Proceedings of the 3rd International Conference on Mechanical Engineering and Mechatronics
Prague, Czech Republic, August 14-15, 2014
Paper No. 145

Effects of Different Tire Pressures on Vibrational Transmissibility in Cars

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Abstract **-** Excessive vibrational resonance results in industrial injuries, like vibration white finger, adversely affecting blood vessels, nerves and muscles, and cause equipment failures and electronic equipment failure during the transportation of apparatus. It also critically limits vehicle life due to cyclic loading and vibrational resonance. In this paper, the effects of varying tire pressures on vibrational transmissibility in cars is studied, and pressure changes are tied to correspondingly different root-mean-square values of amplitudes of vibrations. Then, the effects of varying the tire pressures (from 20 psi up to 40 psi) on the amplitudes of vibrations at certain frequencies are studied via the use of the FFT. As the vibrations were induced via driving cars over the same path of a bumpy road, vibrational transmissibility was found to decrease as pressure is reduced, but reducing it after a certain threshold will reduce the driver's car control and pose a danger to him and his surroundings; therefore, an optimum pressure is sought and found on a finite and safe pressure interval.

Keywords**:** Measurements, Vibrations, Transmissibility, FFT.

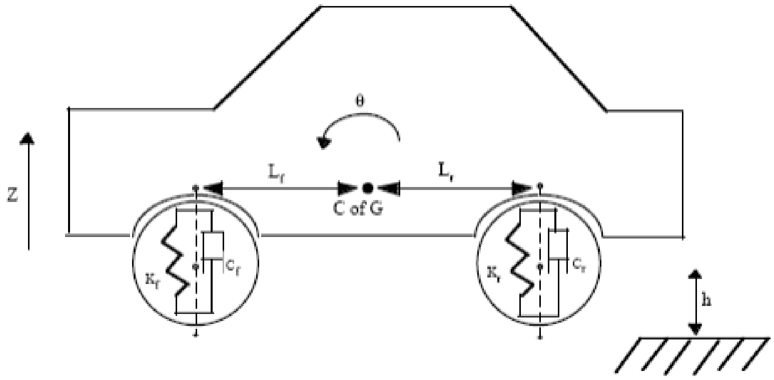
1. Introduction

This paper is a project for the MEEN 260 Mechanical Measurements class at Texas A & M University at Qatar, which is a project-based learning course. The project was conducted to test two hypotheses and, eventually, prove the consistency of one of the two hypotheses with experimental results; one hypothesis assumes a single optimum pressure exists, so that it produces the least vibrational transmissibility possible, while the other hypothesis predicts that vibrational transmissibility fits a model that is dependent on pressure, where the minimum transmissibility is sought on a finite interval of pressure domain through testing various tire pressures. Four separate experiments were carried out on four different cars; each experiment was run with varying tire pressures and at constant speed per experiment. The frequency contents of the runs for each pressure on every car were collectively plotted to represent the total frequency content for all runs of the same pressure. Comparing the total frequency content for every pressure, conclusions were drawn about how the amplitudes vary over the frequency range for every pressure change.

2. Theory and Analysis Methods

2.1 Theory

A car can be thought of as two-degree-of-freedom mechanical vibration system, as seen in figure 2.1, if both axles are held firmly and the car is not allowed to tilt sideways. Thus, the only vibrational motion considered would be vertically up and down (heaving), and tilting forward and backward (pitching). A better insight into this system suggests that it should be regarded as a two-spring-damper system in a car. A simplifying assumption made is that each axle and suspension partition quarter car model (front and rear), and two tires attached, are regarded are the only sources of vibration transmissibility onto a car's body. The car is assumed not to swivel sideways (rolling) or pivot side to side (rolling). By measuring different tire pressures, a correlation between the vibrations "felt", or transmitted, onto the car's chassis and body and the tire pressure can be made, and optimum gas pressures could then be chosen to reduce transmissibility and optimize comfort inside a car.



Automotive Suspension. Retrieved from http://www.mathworks.com/products/demos/shipping/simulink/sldemo_suspn_figure1.png.

Fig. 2.1. Schematic diagram of a car's suspension system. The car is assumed to only vibrate vertically up and down (heaving).

The excitation sources in a motor vehicle can include mainly engine, car applications as air-condition, wheel bearing, aerodynamic effect of wind and speed, and road excitation. Ignoring the resonance frequencies and forced vibrations from the engine revs and the aerodynamic effects and damping of forced excitations from the road can be attempted but cannot be completely achieved. Realizing the assumptions above, the damping occurs at two points: the car suspension, which consists of a combination of bushes and the shock absorber with its different types depending on the car model, and the tires. This shock absorber is connected in parallel with a helical spring coil. In addition to shock absorbers and springs, the tires damp the road excitations. Although, the damping effect of tires is small when compared to that of that of the shock absorbers and springs, this damping effect cannot be ignored. Under rough road excitation, tire sidewall and tire stiffness affect the dampening. Varying tire pressure will have a great impact on the damping coefficient of the tires; at high pressures, 40-55 psi tires tend to be stiff and transmit vibrations directly to the shock absorbers and other suspension components. Since decreasing the pressure will decrease the stiffness of the tires, the effect will be greater damping before transmitting the excitation to the suspension components.

Assuming the damping effect that occurs at the suspension parts is controlled and that suspension components act consistently under different excitation levels, the damping variations will occur due to variations in the tires' stiffness with respect to their pressure, disregarding the sidewall length and the tire material and condition.

There is a domain of pressures that produce a range of vibrational transmissibilities, where a minimum and maximum transmissibility are located on a finite pressure interval. According to every suspension configuration, this function shifts by a certain phase.

2.2 Analysis Methods

The true value range, $\mu \pm t_{\propto/2,\nu}\frac{S_x}{\sqrt{n}}$, of the vibrations' RMS values is found for each pressure value by using the Central Limit Theorem, and implementing the desired confidence interval, standard deviation and degree of freedom to get the uncertainty of the readings. However, increasing the confidence interval will increase the μ range; therefore, a balance must be found between a solid confidence interval and an acceptable μ range that is not too wide.

Using Vernier Wireless Dynamics Sensor System (WDSS) accelerometer to measure the vertical displacement due to the rough road excitation and the LoggerPro™ program, data was exported to a series of CSV files that can be manipulated via Microsoft Excel™ and imported to MatLab™ for analysis and for graph generation. Microsoft Excel 2013™ was used to compute the RMS and standard deviation and to perform the t-tests on the data, while MatLab™ was used to generate the FFT graphs.

For each trial, the RMS of each test run was calculated according to the following formula:

$$rms = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + x_3^2 + \cdots \ldots\ldots\ldots\ldots\ldots + x_n^2)} \tag{1.1}$$

After finding the RMS of the vertical acceleration, the average RMS of each tire pressure for each car was calculated as follows:

$$rms_{avg} = \frac{\sum_0^n RMS_x}{n} \tag{2.1}$$

Using the average RMS for each tire pressure, a graph of the average RMS acceleration against the tire pressure was plotted. For this graph, the associated uncertainty was generated using an Excel™ built-in function. Uncertainty was calculated for each pressure using equation (6) and the standard deviation for the RMS values of each pressure. FFT plots were found using MatLab™ for the car samples.

3. Experimental Procedure

Vernier WDSS is placed on a flat surface on the dashboard of each car. Resetting is undertaken when the WDSS sensor is fixed into position by means of adhesive tape. Before every run, the car is stopped and acceleration is zeroed to account for gravity. A bumpy road is used to generate sufficient vibrations that would cause normal discomfort during driving, and the same path is used for each test for every car. The experiment is conducted with varying tire pressures and at a constant speed. Up to seven runs were conducted to minimize random error, and the RMS from all the runs were averaged and plotted versus tire pressure. A sampling rate of 100 samples per second was used in LoggerPro™.

The first experiment, conducted on a Toyota Camry, had only three runs for each pressure. After the results were discussed, it was decided that there should be more trials with a wider a range of different pressures and with more runs per pressure to minimize random error.

The last two experiments, conducted on a Toyota Land Cruiser and a Kia Rio, were run with seven runs for each pressure and covering a wide range of pressures with a quantization level as small as 2 psi between every two pressures.

The road used for all experimental runs was an unfinished and erratically bumpy road with a minor arc bend. The WDSS accelerometer was programmed to measure vibrational accelerations in the z-axis direction only, thus eliminating acceleration contributions in other directions.

The sample car specifications are given in the table 1.

Table 1. Specifications of the cars used in the experiment.

	Holden Commdore Ve 2007	**Toyota Land cruiser 2009**	**Toyota Camry 2011**	**Kia Rio 2005**
Wheel base	2915 mm	2849 mm	2777 mm	2410 mm
Width	1899 mm	1970 mm	1822 mm	1680 mm
Width of the Tires	225/60R16	275/65R17	205/65R16	175/65R14
Curb weight	1690 kg	2580 kg	1446 kg	1109 kg

4. Results

Using the analysis method discussed above, the vertical acceleration data was analyzed via statistical analysis.

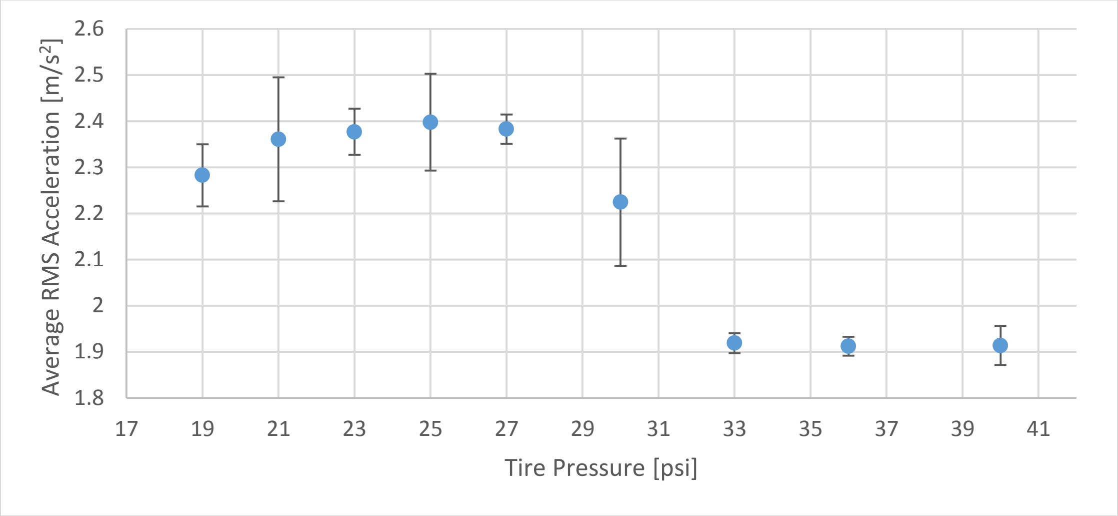


Fig. 1. Average RMS acceleration vs. Tire pressure with uncertainty bars for Car 1 (Toyota Camry).

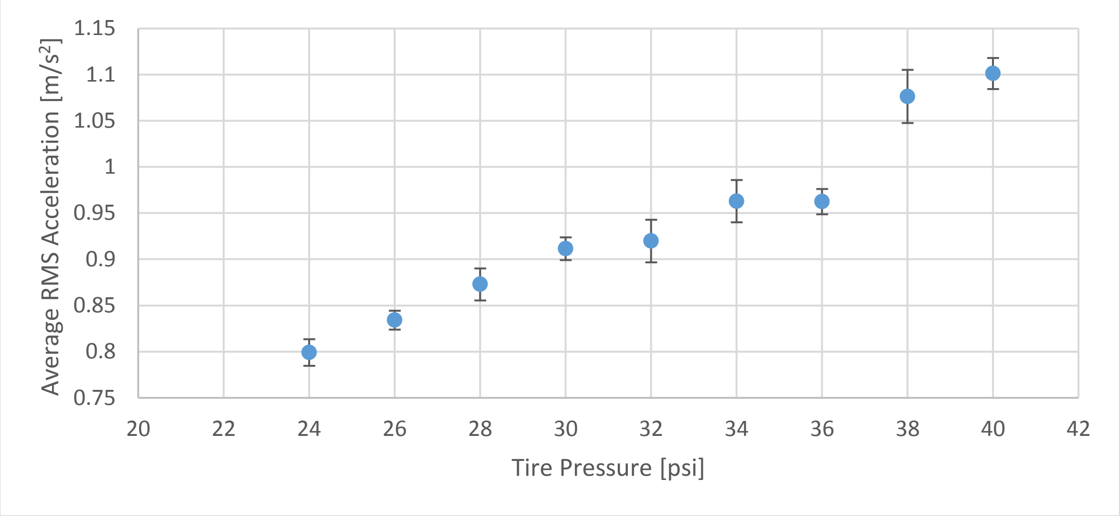


Fig. 2. Average RMS acceleration vs. Tire pressure with uncertainty bars for Car 2 (Toyota Land Cruiser).

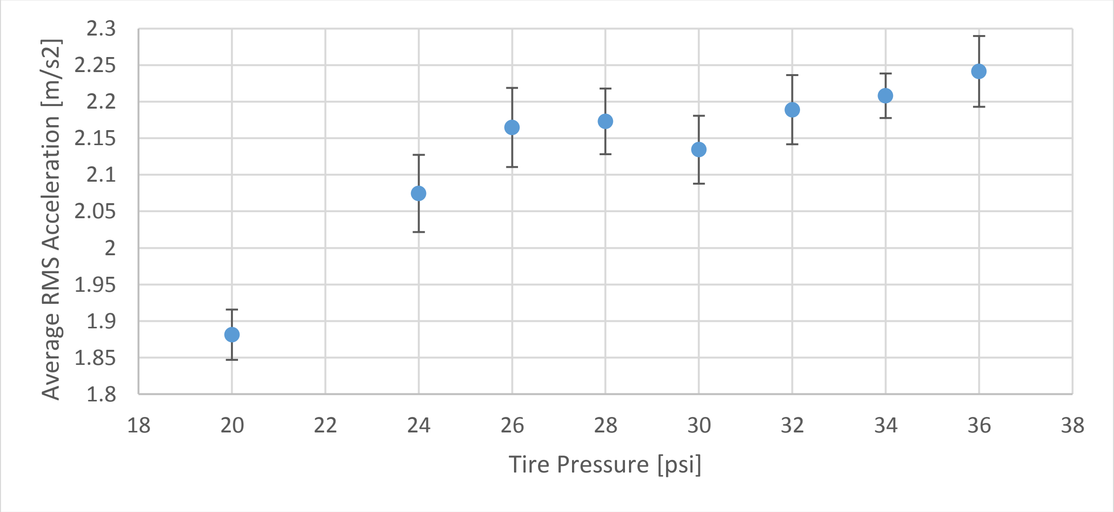


Fig. 3. Average RMS acceleration vs. Tire pressure with uncertainty bars for Car 3 (KIA Rio).

Table 2. Comparing different pressure sets in Car 1.

Pressure [psi]	**t-test experimental**	**t-table values at 90% confidence**	**v actual**
19→21	0.85	2.92	2
21→23	0.19	2.92	2
23→25	0.30	2.92	2
25→27	0.23	2.92	2
27→30	1.84	2.92	2
30→33	3.59	2.92	2
33→36	0.38	2.353	3

Performing the t-test on car sample 2 showed inconsistent transmissibility changes, which is shown by the t-test. Only when decreasing the pressure from 33 to 30 psi shows a change of transmissibility with a confidence level of 90% but less than 95%.

Table 3. Comparing different pressure sets in Car 2.

Pressure [psi]	**t-test experimental**	**t table values at 95 %confidence**	**v actual**
24→26	3.27	2.228	10
26→28	3.18	2.262	9
28→30	3.00	2.228	10
30→32	0.52	2.262	9
32→34	2.18	2.201	11
34→36	0.02	2.262	9
36→38	5.89	2.306	8
38→40	1.23	2.262	9

For car sample 3, most of the data were highly reliable and consistent. Decreasing the pressure from 40 to 38 psi didn’t show any significance difference between transmissibility. Also between 36 to 34 and 32 to 30 there is no evidence of change between transmissibility. While decreasing the pressures from 38 to 36 psi and 34 to 32, 30 to 28, 28 to 26, and from 26 to 24 psi, showed a transmissibility difference with a confidence of 95% but not 99%.

Table 4. Comparing different pressure sets in Car 3.

Pressure [psi]	**t-test experimental**	**t-table values at 95% confidence**	**t-table values at 90% confidence**	**V actual**
20→24	5.04	2.228	1.812	10
24→26	1.96	2.201	1.796	11
26→28	0.20	2.201	1.796	11
28→30	0.99	2.201	1.796	11
30→32	1.35	2.201	1.796	11
32→34	0.56	2.228	1.812	0

For car sample 4, only significance between transmissibility was observed at low pressures, between 24 and 20 psi with a confidence level of 95% but less than 99%, while between 26 to 24 psi the data shows only 90% level of confidence but less than 95%.

5. Discussion

The common feature in all cars tested, was that the high frequency content of their vibrations increased steadily and exponentially in amplitude as pressure was increased in the cars' tires. Low frequency content of the cars' acceleration also increased, but to a lesser degree, as the tire pressure increased.

The RMS of the cars' vibrations showed a similar trend, although results of that form were sometimes inconsistent due to the added error factors that can affect this kind of measurement technique. In considering the frequency content of the signal, a clearer image is drawn on the effect of tire pressures on vibrational transmissibility from the road's surface to the car than that can be seen from the RMS values from the cars' acceleration. That is because variations in path, test speed, wind speed and transient vibrations when taking off with the car, all contribute highly to the RMS acceleration value, even though efforts were made to be consistent in all the testing procedure. The frequency content however, is affected to a lesser degree than the RMS values by those factors mentioned, and transmits the feeling of the passenger inside the car rather than other factors that don't affect the ride much. The RMS values of the cars' acceleration are still essential in the context of exploring the best pressure on a finite pressure domain.

For Car 1, pressure was not increased beyond 40 psi, which was expected to cause an increase in the RMS of vibrations, resulting in the trend followed by Cars 2 and 3.

In support of the second hypothesis, the FFT plots of the cars' acceleration show that as pressure drops, high frequency vibrations drop accordingly, showing that there is no single optimum pressure for minimum vibrational transmissibility. The RMS plots of the cars' acceleration, on the other hand, guide us to pinpoint the optimum pressure on a finite pressure domain deemed operationally safe. This pressure domain varies and is dependent on the car's model and mass and on the terrain on which the car is driven.

Filtering is irrelevant to the research conducted, for every frequency is accounted for and required to analyze the effect of tire pressures on vibrational transmissibility; therefore, no frequency range, high or low, will be discarded from the signal content acquired. The importance of all frequency signals in testing tire pressures' effect on cars' ride quality and passenger comfort comes from the fact that, although high frequency vibrations are not felt due to damping from car seats, the full frequency spectrum of the signal recorded by the sensor is actually transmitted to the car parts, which can be detrimental to its life time. Filtering is useful when trying to obtain a certain signal amid unwanted noise; however here as explained the full frequency content of the signal should be studied, and thus no definition to noise in this context was applicable.

The optimum pressures were found from the plot of RMS acceleration values versus pressure. For Car 1 (Toyota Camry), the optimum pressure was found to be 36 psi; for Car 2 (Toyota Land Cruiser), 36 psi; and for Car 3 (KIA Rio), 30 psi.

6. Conclusion and Summary

The findings of the research conducted agree with the second hypothesis proposed, using the FFT and RMS values of the cars' acceleration. Vibrational transmissibility will continue decreasing as pressure is reduced, but as decreasing it after a certain threshold will reduce the driver's car control and pose a danger to him and his surroundings; therefore, an optimum pressure was sought and found on a finite and safe pressure interval. In the Toyota Land Cruiser, this pressure was found to be 36 psi, while in the KIA Rio it was found to be 30 psi. In finding this optimum pressure, at which the least vibrational transmissibility is obtained, numerous parameters are enhanced: the physical well-being of the driver is improved on the long run, a more comfortable ride is delivered to the passenger, transported equipment incur minimal damage during the transportation process, and car parts life time is extended all due to the reduced vibrations felt by the car and passenger.

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