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Dynamická interakce mostů a těžkých vozidel s pérováním šetrným k mostu

Dynamic Interaction of Bridges and Trucks with Bridge-Friendly Suspensions

Summary

Unevenness on the road surface generates, aside from static, a dynamic contact force which can be controlled and possibly reduced. In order to extend the useful service life of bridges some efforts have been done to control the vibration bridges. While direct reduction of bridge deflections was found too complicated new trends in the vehicle suspension development follow the concept of tuning the vehicles to minimize the road-tyre contact forces – such vehicles are called road-friendly vehicles. Road damage generated by a wheel is proportional to the fourth-power of the dynamic road-tyre forces.

In the development of road-friendly truck suspensions, passive, active and semi-active control systems have been considered. A truck with controlled semi-active suspensions traversing a bridge is examined for benefits to the bridge structure. Original concept of a road-friendly truck was extended to a bridge-friendly vehicle using the same optimization tools.

The control concept of extended ground-hook has been implemented on the controller. The basic idea of the extended ground-hook (EGH) is to combine a ground-hook fictitious damper force, skyhook fictitious damper force and traditional shock absorber force and reduce the road damage as well as keep ride comfort. Set of the control law coefficients has been tuned by MultiObjective Parameter Optimization approach (MOPO method) for typical excitations. The MOPO method within the environment MATLAB/ SIMULINK with the genetic algorithm toolbox allows one to find a satisfactory compromise among the performance criteria despite the fact that they conflict with each other. The design of truck suspension must take into account two basic criteria – ride comfort (given by car body acceleration) and road/bridge friendliness (given by dynamic road-tyre forces).

A half-car model with two independently driven axles is coupled with a FEM model of simply supported reinforced concrete, prestressed and composite steel-concrete bridges with the span range from 5 to 50 m. Surface profile of the bridge deck is either stochastic, or in the shape of a cosine bump or a pot in the mid-span. Numerical integration in MATLAB/SIMULINK environment solves coupled dynamic equations of motion of the bridge and truck with optimized suspensions.

The semi-active suspension, when compared to the commercial passive one, reduces dynamic contact force in all cases (the average reduction is about 25%) and shifts the contact force peaks after unevenness crossing. Bridge-friendly truck suspensions are beneficial for the decrease of road damage, mainly the rear axle that carries prevailing truck load. Dynamic contact force is influenced mainly by the unevenness shape and the control strategy of the damper, bridge span plays a minor role there. The mid-span bridge deflections are on average smaller, when compared to commercial passive suspensions (the average reduction is about several percent). The bridge-friendly truck with semi-active optimized EGH suspension is also road-friendly and vice versa.

Souhrn

Nerovnosti na vozovce jsou příčinou vzniku kontaktních sil, vedle statických vznikají i dynamické síly, jejichž velikost může být řízena a případně i snížena. Byly prováděny pokusy řídit kmitání mostů s cílem prodloužit jejich životnost. Přímé snahy o redukci průhybů mostů se ukázaly jako příliš komplikované. Novým trendem je proto vývoj optimálně laděného pérování vozidel s cílem minimalizovat kontaktní síly mezi kolem a vozovkou – taková vozidla se pak nazývají vozidly šetrnými k vozovce. Míra poškození vozovky od vozidel je totiž úměrná čtvrté mocnině dynamických kontaktních sil.

Pro pérování vozidel šetrných k vozovce se používají pasivní, aktivní a poloaktivní systémy řízení. V této práci se pro vyšetřování vlivu těžkých vozidel na mosty požívá vozidlo se poloaktivním pérováním. Původní koncepce šetrnosti k vozovce bylo pomocí stejných optimalizačních nástrojů rozšířena též na šetrnost k mostu.

Použitý princip řízení je založen na koncepci rozšířeného zemského háku. Základní myšlenka rozšířeného zemského háku (EGH) je založena kombinaci tlumící síly fiktivního zemského háku, tlumící síly fiktivního nebeského háku a síly běžného tlumícího prvku s cílem snížit poškození vozovky a zachovat komfort jízdy. Koeficienty zákona řízení tlumící síly musejí být pro typické případy buzení stanoveny pomocí vícekriteriání parametrické optimalizace (metoda MOPO). Pomocí této metody v kombinaci s genetickými algoritmy lze v prostředí MATLAB/ SIMULINK nalézt přijatelný kompromis mezi vzájemně konfliktními kritérii. Při návrhu pérování vozidla je nutné uvážit dvě základní kritéria – komfort jízdy (daný zrychlením rámu vozidla) a šetrnost k vozovce/mostu (danou dynamickými silami mezi vozovkou a kolem).

Při modelování se používá diskrétní model půlauta se dvěma nezávisle tlumenými nápravami a MKP model prostě podepřených železobetonových, předpjatých a spřažených ocelobetonových mostů o rozpětí 5 až 50 m. Nerovnosti na vozovce jsou jak stochastické, tak ve tvaru kosinového hrbolu nebo prohlubně ve středu rozpětí. Společné podmínky dynamické rovnováhy mostu a vozidla s optimalizovaným pérováním jsou řešeny pomocí numerické integrace v prostředí MATLAB/ SIMULINK.

Ve srovnání s komerčním pasivním pérováním snižuje poloaktivní pérování ve všech případech dynamickou kontaktní sílu (průměrné snížení je kolem 25%) a redukuje její vrcholy následující po přejezdu překážky. Pérování šetrné k mostu tak omezuje poškození vozovky, zejména díky zadní nápravě, která přenáší většinu zatížení. Dynamická kontaktní síla je ovlivněna zejména tvarem nerovnosti a strategií řízení tlumení, rozpětí mostu její velikost příliš neovlivňuje. Také průhyby ve středu mostu jsou menší ve srovnání odezvou vozidel s komerčním pasivním pérováním (průměrné snížení je několik procent). Vozidla s optimalizovaným EGH pérování šetrným k mostu jsou šetrná též k vozovce a naopak.

Klíčová slova: Dynamika konstrukcí, těžké vozidlo, most, interakce, poškození vozovky, kontaktní síla, poloaktivní pérování, šetrnost k vozovce, šetrnost k mostu, řízení, optimalizace.

Keywords: Dynamics of structures, truck, bridge, interaction, road damage, contact force, semi-active suspension, road friendliness, bridge friendliness, control, optimization.

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1. INTRODUCTION

One of the most important factors determining the road design is the intensity of heavy trucks, often higher than originally assumed by the designers. According to the traffic prognosis of Europe and USA, annual increase of such vehicles occurs and new trucks with multiple axles or trails appear. Additional costs for road repair and maintenance are required.

A world-wide reduction in the availability of funds for infrastructure construction and maintenance, along with rapidly-expanding demands for freight transport, requires scientific and engineering responses to the issues of reducing pavement and bridge maintenance costs related to truck use and to better, more-integrated, design of vehicles, pavements and bridges.

Despite the fact that proper mechanisms of road damage are not yet precisely known, it is proven that the road damage depends significantly on the traffic of the *heavy-duty vehicle fleet*, which in turn is related to axle load. It is also well known that the construction and maintenance costs increase at a faster rate than the axle loads.

A higher level of scientific knowledge of the interaction between trucks and pavements, and between trucks and bridges will open the way for regulations based on vehicle performance, in terms of road-friendliness. The so-called *road/bridge-friendly vehicle* is one whose operation in the road/bridge system will bring about marginally less need for road/bridge maintenance, for a given level of axle load. Bridge construction costs could potentially be reduced as a result of better knowledge of the design traffic loads. One of the critical technical problems is a question whether vehicle technologies which are road-friendly are also *bridge-friendly.*

The objective of the GAČR project 103/01/1528 “Dynamic Heavy Vehicle – Bridge Interaction” was to provide scientific evidence of the effects of heavy vehicles and the developed semi-active suspension system on the bridges. Deeper investigation of interaction between bridge and truck with semi-active suspensions is necessary to judge whether road-friendly suspension can also be considered as a *bridge-friendly* one. It is well known that the dynamic response of bridges can only be understood when it is considered as part of a system which incorporates the bridge, the road profile, the vehicle mass, configuration and speed as well as the vehicle suspension, e.g. [1].

The main subject of this paper will be the description of dynamic interaction of heavy vehicles (trucks) and bridges. The question whether the road-friendly suspension can also be considered as a bridge-friendly one will be discussed.

The main objective of this paper is to outline:

- Development of the vehicle – bridge interaction model;
- Synthesis of the bridge-friendly control;
- Comparison of the bridge-friendliness of different types of truck suspensions.

2. ROAD DAMAGE

The vehicle generated road damage is caused by forces between road and tyre, the so-called *road-tyre forces*, [2]. The road-tyre forces are affected by design of a vehicle, such as total weight, axle configuration, tyre configuration and suspension configuration. The vertical road-tyre forces, applied to the road by each vehicle tyre, can be divided into two components: the *static forces* due to vehicle weight and *dynamic forces* which are caused by a vibration of the vehicle excited by road surface.

The road damage can be reduced by decreasing road-tyre forces. Since the static axle loads are already fixed, further investigations must be focused to the *reduction of dynamic forces.* The dynamic loads can be reduced by proper suspension design. Since design of passive systems has been almost driven to its limits, additional improvements can be expected from controllable suspensions, active or semi-active, with suitable, road-friendly oriented, control laws.

Many evaluation criteria are based on the so-called *fourth-power law*, which originates in the AASHO (American Association of State Highway Officials) road tests. This law states that road damage generated by a wheel is proportional to the fourth-power of the wheel force. Generally it should be noted, that the validity of the fourth-power law is questionable and some recent studies indicated that the damage exponent may take a wide range of values. Despite this fact, this approach to estimating road damage has been widely used and has been also considered as a judging basis in our research.

In order to quantify the road load due to the dynamic road-tyre forces, *Dynamic Load Stress Factor*, noted as *DLSF* is used [3]. The dynamic load stress factor is based on the fourth-power law and is defined as follows:

$$DLSF = 1 + 6\,DLC^2 + 3\,DLC^4\,, \tag{1}$$

where *DLC* is the *Dynamic Load Coefficient*

$$DLC = \frac{RMS\ dynamic\ tyre\ force}{static\ tyre\,force}\ , \tag{2}$$

where the *RMS* (Root Mean Square) value of the dynamic tyre force is the standard deviation of the probability distribution of the wheel force. Under normal operation conditions, *DLC* values of 0.1 to 0.4 are typical.

If taking the *spatial repeatability* into account, the peak forces applied by the heavy duty vehicle fleet are concentrated at specific locations on the road and the peaks are important for the road damage. In this case *95th percentile dynamic road stress factor*, $DLSF_{95\%}$, [4], which includes 95% of dynamic forces assuming Gaussian distribution function and is based on fourth-power law, is proposed as follows:

$$DLSF_{95\%} = (1 + 1.645 DLC)^4 \ . \tag{3}$$

Highway bridges have suffered a sharp decrease in service life, in part due to loading induced by heavy truck traffic occurring at levels in excess of those originally assumed by the designers. As a result, many bridges are approaching the end of their useful life and will require extensive repair and/or replacement unless other ways are found to reduce stresses and strains due to these loads and to sustain the safety of the bridges. It is important to be able to accurately predict both bridge and vehicle responses, in order to effect a reduction strategy such as semi-active control.

In order to extend the useful service life of bridges some efforts have been done to control the vibration of bridges. All these efforts of bridge control are based on equipping a special device such as tuned mass damper [6], intelligent stiffener [6] or magneto-rheological fluid damper [5] directly on the underside of the bridge deck. An obvious disadvantage of this kind of bridge control strategy is the reduction of the permitted height of vehicles passing under the bridge. Inspired by the results of GAČR project 101/95/0728 "Optimization of Motion of Flexible Mechatronic Systems" on the design of *road-friendly* suspensions to minimize damages on road pavement, our goal was to explore various designs of smart suspension systems for *bridge-friendly vehicles.* The suspension systems of these vehicles are tuneable to minimize the contact loading and stress of the bridge.

3. VIBRATION CONTROL

While direct reduction of bridge deflections was found too complicated new trends in the vehicle suspension development follow the concept of tuning the vehicles to minimize the tyre-road contact forces – such vehicles are called bridge-friendly vehicles.

In the development of vibration control

- passive,
- active,
- semi-active

control systems have been considered.

The control force in a *passive control* (Figure 1a) is developed as a result of the motion of the structure itself and therefore does not require external power. It is inexpensive, simple and reliable but it has a distinct performance limitation.

A tuned mass damper (TMD) consists of an absorber mass (m_2), a spring (k_2), and a damping device (b_2), which dissipates the energy created by the motion of the mass (usually in a form of heat). In this figure, primary mass is the structure to which the damper would be attached. In order to make the occupants of the building feel more comfortable, tuned mass dampers are placed in structures where the horizontal deflections from the wind or earthquake force are felt the greatest, effectively making the building stand relatively still. When the building begins to oscillate or sway, it sets the TMD into motion by means of the spring and, when the building is forced right, the TMD simultaneously forces it to the left. The effectiveness of a TMD is dependent on the mass ratio of the TMD to the structure itself, the ratio of the frequency of the TMD to the frequency of the structure (which is ideally equal to one), and the damping ratio of the TMD.

Examples of buildings and structures with tuned mass dampers:

- The Citigroup Center in New York City (278 m), one of the first skyscrapers to use a TMD 370 t to reduce swaying
- John Hancock Tower (244 m) in Boston, 2 passive TMD added to it after it was built
- Taipei 101 (509 m), Taiwan, contains the world's largest TMD 730 t
- London Millennium Bridge
- CN Tower TV antenna (553 m) in Toronto

The *active control* (Figure 1b) system can provide better performance, but is more costly and less reliable and robust due to complex design. The control force is generated by electro-hydraulic or electromechanical actuators that usually require large power sources.

Examples of buildings and structures with active tuned mass dampers:

- Yokohama Landmark Tower (296 m), with 2 active TMD 340 t
- Shinjuku Park Tower (227 m) in Tokyo, with 3 active TMD 330 t
- ORC 2000 Symbol Tower (188 m) in Osaka, with 2 active TMD 200 t

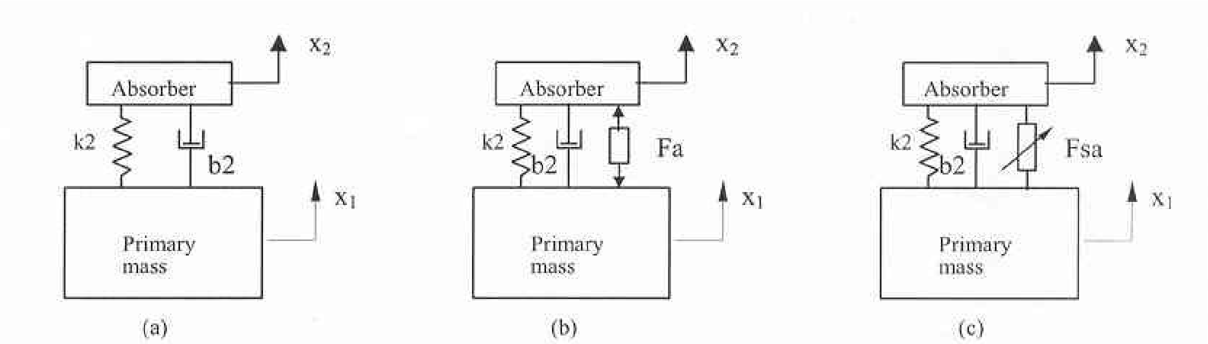
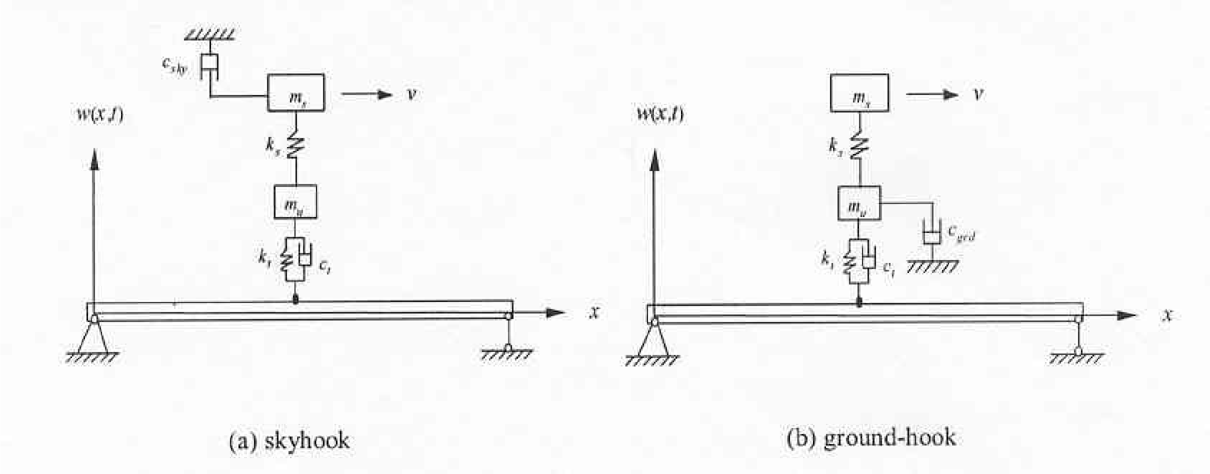


Figure 1: Vibration control systems: (a) passive, (b) active, (c) semi-active

Semi-active suspensions (Figure 1c) are good compromise between the performance and price. The term semi-active control system can be used to refer to any policy in which the damping force is controlled and can be adjusted between a minimum and a maximum level.

In the development of road-friendly truck suspensions the semi-active control system can be based on (Figure 2)

- skyhook or
- ground-hook scheme.



(a) skyhook

(b) ground-hook

Figure 2: Vibration control policies (a) skyhook, (b) ground-hook

The control policy is designed to modulate the damping force by a passive device to approximate the force that would be generated by a damper fixed to an inertial reference (so this is called *skyhook*). The device can only absorb vibration energy by a variable actuator with low power operation. It has the flexibility of active systems and the reliability of passive systems.

Another semi-active control policy is so called *ground-hook* control which is introduced by the motivation of developing an equivalent of skyhook for the reduction of dynamic road-tyre forces. It was shown that skyhook control generally improves the ride comfort, while the ground-hook control improves vehicle stability and reduces road damage.

4. EXTENDED GROUND-HOOK CONTROL

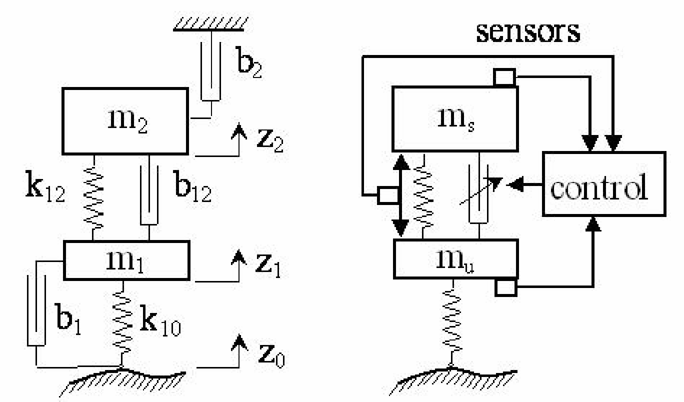
The DIVINE Project (Dynamic Interaction between Vehicle and INfrastructure Experiment) [4], has confirmed that the dynamic wheel forces depend on the suspension type, the profile of the road pavement, and the speed of the vehicle. It has been recommended that the *road-friendly* suspension should be defined by the following criteria:

- frequency of 1.5 Hz or less,
- damping of 20% or more.

One of the main results of GAČR project 101/95/0728 “Optimization of Motion of Flexible Mechatronic Systems” is the development of a new concept of semi-active control of truck suspension.

The control concept of extended ground-hook has been implemented on the controller. The basic idea of the extended ground-hook (EGH) is depicted in

Figure 3 (e.g. [7]). By changing the parameters (e.g. b_1, b_{12}, b_2 on Figure 3) a variety of modified nonlinear control laws for the system can be obtained. For the systematic determination of these parameters, the MultiObjective Parameter Optimization approach (MOPO method) was applied for a set of typical excitations. The left part of Figure 2 shows an ideal concept of this control, whereas the right part depicted realization by actuator mounted between axle and car body.



a) Ideal concept b) Realization

Figure 3: Extended Ground Hook control system

The required force F_{act} combines ground-hook fictitious damper force, skyhook fictitious damper force, traditional shock absorber force and some stiffness cancellation terms

$$F_{act} = b_1(\dot{z}_1 - \dot{z}_0) - b_2\dot{z}_2 - b_{12}(\dot{z}_2 - \dot{z}_1) + \Delta k_{10}(z_1 - z_0) - \Delta k_{12}(z_2 - z_1) \quad (4)$$

The control gains are often considered as functions of damper velocity in order to take into account nonlinear damper characteristics

$$b_1, b_2, b_{12} = f(\dot{z}_2 - \dot{z}_1) \quad (5)$$

For the car model there is used the model of nonlinear control damper on Figure 4 with internal dynamics.

The real damper force F_d is typically very different from ideal requested force F_{act} computed by EGH controller, especially for semi-active devices like considered dampers. Therefore the control law coefficients must be optimized by simulation model including realistic model of controllable damper.

The principles of semi-active control are based on the transformation from the required (active) force F_{act} to the setting of the damping rate $b_{semi\text{-}active}$ such that

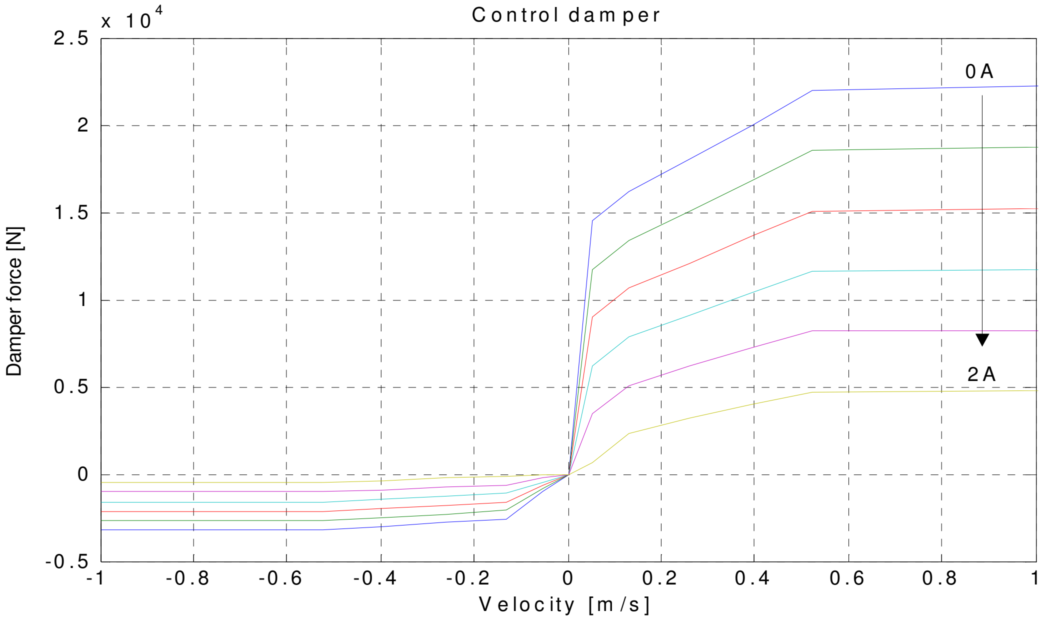


Figure 4: Nonlinear controlled damper

the damping force is nearest to the desired one. For an ideal linear variable shock absorber the damping rate $b_{semi\text{-}active}$ is set for the interval $/b_{min}, b_{max}/$ as

$$\begin{aligned} b_{act} &= \frac{F_{act}}{(\dot{z}_2 - \dot{z}_1)} \\ b_{semi-active} &= b_{act} \cap [b_{\min}, b_{\max}] \\ F_{semi-active} &= b_{semi-active}(\dot{z}_2 - \dot{z}_1) \end{aligned} \tag{6}$$

The full 3-D simulation and simplified design models of truck prototype have been used when passing very good, good, and bad stochastic roads and deterministic unevenness. The experiments and evaluation of road-friendliness have been performed with conventional, i.e. passive, and semi-active trucks [8]. The improvement of road-tyre forces for very good stochastic road compared to the passive suspension is 20% reduction of *DLC*, 5% reduction in road damage measure $DLSF_{95\%}$. In the case of Copernicus ramp the improvement is 26% reduction of *DLC* and 39% reduction of $DLSF_{95\%}$. These results indicate the potential of allowed payload increase up to 1-1.6 ton for 10 tons truck payload and the developed semi-active truck suspension can be classified as *road-friendly* suspension.

5. DYNAMIC INTERACTION OF BRIDGES AND TRUCKS

The DIVINE research has shown that the dynamic response of bridges can only be understood when it is considered as part of a system which incorporates the bridge, the road profile, the vehicle mass, configuration and speed as well as the vehicle suspension. The need to understand this complex system is becoming increasingly important in an era when an ageing and deteriorating bridge infrastructure is being asked to carry ever increasing loads as industry and governments seek improvements in transport efficiency. The bridge testing found that the *surface profile* of a bridge and its approaches are fundamental to the response of the truck suspension and in turn the dynamic response of the bridge. For a smooth profile, the influence of the truck suspension is insignificant. The importance of the suspension increases as the unevenness of the profile increases.

For *medium-span bridges* ($L \cong 30 - 100$ m) with smooth profiles, dynamic responses are relatively small for both air-suspended and steel-suspended vehicles. Frequency matching with the truck bounce frequencies occurs for steel-suspended vehicles and bridges with the natural frequencies in the range $f = 1.5 - 1.8$ Hz (maximum span $L \cong 60 - 70$ m). For air-suspended vehicles the "quasi-resonance" occurs in the case of bridges with the natural frequencies in the range $f = 2 - 4$ Hz ($L \cong 30 - 60$ m).

For *short-span bridges* ($L \cong 8 - 15$ m) with poor profiles, large dynamic responses occur for both air-suspended and steel-suspended vehicles. Dynamic responses are well above current dynamic load allowances in a significant number of cases. So-called "road friendly suspensions" may not be "bridge friendly suspensions".

A modification by combining ground-hook with passive control was introduced to reduce the road damage as well as ride comfort. Mechatronic solution combined with controlled damper provides the tool of its optimization and reduction of dynamic contact force after all. The concept of road-friendliness has been extended to the bridge-friendliness by means of optimization of damper parameters on bridges, e.g. [8]. The aim of this work was to explore benefits of bridge-friendly trucks on ordinary, simple supported bridges.

Results from previous studies with a quarter-car model were so promising that the more accurate model with a half-car and a slab bridge was brought together, e.g. [9]. Similar model was solved for a simply supported bridge with specific road profile, traversed by a quarter-car model with passive, sky-hook and ground-hook control configuration. The effect of semi-controlled damper is significant on the bridge response for close natural frequencies of the vehicle and the bridge.

5.1 HALF-CAR MODEL

The proposed half-car model is based on parameters of commercially available truck LIAZ, simplified to four DOF. Figure 5 displays the configuration of the truck together with a bridge. The front axle comprises of two axles of the real car, the rear axle of the four axles, respectively.
Model parameters were set to: $m_1 = 15$ t, $m_2 = 0.75$ t, $m_3 = 1.5$ t, $a = 4$ m, $b = 1.3$ m, $k_{12} = 430$ kN/m, $k_{13} = 650$ kN/m, $k_{20} = 1700$ kN/m, $k_{30} = 4900$ kN/m, $I_\omega = 50$ tm^2, damping factors of the tyres b_{20} and b_{30} were set to zero. Damper forces F_{d12} and F_{d13} result from the movement of damper attachment and they depend on operative algorithm as will be explained further. All springs in the car model are considered to be linear without the hysteresis.

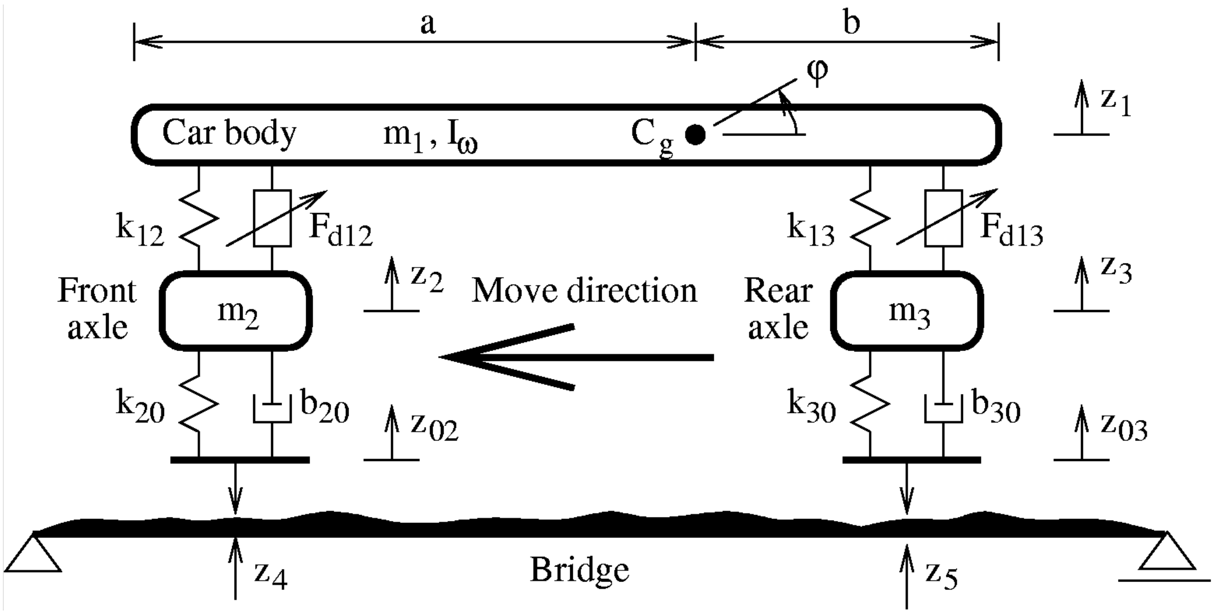


Figure 5: Half-car model

The road profile superimposed on the bridge deck deflection determines the position of the tyre contact area. Equations of motion describing dynamic behaviour of the vehicle and the damper force are as follows:

$$m_1\ddot{z}_1 = -k_{12}(z_1 - z_2 - a\varphi) + 2F_{d12} - k_{13}(z_1 - z_3 + b\varphi) + 4F_{d13} \tag{7}$$

$$I_\omega\ddot{\varphi}_1 = ak_{12}(z_1 - z_2 - a\varphi) - 2aF_{d12} - bk_{13}(z_1 - z_3 + b\varphi) + 4bF_{d13} \tag{8}$$

$$m_2\ddot{z}_2 = k_{12}(z_1 - z_2 - a\varphi) - 2F_{d12} - k_{20}(z_2 - z_{02}) - b_{20}(\ddot{z}_2 - \ddot{z}_{02}) \tag{9}$$

$$m_3\ddot{z}_3 = k_{13}(z_1 - z_3 + b\varphi) - 4F_{d13} - k_{30}(z_3 - z_{03}) - b_{30}(\ddot{z}_3 - \ddot{z}_{03}) \tag{10}$$

$$z_{02} = z_4 + z_{r4} \qquad z_{03} = z_5 + z_{r5} \tag{11}$$

where m_1 is mass of car body, m_2 and m_3 are masses of front and rear axle, k_{12} and k_{13} are stiffness of main springs, k_{20} and k_{30} stiffness of tyres, F_{d12} and F_{d13} are forces of passive or semi-active dampers, z_4 and z_5 are the bridge displacements, z_r is road irregularity. All used parameters correspond to Fig. 5.
For the car model there is used the model of nonlinear semi-active damper on Figure 2, there were used for front axle two and for rear axle four controlled dampers. Other parameters (masses, stiffness and damping) correspond to ordinary truck model.
The ideal forces F_{d12}, F_{d13} of this element, according to the control law of the nonlinear extended ground-hook, are as follows:

$$\begin{aligned} F_{d12} &= b_{f1}(\dot{z}_2 - \dot{z}_{02}) - b_{f2}(\dot{z}_1 - \dot{\varphi}a) - b_{f12}(\dot{z}_1 - \dot{\varphi}a - \dot{z}_2) \\ &\quad + \Delta k_{f10}(z_2 - z_{02}) - \Delta k_{f12}(z_1 - \varphi a - z_2) \end{aligned} \tag{12}$$

$$\begin{aligned} F_{d13} &= b_{r1}(\dot{z}_3 - \dot{z}_{03}) - b_{r2}(\dot{z}_1 + \dot{\varphi}b) - b_{r12}(\dot{z}_1 + \dot{\varphi}b - \dot{z}_3) \\ &\quad + \Delta k_{r10}(z_3 - z_{03}) - \Delta k_{r12}(z_1 + \varphi b - z_3) \end{aligned} \tag{13}$$

where b_{f1}, b_{f2}, b_{f12}, Δk_{f10} and Δk_{f12} are state dependent gains of extended ground hook EGH controller for the front axle and b_{r1}, b_{r2}, b_{r12}, Δk_{r10} and Δk_{r12} for the rear axle.
The road-tyre forces F_{1dyn} and F_{2dyn} (b_{20} and b_{30} neglected) for front and rear axles are:

$$F_{1dyn} = k_{20}(z_4 - z_{02}) \tag{14}$$

$$F_{2dyn} = k_{30}(z_5 - z_{03}) \tag{15}$$

This extended ground-hook model consists of three damping rates where $b_{f(r)1}$ and $b_{f(r)2}$ correspond to the damping factor of the ground-hook and sky-hook respectively and the passive damper to the damping factor $b_{f(r)12}$. Semi-active damper forces F_{d12} and F_{d13} are changed with the setting of the damping rate $b_{f(r)1}$, $b_{f(r)2}$ and $b_{f(r)12}$ in such manner that the damping force approaches to the desired one. Typical 17ms delay response of the damper is further considered. Four values to each damping factor can be assigned, depending on the velocity and direction of the damper attachment. Numerical experiments proved small dependence on the change of fictitious stiffness $\Delta k_{f(r)10}$ and $\Delta k_{f(r)12}$, therefore only damping factors are employed in optimization process. During the optimization, 4*3=12 free damping parameters are involved for each axle. Since the half-car model holds two independently controlled dampers, 24 free parameters in total are optimized using genetic algorithms. Multi objective parameter optimization method (MOPO) within the environment MATLAB/SIMULINK was found appropriate for such large task.

5.2 OPTIMIZATION OF EGH CONTROL

The optimization of damper control for car suspension is multiobjective and complex. The design of truck suspension must take into account two basic criteria [9]:

- ride comfort evaluated for example by integral of square of sprung mass acceleration,
- road/bridge friendliness evaluated for example by integral of square of road-tyre forces.

The first part of the objective function for optimization on both axles takes the form of square root of the time integral of the dynamic contact forces F_{1dyn} and F_{2dyn} for front and rear axles:

$$sumRF_{RMS} = sumRF_{front\_RMS} + sumRF_{rear\_RMS} \tag{16}$$

$$sumRF_{front\_RMS} = \sqrt{\int_0^t F_{1dyn}^2 dt} \tag{17}$$

$$sumRF_{rear\_RMS} = \sqrt{\int_0^t F_{2dyn}^2 dt} \tag{18}$$

The second part of the objective function for optimization is used a driver comfort in the form of truck sprung mass acceleration:

$$sumACC = \sqrt{\int_0^t (\ddot{z}_1 - \ddot{\varphi} a)^2 \, dt} \tag{19}$$

These criteria are conflicting and corresponding Pareto sets were determined. This was done by running several optimization processes by genetic algorithms for weighted criteria function *CF*:

$$CF = \mathrm{A}{*}sumRF + \mathrm{B}{*}sumAcc \tag{20}$$

$$CF = \min_{b_1, b_2, b_{12}} CF$$

where A=[0:1], B=[0:1] are weights of particular criteria. The optimization processes were run for weights ranging the whole intervals. All investigated cases within genetic algorithm were saved and based on them the boundary curve of Pareto set was determined (Figure 7). The line at this figure represents the available limits by passive dampers. The shape of boundary of dots area creates the boundary curve of Pareto set of controlled dampers.

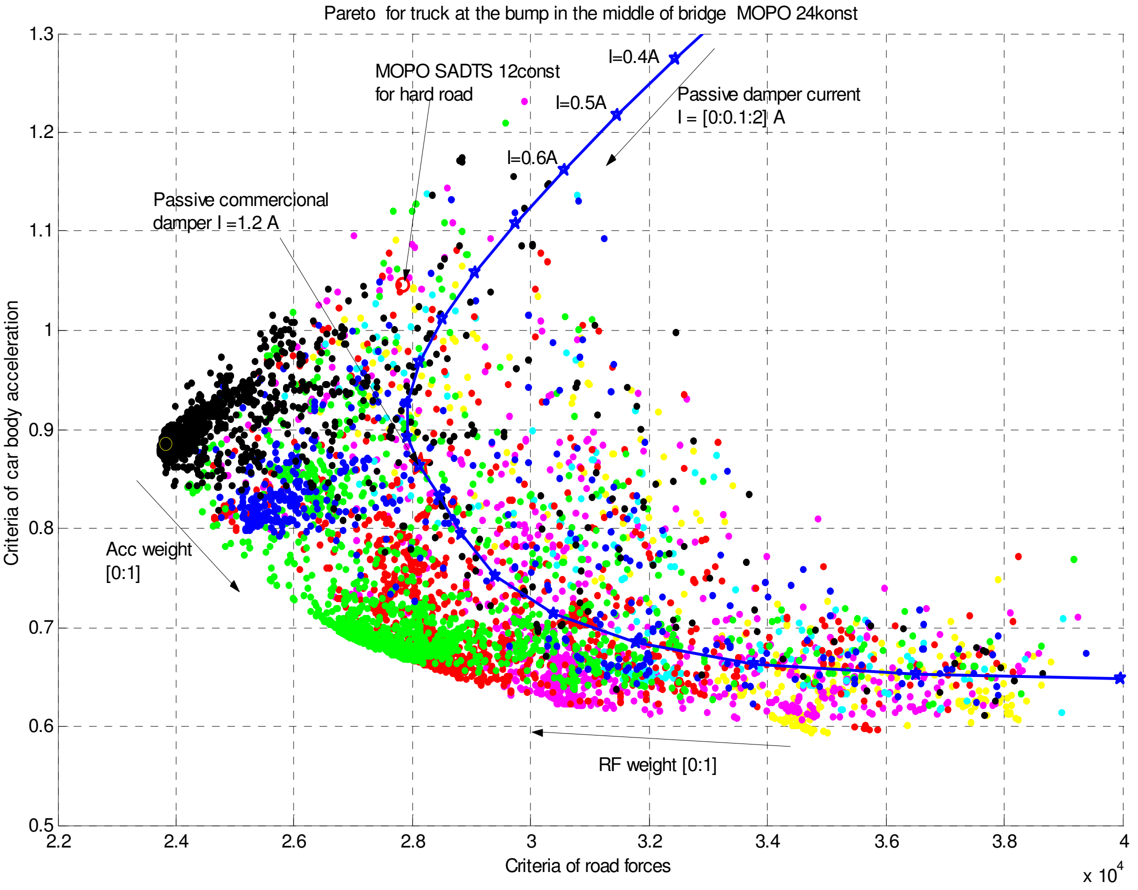


Figure 7: Result Pareto set of bridge forces (horizontal) and acceleration (vertical) for passive and controlled dampers - truck on the bridge with bump

5.3 BRIDGE MODEL

The dynamic response of bridges is a function of many parameters. The response to the passage of heavy commercial vehicles is influenced mainly by:

- bridge natural frequencies and damping,
- road and bridge profile,
- frequencies of the vehicles,
- magnitude of the dynamic wheel loads.

To further complicate the issue, significant and important *interaction between bridge and vehicle* can and do occur.

The bridge is modelled as a simply supported Euler-Bernoulli beam (2-D analysis) or as a slab bridge for shorter spans in order to include a bridge torsional effect (3-D analysis). Bridge span varies from 5 to 50 m, covering the majority of real bridges made from concrete or steel of such structural system, e.g. [10]:

- reinforced concrete bridges - span of 5 to 12 m
- prestressed concrete bridges - span of 12 to 30 m
- composite steel-concrete bridges - span of 15 to 50 m

Each bridge consists of two road lanes and two sidewalks, preliminary design calculations provide bridge parameters for the simulation, e.g. [11].

The first eigenfrequency for all considered bridges is shown in Figures 9. First truck eigenvalue is 9.3 Hz.

Truck moved by the velocity of 50 km per hour during the most of simulations (the velocity was changed from 20 to 130 km per hour with minor effect on the response), passive or bridge-friendly damper control was adopted for comparison reasons. Unevenness amplitudes of the road profile were set to 20 mm for a bump or a pot in the mid-span or for a stochastic road (Figure 8).

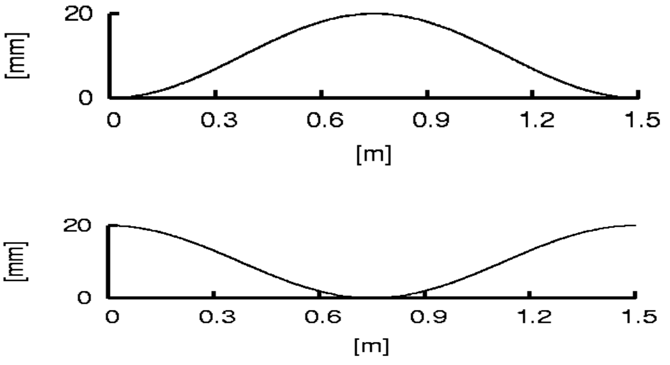


Figure 8: Bump and pot used for damper response on the bridges

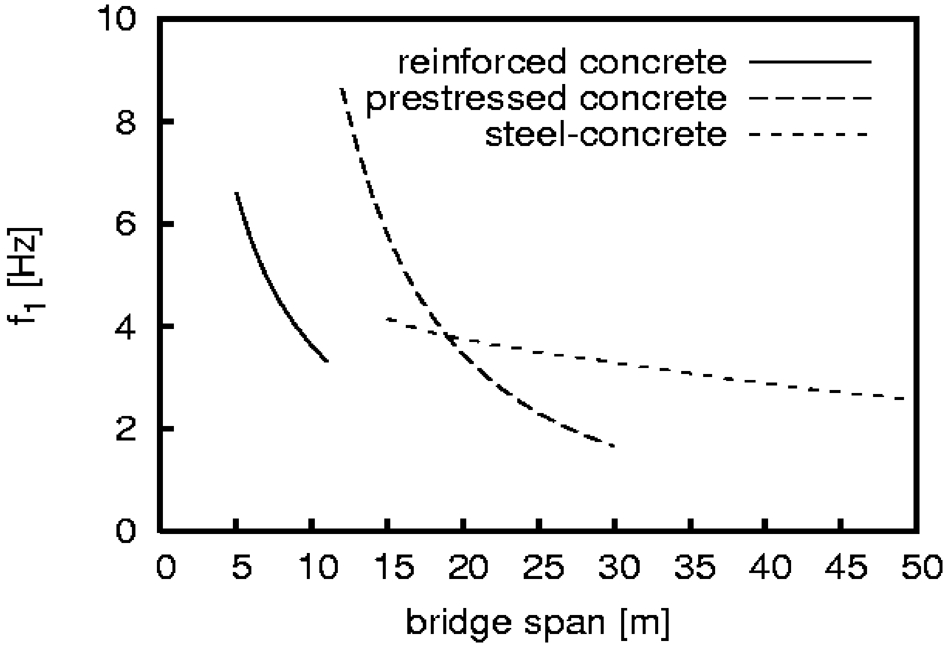


Figure 9: The first eigenfrequency f_1 of bridges 5 – 50 m

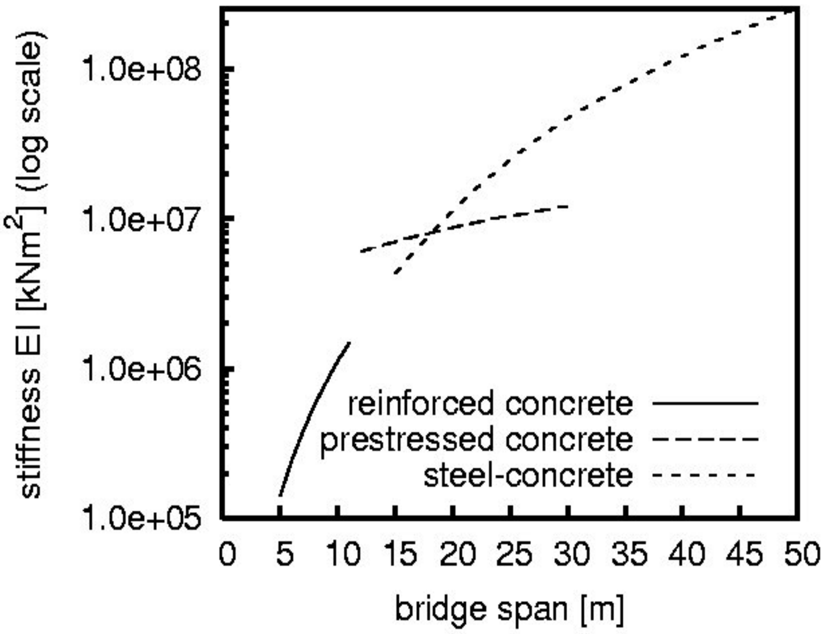


Figure 10: The bending stiffness *EI* of bridges 5 – 50 m

It is assumed that the vehicle passes over the beam bridge on the symmetry axis and on the slab bridge as close as possible to the sidewalks. FEM with equally spaced nodes in combination with the bridge parameters provides the equation of motion in the form:

$$\mathbf{M}_b\,\ddot{\mathbf{r}}(t)+\mathbf{B}_b\,\dot{\mathbf{r}}(t)+\mathbf{K}_b\,\mathbf{r}(t)=\mathbf{F}_{dyn}(t) \tag{21}$$

where $\mathbf{M}_b$**,** $\mathbf{B}_b$ and $\mathbf{K}_b$ are the mass, damping and stiffness matrices of the bridge, $\mathbf{r}(t)$ is the displacement vector and $\mathbf{F}_{dyn}(t)$ the vector of contact axle forces. Rayleigh damping with a logarithmic decrement of 0.05 was used for all bridges for the damping matrix assemblage. Two contact road-tyre forces from the truck axles, given by Eq. (14) and (15), are linearly distributed between adjacent nodes to the vector $\mathbf{F}_{dyn}$(t). Connection links between the bridge and the car model are bridge deflections under the axle and the contact force between the tyre and the road (Figure 11).

The equations of motion (7)-(10) and (21) are simultaneously solved in the MATLAB/SIMULINK environment with implicit trapezoidal integration scheme using variable time step. Figure 12 displays the SIMULINK scheme of the bridge model as an example. The lowest critical speed of the vehicle is over 220 km per hour and the first natural frequency is higher than all first bridge frequencies considered. No frequency-matching phenomenon is observed during simulations.

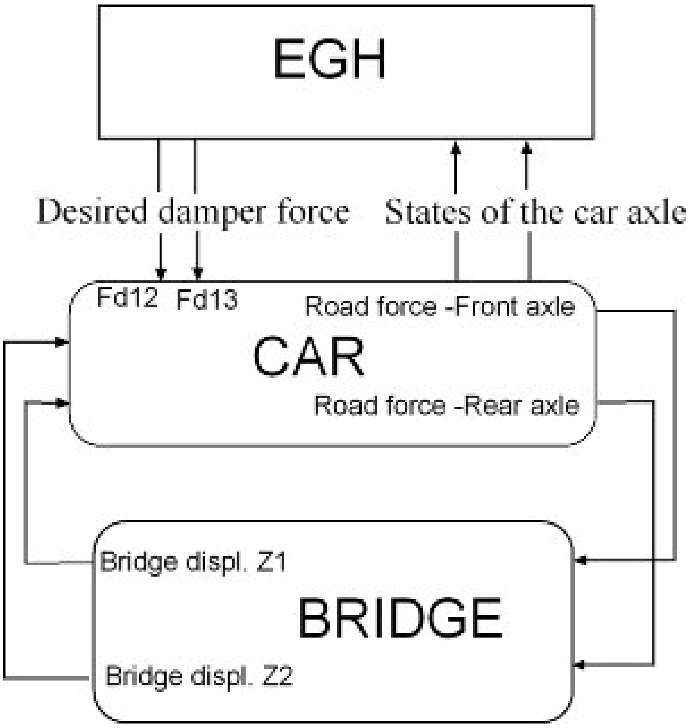


Figure 11: Interaction between bridge-truck model and EGH controller

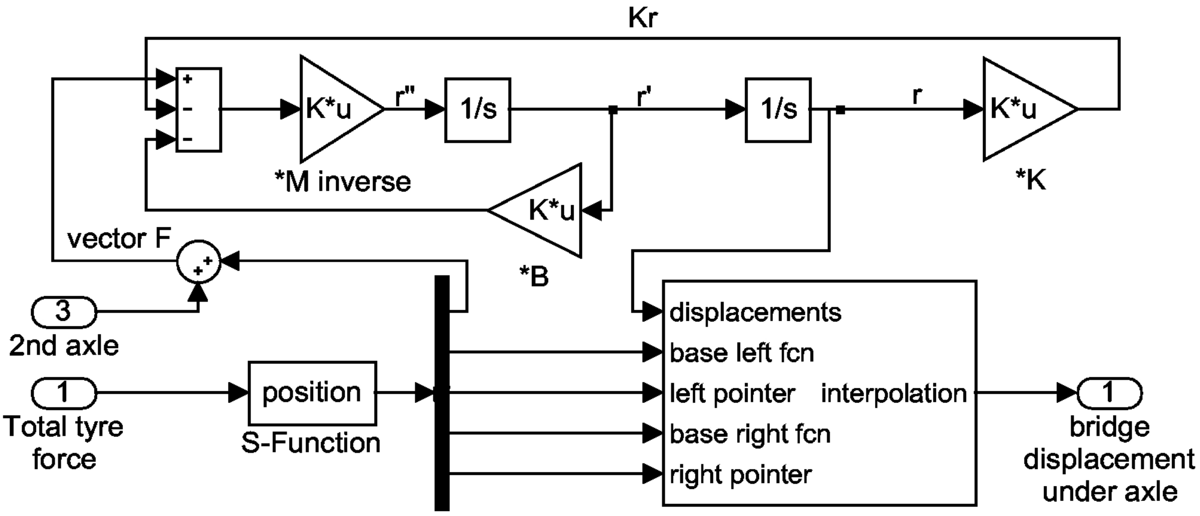


Figure 12: The SIMULINK scheme of the bridge model

6. RESULTS

Using the truck-bridge interaction multi-degree-of-freedom model the following three models with different truck suspensions have been compared (e.g. [11], [12]):

- the truck with commercial passive suspension – PASSIVE,
- the road-friendly semi-active suspension,
- the bridge-friendly semi-active suspension – MOPO.

6.1 DYNAMIC CONTACT FORCE

Dynamic contact force is a variable part of the total contact force between the tyre and the road, with positive direction upward. The slab bridge model as a short bridge with the same parameters as the beam one was proposed and verified. In all such cases, the bump is placed in the mid-span of beam or slab bridge. Figure 13 shows similar behaviour of both bridges with different damper control strategy. Even when compared to the road on the solid base, only the damper control mode plays significant role in the contact dynamic force reduction.

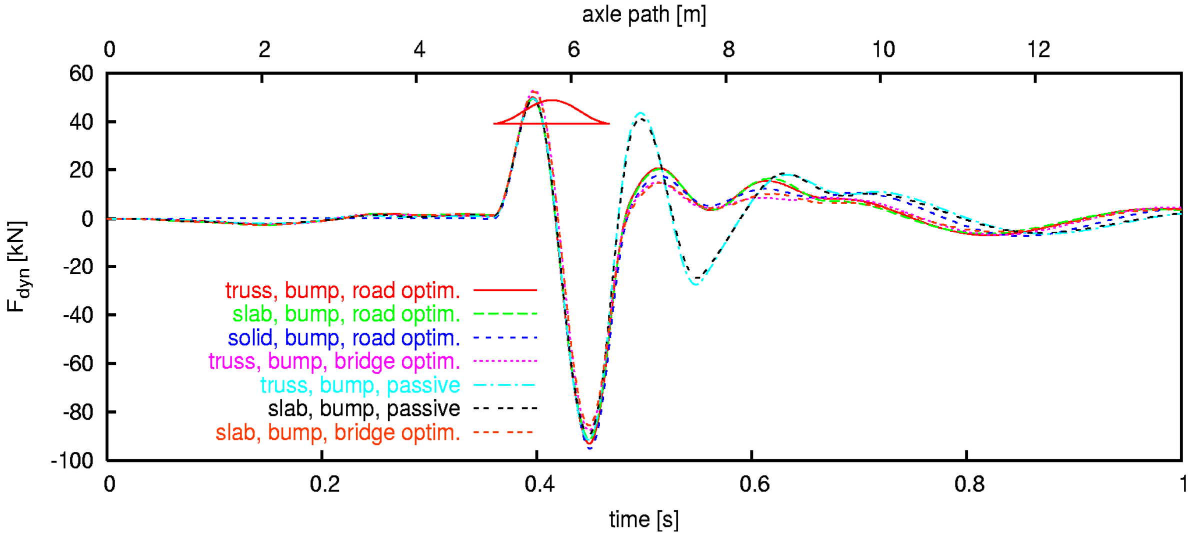


Figure 13: Semi-active and passive truck suspension performance - bump on the bridge with span is 10 m

For the half-car model, the results for the rear axle are in Figures 14 and 15 for the bump and the pot. The change of dynamic contact force is evident shortly after unevenness passing, reducing force value in the next peek. Again, the bridge parameters have minor effect on the truck response.

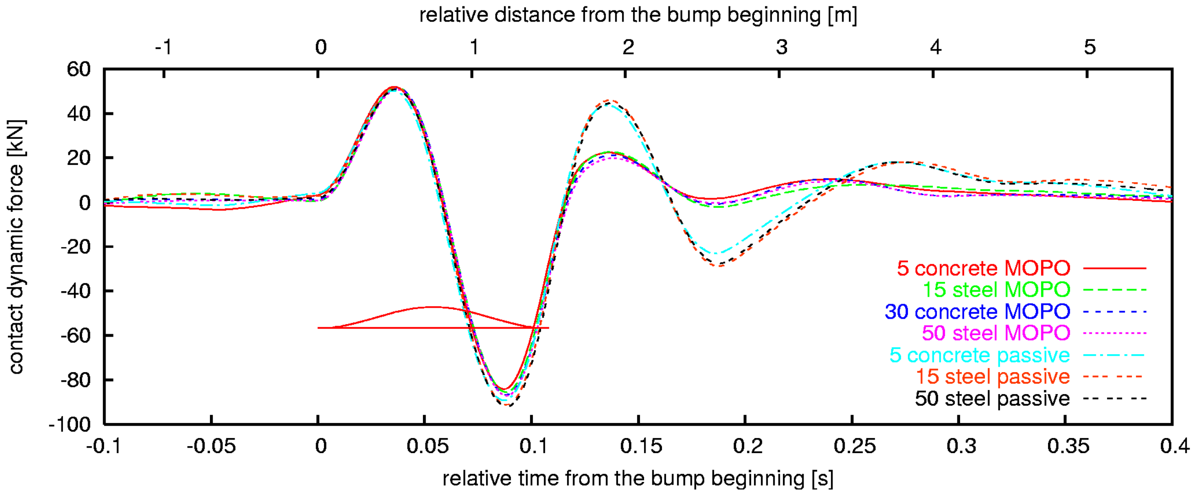


Figure 14: Contact dynamic force of the rear axle – bump on the bridges 5-50 m

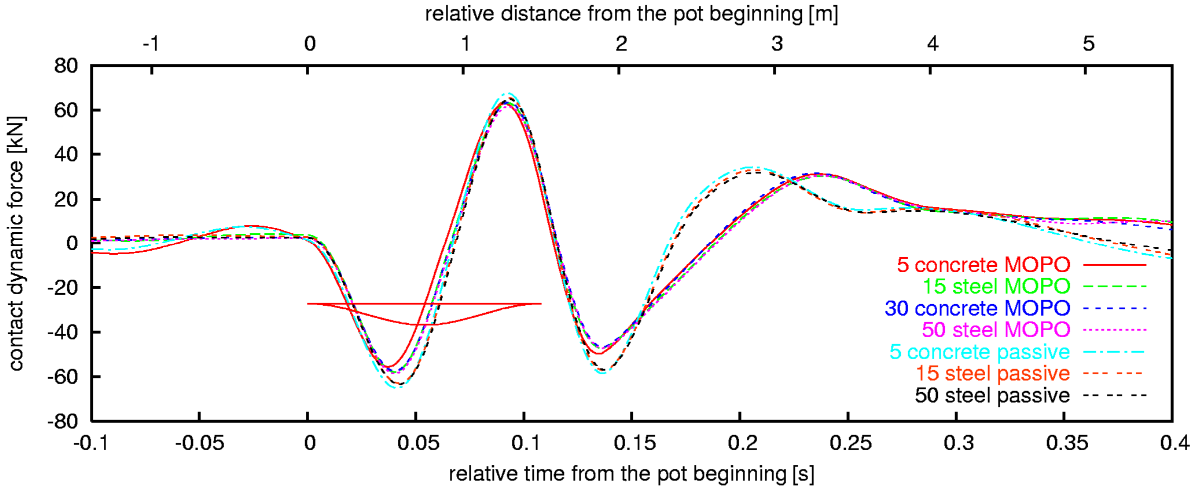


Figure 15: Contact dynamic force of the rear axle – pot on the bridges 5-50 m

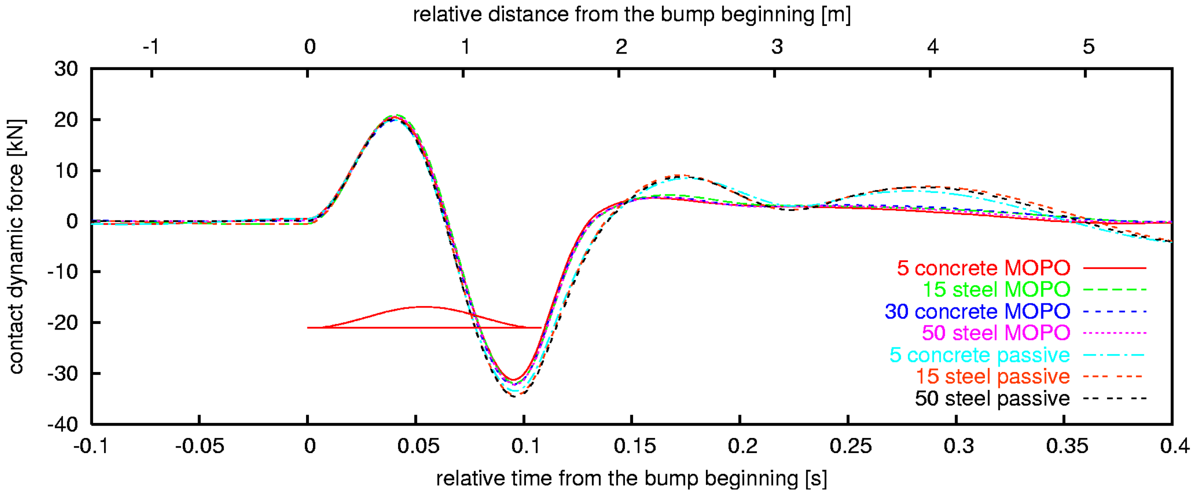


Figure 16: Contact dynamic force of the rear axle – bump on the bridges 5-50 m

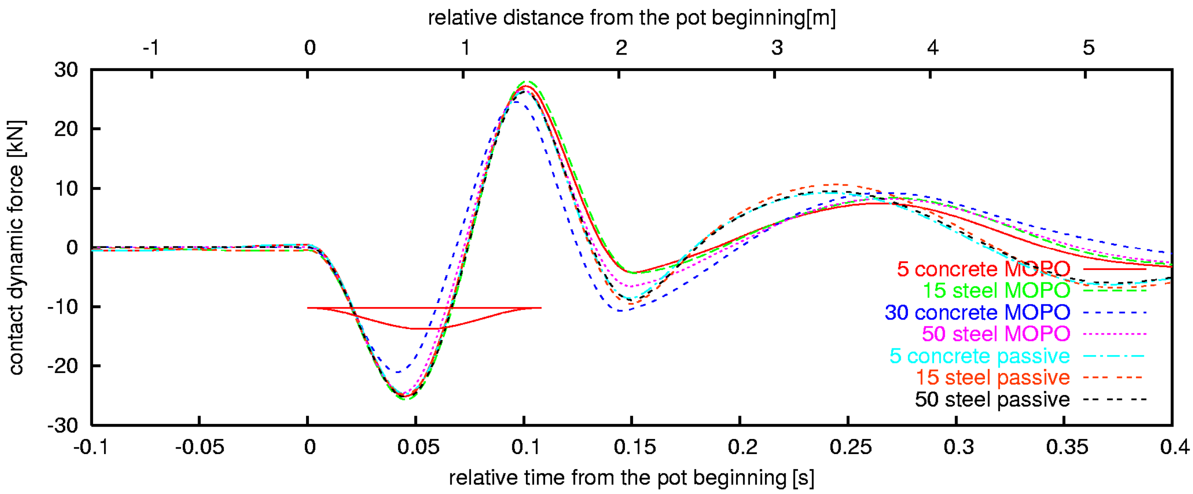


Figure 17: Contact dynamic force of the rear axle – pot on the bridges 5-50 m

It is evident that damper functionality for the pot is not as much effective as for the bump. The reason lies in low damping values when the damper is under contraction. Nevertheless, the phase of dynamic contact force is shifted and its value slightly reduced as well in the case of MOPO control strategy. The front axle carries about a third of the total static truck load and an effect of damper is lower than it is for the rear axle (Figures 16 and 17).

6.2 BRIDGE DEFLECTIONS

Bridge deflections express the effect of the truck on the bridge construction itself. The difference for the beam and slab bridge response reveals qualitative behaviour of these two models. Torsional effect is accounted for the slab bridge hence higher deflection values are expected. Figure 18 shows similar behaviour of both bridge systems and approx. 15% difference of the bridge deflection is observed. Beam bridge model is found to be sufficient even for the bridge of nearly square shape desk.

Short and long bridges are compared as an example of the bridge excitation using the same truck. The majority of the car weight is located in the rear axle and the reading on the graph is therefore from this axle. Short bridges are mainly influenced by the unevenness shape, Figure 19. There are two reasons for their excitation: the truck load prevails on the short bridges because of available space and the bridge stiffness as well as its mass is low. No significant force impulse would appear for the stochastic road and the deflections are then closed to the static ones.

An overall response of 5-50 m spans is illustrated in Figure 20, depending on the damper control strategy. Semi-active dampers reduce on average maximal deflections on the stochastic road by 2.5%, on the bump unevenness by 3.6%.

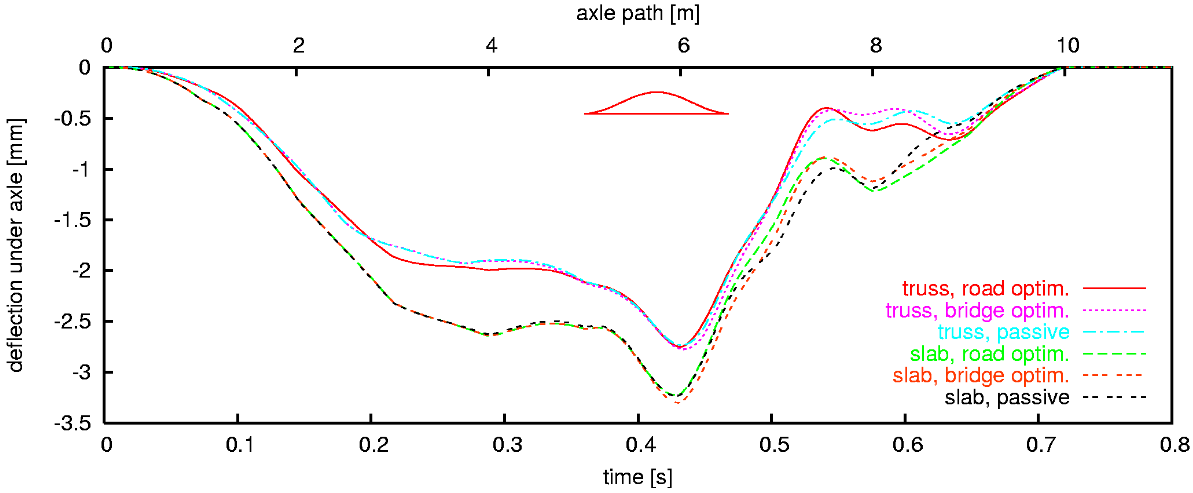


Figure 18: Deflections of the beam and slab bridge with 10 m span

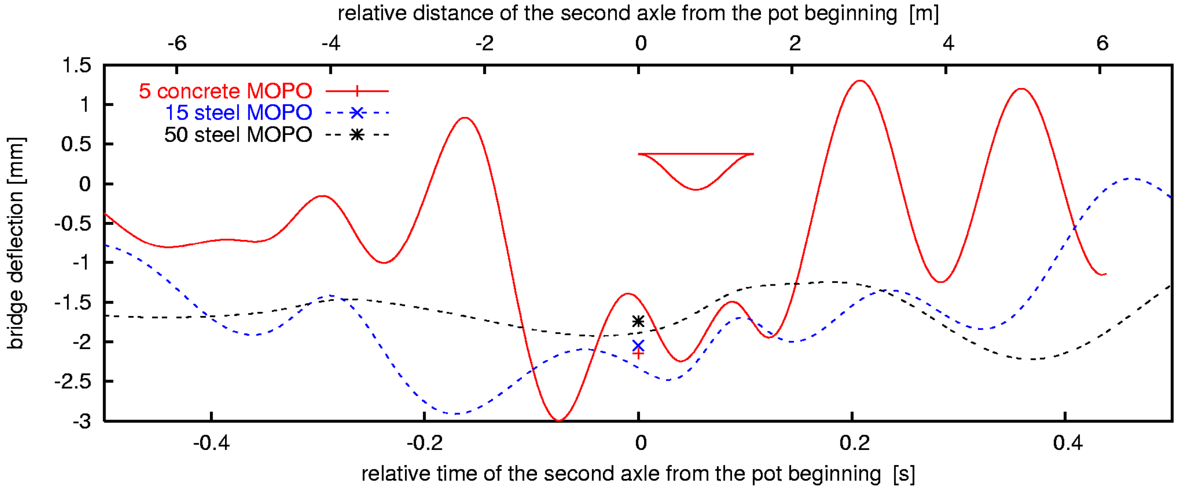


Figure 19: Mid-span bridge deflections - spans 5-50 m and comparison with the static displacements

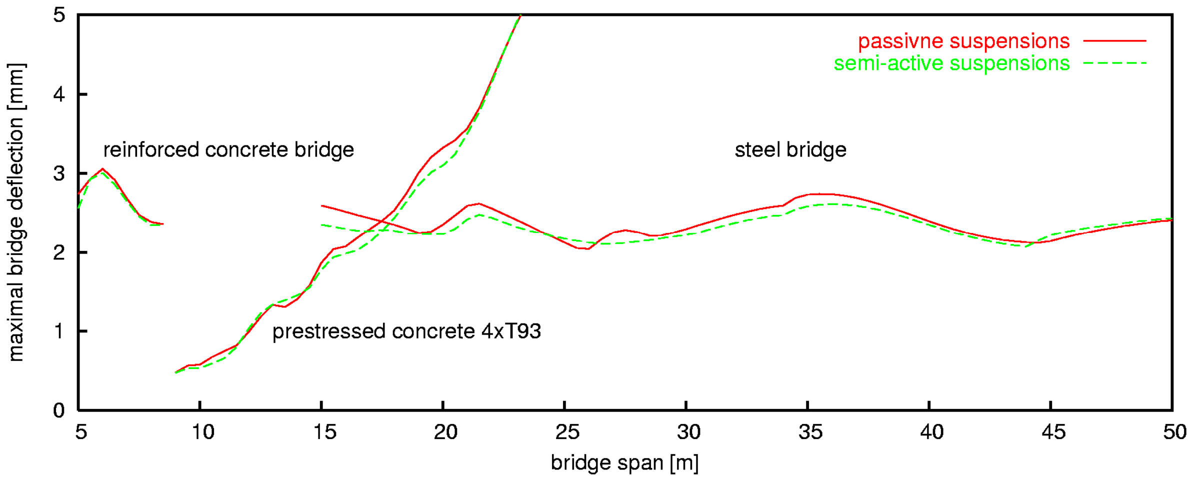


Figure 20: Max. bridge deflections on the stochastic road on 5-50 m spans

7. CONCLUSIONS

This paper describes the concept of bridge-friendly truck suspension and proves that there exists a specific bridge-friendly semi-active truck suspension. The results of behaviour simulations of commercial passive, road-friendly and bridge-friendly suspensions within the several important excitation cases on the roads and on the bridges are summarized in the following sections (see e.g. [8],[13]).

7.1 ROAD-FRIENDLY AS BRIDGE-FRIENDLY TRUCK SUSPENSION

The EGH control was determined for road-friendly truck behaviour within truck – road interaction using the procedure from Section 4. Then the truck with commercial passive suspension and with road-friendly semi-active suspension has been investigated within the truck – bridge interaction using the truck – bridge interaction model from Section 5. The comparison of their behaviour on the bridge excited by the cosine bump is on Figure 21. It is clear that the behaviour of road-friendly suspension is much better than the passive suspension and that the road-friendly suspension can be designated also as the bridge-friendly suspension.

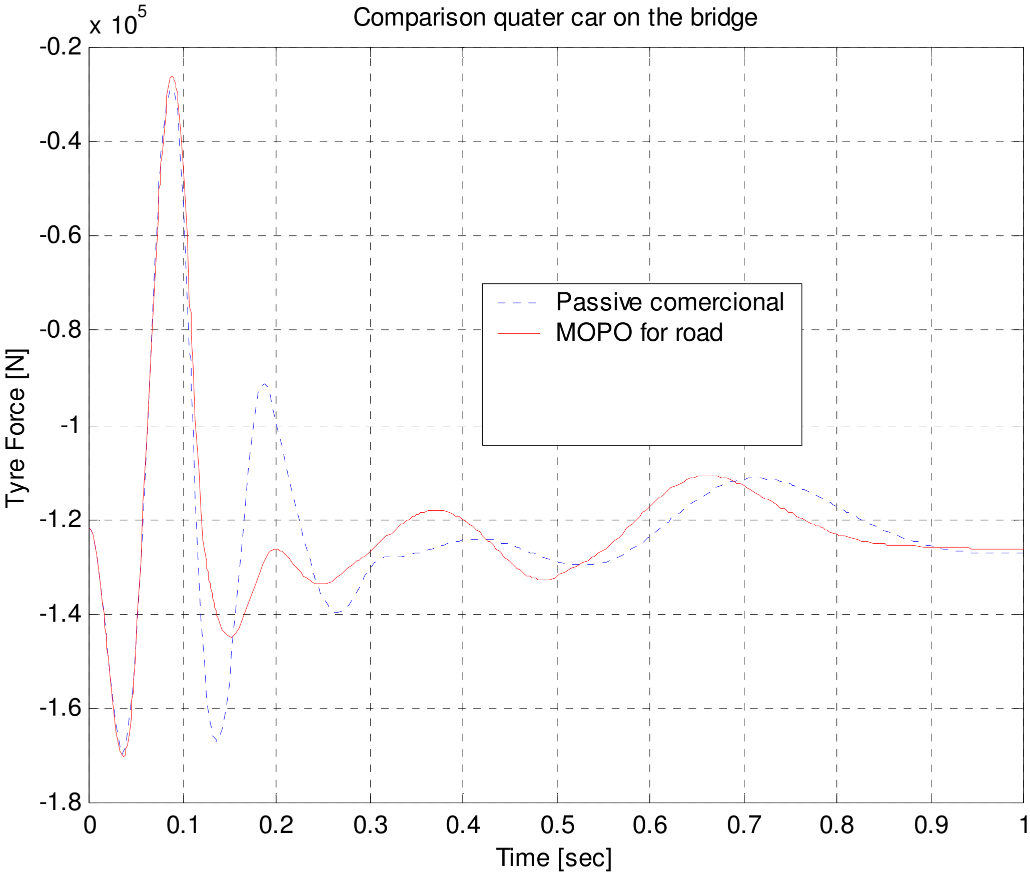


Figure 21: Comparison of commercial passive damper and road-friendly EGH on the bridge

7.2 BRIDGE-FRIENDLY TRUCK SUSPENSION

Using the same approach described in Section 4 for the synthesis of road-friendly semi-active truck suspension, the bridge-friendly semi-active truck suspension was developed. The control algorithm is EGH, however with different feedback coefficients based on the optimization of performance criteria on the model of truck – bridge interaction.

Then the truck with commercial passive suspension and with road-friendly semi-active suspension has been compared with bridge-friendly semi-active suspension within the truck – bridge interaction using the truck – bridge interaction model from Section 5. The comparison of their behaviour on the bridge excited by the cosine bump from is on Figure 22. It is clear that the behaviour of bridge-friendly suspension is the best one and it proves that there exists specific bridge-friendly suspension.

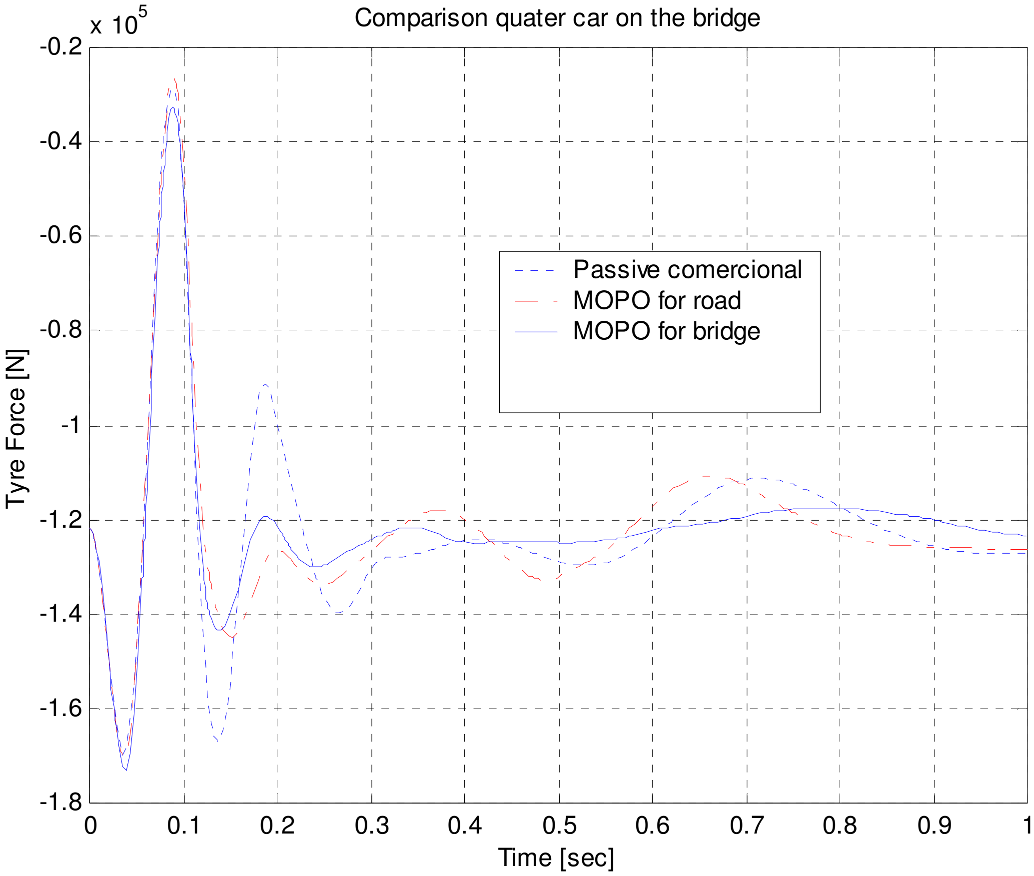


Figure 22: Comparison of passive damper, road-friendly EGH and bridge-friendly EGH on the bridge

7.3 BRIDGE-FRIENDLY AS ROAD-FRIENDLY TRUCK SUSPENSION

There exist specific road-friendly and bridge-friendly semi-active truck suspensions. The behaviour of road-friendly suspension for the bridge-friendliness has been tested in the Section 7.1. Now the vice versa case is investigated.

The trucks with commercial passive suspension, with road-friendly semi-active suspension and with bridge-friendly semi-active suspension have been compared within the truck – road interaction. The comparison of their behaviour on the road excited by the cosine bump is on Figure 23. It is clear that the behaviour of bridge-friendly suspension is much better than the passive suspension and that the bridge-friendly suspension can be designated also as the road-friendly suspension.

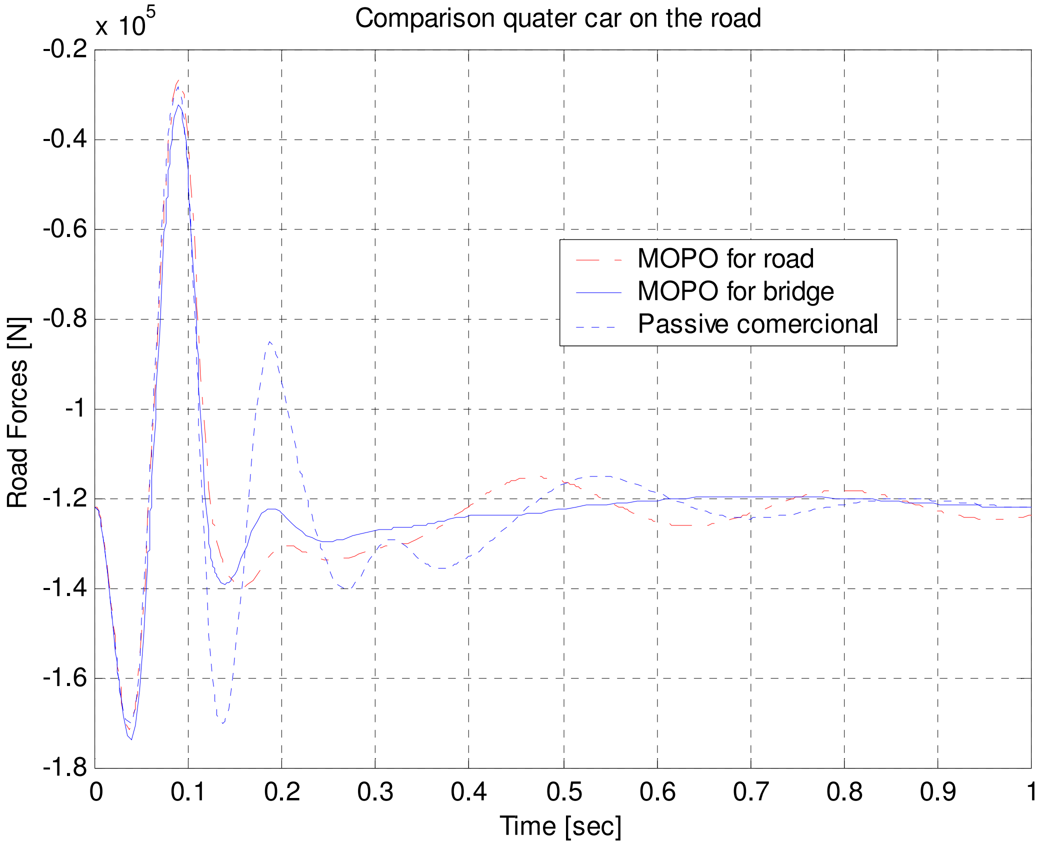


Figure 23: Comparison of passive damper, road-friendly EGH and bridge-friendly EGH on the road

7.4 COSINE BUMP AHEAD OF THE BRIDGE

The truck passing the bridge is usually excited mostly by excited by the cosine bump ahead of the bridge which is caused by the dilatation mechanism in the connection bridge – road. A model of such excitation is cosine bump. Again there have been compared the behaviour of the truck with commercial passive suspension, with road-friendly semi-active suspension and with bridge-friendly semi-active suspension within the truck – road interaction excited by the cosine bump ahead of the bridge using the truck – road interaction model from Section 5. Such excitation usually occurs for every bridge, but is important only for very short bridges. The comparison of their behaviour is on Figure 24. Similarly as in Section 7.2 it is clear that the behaviour of bridge-friendly suspension is the best one and it proves that there exists specific bridge-friendly suspension.

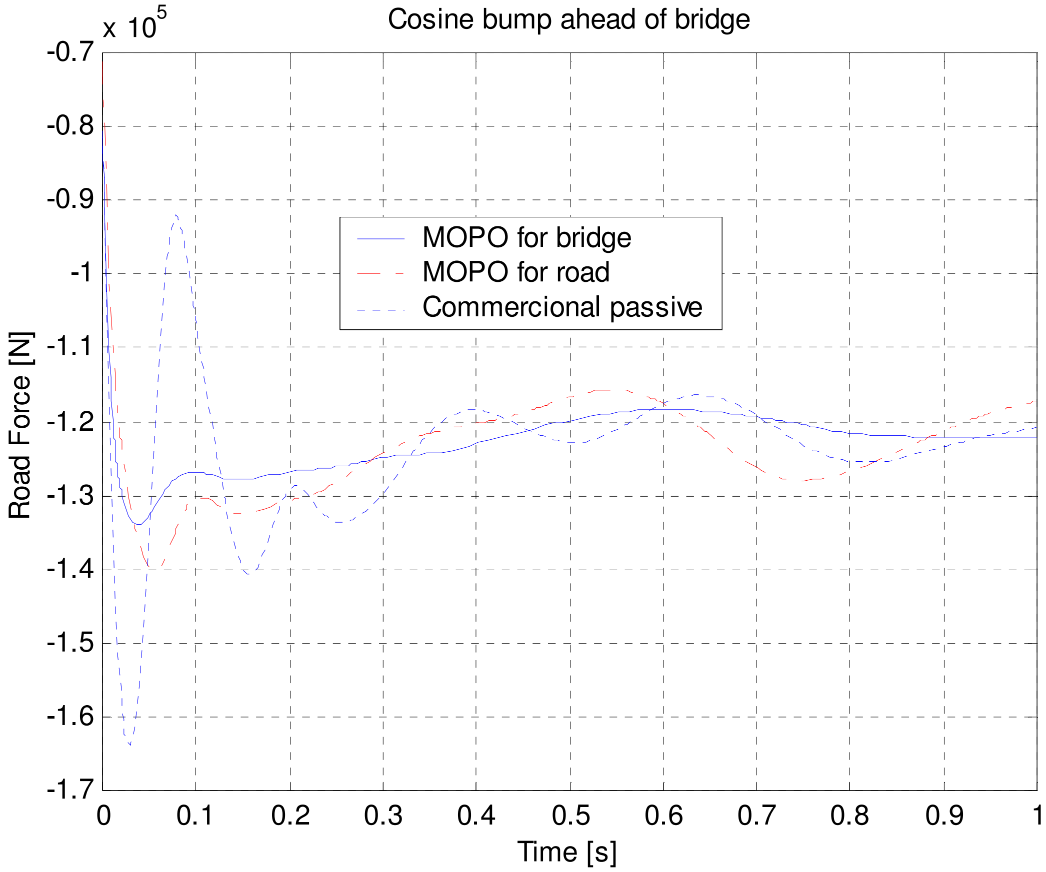


Figure 24: Comparison of passive damper, road-friendly EGH and bridge-friendly EGH on the bridge excited by the cosine bump ahead of the bridge

7.5 FINAL CONCLUSIONS

The semi-active optimized EGH suspension, when compared to the passive one, reduces local contact force in all cases (the average reduction is about 25%) and shifts the contact force peaks after unevenness crossing. Bridge-friendly truck suspensions are beneficial for the decrease of road damage, mainly the rear axle that carries prevailing truck load. Dynamic contact force is influenced mainly by the unevenness shape and the control strategy of the damper, bridge span plays a minor role there. Average reduction of deflections on the bridge spans 5-50 m using semi-active suspensions is found to be by 2.5% lower for the stochastic road on average whereas by 3.6% for the bump respectively, when compared to the passive dampers.

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