COMPUTATIONAL DESIGN OPTIMIZATION OF ROAD SPEED BUMPS

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Abstract: In this study, for urban traffic control; several speed bump forms are proposed as novel designs by the usage of design optimization algorithm. A generic automobile suspension and standard speed bump relations are modeled as dynamic systems and processed in a computerized simulation. In established simulation model, the speed bump form is assumed as road input and its cross section curve is polynomial. The optimization algorithm minimizes the vehicle oscillation when the vehicle passes over the speed bump within the range of determined speed limits and elevates the vehicle oscillation to a safe but higher pre-defined value when the vehicle passes over the speed bump with much higher speeds. Optimization is carried out by entering the required parameters to design optimization toolbox and the obtained simulation and optimization values provides different speed bump forms for different speeds.
Keywords: Road Speed Bump, Computational Design

Introduction

The increase of the human population in cities lead to congestion of the urban traffic elements. Also it is an indisputably fact that the unavoidable increase in the count of motorized vehicles impacts this situation badly. When any component within a system causes this much concentration, some variety of methods, rules and protocols must be established in order to regulate their relations with each other. Therefore when this situation considered under the traffic regulations, the thing that first comes to mind is general traffic rules. But determining regulators of this rules cannot enforce these effectively all the time, so some enforcing precaution applications must be developed.

To control motorized vehicles - mostly automobile speeds in urban areas, some mandatory speed reducing methods are applied on several roads. These are called traffic calming devices and there are several different types such as speed humps, speed bumps, raised intersection, raised pedestrian crossings, chokers etc. Speed bumps or humps are much widely used comparing to others. However, commonly used speed bumps hardly fulfill their functions on applied roads. The expected functions from these devices are; when vehicles pass them over at the speed limit or lower, there should not be very high amplitude and / or very high frequency oscillations on the vehicle body, so the passengers and the driver feel little discomfort and when vehicles pass them over with a speed higher than the limit, there will be considerable discomfort level but those oscillations amplitude and frequencies should not be as high as they could cause injuries on the passengers. However this is hardly the case. Even if vehicles pass some types of this bumps over with very low speeds for speed limits, there could be some high level of discomfort. Contrarily to this situation, when vehicles pass same type bumps over with high speeds than the limit, passengers could feel much less discomfort. Apart from these problems, if a driver realizes these bumps at the last moment, they could break suddenly or could not break at all and vehicles could pass over some bumps unbalanced or passengers in an unexpected sitting position could experience sudden vertical accelerations. As a result of these, accidents and variety form of injuries may occur. Besides, drivers who realize these problems develop a bad driving habit which is slowing down swiftly while approaching a bump and as soon as vehicle passes over the bump accelerating at once. This driving cycle increases fuel consumption and the release of harmful emission gases compared to normal driving.

In order to solve these problems some design propositions are made in the literature by researchers. Moreno et. al. (2012) developed a novel traffic calming device which is called speed kidney and by this design it is aimed that general problems with current designs can be minimized. As the name suggests, this device is a kidney-shaped speed hump. If a vehicle passes over this hump with a straight path, one or two wheels of the vehicle passes over the hump. After that, the driver and the passengers would experience discomfort. Therefore driver would be forced to slow down the vehicle. On the other and if vehicle passes the hump with a curved path with an appropriate speed which is close the limit, there would be no discomfort. By this maneuver, discomfort levels can be reduced on speed limits and other negativities can be prevented. Pedersen (1998) optimized the shape of a speed bump (sleeping policeman) with respect to the response characteristic of a car going over the bump. The shape of the bump is controlled by amplitudes of basic functions that are orthogonal in the sense that each contributes something new to the design space. Optimization is performed with numerical sensitivities, from a planar multibody system simulation. Khorsid and Alfrared (2004) proposed an optimum speed hump design by using second degree sequential programming method. Dynamic behavior of the automobile and drive components are theoretically inspected while the vehicle passing over the hump and vehicle – passenger model is presented as a 12 degrees of freedom mathematical model. A comfort criteria is defined for comfortable or uncomfortable drive, and it is modeled using driver's vertical head acceleration. Three types of humps are discussed and evaluated in the optimization technique. These humps are Watts, flat-topped and polynomial humps. The global design is selected from 42 optimal designs which are found by combining different rise/return profiles for the three types of humps. Ardeh et. al. (2008) proposed an approach which is based on multiobjective genetic optimization of the hump profile. A 6-degree of freedom non-linear dynamic model is used to identify the speeds at which separation occurs, and three independent objective functions are selected for optimization. As a result, two optimal designs were found and a Pareto front of at least ten optimal points is achieved for each of the two hump profile types.

The Study

In this study, first of all 5 degrees of freedom mathematical model is created (Figure 1). To solve the differential equations which are obtained from the model, the boundary conditions should be determined.

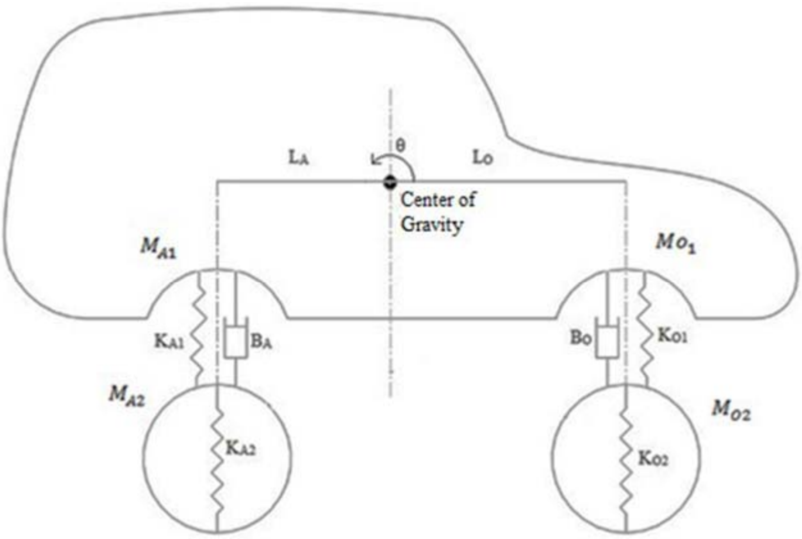

Figure 1. 5 degrees of freedom dynamic half automobile model

The dimensions of 45 mm x 600 mm (height x width) standard PVC speed bump as vertical coordinates, and the passing over the bump times at different velocities of 30 km/h, 50 km/h and 70 km/h as horizontal time coordinates inserted to the curve fitting algorithm. As a result of evaluating this algorithm three different form of input Cartesian coordinate groups are obtained as curve graphics (Figure 2).

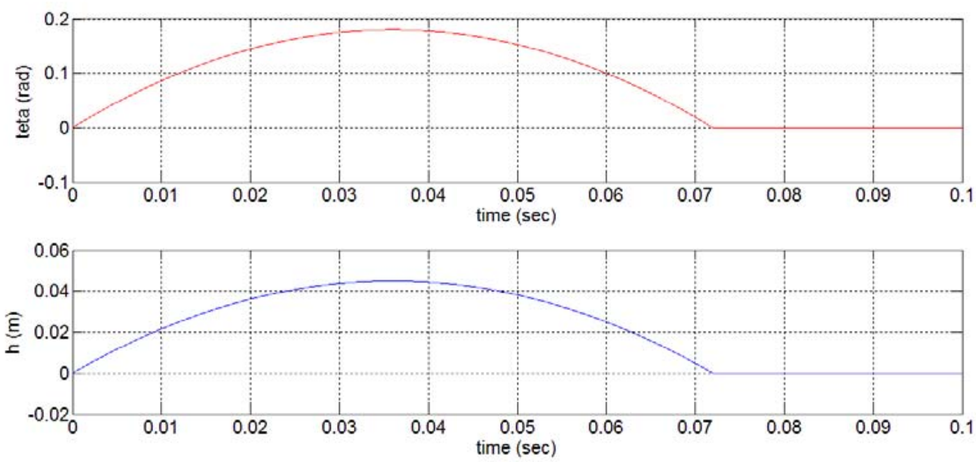

Figure 2. The input signals

Equations of motions derived from Newton's second law are given below.

Vertical movement of the vehicle body on the front wheels:

$$\ddot{Z}_1 = \frac{K_{O1}}{M_{O1}}(-Z_1 + Z_2 + L_0\theta) + \frac{B_O}{M_{O1}}(-\dot{Z}_1 + \dot{Z}_2 + L_0\dot{\theta}) \quad (1)$$

Vertical movement of the unsprung mass on the front wheels:

$$\ddot{Z}_2 = -\frac{K_{O1}}{M_{O2}}(-Z_1 + Z_2 + L_0\theta) - \frac{B_O}{M_{O2}}(-\dot{Z}_1 + \dot{Z}_2 + L_0\dot{\theta}) + K_{O2}(H - Z_2) \quad (2)$$

Vertical movement of the vehicle body on the rear wheels:

$$\ddot{Z}_3 = -\frac{K_{A1}}{M_{A1}}(-Z_3 + Z_4 + L_A\theta) - \frac{B_A}{M_{A1}}(-\dot{Z}_3 + \dot{Z}_4 + L_A\dot{\theta}) \quad (3)$$

Vertical movement of the unsprung mass on the rear wheels:

$$\ddot{Z}_4 = -\frac{K_{A2}}{M_{A2}}(-Z_3 + Z_4 + L_A\theta) - \frac{B_A}{M_{A2}}(-\dot{Z}_3 + \dot{Z}_4 + L_A\dot{\theta}) + K_{A_2}(H - Z_4) \quad (4)$$

The numerical values of these parameters are given below (Table 1).

Table 1. The numerical parameter values which are used in the 5 degrees of freedom automobile model

Parameter	*Verbal equivalent*	*Value*
Mo_1	Vehicle mass on the front wheels	300 kg
M_{O2}	Unsprung mass on the front wheels	70 kg
M_{A1}	Vehicle mass on the rear wheels	300 kg
M_{A2}	Unsprung mass on the rear wheels	60 kg
K_{O1}	Spring constant of the front suspension	25000 N/m
K_{O2}	Spring constant of the front wheels	200000 N/m
K_{A1}	Spring constant of the rear suspension	22000 N/m
K_{A2}	Spring constant of the real wheels	180000 N/m
B_O	Damper constant of the front wheels	1900 N.s/m
B_A	Damper constant of the real wheels	1600 N.s/m
L_O	Front suspension distance from center of gravity	1.2 m
L_A	Rear suspension distance from center of gravity	0.9 m
H	Road input	Polynomial signal

Findings

The simulation of the mathematical model carried out for 4 seconds, and the graphical results of vertical displacements for different velocity values are shown at figures 3, 4 and 5.

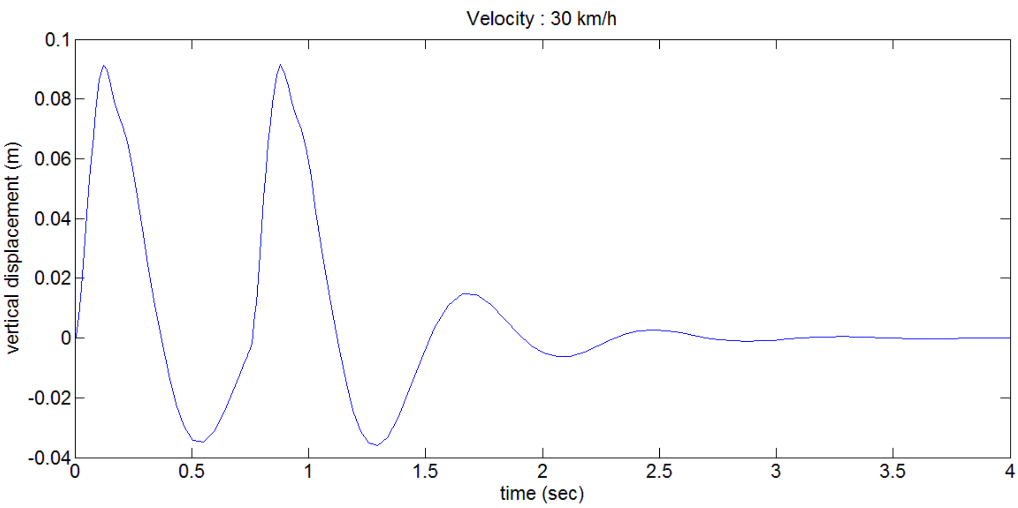

Figure 3. Vertical displacement of a vehicle which passes over a standard bump with a velocity of 30 km/h

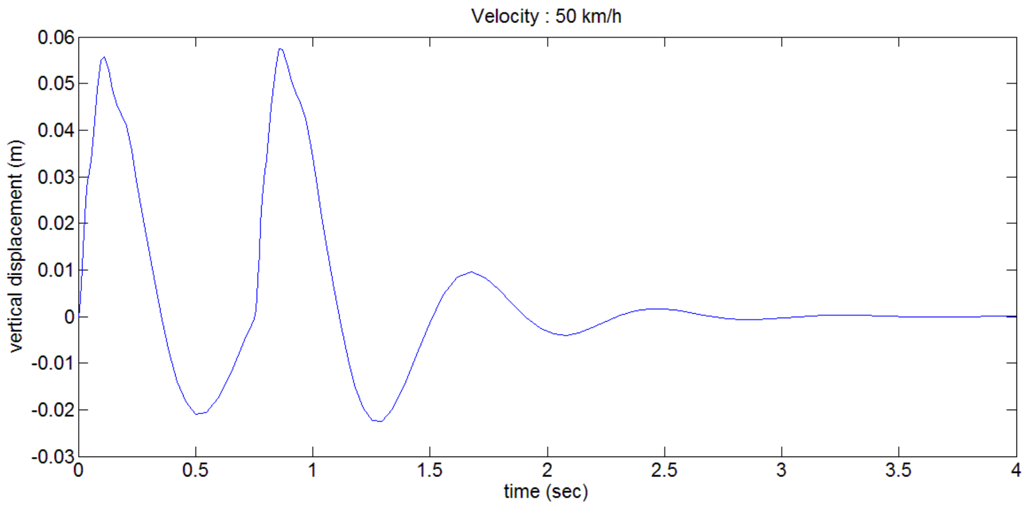

Figure 4. Vertical displacement of a vehicle which passes over a standard bump with a velocity of 50 km/h

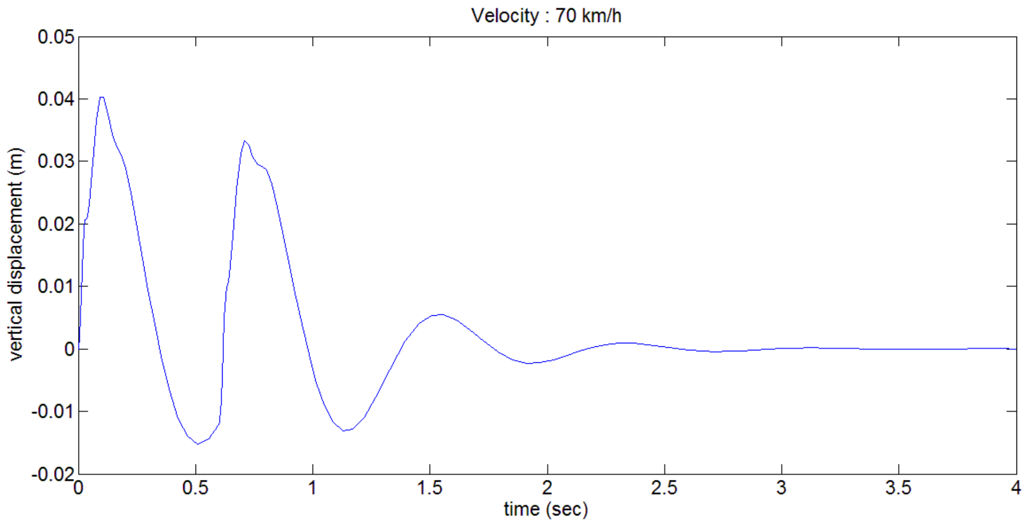

Figure 5. Vertical displacement of a vehicle which passes over a standard bump with a velocity of 70 km/h

At the last phase of this study, an optimization algorithm developed based on vertical displacement results. For this algorithm, non-linear dynamic system parameters inserted into the design optimization technique. This technique uses least squares method to solve curve fitting problems as shown below.

$$min_x \|f(x)\|_2^2 = min_x(f_1(x)^2 + f_2(x)^2 + \cdots + f_n(x)^2) \quad (5)$$

Optionally x's components lb and ub can be lower and upper bounds. x, lb, and ub can be vectors or matrices. Rather than to compute the $\|f(x)\|_2^2$, it is required that user-defined function to compute the vector-valued function (6).

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \cdot \\ \cdot \\ f_n(x) \end{bmatrix} \quad (6)$$

An optimized response result for 50 km/h velocity is shown below (Figure 6).

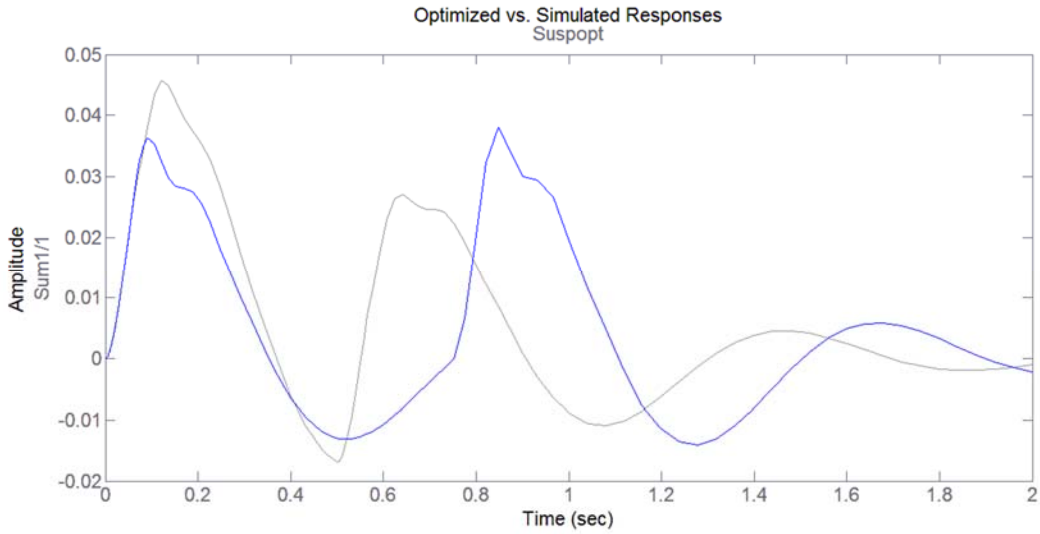

Figure 6. Optimized vs. Simulated Responses for 50 km/h velocity

Conclusions

The simulation result data for respectively 30 km/h and 70 km/h velocities are shown at figure 3 and figure 5. When these graphics carefully examined, it's clear to notice that related speed bump causes a response quite the opposite of what is expected to. Also, vertical displacements at low velocity are higher than high velocity and it seems that the damping of the system takes longer than at low velocity.

The obtained optimum forms are given at figure 7. The obtained optimum solutions provides different forms for different speed limits. In this graph, red line shows the original standard bump form, black line is for low speed limit roads (30 km/h – 50 km/h) and blue line is for high speed limit roads (70 km/h and above). When these forms are used in appropriate ways, it is expected to provide considerable advantages over the currently used forms and it is also expected that the situation of speed bumps have not been fulfilling their functions properly would be substantially neutralized.

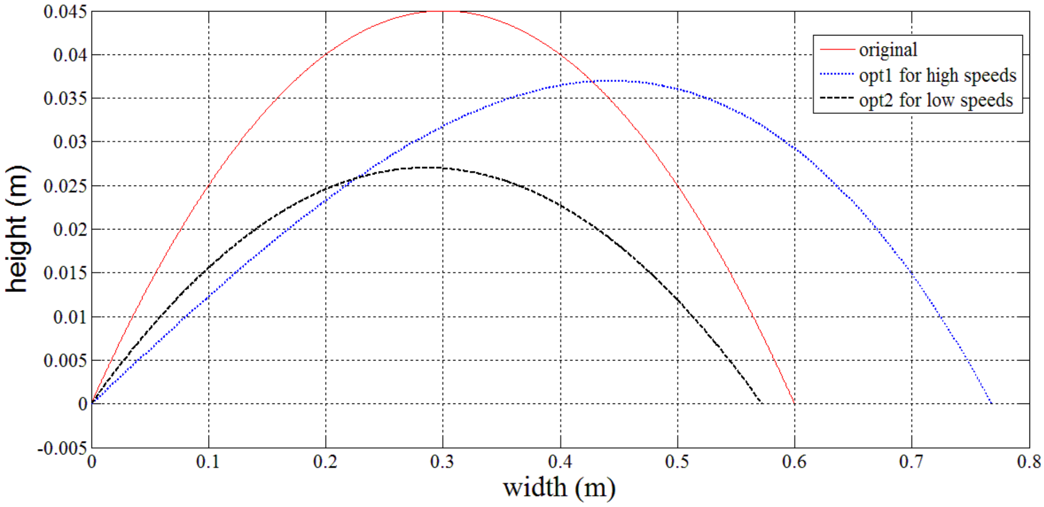

Figure 7. Optimum speed bump forms for low and high speeds

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