Study of Horizontal Impact Forces Arising from Terrain on Off-Road Vehicles and Minimizing Their Effects on Ride Quality

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ABSTRACT

Vehicles with off-road capabilities in the present times have begun to focus more on ride comfort. One of the most common uses of such vehicles is to help commuters travel on rough terrain, away from paved roads. Vertical suspensions carry out the work of minimizing the impact from objects like rocks and stones that comprise the terrain. However, such undulations in the terrain are not just vertically bulged. The geometry of the object, i.e., the rock/stone and the wheel coming in contact with the object gives rise to the familiar vertical impact forces for which vertical suspensions are provided. The other component of the impact force arising from the same irregular geometry of the undulation, i.e., the horizontal component of impact force which acts parallel to the axle of the wheels remains neglected. This might lead to passengers experiencing sideways swaying while inside the vehicle, even if there are independent vertical suspensions. In this paper, a study of the effects of horizontal component of impact forces on off-road vehicles was done and after that, spring-shock absorber arrangements to counter these forces were analyzed with springs of different spring-stiffness values.

Keywords: Off-road vehicles, impact forces, springs, shock absorbers, ride quality, damping.

1 Introduction

Vehicles with off-road capabilities like SUVs and pickup trucks have risen to popularity in the recent times. While a lot of people may use them as daily-drivers in cities and towns on well laid roads, the other objective of these vehicles is to provide people a capable and robust means of traversing through difficult terrain that is far from roads or highways [7], [8]. Although, in the beginning, these vehicles focused purely on functionality, later, comfort and luxury were added to attract more buyers. One of the most important factors that affect smooth ride on off-roads is the terrain which is very irregular and bumpy. The ride quality on such roads is maintained by providing springs and shock absorbers which reduce the impacts from the terrain on the passengers. Normally, the springs in the vertical suspensions compress to prevent the shock from reaching the main body of the vehicle and the energy stored in the spring as a result of this compression is dissipated by a shock absorber in the form of heat, which effectively smoothens the driving experience [3], [5].

However, traditional spring and shock absorber arrangements are meant to counter only the vertical impacts from the bumps. Although this proves useful, still, passengers can feel sideways swaying on hitting bumps. The sideways swaying in the case of rigid axle suspensions occur because of the fact that when one wheel hits a bump, the other wheel experiences a displacement as there is a single rigid axle connecting the two wheels. But for independent suspensions like double wishbone suspensions, the presence of sideways swaying can be accounted to horizontal forces being exerted on the wheel [4].

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Clearly, these horizontal forces have to originate from the tire interacting with the terrain. This study aims to understand the effect of the horizontal component of such impact forces. A rock of arbitrary shape is taken as the test undulation in the terrain. If the effect of horizontal forces from a single undulation is analyzed, it will help provide an insight as to how such undulations when present in a continuous form over a terrain affects the lateral dynamics of the vehicle. Thereafter, the aim will be to see how the proposed solution, i.e., the use of springs and shock absorbers (dampers) counters the effects of such horizontal forces.

2 Methodology

Off-road characteristics refer to natural elements like rocks, stones, water bodies, debris and fauna. The objects which are most common in off-road conditions are rocks/stones. So, a rock of arbitrary shape is taken and the components of forces on one of the wheels is calculated. Now off-road activities can include a number of things like riding at normal speeds over terrain, climbing, crawling over and out of obstacles and crossing mud puddles and shallow water bodies. The particular activity of focus in this study is riding at normal speeds over terrain since, in all the other off-road activities, the vehicle is brought down to very low speeds to overcome the obstacle on the path primarily and the ride quality is not the main concern in those situations.

The method in which the study will be done is first, the impact of horizontal components of forces is calculated on a test wheel and then spring and shock absorber arrangements with springs of different spring constants are used to counter the effect of the horizontal component of force. The effects of the spring and shock absorber arrangements are then evaluated numerically on a competent software and the results are analyzed.

3 Theory and Calculation

3.1 The Horizontal Component of Force Due to Impact

In this study, the vertical suspensions are considered to be independent as independent suspensions do not transfer vertical motion from one wheel to the other. The travelling speed of the vehicle is taken as 35-40 km/hr. The vehicle is considered to be loaded with four passengers and luggage of 3100 kg. The front right wheel is taken as the test wheel and the mass distribution on it is estimated as 775 kg. From the figure below, it can be seen the geometry of the rock leads to a horizontal component of the impact force designated as $Nsin\theta$ where N is the net reaction force acting on the wheel. The height of the contact point 'P' from the ground is taken as 8 cm. Since, in a normal vehicle, springs would be present to counter the jolts from vertical shocks, the springs on the vertical suspension over the wheel in this case is considered to have a stiffness of 200kN/m and the coefficient of friction(μ) between the tires and the rock is taken as 0.7.

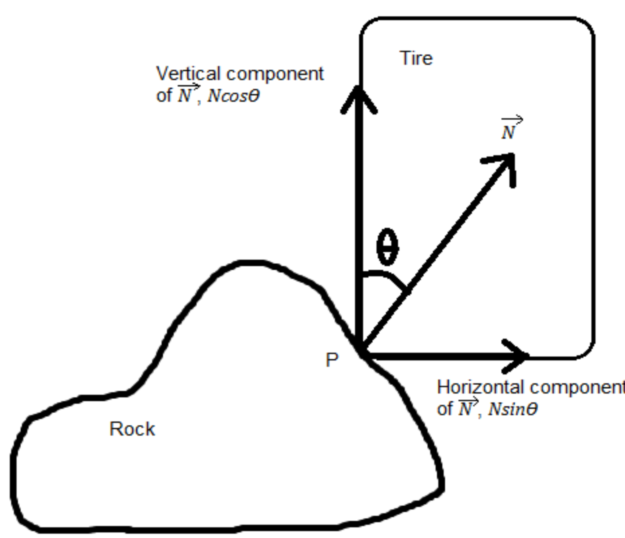

Figure 1: *Vehicle passing over test rock with 'P' being the contact point between the wheel and the rock*

When all the forces acting vertically are resolved, the following equation is obtained-

$$\sum F_y = 0 \qquad \text{(i)}$$

or

$$N cos\theta + f sin\theta = m g_y + F_{spring} \qquad \text{(ii)}$$

where N is the normal force acting on the wheel, f is the force due to friction, g_y is the acceleration due to gravity and F_{spring} is the spring force.
Since Spring Force = μ . Normal Force,

$$N = (m g_y + F_{spring}) \div (cos\theta + \mu sin\theta) \qquad \text{(iii)}$$

Again,

$$F_{spring} = -kx$$

Here $k =$ 200kN/m and when this value of k is put in the Spring Force Equation for the instant before the wheel hits the rock , the mass of 775 kg over the wheel compresses the spring by 0.0379 m which can be designated as $x_{initial}$. Since point 'P' is located 8 cm above the ground level, the total compression of the spring when it hits the rock is

x_{net} = ($x_{initial}$ + 0.08) m
= 0.1179 m

When this value of x_{net} is used in equation (iii) along with the values of m, k, θ, g_y and μ; the value of N comes out to be 25,649.76 Newton.

Therefore, $N_x = N sin\theta$
= 25649.76 sin (40°)
= 16,487.35 Newton

This is the value of the horizontal component of the reaction force due to the impact.

3.2 Countering the Impact Force

To counter this force, a spring and shock absorber arrangement is considered. The exact mechanism is not concentrated upon, only the effect of using such an arrangement is studied.

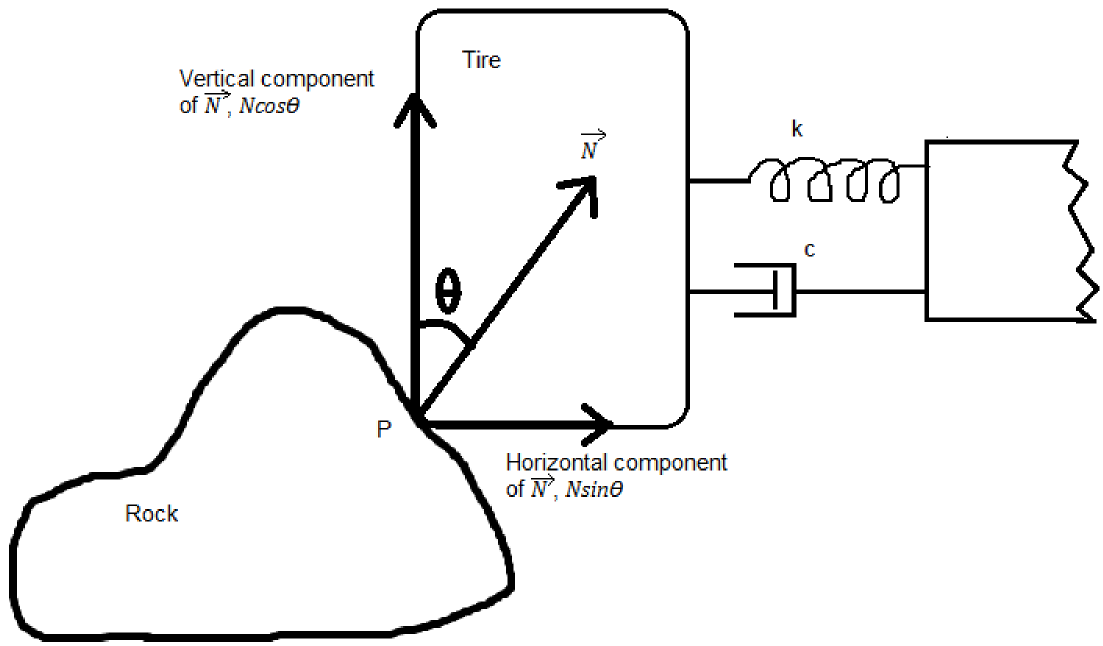

Figure 2: *Spring and shock absorber provided to counter the horizontal component of impact force*.

The governing equation of motion when springs and shock absorbers are used is [1]-

$$m\ddot{z}+c\dot{z}+kz=-m\ddot{y} \quad \text{(iv)}$$

In the differential equation above, c and k represent the damping coefficient and the spring constant respectively while $m\ddot{y}$ represents the impact force and z represents the displacement.

Upon simplifying Equation (iv), we get

$$\ddot{z}+\frac{c}{m}\dot{z}+\frac{k}{m}z=-\ddot{y} \quad \text{(v)}$$

From equation (v),

$\frac{k}{m}=\omega_N^2$, ω_N → Natural Frequency

And

$\frac{c}{2m}=\zeta\,\omega_N$, ζ → Damping Ratio

Equation (v) is a second order non-homogenous differential equation. For solving this equation, first, a Laplace transformation is done. Laplace transformations help convert differential equations to algebraic equations. Then, a convolution integral is used to find z(t) since the differential equation here is a non-homogenous one.

The value of ζ is considered as 1, i.e., critical damping is considered for optimum results.

The form of the equation after the convolution integral operation [2] is done is:

$$z(t)=\frac{1}{m}\int_0^t F(\tau)(t-\tau)e^{-\omega_N(t-\tau)}\,d\tau \quad \text{(vi)}$$

or

$$z(t)=-\int_0^t \ddot{y}(\tau)(t-\tau)e^{-\omega_N(t-\tau)}\,d\tau \quad \text{(vii)}$$

Note that 'ζ' and 'τ' are different; 'ζ' is the damping ratio whereas, 'τ' is the time to which shifting is done in the convolution integral in Equation (vi).

The impact force is considered to act from t =4 to t =6 seconds, i.e., the wheel encounters and passes over the rock during this time interval. The impact force is taken as sinusoidal in nature.

This equation is then converted into an equivalent code for a numerical analysis program, MATLAB. For the impact force from t =4 to t =6 seconds, a Heaviside step function of the form $u(t-4)-u(t-6)$ is used to represent the same with the sinusoidal part being $16487.35sin(\frac{\pi}{2}(t-4))$.

Springs of stiffness values 100 kN/m, 125 kN/m, 150 kN/m and 180 kN/m are used separately to find how the displacement z(t) varies for different spring-stiffness values. The corresponding values of damping coefficients with critical damping are 17,607 Ns/m, 19,685 Ns/m, 21,564 Ns/m and 23,622 Ns/m. The camber angles have not been taken into account which are considered to be very small and therefore done without. The damping effects arising from the tires have not been taken into account. The impact of the force from t =4 to t =6 seconds is shown in Fig. 3.

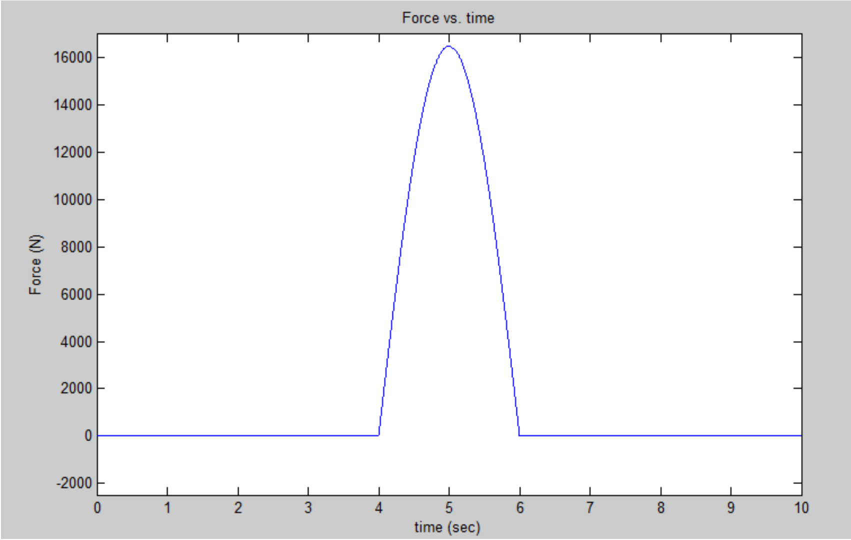

Figure 3: *Horizontal component of force due to the impact from t=4 to t=6 seconds*

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4 Results and Discussion

The code was run on MATLAB and the following plots of responses for different values of spring-stiffness were obtained-

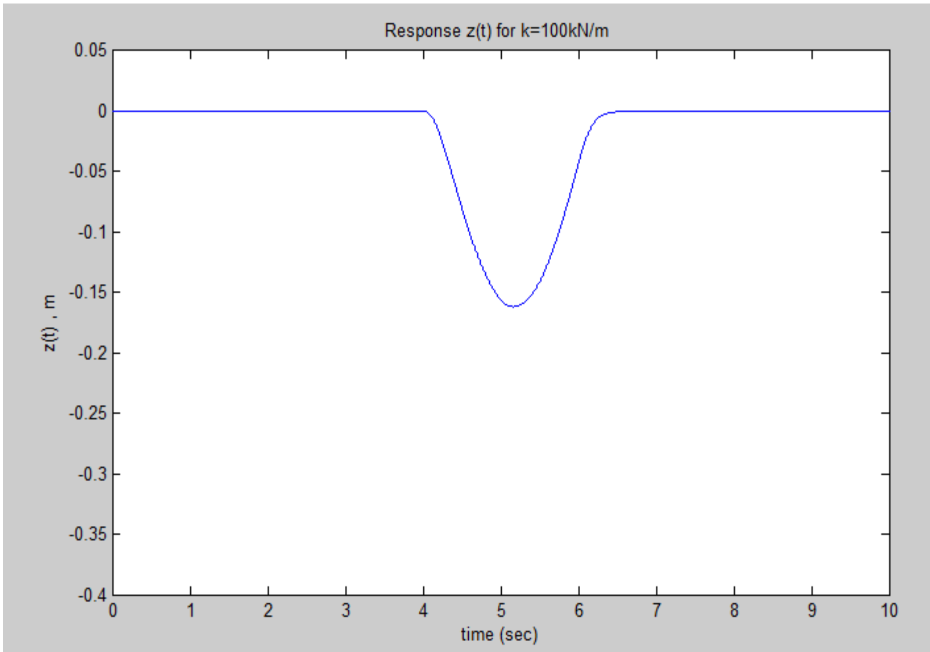

Figure 4: *Displacement for k=100 kN/m and c= 17,607 Ns/m*

In the case of spring stiffness being 100 kN/m, the relative displacement is 0.17 m.

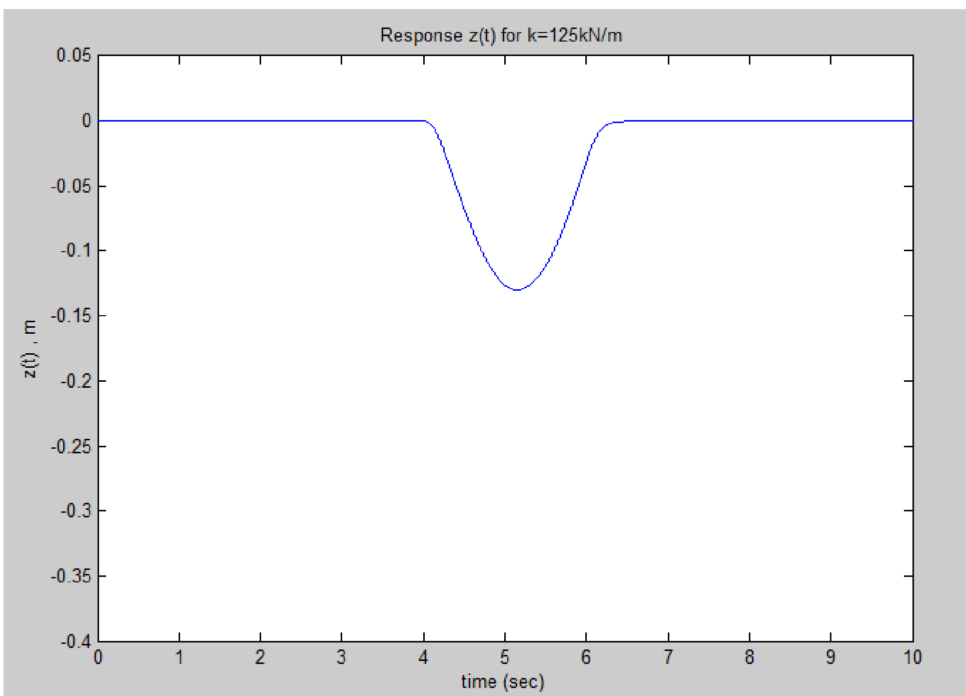

Figure 5: *Displacement for k=125 kN/m and c=19,685 Ns/m*

In the case of spring with spring stiffness 125 kN/m, the relative displacement is 0.135 m

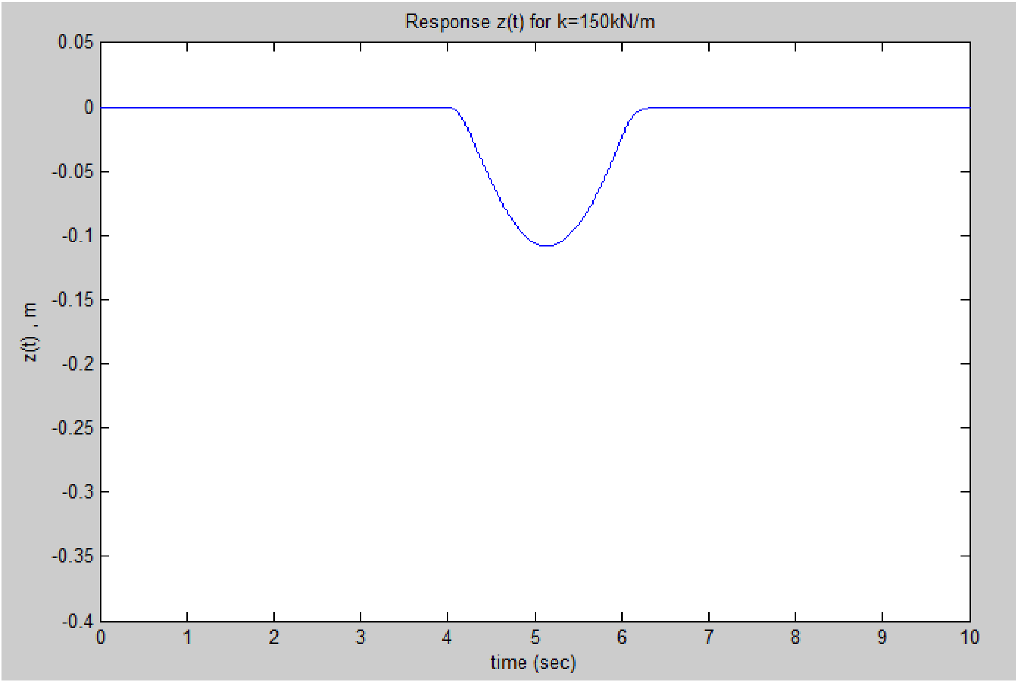

Figure 6: *Displacement for k=150 kN/m and c=21,564 Ns/m*

The displacement for k= 150 kN/m is 0.12 m.

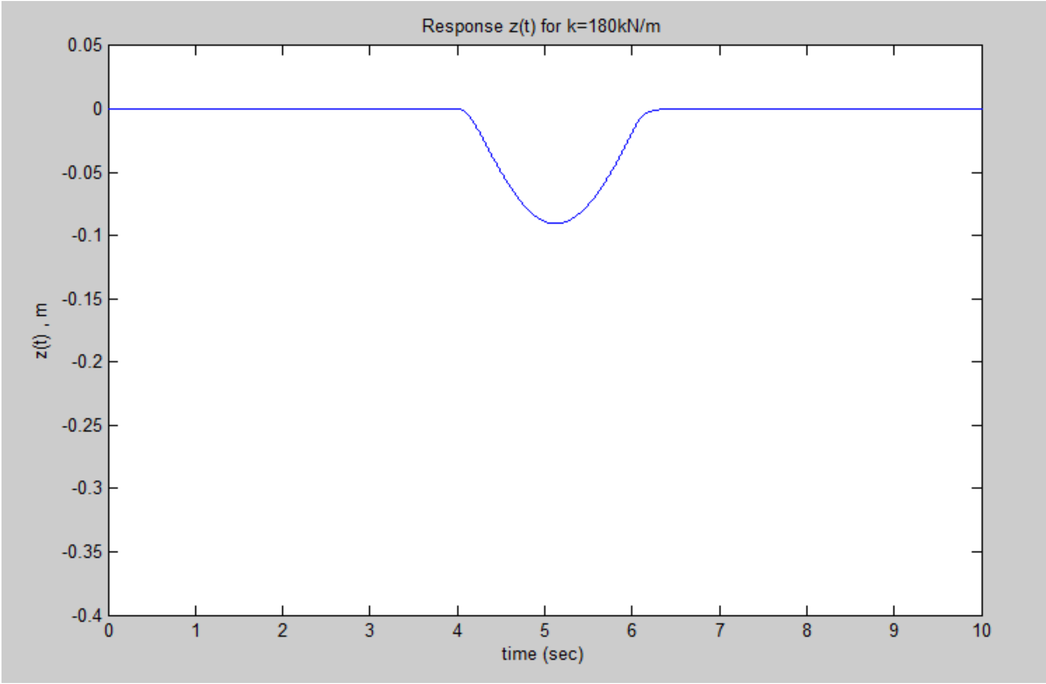

Figure 7: *Displacement for k=180 kN/m and c=23,622 Ns/m*

In the case of k=180 kN/m, the displacement was the least of all three being about 0.095 m.

From the plots of displacement vs. time, it can be seen that more the value of spring-stiffness, less is the displacement response. In other words, the values of the displacement responses are higher when spring-stiffness values are low. The displacement in Figure 4 at about 0.17 m, where k=100kN/m is the highest of all four cases followed by Figure 5 at about 0.135 m where k=125kN/m; Figure 6 at 0.12 m where k=150 kN/m and finally, Figure 7 where k=180 kN/m has the lowest displacement of all, less than 0.095 m. The results from this study should not be confused with the countering of forces which are horizontal but perpendicular to the axis of the axle; this paper only discusses about countering the forces acting laterally, i.e., horizontal forces acting parallel to the axle's axis.

5 Conclusions

From the plots above, it can be seen that, lower the spring-stiffness, more is the displacement. Since, ride comfort is the focus here, this means that for springs with low stiffness values, the displacement of the wheel relative to the chassis of the vehicle is more and with the provided dampers, less of the impact will be transferred to the actual body of the vehicle. Since these springs do not have to bear the load of the vehicle throughout, the problem of compromise of handling from low-stiffness value springs are not significant. So, with low spring-stiffness values and the corresponding damping coefficients, the effects of horizontal component of forces on passengers will be less as can be seen from the amplitude of each of the responses in the displacement-time plots. However, the spring-stiffness values should not be too low as there must not be any unwanted interference with the functioning of the vertical suspension and other mechanical parts. Also, too low spring-stiffness values reduce the effective lifetime of both the spring and the shock absorber.

Again, this might not be of much significance to vehicles which run mostly on constructed roads as the road structures are flat, leading to almost negligible horizontal component of impulse forces. The scopes of this study are that such systems may be used for the delivery of very fragile commodities where damping of forces from shocks and movements is important. Such arrangements may also be used in transporting patients. Future works on this topic will focus on developing mechanisms for the proposed arrangements.

6 Declarations

6.1 Study Limitations

One of the limitations of this study is that having additional springs and shock absorbers along with the existing vertical suspensions takes up a considerable amount of space in a vehicle whereas, such spaces are either very scarce or are already occupied by other mechanical parts. The damping effects from the tires were not considered in this study.

6.2 Funding source

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