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Mobility Analysis of a Heavy Off-Road Vehicle

Using a Controlled Suspension

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Summary

Driving safety and ride comfort of cross-country vehicles can be improved with the help of a controlled spring/suspension system. The present paper describes the impact of a semiactive and partially active chassis system on the driving behaviour of a cross-country 8x8 wheeled vehicle. The mobility analysis is based on a multibody vehicle model used for simulating cross-country drives and handling. To start with, the fundamental "Skyhook"-principle is used for controlling; vertical accelerations and vehicle movements are clearly reduced on rough tracks and sine wave lanes.

1. Introduction

Especially for cross-country vehicles, the active chassis instead of a conventional chassis offers numerous advantages. Adjustment of the chassis to the road and to the driving situation offers numerous possibilities for improving the driving safety and the ride comfort and for reducing component wear and surface load, at the same time.

Upon closer examination of the total vehicle system from the point of view driving safety and ride comfort, next to the tyres the wheel suspension system has the greatest effects. Hence, interventions in this area will make sense in order to obtain fundamental improvements as regards driving safety and ride comfort.

Priority was given to this part of the investigation which was made with the help of a multibody simulation tool. Starting point was a cross-country 8x8 wheeled vehicle, fig. 1, which in the simulation was provided with a basic Skyhook chassis control and compared to the conventional chassis. With the help of vehicle simulations, the possibilities for mobility improvements with the help of controlled chassis were to be investigated.

As a rule, the mobility of a vehicle is determined by the possible maximum cross-country speed of the vehicle. On rough tracks and on good roads, maximum speed is mainly limited by the comfort of the ride, with due consideration of the driving safety. This is why the present investigation is mainly concentrating on the consequences for the comfort of the ride.

2. Controlled Chassis Systems

In chassis engineering, balancing of the chassis is a difficult and often quite demanding optimization task. For optimum ride comfort, spring and suspension rates should be as soft as possible. However, the related heavy body movements are detrimental for the driving safety. This is why for reasons of driving safety, the spring and suspension rates should be as hard as possible, in order to reduce body movements and dynamic wheel load deviations to a minimum. This will ensure good road contact and uniform load transmission of all wheels.

Fig. 2 is a graphic description of the target conflict between ride comfort and driving safety. If we take the body acceleration - as a measure for the ride comfort – in dependence on the dynamic wheel load – as a measure for the driving safety, a limiting curve of the physically possible can be derived for fixed pairs of shock absorbers and spring rigidity /1/. Due to the fixed characteristic curves, a vehicle with passive spring/suspension system can only cover one point on the envelopment curves, which will be either in favour of ride comfort or of driving safety, depending on the vehicle philosophy. In this context, the specific requirements of the vehicle, the expected road excitation and the driving situation must also be taken into consideration.

Active chassis systems are characterised by the fact that the loads between wheel and body are not created in dependence on the spring and damper rate, but can be applied according to requirements by means of external energy admission. By this means, the physical limits of passive wheel suspension systems shown in fig. 2 can be overcome.

Today, various systems are used for controlled chassis which can be subdivided into 3 groups, as can be seen from fig. 3 /2,3/:

- *Adaptive systems* are characterised by slowly adjustable spring-/suspension elements, the load characteristic of which can be adapted to the ride situation; i.e. in dependence on the speed, the driving manoeuvres or the condition of the road.

- *Semiactive systems* operated with rapidly adjustable spring/suspension elements, which facilitate controls

within the characteristic oscillation time of the body and/or the wheel.

– *Active systems* function essentially with hydraulic servo components, where the load is generated through external energy admission and controlled pursuant to a law of control /4/.

In chassis engineering, additional comfort through controlled chassis must always be seen in relation with the operational conditions, the higher purchase price and the additional power requirements. This is why vehicle simulations are an effective means for assessing possible improvements through controlled chassis as early as in the design phase

3. Model Description

3.1 Vehicle Model

To analyse the dynamic behaviour, a physical and a mathematical model is required. The entire vehicle model is built up in parameters with a multibody simulation tool (MBS) /5/. The necessary data have been taken from measurements, as far as possible, and compared to a test vehicle.

The MBS-total vehicle model, fig. 4, represents the following components and functions:

– chassis and wheel steering components
– axle- and steering kinematics
– drive train with all-wheel drive, longitudinal and transversal differentials
– wheels with internal emergency ring
– springs, passive and active shock absorbers
– hydraulic bump stop shock absorbers
– Skyhook control
– driver model
– road profiles, sine-wave lane, rough track, individual obstacles

3.2 Skyhook Control

The basic concept of the Skyhook control is the introduction of an additional shock absorber between the body and the inertia reference system, fig. 5. In this configuration, shock absorption counteracts the vertical acceleration of the body load independent of the influence of the wheel load. For technical realisation, an adjustable shock absorber is installed between wheel and body; the absorption capacity is controlled in dependence on the absolute velocity of the body v_a. External energy is required for this final control element. In the simulation model, the absorber force F_d between wheel and body is computed with the help of the following equation:

$$F_d = d_p * v_{rel} + d_a * v_a \ (1)$$

The velocity of the body v_a is determined for each wheel station in the area of the chassis connection. In (1), the coefficients d_a correspond to active Skyhook suspension, d_p is the passive shock absorption and v_{rel} the velocity difference between wheel and body.

To represent the semiactive Skyhook control, and in contrast to active Skyhook suspension, no external energy is supplied to the system. This corresponds to an adjustable shock absorber; where the characteristic curve is controlled in dependence on the absolute velocity of the body v_a. In the simulation model the resulting absorption is computed as follows:

$$F_d = d_p * v_{rel} + d_a * v_a \quad \text{for} \ v_a * v_{rel} > 0 \ (2)$$
$$F_d = d_p v_{rel} \quad\quad\quad \text{for} \ v_a * v_{rel} < 0 \ (3)$$

Since Skyhook suspension is only controlled via the body velocity, the effect is unsatisfactory as regards intrinsic wheel frequency and higher frequencies /1/. This is why a frequency-dependent control is required for higher frequencies. For this purpose, an additional conventional shock absorber is used in the simulation.

4. Investigated Chassis Systems

The passive wheel suspension of the investigated vehicle consists of two spring/suspension elements for each wheel station. For hard shocks, a hydraulic bump stop shock absorber with high energy absorption has been installed on the hull which reacts after half of the spring travel, fig. 6. The bump stop absorber enables better tuning of the conventional shock absorbers and contributes to thermal relieve. In addition, the vehicle is equipped with a tyre pressure control system, to enable adapting the air pressure of the tyres to the condition of the road. The considerable mobility demands as regards quick traversing of obstacles, such as ramps, 10" individual TRAPEZOIDAL obstacle or 7 m sine-wave lane require a high energy absorption of the spring/suspension system, which can only be achieved through rigid tuning of the shock absorbers. In the following investigation, this standard configuration is called "rigid".

In the simulation model an adaptive, semiactive and a *partially active chassis system* are shown based on the passive chassis system. To determine the influence of an adaptive chassis control, a soft absorber characteristic is used, which corresponds to 50% of the standard design. The partially active chassis system is represented in the simulation model by means of an active Skyhook absorber replacing one of the two conventional shock absorbers. The essential objective of the Skyhook control is to stabilise long-wave body oscillations. The conventional shock absorber is used for the intrinsic wheel frequency, which is to be recommended also for real-time operation to ensure basic shock absorption in case of system failure. To reduce power requirements to a minimum, the passive spring elements are maintained for supporting the static body load. The total power consumption of the active actuator components is limited to 5% of the driving power. The semiactive chassis control takes place with a semiactive Skyhook shock absorber in accordance with the semiactive system.

5. Results of the Simulation

In the simulation typical test runs with various lanes, corrugated track, 7 m sine-wave lane and 10" individual

trapezoidal-obstacle are used for evaluating the ride comfort during cross-country driving. In the simulation, the possible maximum speed on the test runs is limited by the following quantities:

- Max. vertical acceleration in the driver's seat
  < 2,5 g for individual obstacles
- Max. vertical acceleration in the driver's seat
  < 1 g   for sine-wave lane
- Pitch angle < 6°
- Power consumption in the driver's seat
  < 6 W

5.1 Corrugated Track

Fig. 7 shows the computed power consumption in the driver's seat for a typical corrugated track for different velocities. In the simulation a tyre pressure for road driving was selected. The effective value of oscillation power was computed as $m \, |a| \, |v|$, with v and a being the velocity and the acceleration. 80 kg were chosen for the vibrating load m. The results show the advantage of a soft-tuned or controlled absorber as compared to the standard configuration. With the help of a soft absorber (= adaptive control) maximum vibration in the driver's seat can be reduced in the area of the body natural frequency by 65% compared to the hard standard configuration. With semiactive and active dampers a reduction in power consumption of 64% and 77% is possible compared to the hard configuration.

The dynamic wheel load of a front wheel is shown in fig.8. A comparison of the different damper systems shows the advantage of the hard standard configuration for the areas around the natural frequencies of the wheel (~23 km/h) and the body (~5 km/h). With the help of a soft or controlled absorber the dynamic wheel load can be reduced in the area between the body and wheel natural frequency (around 10 km/h).

5.2 Sine-Wave Lane 7 m

Figs. 9-12 show the pitch angle, vertical acceleration and the wheel load during drive over the 7 m sine-wave lane as regards intrinsic body frequency. The results show that relatively small pitch angles (< 4 °, peak-peak) are achieved with the hard standard configuration. The essential advantage of the controlled chassis will be the reduction of the dynamic wheel load fluctuations.

Single Trapezoidal Obstacle (h = 250 mm)

Fig. 13 shows the vertical acceleration, the wheel load fluctuation and the pitch behaviour during drive over the individual trapezoidal obstacle. The shown vertical acceleration was filtered with a cut-off frequency of 16 Hz. The behaviour directly at the obstacle is hardly different, since it is mainly determined by the energy absorption of the hydraulic bump stop absorper. However, secondary vibrations are clearly reduced through active shock absorption. Compared to the standard configuration, vertical accelerations, pitch

behaviour and wheel load fluctuations are reduced much faster.

5.4 ISO-Double Lane Changing

Fig. 14 shows the steering wheel angle, the roll angle and the wheel load during ISO-double lane changing at 70 km/h. The simulation results show that the transversal dynamics are hardly influenced by the various shock absorbers. However, the roll angle movement can clearly be influenced with the help of active absorption. But it is difficult to assess the related increase of comfort since this depends on subjective perception /6/. During this manoeuvre, reduction of wheel load fluctuation through controlled chassis is an advantage for improving the lateral guidance potential of the tyres /7/. For this purpose, a frequency-dependent control of the intrinsic wheel frequency is required.

6. Summary

This paper describes the investigations made with the help of dynamic driving simulations to improve the ride comfort of cross-country vehicles through controlled chassis. The investigations were based on a four-axle, all-wheel driven cross-country vehicle of the 33 t weight class, designed for high average speed on roads and in terrain. The spring/suspension system is characterised by its high energy absorption to enable rapid crossing of high individual obstacles, ramps and long ground humps. The individually installed hydraulic limit-stop shock absorbers absorb a large amount of the shock energy and by this means enable influencing the vibration absorbers as regards improvement of ride comfort.

Taking the example of the elementary Skyhook control, the simulation results show that on corrugated tracks and sine-wave lanes both the vibrational behaviour, the maximum vertical accelerations and the pitch movement can be noticeably reduced with the help of a controlled chassis. No negative consequences as regards increase of maximum vertical acceleration in case of individual obstacles could be found; this is essentially influenced by the separate hydraulic limit-stop shock absorbers.

As regards handling, the simulation results show that roll and pitch movements due to steering and braking can be considerably reduced with the help of the active control.

The high mobility requirements for the investigated vehicle in heavy terrain resulted in a relatively rigid tuning of the spring/suspension system. When looking at the typical operational profile of these vehicles it becomes clear that more than 90% of the rides take place on roads, tracks and rough tracks. A controlled chassis would ensure the same mobility in heavy terrain and improve the ride comfort both on bad road stretches and in easy terrain. By this means the average speed can be increased while reducing the stress for the crew at the same time. A high ride comfort is especially necessary for fatigue-free driving over long distances and will essentially contribute to the operational security for the crew.

It was only possible to deal with some aspects of chassis control in this preliminary investigation, this is why further investigations as regards mobility and control strategies will be required. The next step would be to design a controller for road and terrain operation to take also higher frequency excitations into account.

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/3/ Kallenbach, R.; Optimierung des Fahrzeugverhaltens mit semiaktiver Fahrwerkregelungen, VDI Bericht Nr. 699, 1988, Seite 121-134

/4/ Breuer, W.; Mechatronische Elemente bei der Untersuchung eines vierachsigen Geländefahrzeugs, VDI-Bericht Nr. 1293, 1996, Seite 585-601

/5/ ADAMS, Using Adams/Solver/Driver, Mechanical Dynamics, 1997/1998

/6/ Mitschke M.; Dynamik der Kraftfahrzeuge, Bd C: Fahrverhalten; Springer Verlag; Berlin, 1990

/7/ Alberti, V.; Beurteilung von Fahrzeugen mit adaptiver Fahrwerkdämpfung; VDI-Bericht Nr. 916, 1991, Seite 469-489

Fig. 1: 8x8- Off- Road Vehicle (33t)
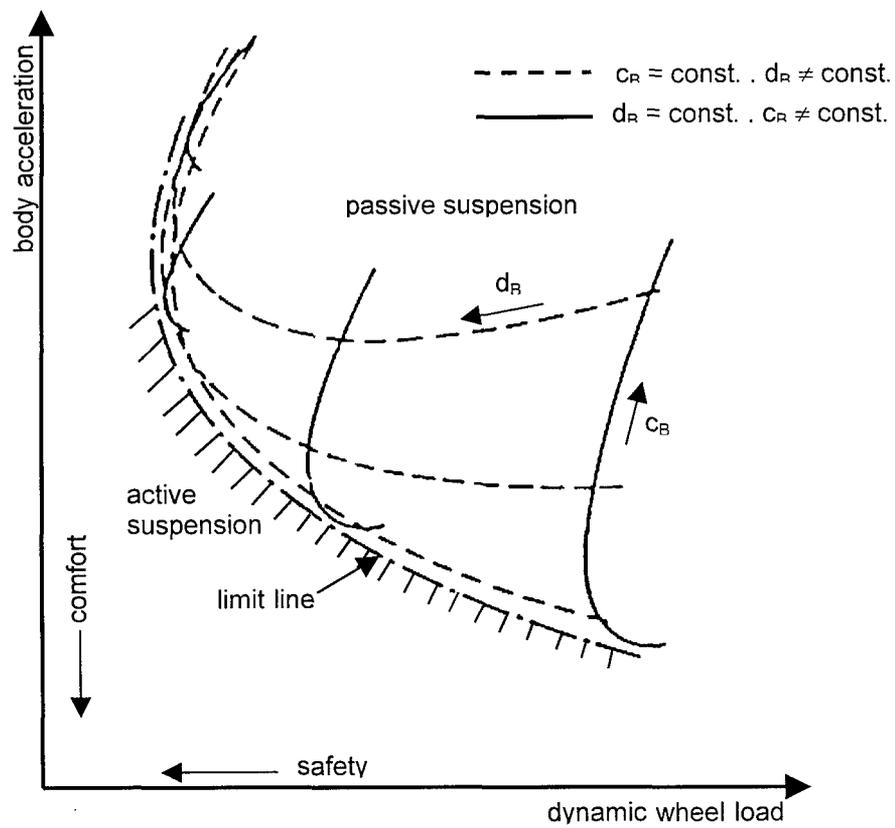
Fig. 2: Design of suspension systems

	Model	Force characteristic	Energy consumption	Control Frequency
passive				
adaptive			low	slower than the bodynatural frequency
semiactive			low	faster than the bodynatural frequency
active			high	faster than the bodynatural frequency
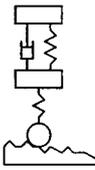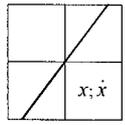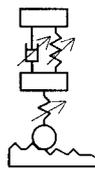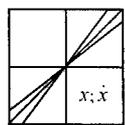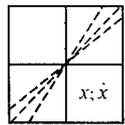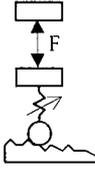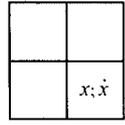
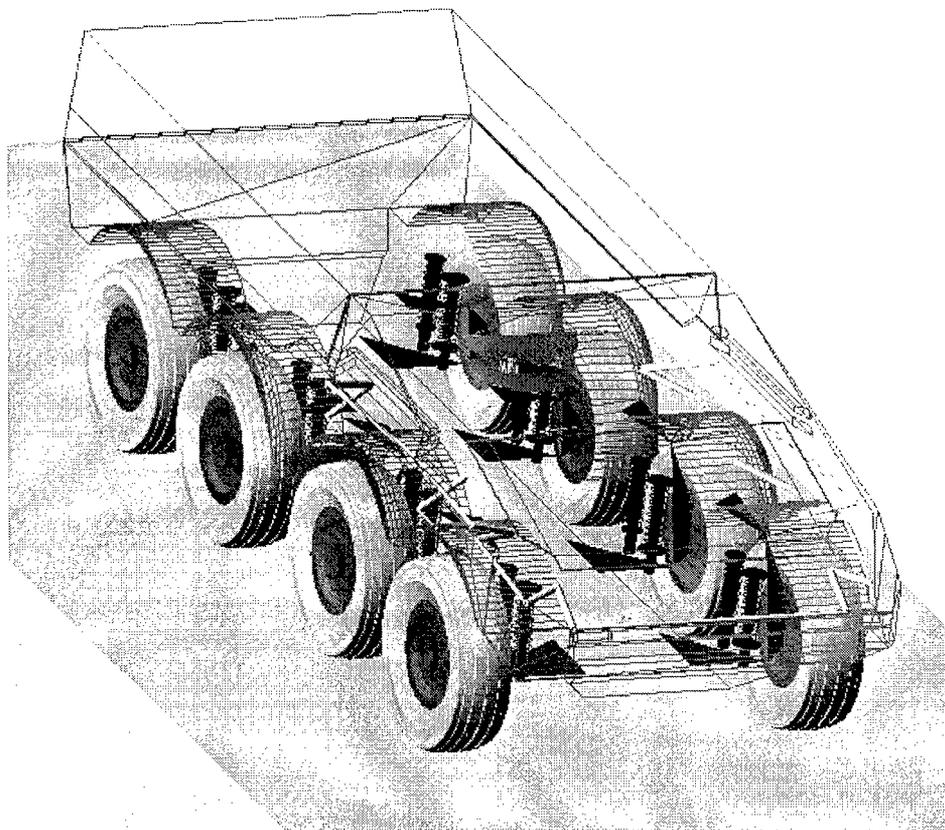Fig. 3: Classification of suspension systems
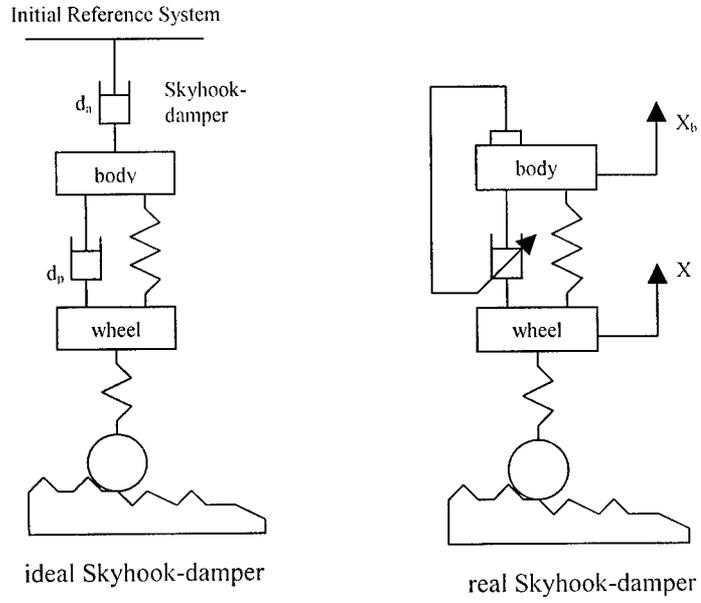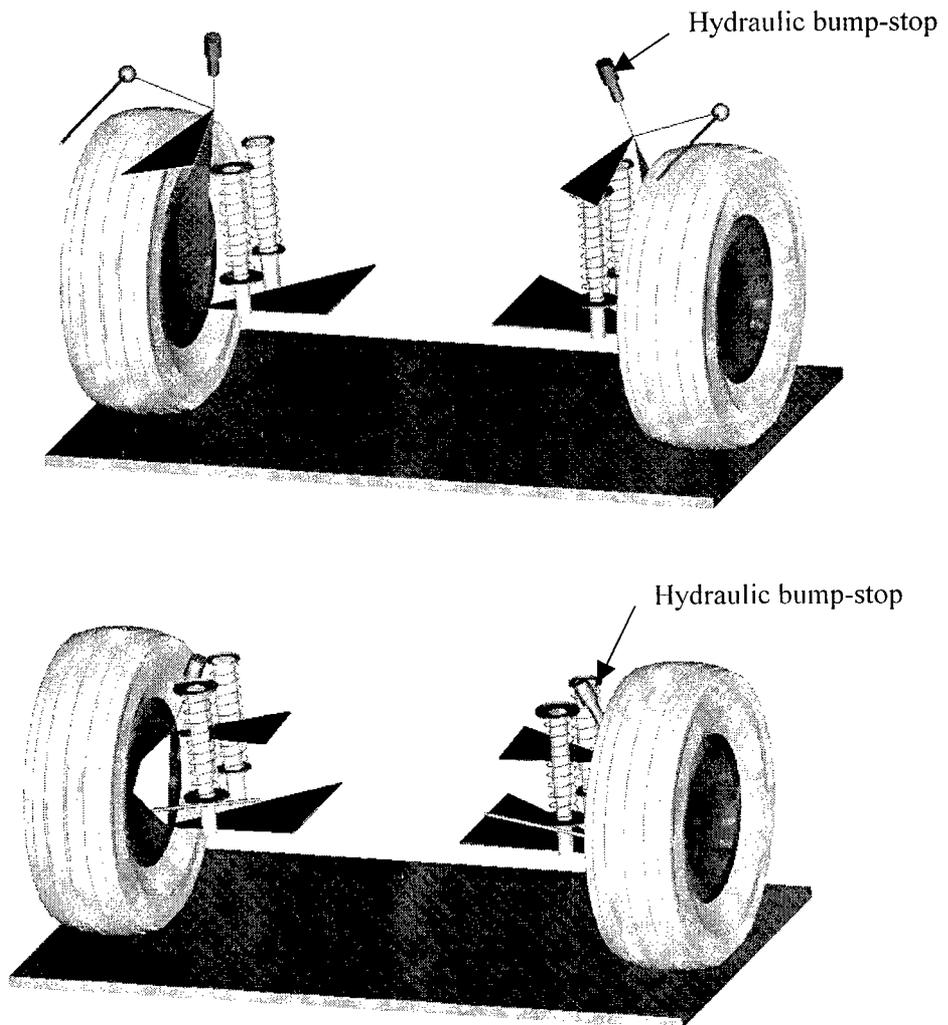
Fig. 4: MBS- Model 8x8 Off- Road Vehicle

Initial Reference System

ideal Skyhook-damper

real Skyhook-damper

Fig. 5: Model of an active Skyhook-

Hydraulic bump-stop

Hydraulic bump-stop

Fig. 6: Front and Rear axle

corrugated track
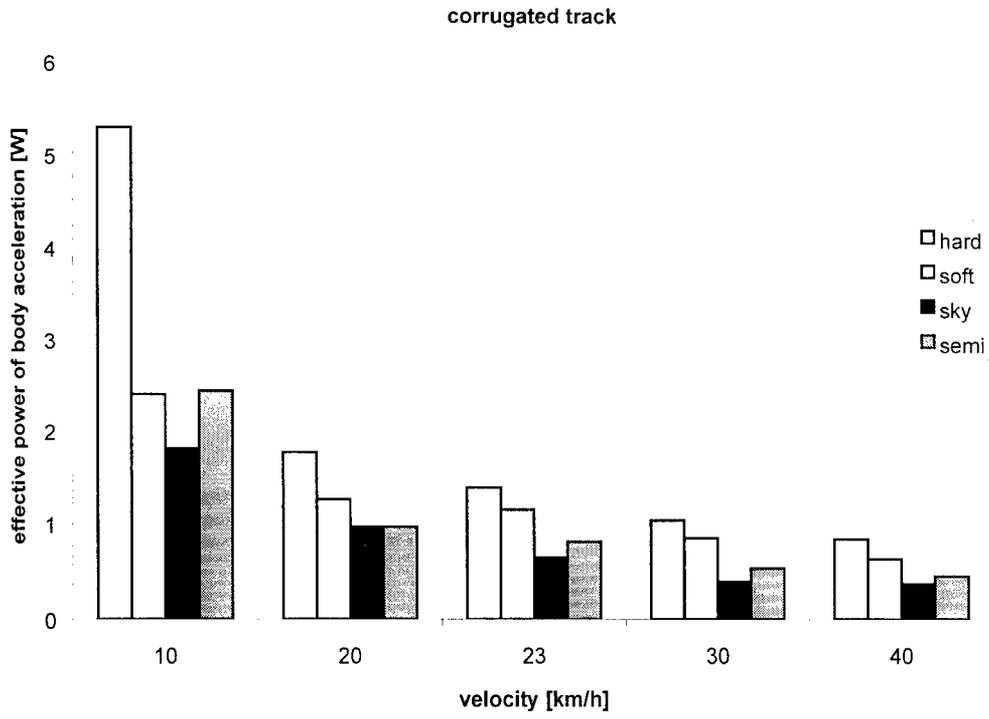
Fig. 7: Effective power of body vibration

corrugated track
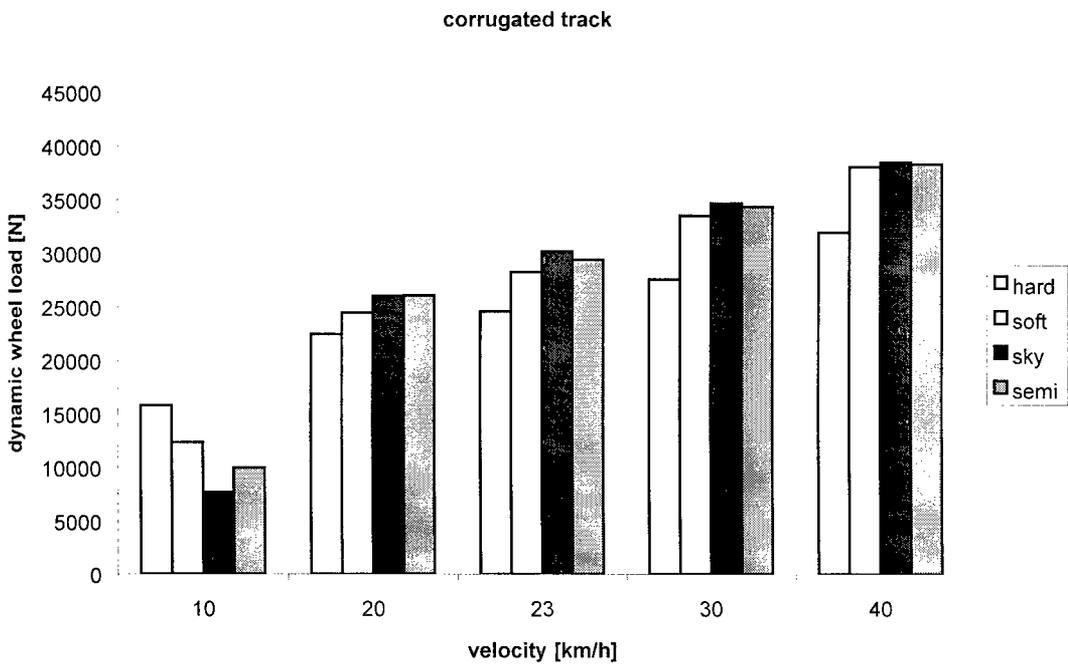
Fig. 8: Dynamic wheel load
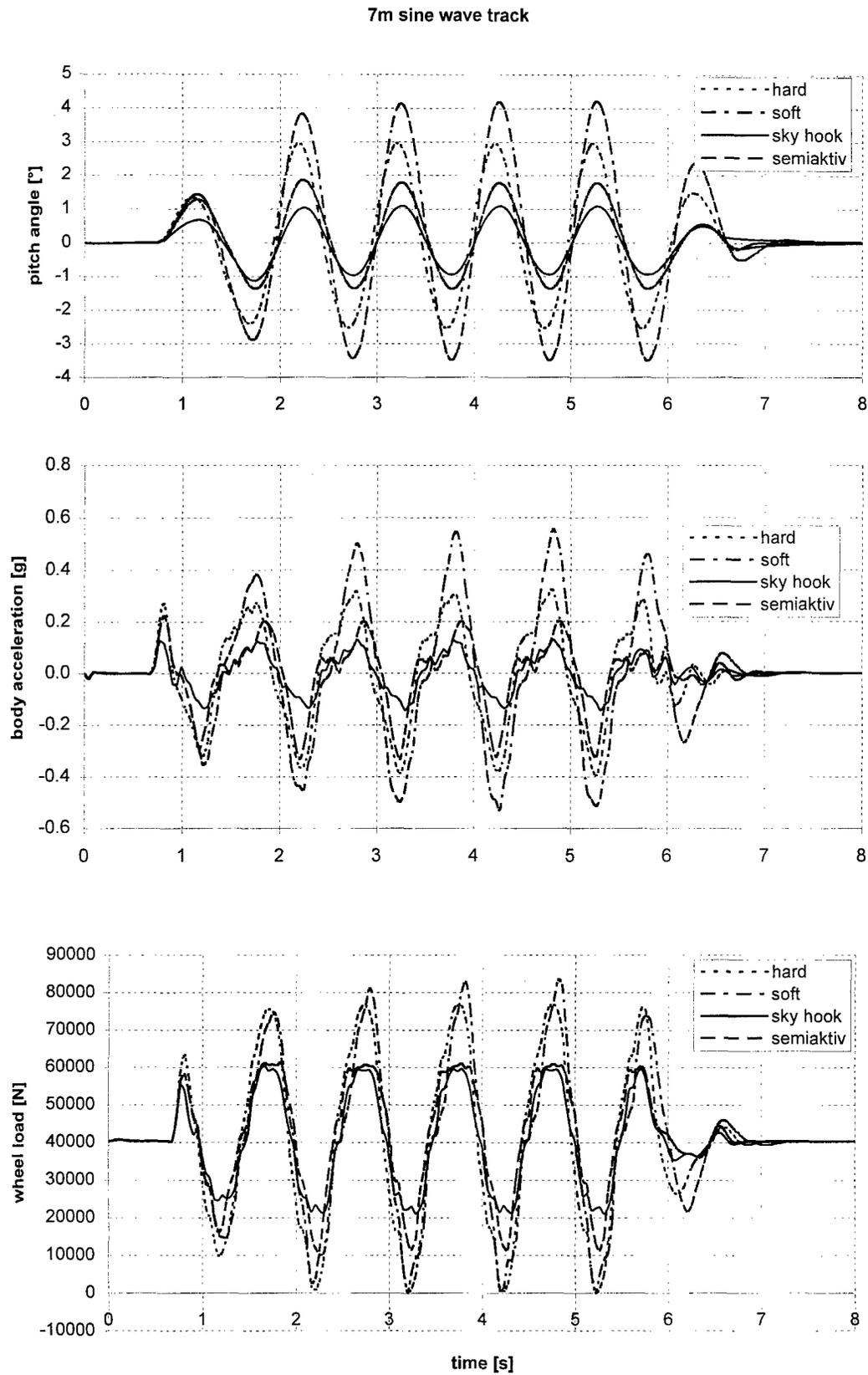
7m sine wave track

Fig. 9: Seven metre sine wave track at 25 km/h (Amplitude 100mm)

7m sine wave track
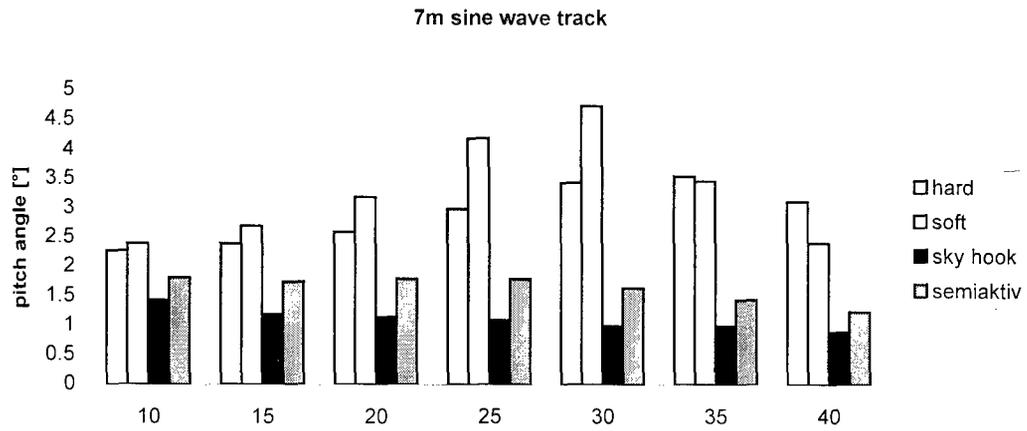
Fig. 10: Pitch angle with different damper systems
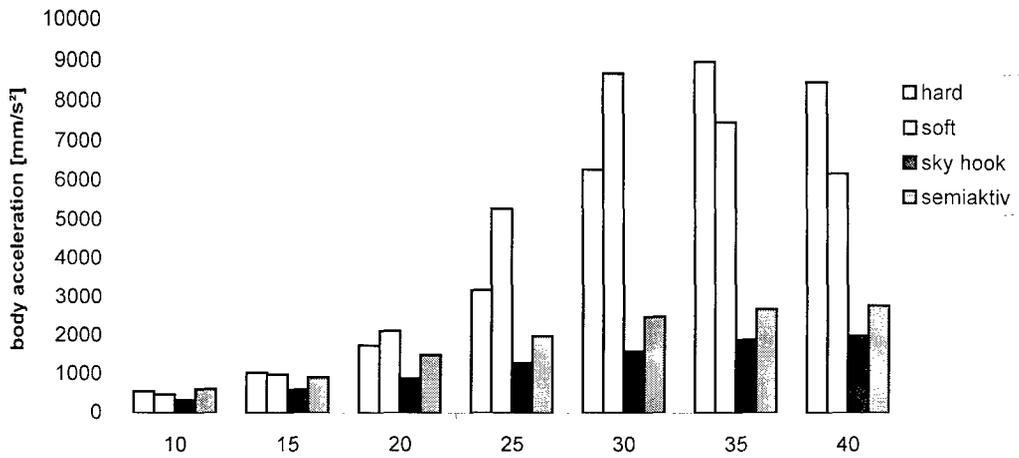
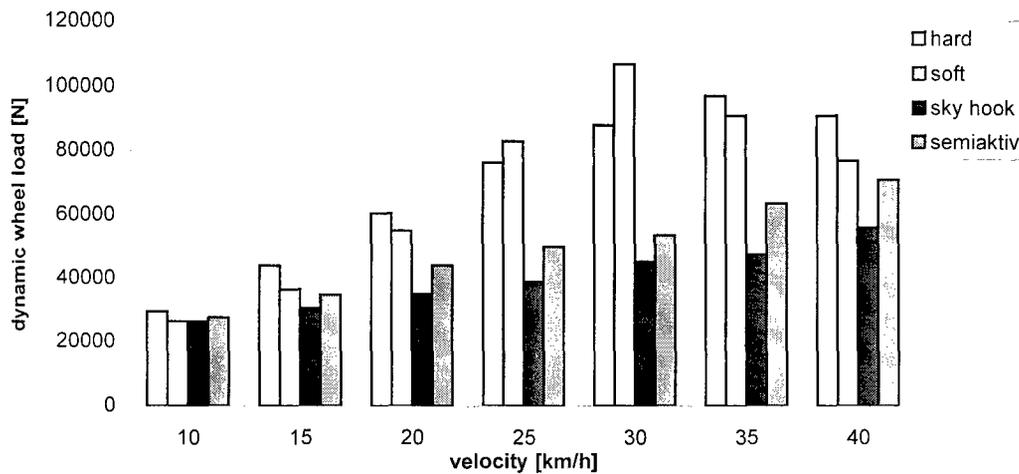
Fig. 11: Body acceleration with different damper systems

Fig. 12: Dynamic wheel load with different damper systems

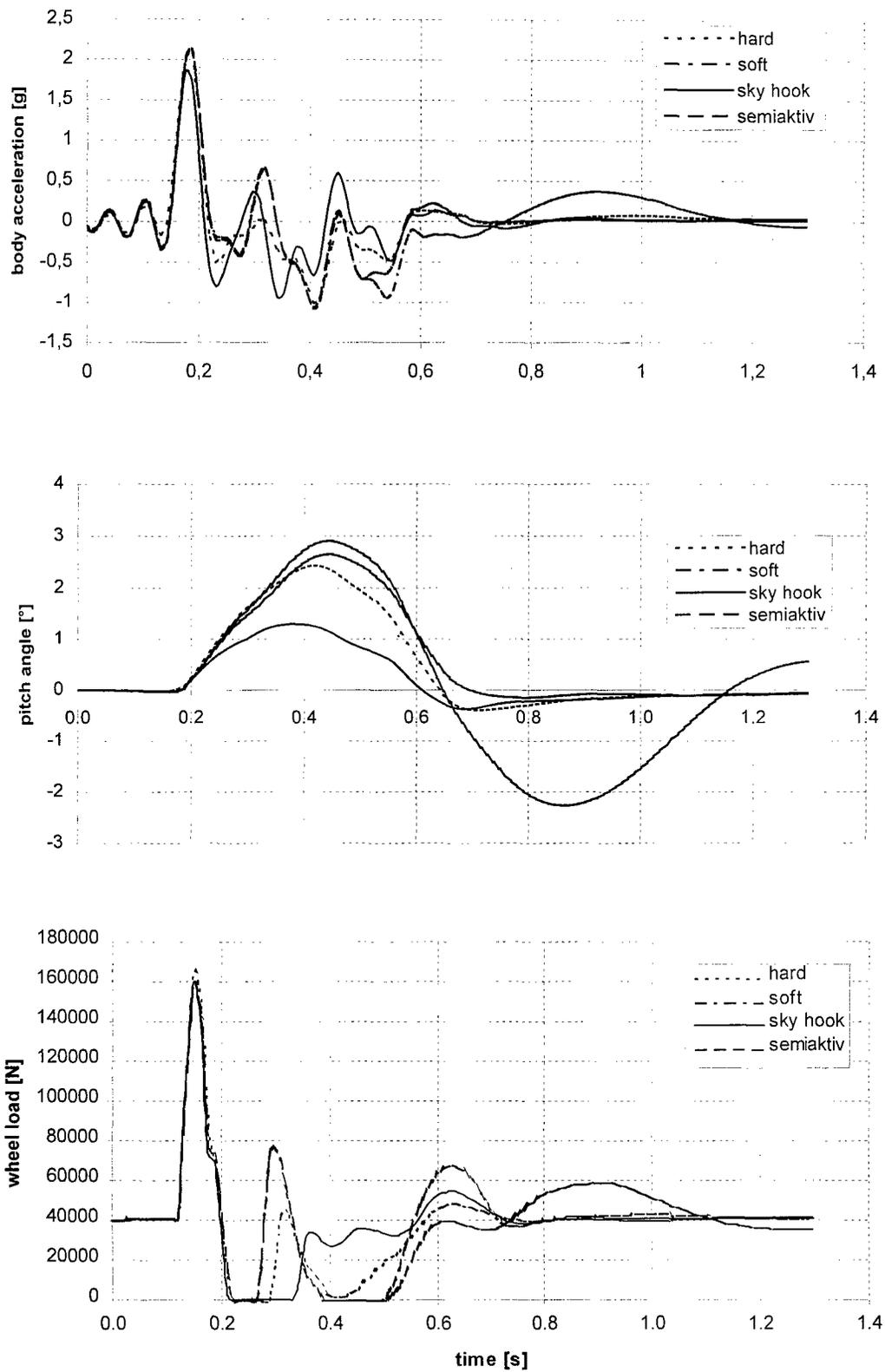**Trapezoidal Obstacle   50 km/h**
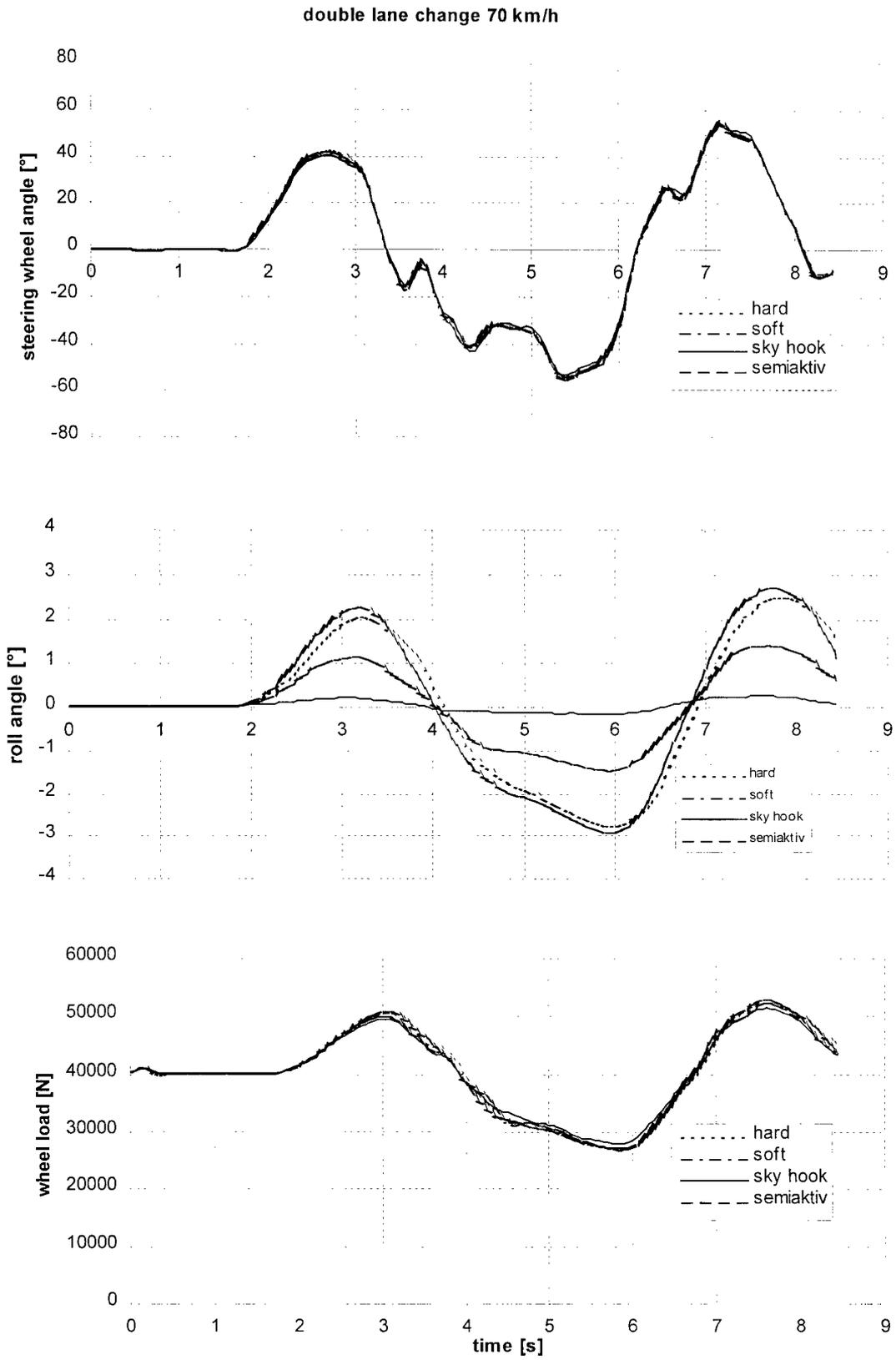

Fig.13: Trapezoidal obstacle clearance at 50 km/h (h=250 mm)

double lane change 70 km/h

Fig.15: double lane change at 70 km/h