ANALYSIS OF THE EFFECTS OF SPEED BUMPS ON VEHICLE VERTICAL PATH

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ABSTRACT

One of the urban safety devices used for traffic calming is the artificial speed bump, a local means for protecting vulnerable road users (mainly pedestrians).

It is a particular configuration of the pavement surface, short in length, which is designed to enforce correct road use on the part of the driver.

The effectiveness of the system lies in enforced speed reduction; however, the regular driver who does not perceive any obvious hazard may attempt to maintain an unchanged speed, submitting the car to dynamic stress and experiencing some marked discomfort, rapidly extinguished, due to being in a hurry.

Sometimes the dynamic load can induce a decrease of the adherent weight down to zero value, with dangerous contact loss between the tyre and the wearing course.

In order to examine these tyre path anomalies, an analytical bi-dimensional vehicle-pavement interaction model, able to evaluate the state variables of motion and the trend of contact strength between the tyre and the road, is proposed.

The vehicle was modelled as a lumped parameters system and the pavement surface was modelled using a profile obtained by numerical simulation based upon its power spectral density. Afterwards, the speed bump geometry was added to the profile.

Road-vehicle interaction was developed by solving a dynamic equations system involving both vehicle and road surface.

The model allows the analysis of contact force evolution and detection of the space-time gaps in which car safety may be reduced; it becomes possible to identify some of the scenarios in which the driver runs the risk of losing adherence; the results suggest that great care is needed in speed bump design.
Keywords: traffic calming, road bump, tyre-pavement surface contact, vibrations, numerical simulations.

1. INTRODUCTION

One of the safety devices adopted in urban areas in order to moderate vehicle speed (traffic calming device) is the artificial road bump, which is a particular configuration of the pavement surface, short in length, designed to enforce correct road use on the part of the driver.

However it has been observed that this device is sometimes rendered ineffective: when crossing the bump, the regular driver may not perceive any obvious hazard, and being in a hurry, may attempt to maintain an unchanged speed, even though this subjects the car to dynamic stress and the driver experiences some discomfort due to generated vibrations.

In some unfavourable circumstances, subsequent variations in the dynamic load can cause a decrease in terms of adherent weight down to zero value, with dangerous contact loss between the tyre and the wearing course. It is therefore important to verify whether and at what moment the bump becomes a safety deficit.

In this paper, in order to examine these tyre path anomalies, we have investigated the influence of the device on the dynamics of vehicle motion, using a simulation that inserts the localized discontinuity of a trapezoidal shaped bump into the road profile.

2. CONSTRUCTION TYPES AND GEOMETRIC CHARACTERISTICS OF THE SPEED BUMP

The speed bump (or road hump) constructed on the road pavement may be in one of a variety of shapes (trapezoidal, circular, parabolic, sinusoidal shape…); it may be made using embossed pre-cast elements in relief, often with modular elements in natural rubber highlighted with yellow and black zebra stripes, or by pavement waves with a convex profile, or in asphalt concrete.

The rubber speed bump has many advantages, such as that of increasing wheel adherence and therefore safety; the yellow inserts (in elasto-plastic laminate) improve refractivity and decrease slipperiness, and the elements are connected by a special joint for distributing the mechanical stress on the whole series, etc.

Speed bumps in Italy are regulated by the rules regarding construction and performance under article 179 of the new Road Legislation: their geometry as a function of the maximum speed allowed on the road section is set (Figure 1).

According to this legislation, bump location must be indicated beforehand by a speed bump sign, and the design of the whole area has to allow superficial water flow. The distance between two consecutive bumps has to range between 20 and 100 metres.

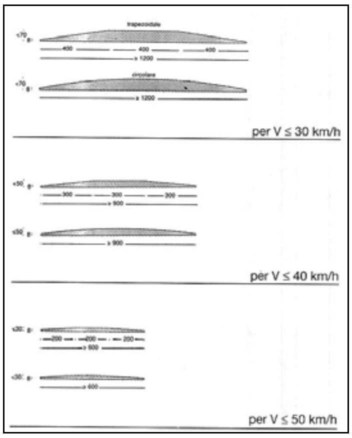


Figure 1 Geometry and shape of the bump as a function of the speed limits in force (art. 179 regarding the rules regarding construction and performance under the new Road Legislation)

Artificial Speed bump in asphalt

Artificial Speed bump (or sleeping policeman) in rubber

Figure 2 Examples of artificial speed bumps

3. MODELLING OF THE INTERACTION BETWEEN ROAD VEHICLE AND PAVEMENT SURFACE

Among the problems regarding dynamic interaction between road vehicle and pavement surface, one of the most significant issues concerns the quality of the wheel–wearing course contact and the phenomena that are correlated to the possible lack of regularity in the interchange of pressures between the two surfaces, responsible for adherence.

In order to analyse this phenomenology, a bi-dimensional mathematical model was developed, capable of simulating the dynamic equilibrium of a moving vehicle on a road surface. The model allows prediction of the influence that distributed or punctual unevenness of the road surface may have on the correct progression of motion (La Torre F. et al., 1999).

The effects produced by a localized, convex-shaped irregularity which simulated the presence of a speed decelerator inside the roadway, were studied using a lumped masses model: the half car (see Figure 3) (Todd Kevin B. et al.).

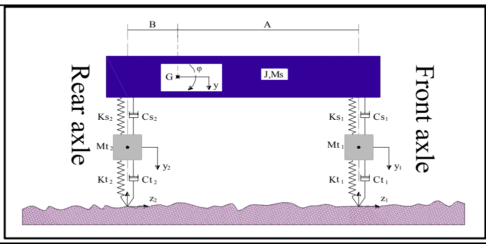
During the motion of the vehicle along the road, which was reproduced by means of a generic road profile (the speed bump was subsequently superimposed on it), the tyres are presumed to be in contact with the surface.

Assuming that the road surface can be modelled as a perfectly rigid guide, because of the tyre deformability, the vehicle masses, moving on an irregular support, are subjected to prevalently vertical vibratory phenomena (Domenichini L. et al. 1999).

The vertical dynamics of such a system, moving at a constant speed V, upon a road profile Z(x(t)), where $x(t) = V \cdot t$, can be expressed via an elastic equilibrium equations system, in differential terms, whose integration allows the vehicle dynamic response to be derived at each instant t.

The equilibrium dynamic system, in matricial form, can be expressed by the following relation:

$$\underline{\underline{M}} \cdot \ddot{\underline{y}} + \underline{\underline{C}} \cdot \dot{\underline{y}} + \underline{\underline{K}} \cdot \underline{y} + \underline{G} + \underline{L} = \underline{0} \qquad \text{(Eq.1)}$$



Ms	One half vehicle sprung mass	Ks_1	Front suspension spring constant	A	Horizontal distance from front axle to sprung mass centre of gravity
J	One half vehicle pitch moment	Ks_2	Rear suspension spring costant		
Mt_1	One half front axle unsprung mass	Ct_1	Front tire damping costant	B	Horizontal distance from rear axle to sprung mass centre of gravity
Mt_2	One half rear axle unsprung mass	Ct_2	Rear tire damping costant		
Kt_1	Front tire spring constant	Cs_1	Front suspension damping costant		
Kt_2	Rear tire spring costant	Cs_2	Rear suspension damping costant		

Figure 3 Half car model – four degrees of freedom

where $\underline{G}$ represents the weight (or static) force vector, $\underline{L} = \begin{bmatrix} 0 \\ 0 \\ -K_{t1} \cdot Z_1 - C_{t1} \cdot \dot{Z}_1 \\ -K_{t2} \cdot Z_2 - C_{t2} \cdot \dot{Z}_2 \end{bmatrix}$ the load vector and the initial conditions of motion: $\underline{y}_0 = \underline{y}(0)$, $\underline{\dot{y}}_0 = \underline{\dot{y}}(t)\big|_{t=0}$ are presumed to be known.

The vector $\underline{L}$ contains the "excitation" of the oscillatory vertical vehicle motion, and it is shown to depend on the road profile unevenness together with the translational vehicle speed; the terms $-K_{t1} \cdot Z_1 - C_{t1} \cdot \dot{Z}_1$, $-K_{t2} \cdot Z_2 - C_{t2} \cdot \dot{Z}_2$ depend, in fact, on the profile elevation trends $Z_1(x(t))$ and $Z_2(x(t))$, respectively covered by the front and rear axle in deferred times ($Z_2(t) = Z_1\left(t - \frac{A+B}{V}\right)$, where A+B is the wheelbase), and on their first-derivates, where the horizontal speed, V, appears:

$$\dot{Z}_1(x(t)) = \frac{dZ_1}{dx} \cdot \frac{dx(t)}{dt} = \frac{dZ_1}{dx} \cdot V \, , \; \dot{Z}_2(x(t)) = \frac{dZ_2}{dx} \cdot \frac{dx(t)}{dt} = \frac{dZ_2}{dx} \cdot V \qquad \text{(Eq. 2)}$$

To solve the differential equations of the vertical dynamics of the vehicle, a mathematical algorithm was developed, based on incremental techniques, i.e. on the Newmak numerical integration method.

The contact between tyre and road pavement was modelled by means of a unilateral constraint; hence we considered the possibility that the wheels can separate from it, because of a drastic reduction of the adherent weight. Input data of the model consisted of the geometrical, cinematic and mechanical properties of the two interfaced systems.

The unevenness of the wearing course was modelled by providing a road surface characterization with the gaussian bi-dimensional aleatory phenomena, with, in addition, properties of homogeneity and isotropy (Dodds and Robson,1973).

Thus it was possible to obtain a complete description of the road surface by observing the elevation trend of its generic profile, which was analytically reconstructed from the PSD-evolution of the displacements, as suggested by the norm ISO 8608, or likewise, by MIRA. These profiles obtained as "realizations" of gaussian aleatory processes, with zero mean value, describe composite signals, distance-variant: z(x), which have to be translated into the domain of time, in order to be inserted in (1).

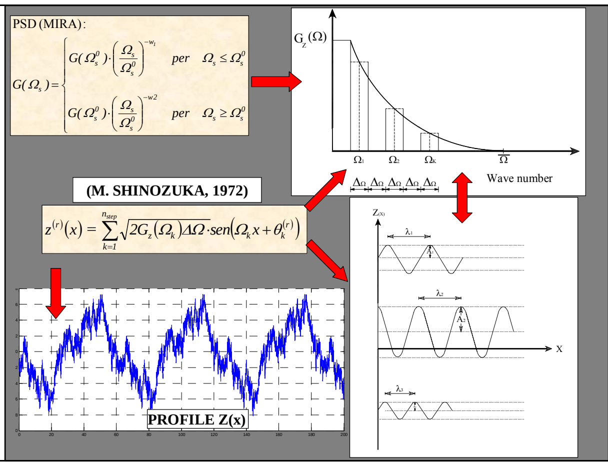


Figure 4 Realization of the road profile by means of its displacements power spectral density (ISO 8608, MIRA)

4. MODELLING OF THE TYRE-ROAD CONTACT

The potential detachment between tyre and road pavement can often be underestimated, and it is therefore necessary to develop a specific analytical formulation, by forcing the vehicle to follow a new governing equations system, once it separates from the wearing course.

The vehicle moving on the road profile transmits to it, through its wheels, a contact force which consists of two contributions, one being static and the other dynamic: $F_c=F_{stat}+F_{din}$, the former is dependent the vehicle weight and the latter is derived from the vertical accelerations of its masses. It sometimes happens that the dynamic load amplitude, prevailing over the static, resets the adherent weight, thus causing the separation of the tyre from the pavement surface. In this case, contact force becomes equal to zero or even negative. By monitoring the time history of the contact force it is possible to identify the instant in which separation occurs, together with the road section; for the half car model, with regard to the front axle, for instance, this condition can be analytically expressed as follows:

$$Fc(t)=\frac{B}{A+B}\cdot Ms\cdot g+M_{t1}\cdot g+K_{t1}\left(y_1(t)-Z_1(t)\right)+C_{t1}\left(\dot{y}_1(t)-\dot{Z}_1\left(x(t)\right)\right)\leq 0 \qquad \text{(Eq. 3)}$$

It is easily understood that equation system (1) is no longer suitable for describing the vertical dynamics of the vehicle. The vehicle motion undergoes a new governing equations system in which the term concerning contact, in correspondence to the degree of freedom pertinent to the separated wheel, is absent.

Assuming that such a circumstance may occur, for instance, with regard to the front axle at a certain instant t_1, system (1) will be modified as follows:

$$\underline{\underline{M}}\cdot\underline{\ddot{y}}+\underline{\underline{C}}\cdot\underline{\dot{y}}+\underline{\underline{K}}\cdot\underline{y}+\underline{G}+\underline{L}^{*}=\underline{0} \qquad \text{(Eq.4)}$$

where $\underline{L}^* = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -K_{t2} \cdot Z_2 - C_{t2} \cdot \dot{Z}_2 \end{bmatrix}$ and the initial conditions of motion are given from the state variables evaluated in correspondence to the above mentioned instant.

In order to numerically formulate the condition for the reestablishment of adherence and to detect the instant in which the wheel resumes contact with the profile, a system of inequalities was adopted, proposed by Y. S. Cheng et al. (1998), which contemplated all the probable scenarios of the resuming of contact.

The output obtained by such an analysis is an interaction force, variable as regards time and distance, which becomes equal to zero when the tyre is not in contact with the road surface.

The modifications introduced into system (1), also allow adjustments to the vertical displacements, velocities and accelerations of the masses system, within the space-time interval in which one of the two wheels undergoes unconstrained motion with respect to the road profile.

5. NUMERICAL EXAMPLES

The behaviour of two different dynamic systems was analysed in the following numerical examples, which respectively represent a passenger car and a heavy truck. It is assumed that the vehicle moves over the artificial speed bump at a constant speed.

The road profile is 200 m long and it reproduces the superficial roughness of two distinct typologies of pavement: a very good principal road, characterized by a degree of roughness equal to $G(\Omega_s°) = 5 \cdot 10^{-6} / 4\pi$ and an average principal road characterized by $G(\Omega_s°) = 50 \cdot 10^{-6} / 4\pi$ (classification ISO 8608, MIRA) (Boscaino G. et al., 2001).

The bump has trapezoidal shape and geometrical dimensions related to a maximum speed of 35 km/h; it is assumed, however, that the vehicle does exceed this limit, moving at the following velocities: 35 km/h, 60 km/h and 100 km/h. The geometry of the decelerator can be set: total length: 120 cm; middle tract, of constant altitude, 40 cm long; maximum height :7 cm.

The geometrical and mechanical parameters of the vehicles are given in Table 1.

Table 1 Geometrical and mechanical parameters of the dynamic system half car, schematizing respectively a passenger car and a heavy truck

PASSENGER CAR		HEAVY TRUCK	
A=1,80 (m)	B=1,01 (m)	A=3,78 (m)	B=2,31 (m)
M_{s1}=322,41 (kg)	M_{s2}=574,59 (kg)	M_{s1}=2446,59 (kg)	M_{s2}=4014,10 (kg)
M_{t1}=43,76 (kg)	M_{t2}=70,53 (kg)	M_{t1}=272,03 (kg)	M_{t2}=521,39 (kg)
J=1630,75 (kg. m^2)		J=46438,80(kg. m^2)	
K_{s1}=66793 (N/m)	K_{s2}=18608 (N/m)	K_{s1}=198311,31 (N/m)	K_{s2}=1138713,36 (N/m)
K_{t1}=201021 (N/m)	K_{t2}=201021 (N/m)	K_{t1}=788340,02 (N/m)	K_{t2}=875933,02 (N/m)
C_{s1}=1189 $\left(\frac{N \cdot s}{m}\right)$	C_{s2}=998 $\left(\frac{N \cdot s}{m}\right)$	C_{s1}=2627,80 $\left(\frac{N \cdot s}{m}\right)$	C_{s2}=2627,80 $\left(\frac{N \cdot s}{m}\right)$
C_{t1}=14,6 $\left(\frac{N \cdot s}{m}\right)$	C_{t2}=14,6 $\left(\frac{N \cdot s}{m}\right)$	C_{t1}=14,6 $\left(\frac{N \cdot s}{m}\right)$	C_{t2}=14,6 $\left(\frac{N \cdot s}{m}\right)$

6. ANALYSIS OF THE RESULTS

Figure 5 shows the trend of contact force and of tyre vertical displacement, at a fixed speed of 60 km/h, for the front axle (FA) of an heavy truck (HT), when varying the roughness of the road surface (very good profile in comparison with average profile: VGP versus AP).

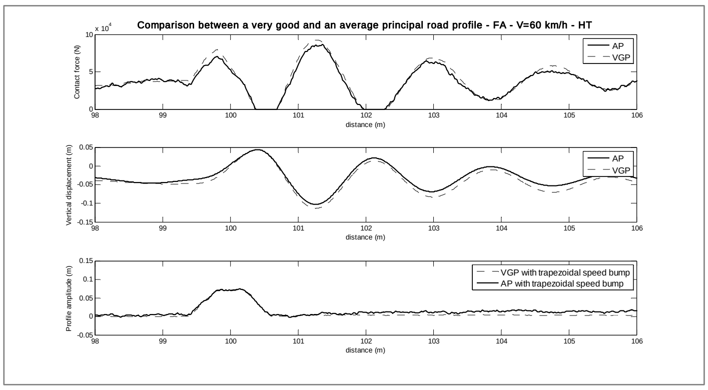


Figure 5 Comparison between a very good and an average principal road profile Front axle

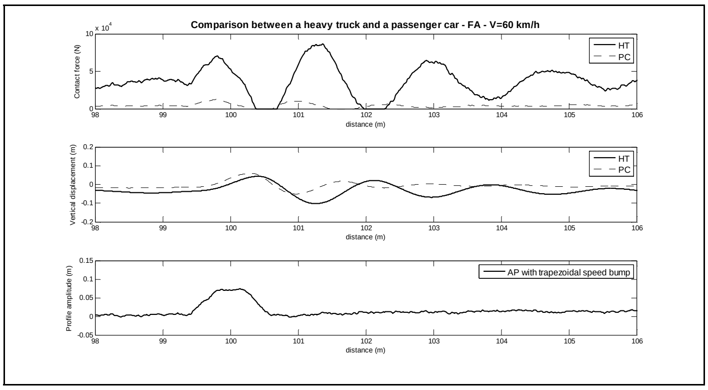


Figure 6 Comparison between an heavy truck and a passenger car – Front axle

It may be seen that the curves relating to the very good profile (VGP) show more regular trends and minor asperities. Beginning from the initial section of the artificial speed bump, perturbation in the contact force signal and in the vertical displacement of the tyre was observed, and tyre detachment from the pavement was noted.

Figure 6 shows a comparison between the contact force curves and those of the tyre vertical displacement for both the heavy and the light vehicle, regarding the front axle, at a fixed speed of 60 km/h.

It may be observed that a greater extent of discontinuity in tyre trajectory occurs for the passenger car when moving over the speed bump, compared to the heavy vehicle. Figure 7 shows a comparison between the influence of the speed bump on the front axle and on the rear one (heavy truck, speed =60 km/h).

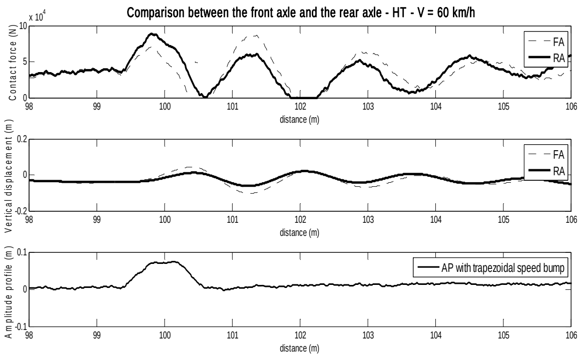


Figure 7 Comparison between front and rear axle

Finally, the incidence of the vehicle speed, with regard to the heavy truck, was analysed (fig. 8 e 9). The images show that an increase in speed produces oscillations of the dynamic load of greater amplitude and consequently wide displacements (differences) from the static values; furthermore, a greater presence of zones characterized by wheel-profile detachments was noted, for the light axle.

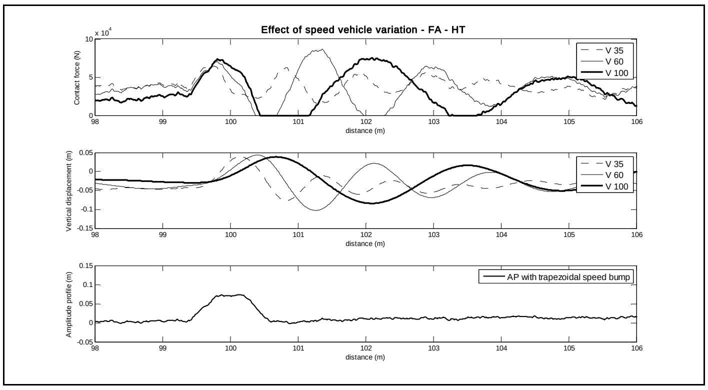


Figure 8 Effect of speed vehicle variation – front axle

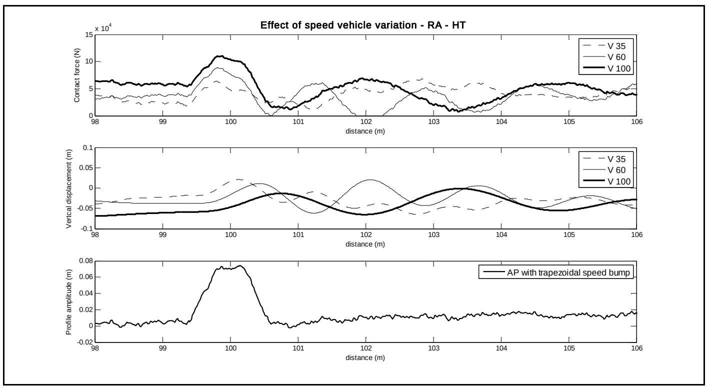


Figure 9 Effect of speed vehicle variation – Rear axle

6.1 Definition of the adherent weight deficit

Once the contact force trend had been obtained, a function was defined which represented the variation of adherent weight undergone by the tyres during motion along a tract of road profile, beginning from the initial section of the speed bump and ending after almost 6 m, where the effects connected with its crossing are extinguished. Therefore, considering that the maximum load value transmitted by the wheels to the wearing course, in absence of motion, is equal to the static weight of the axle, a function of "Deficit of Adherent weight" was defined, obtained by subtracting the dynamic value of the contact force from the static weight: *Deficit of A. W. = Static Weight – Contact Force*. Next, observing that the values of negative deficit should denote increments of adherent weight due to the increase of the load acting on the axle, in order to pursue the objectives of this study and to detect the effective decrease of adherence, the deficit curve was purged of negative contributions, by attributing to them a null ordinate. One thus obtains the representation of a new curve of Deficit*, D*. Therefore D*=0 every time that the adherent weight exceeds the static weight, while D*>0 when there is a reduction of adherent weight, up to a maximum of D*=static force, a condition which represents the separation between tyre and road pavement. In this analysis, rather than assessing the punctual trend of Deficit*, it is more useful to evaluate its integral calculated on profile segments of 40 cm amplitude, in order to consider the three tracts of the speed bump, with different slopes.

When dividing the above mentioned integral by the value obtained by the product of the static load for the amplitude of the tract in study: ΔL, the value of the per cent adherence loss D(%) is derived: $D(\%) = \frac{1}{\text{Static Force} \cdot \Delta L} \int_{\Delta L} \left(\text{Deficit}^*\right) dx$.

Representing, at last, the trend of the deficit per cent of adherent weight D (%) versus the distance (figure 10), by using this model, a level of exposure to the risk of losing adherence may be attributed to every interval ΔL of the profile, beginning from the speed bump, with respect to a fixed vehicle speed. It was observed in the previous examined cases, for example, from the comparison between the percent trends of D and the contact force curves (not all reported in this paper) that, in absence of separation, the parameter D is maintained under a threshold of 20% (field 1) and therefore there are no significant reductions in adherent weight; the observed fluctuations in the static value can be considered physiological and they are bound to the altitude variations of the road profile. When D varies within the gap between 20% and 60% (field 2), some anomalies of the tyre trajectory can be seen, which if they occur, nevertheless produce very little detachment (in terms of amplitude of the space-time gap in which the contact force become zero), insignificant regarding adherence with the road surface.

Corresponding to D >60 % there is a critical zone (field 3), where the real possibility of losing the adherence may unfortunately happen (figure 11, figure 12), as was observed in the comparison between the contact force trend and the "D" curve (see fig. 11), where corresponding to D>60 (%) a dangerous detachment zone is present.

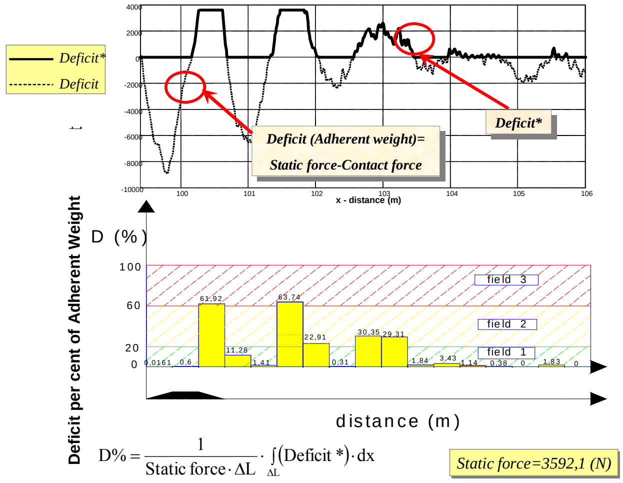


Figure 10 Deficit per cent of adherent weight

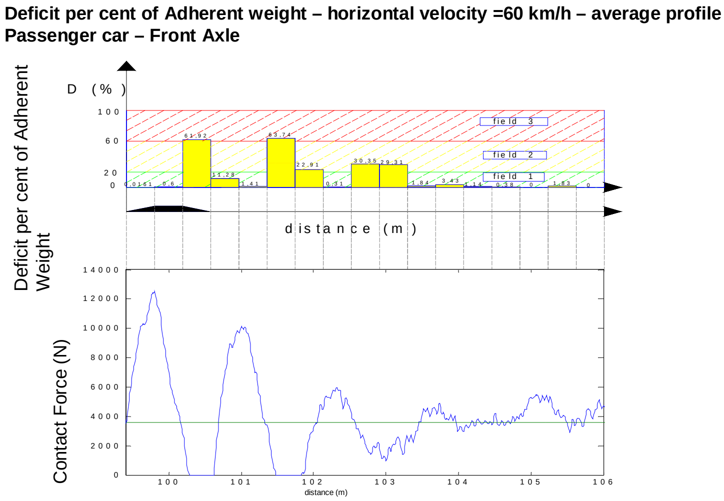


Figure 11 Comparison between D (%) and the contact force trend

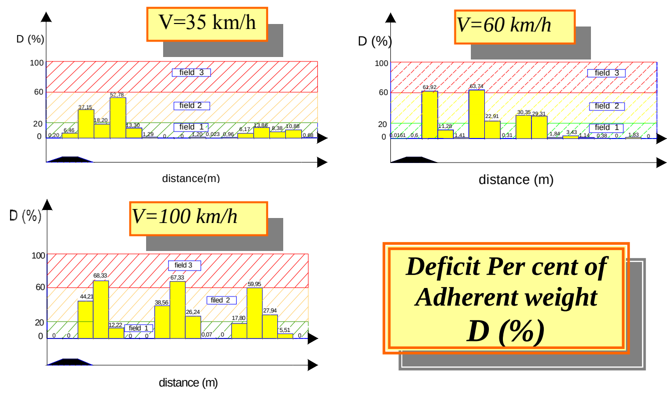


Figure 12 Trend of Deficit per cent of adherent weight, D (%), versus vehicle speed

7. CONCLUSIONS

The artificial road bump is a particular configuration of pavement surface, short in length, designed to enforce correct use of the road on the part of the driver (traffic calming device) in urban areas.

As a local convex discontinuity on a wearing course, sometimes it can also cause a loss of adherent weight down to zero value, with dangerous contact loss between the tyre and the pavement surface.

An analytical bi-dimensional model of vehicle-road interaction is proposed here; using this, it has been possible to examine the state variables of motion as well as investigate contact strength during and after bump crossing.

The model takes into account two different vehicles, three car speeds and two road surface geometrical characteristics. The results emphasize the adherence reduction when the car crosses the bump at an inappropriate speed.

A risk indicator has been proposed, i.e. the deficit per cent of adherent weight (D%); thanks to this indicator it is possible to identify the most dangerous cases.

It was observed from the results of the simulations that when D% does exceed the 60% value, safety conditions are seriously compromised, so great care in speed bump design is recommended.

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