
Identifying with computer	Using special National Instrument program	Needs programming by C++
Ability to change programming	Easy to make change and adapt	Needs reprogramming using C++
Needed skills to build system	Few understood in using LabVIEW	Previous knowledge in programming microcontrollers
Price	8 times microcontroller	1/8 of Data Acquisition

Depending on this comparison; the Data Acquisition is preferred for the desired use, since the researchers can keep up with it easier than the microcontroller, neglecting its cost when comparing with the microcontroller.

The desired application from the Data Acquisition is just getting one signal from the accelerometer, so the needed Data Acquisition must have an accurate connecting with enough number of samples to get the accurate result.

The chosen Data Acquisition is USB-6008 from National Instrument. The characteristics of the Data Acquisition are:

- 8 analog inputs (12-bit, 10kS/s).
- 2 analog outputs (12-bit, 150S/s); 12 digital I/O; 32-bit counter.
- Bus-powered for high mobility; built-in signal connectivity.
- OEM version available.
- Compatible with LabVIEW, LabWindows, and Measurement Studio for Visual Studio.

Since the accelerometer is analog; the needed port in Data Acquisition is analog. 2-input ports are needed to get the signal input.

4.4 Measurement system building

3 ports from accelerometer used in connection: VCC, GND and Z as they are written on the breakout board of the accelerometer.

The VCC is connected with the positive of voltage supply of 3V.

GND is connected with the negative of voltage supply (ground).

And Z is the input data connected with the analog input port in the Data Acquisition.

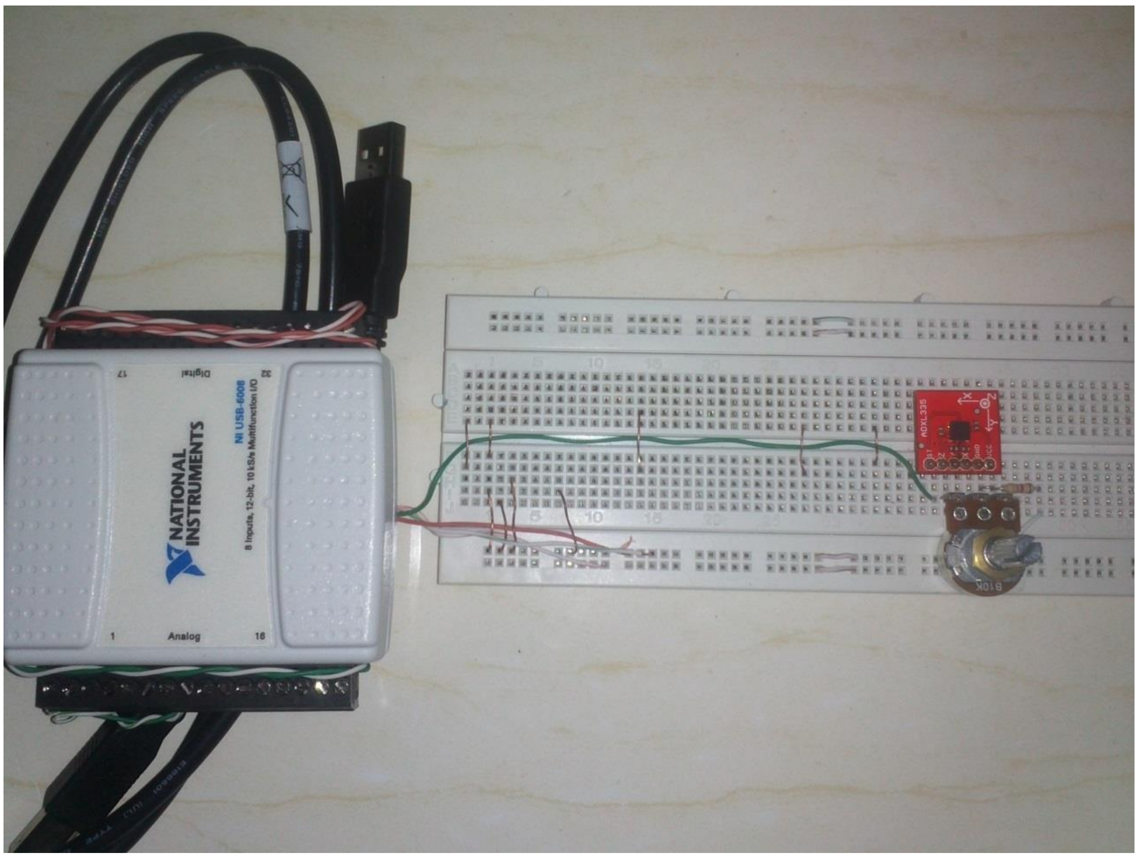

FIGURE 4.4: Connection of accelerometer with the Data Acquisition.

4.5 LabVIEW work

By using specifications of the accelerometer; the circuit on Labview is done to get the signal output as desired, since the output from accelerometer is a voltage. Depending on the specifications; the output value at 0g is 1.5V, so it must be subtracted from the output always to make 0g equal 0V. The other specification needed is the sensitivity; which is 300 mV/g, and it means that for each 300 mV output equal to measuring 1g, so after subtracting the 1.5 V; the value must divided over 0.3 to make y-axis representing the acceleration as g unit.

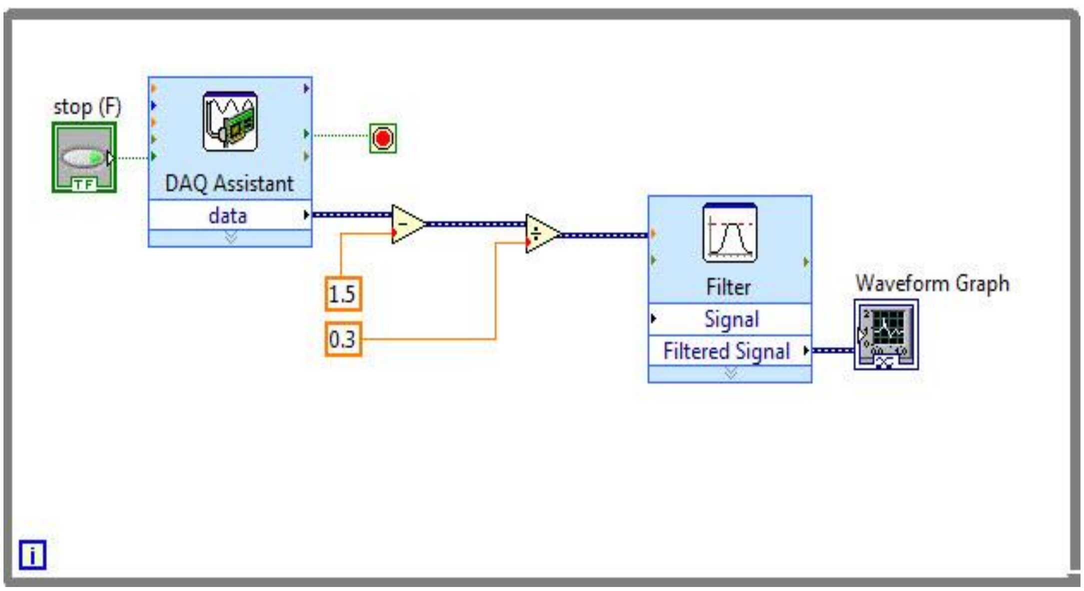

FIGURE 4.5: LabVIEW block circuit.

The output on waveform graph is between acceleration with respect to gravity and time in seconds for all graphs

4.6 Test conditions

1. **Road (bump) geometry**

The testing road condition chosen in this project is a bump with low height to protect vehicles from damaging at the speeds of 20kmph, 40kmph and 50kmph. The maximum height of the bump is 8 cm and the hole length is 300 cm as shown in Figure 4.6.

2. **Speeds**

The test is done at three speeds (20Kmph, 40Kmph and 50Kmph) for the three cars.

3. **System**

Three different cars were tested and the measuring device was fixed with the passenger. Assuming that suspension system in each car has no trouble.

Chapter 5: Testing

Results and Analysis

5.1 Introduction

Projects of testing are different from those making design or model, and the test may be rejected many times if any error done when the results taken, and it is important for each time of taking the results that the measuring device is in exact or accurate position.

5.2 Testing procedure

In this project, it was decided to select three different cars, and their details are explained in the table 5.1.

Table 5.1: Tested vehicles models.

Car No.	Car model	Engine size (cc)
1	Volkswagen Polo hatchback (2005)	1400
2	Volkswagen Golf hatchback (2008)	1600
3	Fiat Ponto hatchback (2006)	1200

Each car was driven at one the same bump and three different speeds: 20, 40 and 50Kmph. For these speeds the readings were taken with the vibration measurement system discussed in chapter 4.

First, the measuring block (accelerometer fixed in breadboard, and the breadboard fixed on wide plate) putted on the right front seat cached by one of the researchers. Then, the car was running at constant speed of 20Kmph and reading was taken. After that the reading was taken at 40Kmph and 50Kmph speeds. These procedures were repeated for other two cars. The data contains frequency and acceleration of vibration at particular time period. x-axis represents the time in seconds and y-axis represents the acceleration transmitted in a unit of gravity [g], and g equal to 9.81 m/s^2.

5.3 Testing results

The data obtained from the accelerometer then transmitted with the help of the Data Aquisition. The transmitted data is in the form of the time and corresponding accelerations of vibration. Then readings at particular time span 5 sec were taken for plotting graphs.

5.3.1 First car

- At speed of 20kmph :

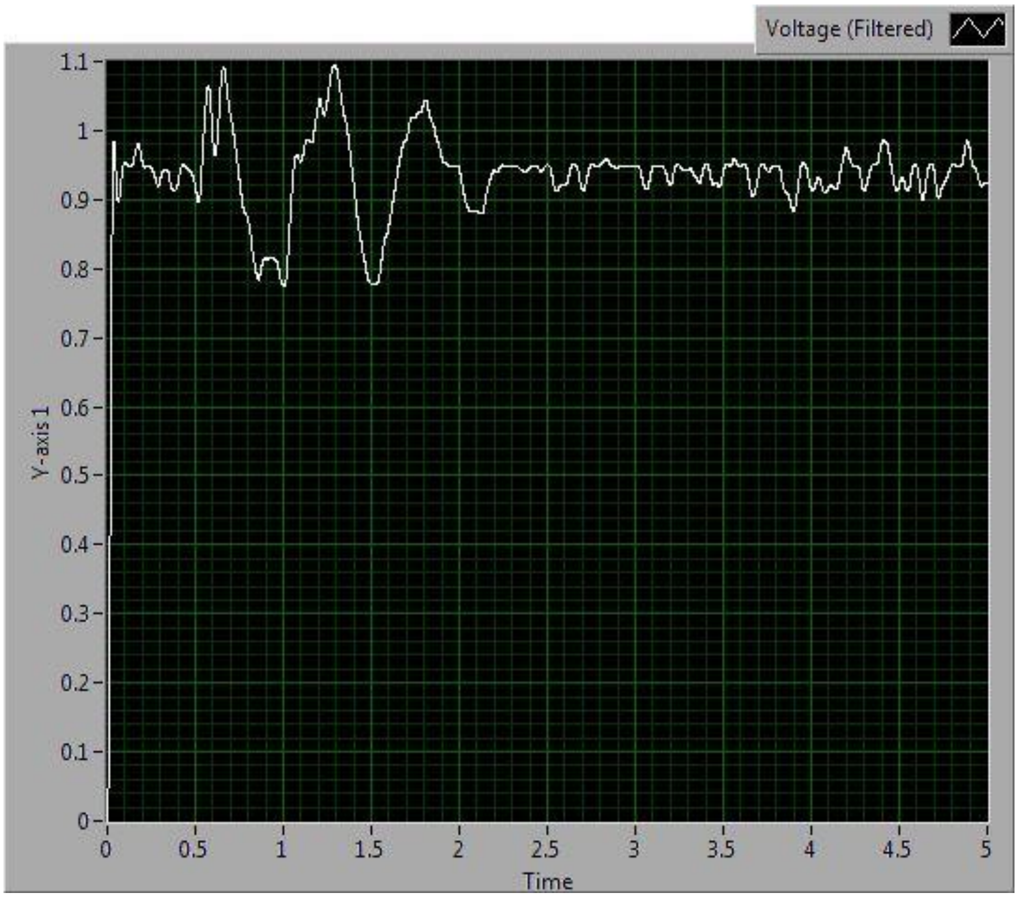

FIGURE 5.1 Acceleration level vs. time for the first car at the speed of 20kmph.

From figure 5.1:

Acceleration transmitted to passenger is: 1.1 - 0.95 = 0.15 g.

Frequency of the acceleration wave on the bump = 3 Hz.

❖ At speed of 40kmph :

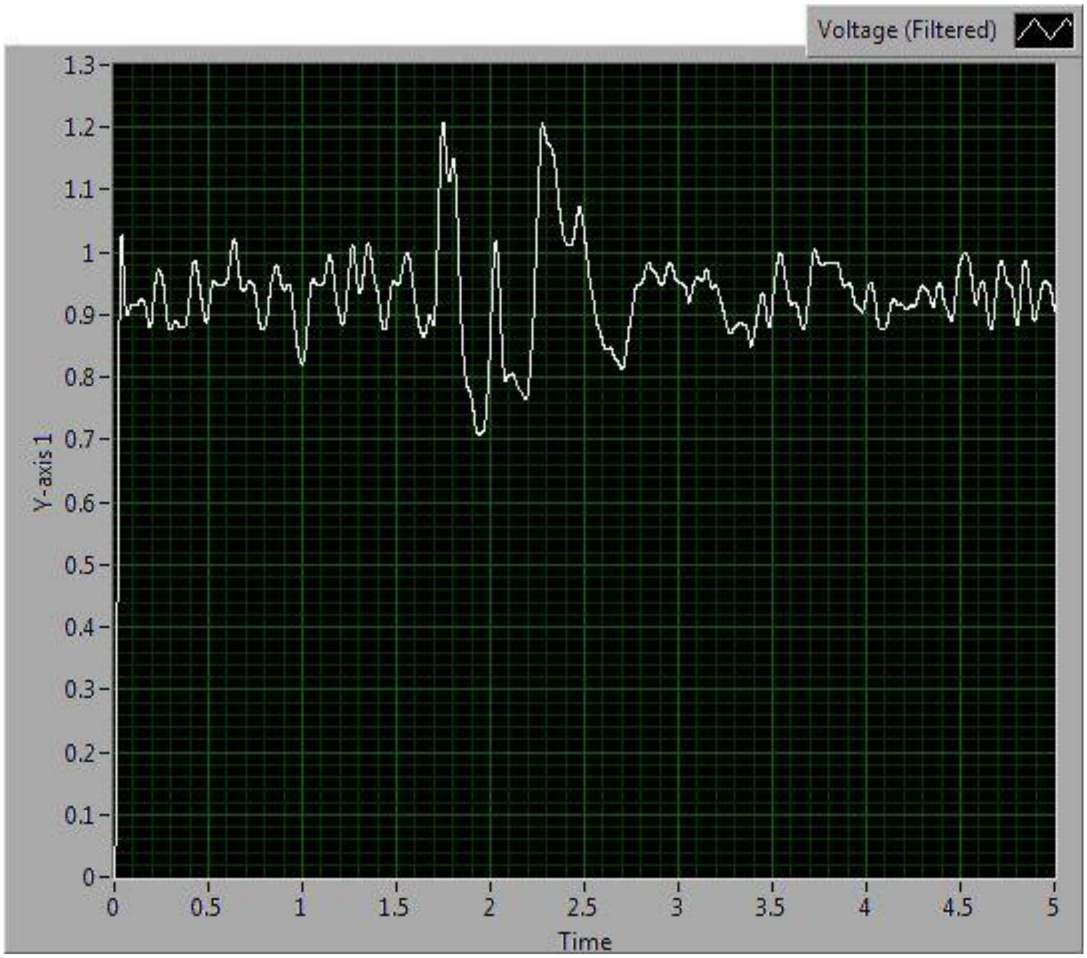

FIGURE 5.2 Acceleration level vs. time for the first car at the speed of 40kmph.

From figure 5.2:

Acceleration transmitted to passenger is: 1.2 - 0.95 = 0.25 g.

Frequency of the acceleration wave on the bump = 3.5 Hz.

❖ At speed of 50kmph

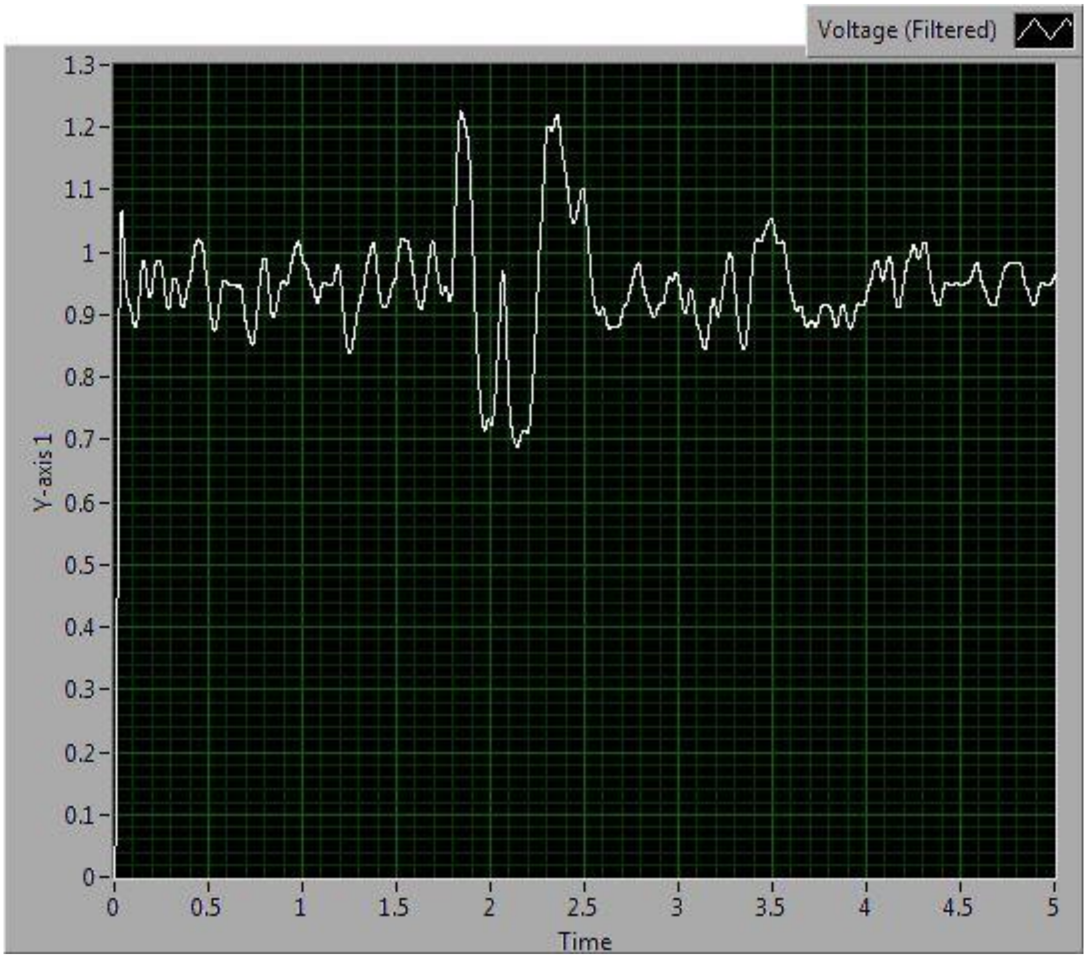

FIGURE 5.3 Acceleration level vs. time for the first car at the speed of 50kmph.

From figure 5.3:

Acceleration transmitted to passenger is: 1.22 - 0.95 = 0.27 g.

Frequency of the acceleration wave on the bump = 4 Hz.

5.3.2 Second car

- At speed of 20kmph

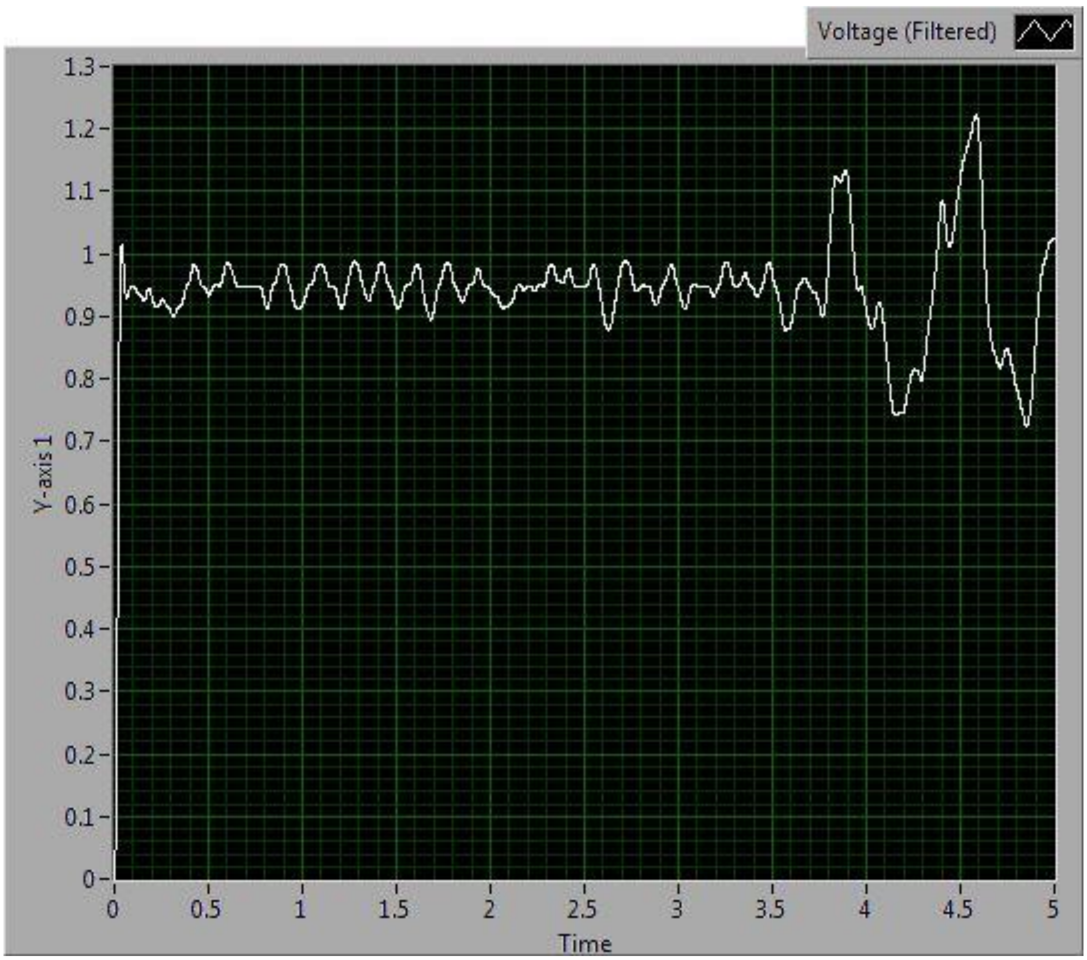

FIGURE 5.4 Acceleration level vs. time for the second car at the speed of 20kmph.

From figure 5.4:

Acceleration transmitted to passenger is: 1.22 - 0.95 = 0.27 g.

Frequency of the acceleration wave on the bump = 2 Hz.

❖ At speed of 40kmph:

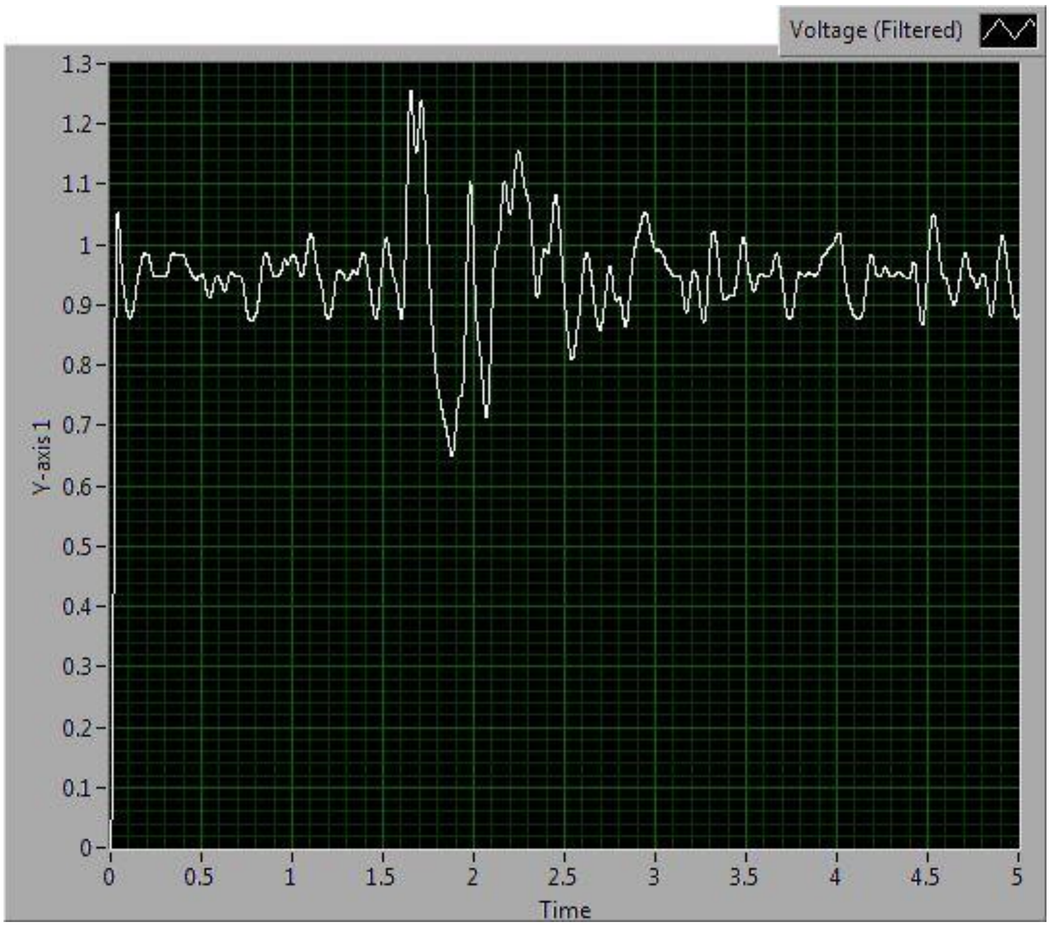

FIGURE 5.5 Acceleration level vs. time for the second car at the speed of 40kmph.

From figure 5.5:

Acceleration transmitted to passenger is: 1.25 - 0.95 = 0.3 g.

Frequency of the acceleration wave on the bump = 4 Hz.

❖ At speed of 50kmph:

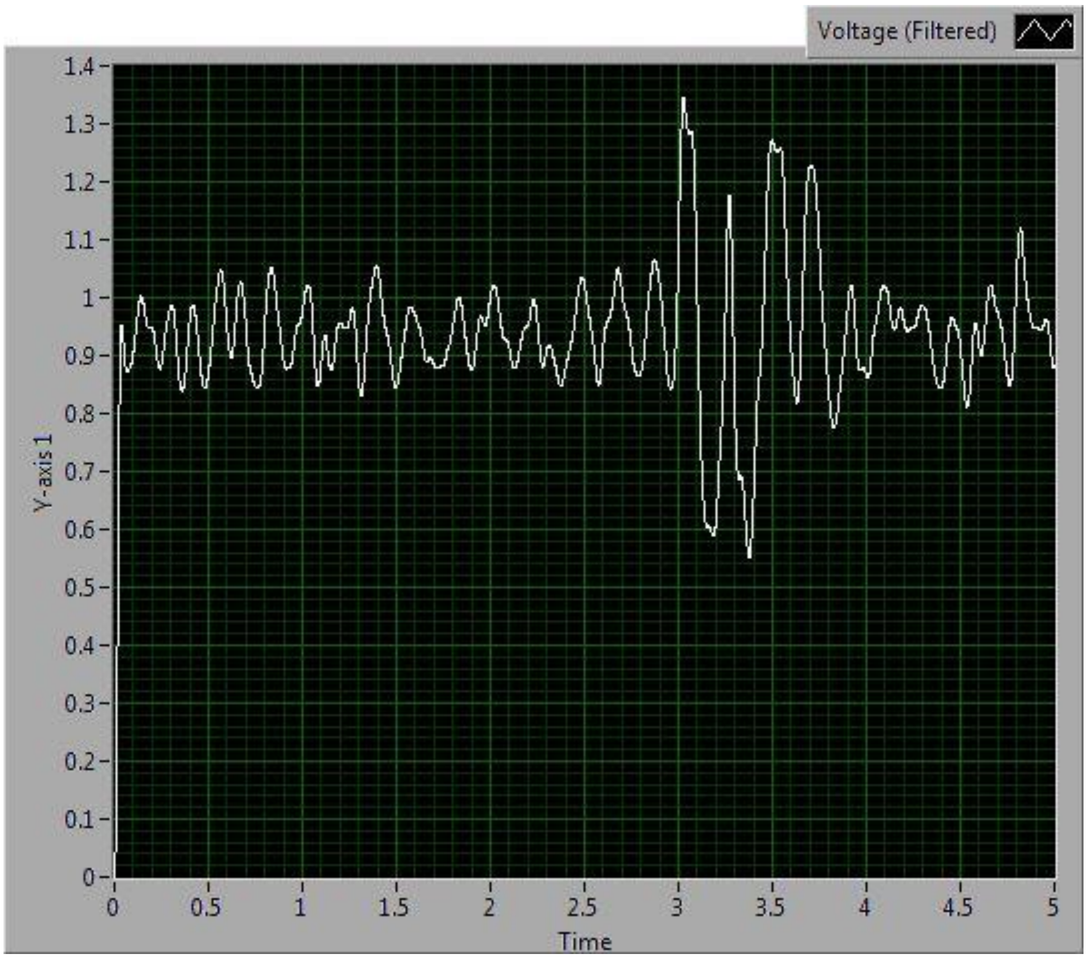

FIGURE 5.6 Acceleration level vs. time for the second car at the speed of 50kmph.

From figure 5.6:

Acceleration transmitted to passenger is: 1.35 - 0.95 = 0.4 g.

Frequency of the acceleration wave on the bump = 4.5 Hz.

5.3.3 Third car

- At speed of 20kmph

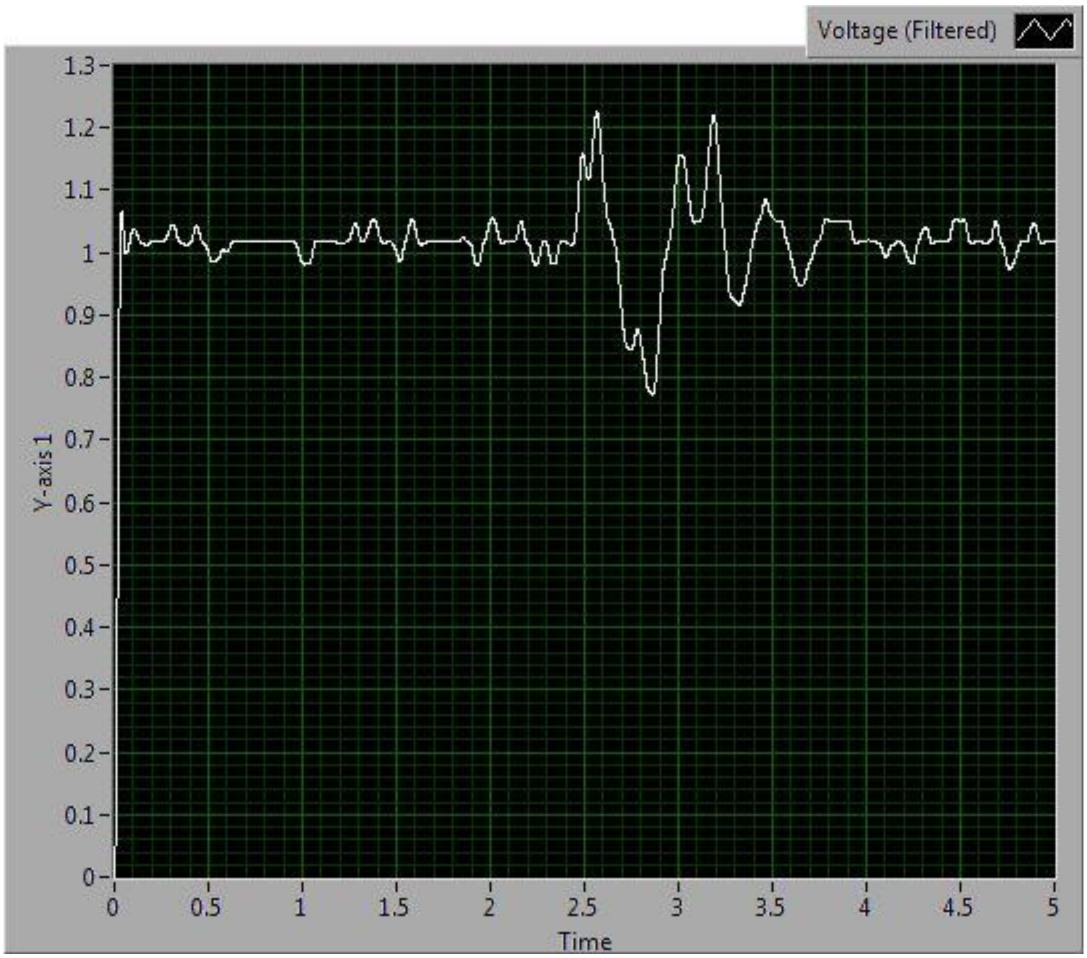

FIGURE 5.7 Acceleration level vs. time for the third car at the speed of 20kmph.

From figure 5.7:

Acceleration transmitted to passenger is: 1.22 – 1.02 = 0.2 g.

Frequency of the acceleration wave on the bump = 3 Hz.

❖ At speed of 40kmph

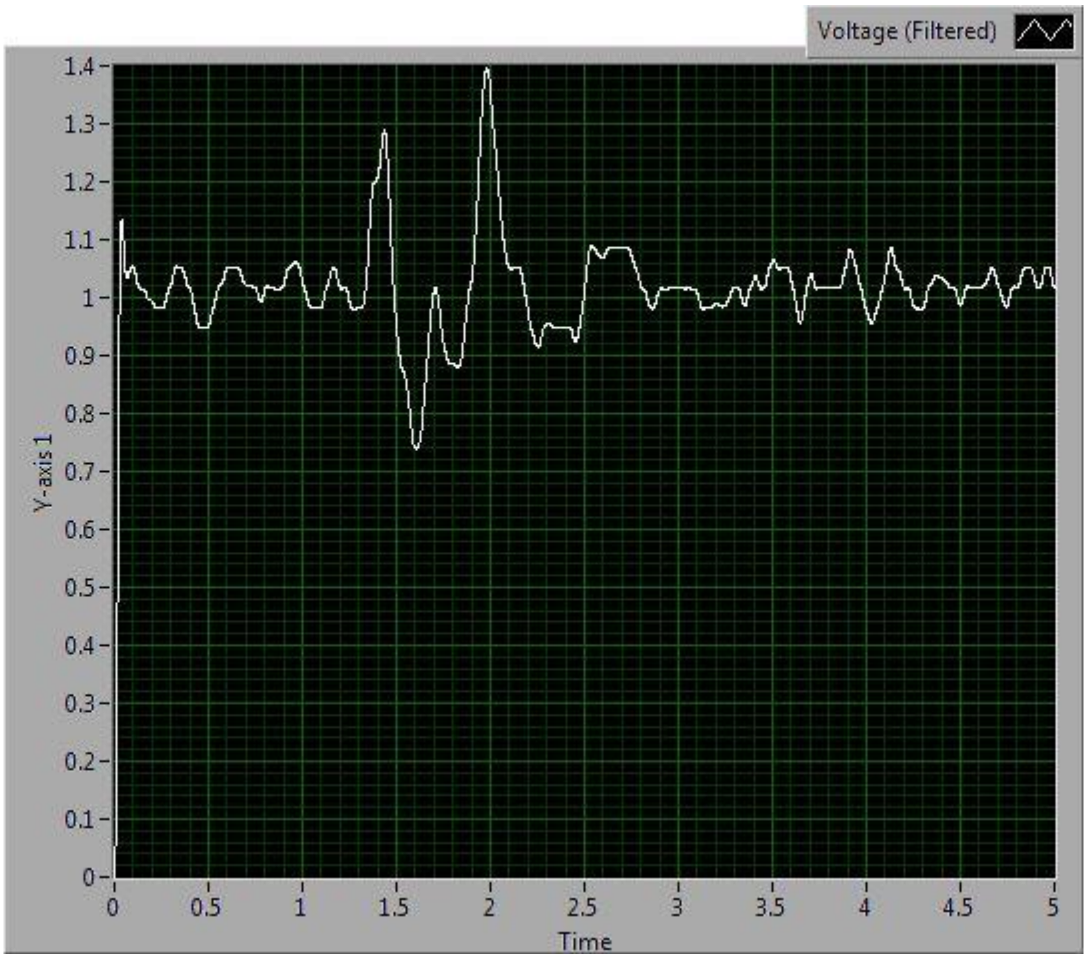

FIGURE 5.8 Acceleration level vs. time for the third car at the speed of 40kmph.

From figure 5.8:

Acceleration transmitted to passenger is: 1.4 – 1.02 = 0.38 g.

Frequency of the acceleration wave on the bump = 3 Hz.

❖ At speed of 50kmph:

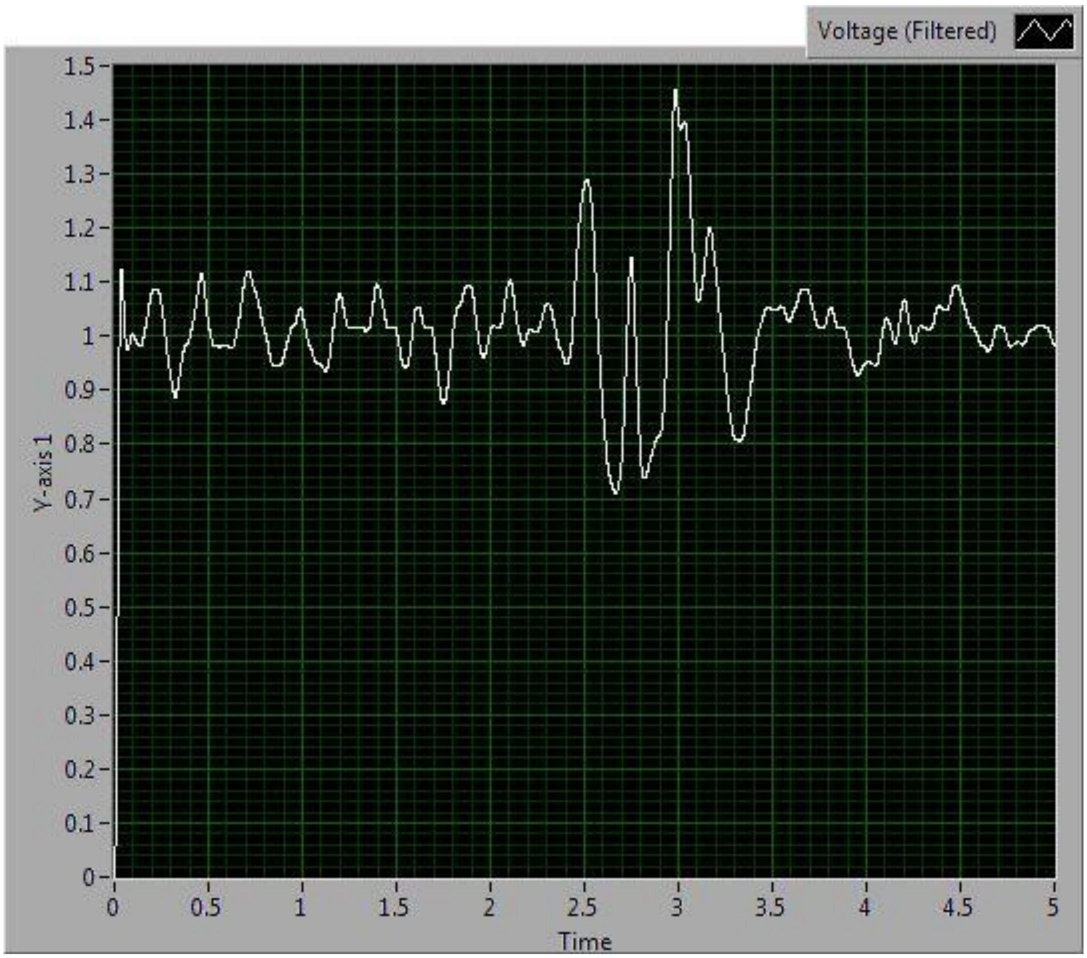

FIGURE 5.9 Acceleration level vs. time for the third car at the speed of 50kmph.

From figure 5.9:

Acceleration transmitted to passenger is: 1.45 – 1.02 = 0.43 g.

Frequency of the acceleration wave on the bump = 4 Hz.

5.4 Results analysis

5.4.1 Effect of road condition on the behavior of damping system oscillation

The road conditions of the test is a bump with the parameters discussed before, and from the results of the test; the acceleration level is increases as the bump is beginning, and after that the acceleration level is return to the initial level, but this action does not be in the same behavior.

The behaviors of vehicles are different between each other, and making a lot of parameters. The results of their behaviors are shown in table 5.2.

Table 5.2: Tested vehicles behavior on bump road condition.

Tested car / speed [kmph]	**First car**	**Second car**	**Third car**
20	The oscillation is continued for 3.5 cycles and then return gradually to it's as before.	The oscillation is continued for 3 cycles, start high, increased once and decreased to return to it's as before.	The oscillation is continued for 3 cycles and then return gradually to it's as before.
40	The oscillation is continued for 4 cycles, start high, decreased, increased again and decreased	The oscillation is continued for 4 cycles, start high, decreased, increased again and decreased	The oscillation is continued for 3 cycles, start high, increased and decreased to return to

	to return to it's as before.	to return to it's as before.	it's as before.
50	The oscillation is continued for 4 cycles, start high, decreased, increased again and decreased to return to it's as before.	The oscillation is continued for 4.5 cycles, start high, decreased, increased again and decreased to return to it's as before.	The oscillation is continued for 3 cycles, start high, decreased, increased again and decreased to return to it's as before.

5.4.2 Effect of speed condition on the level of transmitted acceleration of vibration

When analyzing effect of speed condition on the level of transmitted acceleration; speed condition of vehicle is taken on x-axis and acceleration level corresponding to that speed is taken on Y-axis & then graphs are plotted.

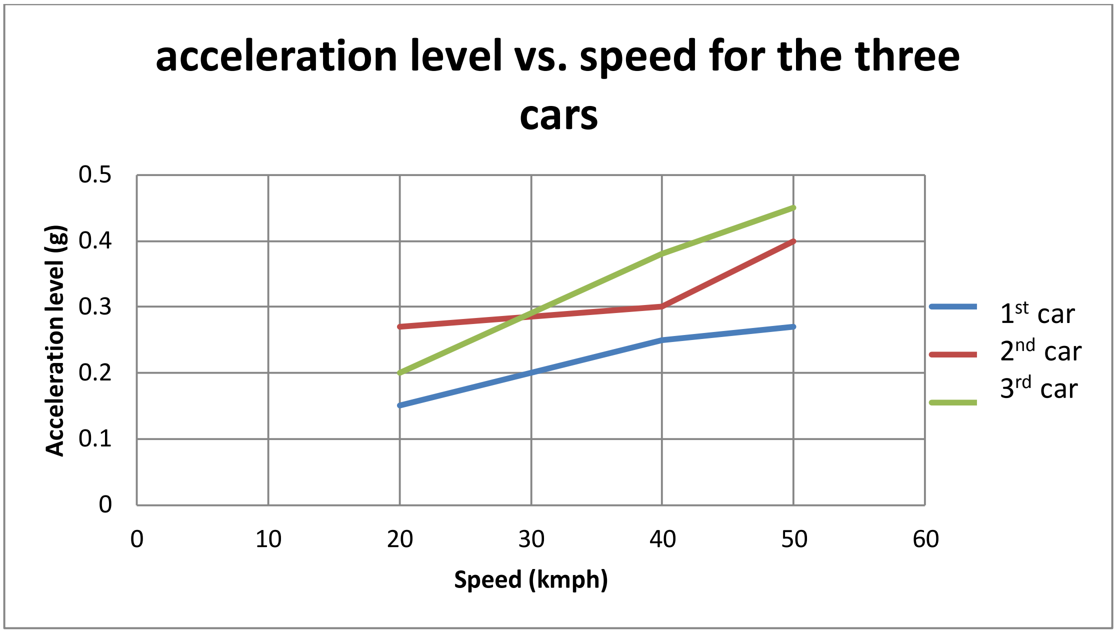

FIGURE 5.10 Acceleration level vs. speed for the three cars

By observing figure 5.10; it is visible that the level of transmitted acceleration for all cars increases as speed increases. The first car has the smallest level of acceleration at the three speeds, the second is better than the third at the speed of 20kmph and the third is better than the second at the speeds of 40 and 60 kmph.

Table 5.3 Maximum acceleration level and the frequency for all cars at each speed

Speed / Car	20 kmph		40 kmph		50 kmph	
	Frequency Hz	Magnitude g [m/s^2]	Frequency Hz	Magnitude g [m/s^2]	Frequency Hz	Magnitude g [m/s^2]
Polo	3	0.15 [1.5]	3.5	0.25 [2.5]	4	0.27 [2.6]
Golf	2	0.27 [2.6]	4	0.3 [2.9]	4.5	0.4 [3.9]
Fiat	3	0.2 [2.0]	3	0.38 [3.7]	4	0.43 [4.2]

Chapter 6: Conclusion and recommendations

6.1 Introduction

The project tests are carried out to make a comparison between three cars, and the criteria of comparison is the acceleration of which the road roughness (bump) with speed of vehicle create it, and transmitted to the passengers. Few recommendations can be done for development this project in subsequent studies.

6.2 Conclusion

The vibration Spectrum obtained for different cars at different speeds are presented in chapter 5. Depending on these results; it can be concluded that:

1. As road condition varies smooth to rough (bump); the acceleration level increases sharply for the three cars and at all speeds.

2. As speed increases, the transmitted acceleration also increases up to maximum level for the three cars.

3. For speed of 50Kmph; the maximum acceleration levels are higher (0.27 to 0.43 g) therefore, passengers feel extremely uncomfortable on this road condition. Volkswagen – Polo is more comfort than Volkswagen – Golf more than Fiat – Ponto at speed of 50Kmph.

4. For speed of 40Kmph; the maximum acceleration levels are from (0.25 to 0.38 g),therefore, passengers feel extremely uncomfortable on that road condition. Volkswagen – Polo is more comfort than Volkswagen – Golf more than Fiat – Ponto at speed of 40Kmph.

5. For speed of 20Kmph; the maximum acceleration levels are from (0.15 to 0.27 g), therefore, passengers feel a very uncomfortable on that road conditions. Volkswagen – Polo is more comfortable than Fiat – Ponto than Volkswagen – Golf at speed of 20Kmph.

6. The frequencies of the vibrations of all cars at all of speeds on that road conditions are between (2 – 4.5 Hz), and this range of frequencies is in the critical range of vibrations frequencies affecting on passenger comfort.

7. For all cars and all speeds the maximum levels of acceleration are from (1.5 – 4.4m/s^2), and depending on ISO ranges explained in chapter one; this range of acceleration classified as a very and extremely uncomfortable range of acceleration, such that this road conditions is very uncomfortable when the car cross that road conditions at those speeds.

6.3 Recommendations

This project shows the measuring of vibrations, and make a comparison between the three cars selected due to comfort. The researchers are looking forward to make few suggestions for people, suggestions about the dimensions of bumps closed to comfort range and suggestions for developing this project in subsequent studies. These recommendations can be as the following:

1. The range of frequencies came from the bump used and the speeds chosen were in the critical range of the bad frequencies, and close to few resonance frequencies, and since the range of bad frequencies starts from 4Hz and ends at 8Hz with another two far frequencies (20.3 and 60 Hz); it is important to be out of that range, but of course the frequency must be in the less range in order to protect the systems of vehicles from damage, so the suggest dimension of forward direction is to be no shorter than 7m to save human bodies from bad frequencies in the range of vehicle velocity of 50kmph and less, since the bumps are exist in roads of which the maximum speed does not exceed 50kmph.

2. The direction of vibrations discussed in this project is the vertical direction; the vertical direction was on the z-axes of the accelerometer. The other directions; x-axes and y-axes can be discussing in coming studies.

3. The road condition used in tests was a bump with certain dimensions. In the subsequent studies the road conditions can be different and used to diagnose the faults of suspension systems of vehicles.

4. The number of cars tested is three cars, the test can be done on a wider sample of cars in other studies to make a new values of comparisons and decisions for comfort on bumps.

5. This project can be used for studying the effect of bumps dimensions on comfort, and determine the ranges of bump dimensions should be to achieve the target of it with the minimum level of uncomfortable.

REFERENCES

[1] ISO 2631-1 Second Edition 1997 – Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration.

[2] Graffin, M. H., "Evaluation of Vibration with Respect to Human Response", Society of Automotive Engineers, Paper 860047

[3] PARSONS, K C,GRIFFIN, M J "Method for Predicting Passenger Vibration Discomfort" Society of Automotive Engineers, Paper 831029

[4] Katu U.S., Desavale R.G. and Kanai R.A. " Effect Of Vehicle Vibration On Human Body" Society of Automotive Engineers, Paper 831149

[5] Keiichi Hanada "Comparison of Vibrational Ride Discomfort in Various Cars by New Quantitative Ride Discomfort Meter" SAE 2003 Noise & Vibration Conference and Exhibition ,Paper 2003-01-1687

[6] Andrew Rusting, EIT, BSME "CBM Suspension Seat Vibration Transfer Test Analysis" American Ergonomics Corporation , www.americanergonomics.com

[7] Singiresu S. Rao , "Mechanical Vibrations" fifth edition ,

[8] Reza N. Jazar, "Vehicle Dynamics: Theory and Applications", 2008

[9] http://shodhganga.inflibnet.ac.in/bitstream/10603/2272/8/08_chapter%202.pdf