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Semi-active Control of a Truck Suspension to Reduce Road Damage

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Abstract: The paper concerns a semi active control system for a halftruck model of an articulated vehicle. A seven degree of freedom model is used to represent the vehicle. An MR damper is considered using the Bouc-Wen hysteresis model. Semi-active 'hybrid balance' control is applied to drive tractor and trailer axle to reduce road damage and the effect on the acceleration level is carefully examined, since it is acceleration that dictates discomfort. Partial cancellation of dynamic tire forces is considered to reduce the road damage. The damper time constant is varied to evaluate the effect on the vehicle performance.

Keywords: vibration, control, truck suspension

NOMENCLATURE

A^4_k= Fourth power aggregate force,
C_{Bound}=Damper rate on bound state,
$C_{Rebound}$=Damper rate on rebound state,
P^4_{jk}= Force applied by the tire j at location k along the road,
N_a=The number of axles on the vehicles,
N_s=Number of measurements stations along the road,
k=1, 2, 3,,,,,, Ns,
Fsf=Tractor steer suspension force,
Fsr=Tractor drive suspension force,
Fst=Trailer suspension force,
Fdf=Tractor steer passive suspension damper force,
Fdr=Tractor drive passive suspension damper force,
Fdt=Trailer passive suspension damper force,
F_{CRear}=Control force applied on Tractor drive damper,
$F_{CTrailer}$= Control force applied on Trailer damper,
m_{u1}=Tractor steer unsprung mass,
m_{u2}=Tractor drive unsprung mass,
m_{u3}=Trailer unsprung mass,
M_T=Mass of trailer chassis,
M_C=Mass of tractor chassis
SA=Semi-active,
br=Proportion of tractor drive dynamic tire force cancellation,
bt=Proportion of trailer dynamic tire force cancellation,
b=proportion of critical damping,

Subscripts

2 additional damper force when the SA damper is ON
3 SA damper is OFF

INTRODUCTION

The objective of heavy vehicle suspensions is to isolate the tractor and trailer unit from the road irregularities by reducing chassis accelerations as well as improving handing behavior and minimizing road damage by cancelling the dynamic tire forces.

One of the first contributions in the field of semi-active dampers was made by Crosby and Karnopp (1973) who studied the operation of an adjustable dissipative damper operating under 'skyhook' logic control. Alony and Sankar (1987) considered not only skyhook logic, but introduced an alternative logic in which spring forces are opposed and partially cancelled.

The name balance control was introduced by Stammers and Sireteanu (1998) who applied this to the commonly studied quarter – car model. A controllable friction damper was employed; the force generated being adjusted by means of control of the normal force between the friction surfaces. For sinusoidal road inputs a reduction of about 50% compared to the passive case is predicted, while with a random (integrated white noise) input the reduction is about 30%.The same logic was applied on the simple quarter car model by the same authors (Stammers and Sireteanu, 2003) examining the effect on the driver body.

A broad analysis of the damage due to dynamic tyre forces and other features that influence the road damage was presented by Cebon (1999). It uses a vehicle based instrumentation system in order to measure the dynamic tyre forces at low and high excitation frequencies. It was concluded that the wheel dynamic load increases with speed and road roughness.

The criterion which was used to calculate the road damage was the aggregate fourth power force, introduced by Cebon,1993. Damage is related to

$$A_k^4 = \sum_{j=1}^{Na} P_{jk}^4 \tag{1}$$

Half Truck-Semi trailer model with controllable suspension

The proposed vehicle model is presented in Figure 1. The controllable dampers (MRD) are assumed to be fitted on the drive tractor and trailer axle while the passive conventional viscous damper is used on the steer axle. The vehicle is formed by the sprung masses of the tractor and trailer unit, assuming that both units are rigid bodies.

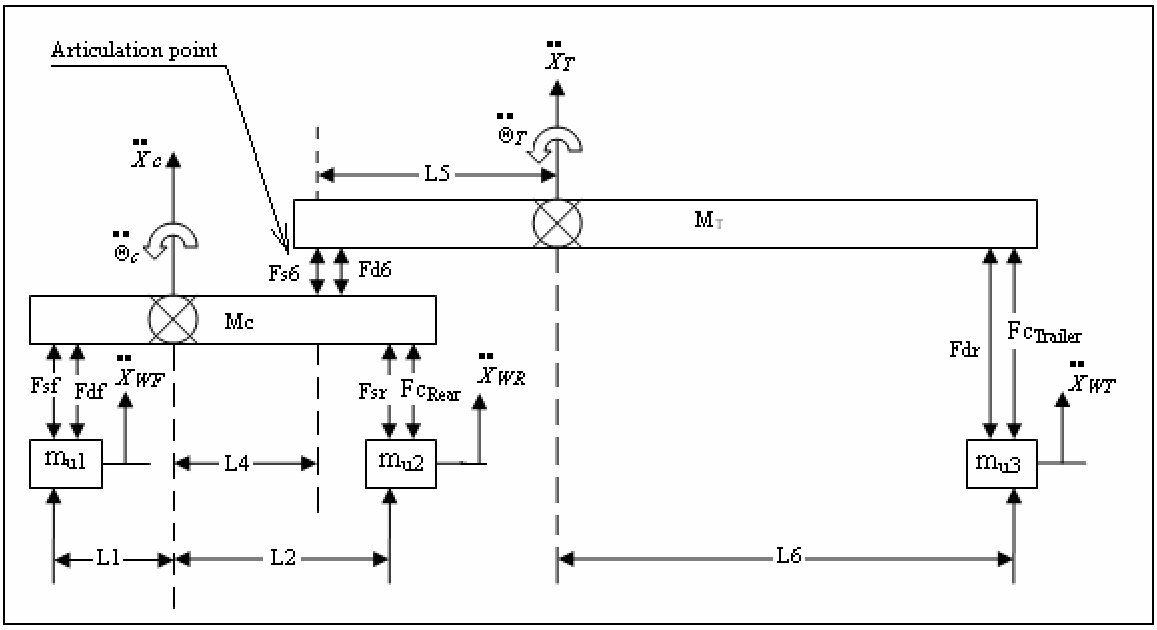

Figure 1 – Schematic diagram of the halftruck vehicle model

Balance semi-active control algorithm

The essence of the proposed control algorithm is to cancel the tire force fluctuations on each axle so that the wheel follows the road profile. The main scope of the control logic is to balance the dynamic tire forces by applying a controlled force to act in the opposite direction. This is only possible when the control force and the relative velocity have opposite sign and hence energy dissipation takes place.

A hybrid version of balance control is presented by the next two control schemes applied on the controllable damper to cancel the drive tractor and trailer axle tire forces.

$$Fc_{\text{Rear}} = \begin{cases} b_r \cdot \left(-Fsr - m_{u2} \cdot \ddot{X}_{WR} \right) + b_2 \cdot Fdr & if \quad \text{Fc}_{\text{Rear}} \cdot \text{Rear\_relative\_velocity} < 0 \\ \text{b}_3 \cdot Fdr & if \quad \text{Fc}_{\text{Rear}} \cdot \text{Rear\_relative\_velocity} > 0 \end{cases} \tag{2}$$

$$Fc_{\text{Trailer}} = \begin{cases} b_t \cdot \left(-Fst - m_{u3} \cdot \ddot{X}_{WT} \right) + b_2 \cdot Fdt & if \quad \text{Fc}_{\text{Trailer}} \cdot \text{Trailer\_relative\_velocity} < 0 \\ \text{b}_3 \cdot Fdt & if \quad \text{Fc}_{\text{Trailer}} \cdot \text{Trailer\_relative\_velocity} > 0 \end{cases} \tag{3}$$

A “passive“damping force is added to the control force to reduce transients. Studies (not shown here) indicate that the optimum values of b_2 and b_3 (to minimize road damage) should be about 20% of critical passive damping. Lower or higher values of b_2 and b_3 produce greater dynamic tire forces and higher vibration levels.

The mathematical model of the passive viscous damper used in simulation is described by the equation.

$$Fd = \begin{cases} C_{Bound} \cdot relative\_velocity & if \quad \text{relative\_velocity} > 0 \\ C_{\text{Re}bound} \cdot relative\_velocity & if \quad \text{relative\_velocity} < 0 \end{cases} \tag{4}$$

Road input

To investigate the vehicle performance it is necessary to develop a road profile in order to simulate real operation conditions. For that reason, two types of road were considered to investigate the vehicle response such as the Smooth highway and Highway with gravel. The spectral densities of each the road profile are determined by using the well known formula $S_g(\Omega) = C_{sp}\Omega^{-N}$. The parameters Csp and N determine the road quality. A smooth highway is modelled by N = 2.1 and Csp = $4.8*10^{-7}$ while a gravel road is determined by setting Csp = $4.4*10^{-6}$ and N = 2.1, (Wong 1978).

The gravel road input is used to examine the performance of the semi-active suspension on damaged roads or in off road operation.

Numerical results

The performance evaluation of the heavy vehicle in terms of the maximum road damage and the level of vibration of the rigid bodies is presented in Figure 2. The damage is normalized with respect to that caused by the static load. A random excitation is used.

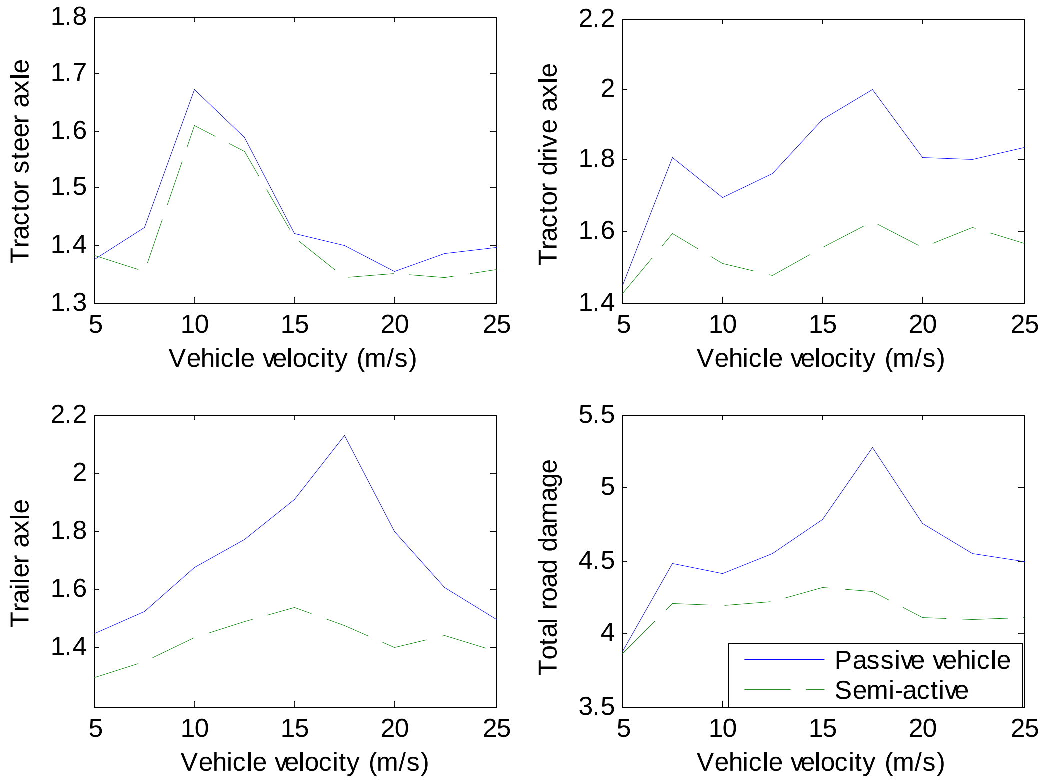

Figure 2 – Maximum normalized road damage.

In Table 1 the predicted reduction of maximum road damage on each axle are compared with the passive case for low, moderate and high vehicle speeds. The maximum reduction is achieved at moderate vehicle velocity (around 17.5m/sec)

Table 1 Reduction in damage achieved by SA suspension relative to passive case

Vehicle velocity (m/s)	Maximum road damage at tractor drive axle. (%)	Maximum road damage at trailer axle. (%)	RMS trailer Heave acceleration (%)
10	12	15	55
17.5	20	34	19
25	12	4	6.7

The comparison between the passive and semi-active suspension in terms of RMS heave and pitch acceleration experienced by the tractor and trailer is presented in Figure 3. The trailer unit is satisfactory isolated from the ground irregularities because two semi-active dampers are employed on the drive tractor and trailer axle. In contrast, the tractor unit receives higher vibration levels due to one semi-active damper on the drive tractor axle. This phenomenon may call for a controlled cab or driver seat to improve ride.

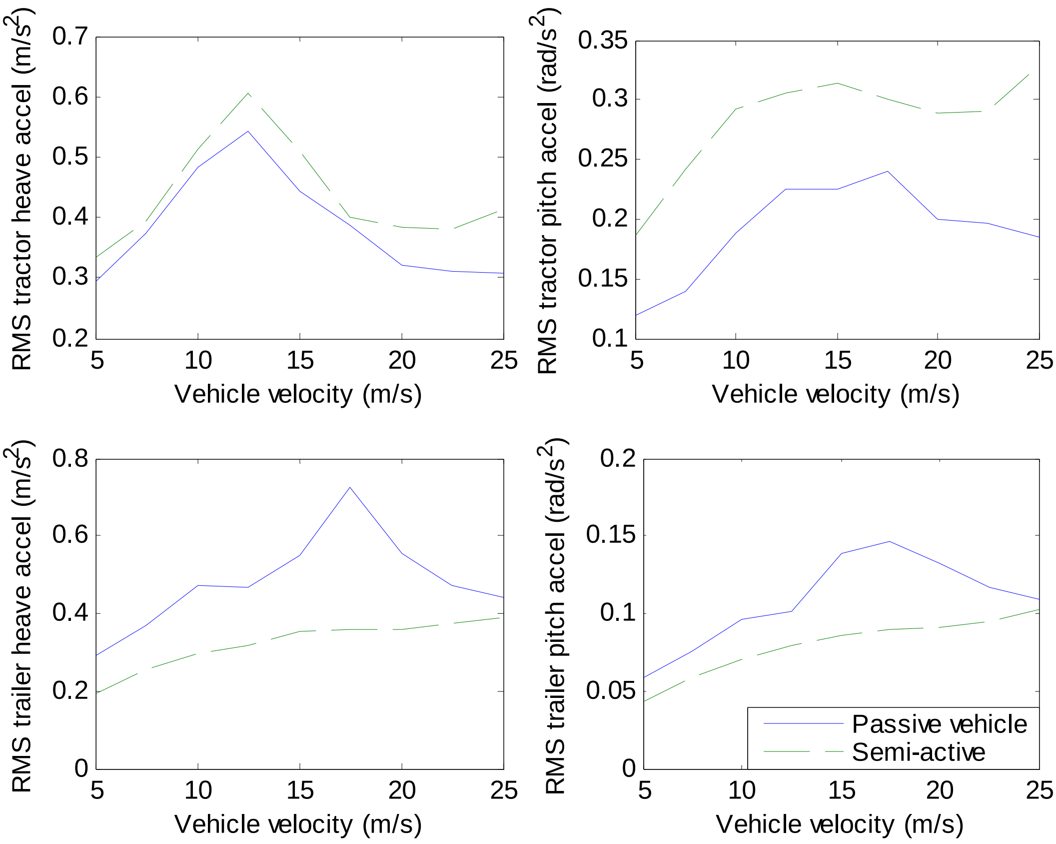

Figure 3 – Comparison of ride criteria. ——Passive viscous damper; — — Semi-active

Table 2 shows that the maximum improvement in ride for the trailer unit is achieved at moderate vehicle velocity (around 17.5m/s) but that the tractor accelerations are increased, particularly at higher speeds.

Table 2 Reduction in accelerations relative to passive response

Vehicle velocity (m/s)	RMS tractor Heave acceleration (%)	RMS tractor Pitch acceleration (%)	RMS trailer Heave acceleration (%)	RMS trailer Pitch acceleration (%)
10	-6	-36	37.5	30
17.5	-5	-20	50	47
25	-25	-46	6	4

The average estimated vehicle velocity of the fully loaded heavy articulated vehicle on a smooth highway is approximately 65 km/h. The semi-active suspension with MR damper reduces the maxim normalized road damage of the vehicle as well as improves the driving performance in terms of comfort. Consequently, the semi-active suspension reduces the vibration levels experienced by the trailer unit protecting the goods carried in the vehicle and the road from fatigue damage. Similar results observed when the vehicle is operated on the poor road (the graphs not shown here).

A study of partial cancellation of the dynamic tire forces is essential to determine the effect of various levels of cancellation on the vehicle performance. In figure 4 is presented the vehicle performance when the level of cancellation on the drive tractor axle varies and the cancellation on the trailer axle is 100%; the other parameters of the control algorithm are kept constant. The semi-active case is compared against the conventional passive non linear viscous damper.

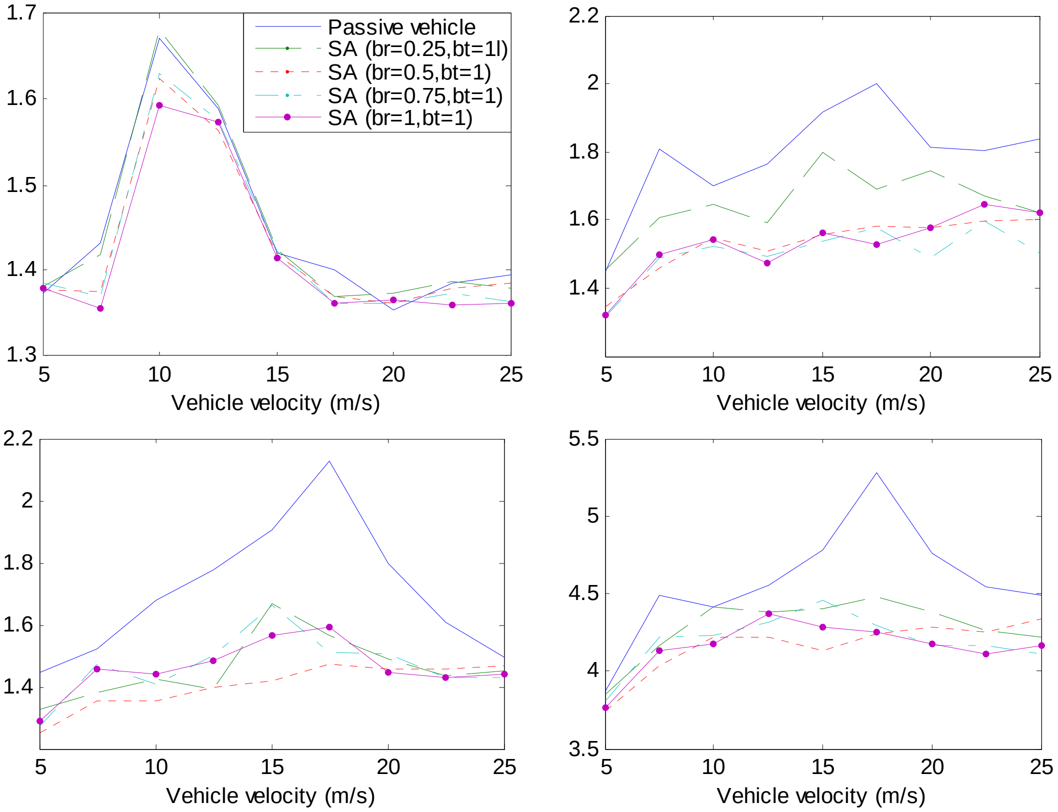

Figure 4 – Partial cancellation of dynamic tire force at the drive tractor axle

The optimum solution for total vehicle damage is achieved with 100% dynamic tire force cancellation. Damage caused by the tractor drive axle alone is optimized by 75% cancellation at most speeds but between 10 m/s and 17.5 m/s 100% cancellation is best.

The response time of MR dampers for vehicle applications is an important factor because it determines the effectiveness of the MR damper used. The response time is defined as the time required for the MR damper to reach 67% of the final exerted force, starting from the initial state. Reducing the time constant improves the vehicle performance at all vehicle velocities.

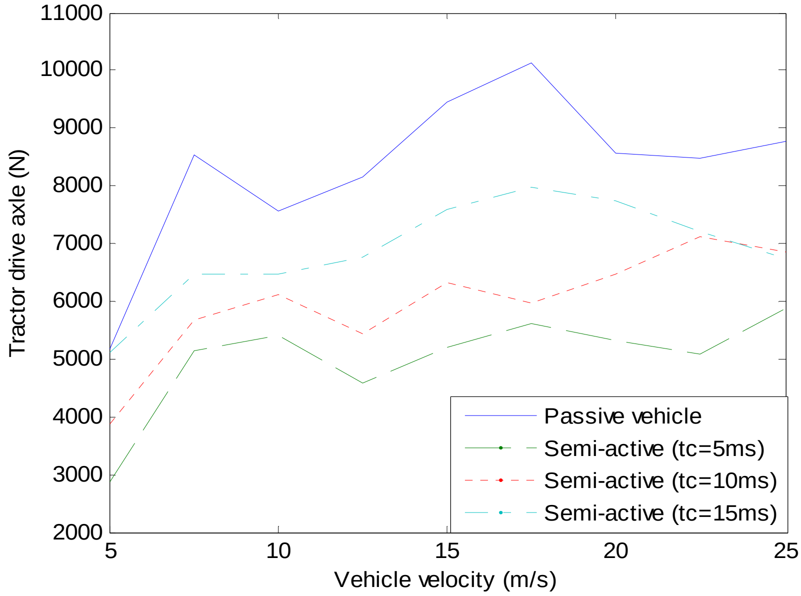

Figure 5 – Maximum dynamic tire force as a function of damper time constant

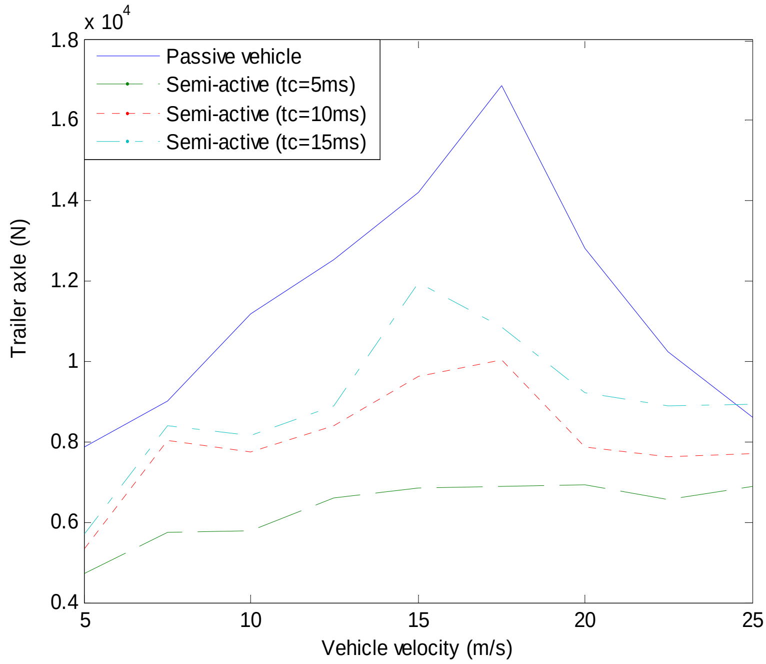

Figure 6 – Maximum dynamic tire force as a function of damper time constant

Conclusions

- The road damage generated by heavy articulated vehicles is appreciably improved when fitted with (semi-active) MR dampers. The suspension is most effective at moderate vehicle velocity speeds (around 17.5m/s or 64km/h);the maximum road damage is reduced by 19%.There is however, a resultant penalty in increase tractor accelerations which may call for control of the cab or driver's seat. Since the mass of the cab is small the effect on the tyre forces should not be significant.

- The time constant of the damper affects the peak values of the MR damper rather than the RMS values. A lower time constant improves the vehicle response at moderate and higher vehicle velocities.

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