The Usage of Semi-Active Cabin and Axle Suspension Systems with Different Objectives to Improve Driving Comfort and Safety

Influences of different control strategies and outlook on the effect of a rear mounted implement

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Keywords: Semi-Active Suspension, Farm Tractor, Driving Safety, Driving Comfort, Skyhook, Groundhook.

Abstract: The operators of mobile working machines such as farm tractors are exposed to a high level of whole body vibration. According to European legislation a certain vibration level should not be exceeded to avoid health risks. To reduce these vibrations, different suspension systems for the seat, the cabin or the axles are being used. Different control strategies for active and semi-active suspensions have been proposed and successfully implemented to reduce whole body vibration and therefore increase the operator's comfort. In the case of axle suspensions not only the comfort but also the driving safety in the form of wheel load fluctuation can be influenced. However, passive configurations of sprung axles are always a compromise between optimal comfort and optimal safety. The very common skyhook and groundhook control algorithms cannot overcome this compromise as their optimisation goal is either to reduce whole body vibration or wheel load fluctuation. A combined control of the cabin and axle suspension can help to further improve the fulfilment of the goals in suspension system design. An outlook is given on the effect of an implement on the dynamic behaviour of a fully suspended tractor.

1 INTRODUCTION

During farm operations such as field work and transport tasks, tractor operators are exposed to high levels of whole body vibration. While early farm tractors where not equipped with suspension systems or only a simple suspended seat, increased driving speeds and health and safety regulations have created the necessity for more efficient systems to avoid unwanted and harmful accelerations at the drivers working place (European Parliament and Council 2002).

Efforts in the development of seat and cabin suspension systems have helped to lower these vibrations substantially. Further improvements were made using active and semi-active systems to increase comfort (Hauck 2001; Scheff 2008; Evers *et al.* 2009; Kieneke, Graf & Maas 2013). While many different control algorithms to minimise vibrations have been proposed, the skyhook control is often used to compare these methods (Karnopp, Crosby & Harwood 1974). The skyhook algorithm tries to reduce the accelerations of a mass (e.g. cabin or seat) and therefore can improve comfort. A virtual damper between the mass and an inert system (the sky) is simulated by using available force elements in the seat, cabin or axle suspension.

If the driving safety should increase i.e. the wheel fluctuations should be reduced the groundhook algorithm can be used (Venhovens 1993; Valásek & Novák 1996). It is based on the idea of a virtual damper between the wheel and the ground to guarantee a reduced oscillation of the contact force between wheel and ground. As the mass of the seat or the cabin is small compared to the mass of the whole tractor, this control approach works best if an active or semi-active suspension system is used between the axle and the chassis. This suspension system is known as axle suspension or chassis suspension.

An ideal controlled suspension system would improve both comfort and driving safety. However, most approaches focus on only one of the objectives while the fulfilment of the other objective might deteriorate. To improve both objectives a combined control of cabin and axle suspension is examined.

While a suspended front axle is common in modern tractors only few have rear axle suspension systems. One of the main advantages of tractors is their flexibility to fulfil different tasks by using different implements. If a rear axle suspension is used the implement can either be mounted to the unsprung mass (the axle) or the sprung mass (the chassis). If, for example, a soil tillage implement such as a plough is being used, this system has an influence on the criteria mentioned above (comfort and driving safety) and the suspension system itself can influence the quality of the tillage process. This paper gives an outlook on the effect of sprung and unsprung rear axles and the impact of an implement on the dynamic behaviour.

2 QUANTIFICATION OF COMFORT AND DRIVING SAFETY

In order to compare different suspension setups a measure has to be determined to quantify the criteria driving comfort and driving safety. For determination of the driving comfort the root-mean-square (rms) values of the seat acceleration are being used according to VDI 2057 (see Equation 1) (Verein deutscher Ingenieure 2002).

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\cdot dt} \qquad (1)$$

The driving safety is determined by the wheel load factor. This factor (see Equation 3) is the quotient of the standard deviation of the dynamic tyre force (see Equation 2) and the static tyre force.

$$\sigma_F = \sqrt{\frac{1}{T}\int_0^T {F_{z,dyn}}^2(t)dt} \qquad (2)$$

$$n_{RLS} = \frac{\sigma_F}{F_{z,stat}} \qquad (3)$$

If n_{RLS} reaches values above 0.33 a stable control of the vehicle cannot be guaranteed (Bauer 2007; Mitschke & Wallentowitz 2014).

3 SIMULATION MODELS

To examine the basic influence of a skyhook and groundhook control strategy on comfort and driving safety two quarter car models were used. Figure 1 shows the model without a separate cabin suspension on the left. The model on the right has a separate cabin suspension consisting of a cabin spring (c_{cab}) and a damper (d_{cab}). Both models incorporate a mass for the wheel (m_w) and the chassis (m_{ch}). The wheel is connected to the ground by the wheel spring (c_w) and a damper (d_w). Wheel and chassis masses are connected to each other by a chassis spring and a damper (c_{ch}, d_{ch}).

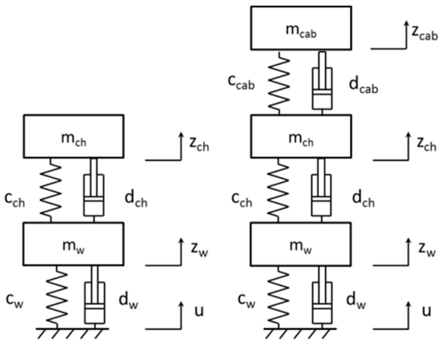

Figure 1: Quarter car models without and with cab mass.

4 SIMULATION RESULTS

4.1 Skyhook Control

To reduce the accelerations acting on the driver the skyhook algorithm was used. The damping constant d_{ch} of the left model in Figure 1 was changed according to Equation 4.

$$d_R(\dot{z}_{ch}, \dot{z}_w) = \begin{cases} d_{SH}\cdot\dfrac{\dot{z}_{ch}}{\dot{z}_{ch}-\dot{z}_w} & \text{if } (\dot{z}_{ch}-\dot{z}_w)\cdot\dot{z}_{ch} \geq 0 \\ d_{min} & \text{if } (\dot{z}_{ch}-\dot{z}_w)\cdot\dot{z}_{ch} < 0 \end{cases} \qquad (4)$$

The minimal damping d_{min} is the lowest damping that can be achieved by a real damper. It is dependent on the physical principle of the damping. In a hydraulic damper it is limited by the friction of the damper, the linkage and the flow losses of the hydraulic liquid.

To compare the skyhook controlled axle-suspension with a passive suspension, different simulation runs were carried out varying the passive damping constant. The skyhook damping d_{SH} was also varied. The rougher track of ISO 5008 was used at a vehicle speed of 5 km/h (International Organization for Standardization 2002). Figure 2 shows the passive curve on the top and the skyhook controlled curve on the bottom of a conflict-diagram comparing driving safety and comfort. The circles mark simulation points at which the spring deflection limit was exceeded. At low passive damping rates the suspension exceeds the maximal spring deflection. This setup can therefore not be used in a real vehicle as it would not be suitable for this track and velocity. At higher damping rates both measures (the dynamic wheel load factor and the chassis acceleration) increase which results in a more unstable driving behaviour and a loss of comfort at the same time. The skyhook controlled suspension shows also an exceedance of the maximal spring deflection at low damping rates. However, the driving comfort can be increased by 42 % (a_{RMS}-reduction from 1.88 m/s^2 to 1.32 m/s^2) on this track. At the same time the skyhook control algorithm shows a reduction of driving stability due to an increased dynamic wheel load factor.

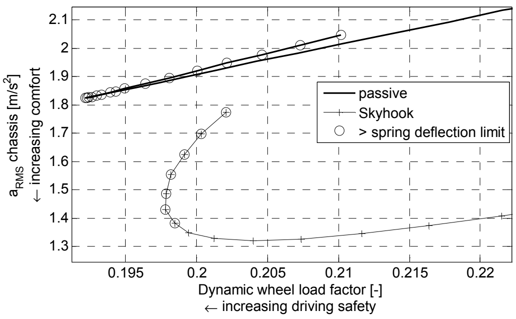

Figure 2: Comparison of passive and skyhook-controlled suspension on the ISO 5008 rougher track.

4.2 Groundhook Control

To reduce wheel load fluctuations the groundhook algorithm was used. The chassis damping was varied according to Equation 5.

$$d_R(\dot{z}_2, \dot{z}_1, \dot{u}) = \begin{cases} d_{GH} \cdot \frac{(\dot{z}_1 - \dot{u})}{(\dot{z}_1 - \dot{z}_2)} & \text{if } (\dot{z}_1 - \dot{u}) \cdot (\dot{z}_1 - \dot{z}_2) \geq 0 \\ d_{min} & \text{if } (\dot{z}_1 - \dot{u}) \cdot (\dot{z}_1 - \dot{z}_2) < 0 \end{cases} \quad (5)$$

Figure 3 shows the simulation results for a groundhook controlled axle-suspension. To compare the results the passive curve that was shown in Figure 2 is also shown in Figure 3. The groundhook-controlled suspension exceeds the spring deflection limit for low damping values. For higher damping values an improvement of driving safety can be seen. The dynamic wheel load factor is reduced by 4 %. At the same time the chassis acceleration is increased resulting in a comfort loss of 8 % compared to the best passive value without exceedance of the spring deflection limit.

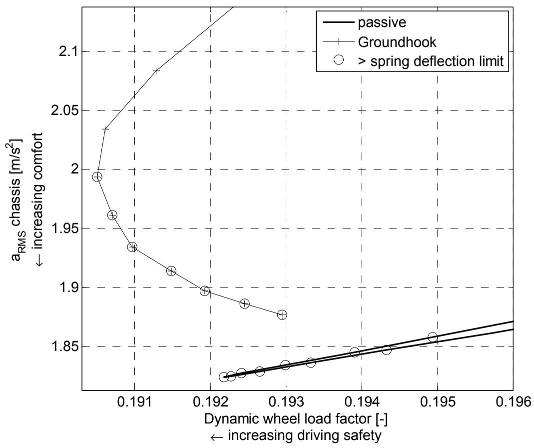

Figure 3: Comparison of passive and groundhook-controlled suspension on the ISO 5008 rougher track.

4.3 Combined control

If either a skyhook or a groundhook control is used on the rougher track at 5 km/h only one of the two objectives can be improved while the second objective deteriorates. This behaviour can also be observed on different tracks like the ISO 5008 smoother track. Therefore a combined control of the axle suspension together with the cabin suspension was tested using the model in Figure 1 on the right. The axle suspension control algorithm's objective was to reduce wheel load fluctuations (groundhook) while the cabin suspension algorithm was focused on the reduction of cabin acceleration (skyhook).

Figure 4 shows the comparison of a passive cabin and axle suspension on the ISO 5008 smoother track at 10 km/h where cabin damping values were set for optimal comfort (thick solid line). The thin solid line shows different setups of combined skyhook-groundhook-controlled suspension systems. The point marked 'OS' uses settings that are optimal for safety while 'OC' denotes the optimal comfort point. Between those two points the suspension properties can be set freely according to the main focus of the suspension setup. That way it is possible to find setups that are more comfortable and safer than the passive suspensions at the same time. It should be noted that the degree of improvement depends on the dynamic behaviour of the actuators used. This simulation results show the optimal values. Different combinations of controlled suspension systems are possible. For example a combination of a skyhook chassis suspension and a skyhook cabin suspension can help to further improve comfort at the cost of road holding.

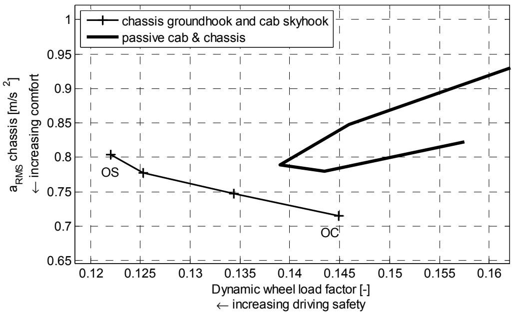

Figure 4: Comparison of passive cabin and axle suspension and skyhook-controlled cabin suspension with groundhook-controled axle suspension on the ISO 5008 smoother track.

5 EXPERIMENTAL SETUP AND RESULTS

Experiments were carried out using a modified Mercedes Benz Trac Turbo 1600 ('TUB-Trac'). The tractor is equipped with a hydro-pneumatic suspension at the front and the rear axle. The cabin suspension consists of four hydro-pneumatic elements. The damping can be modified by varying the orifice of electronically actuated proportional valves. Acceleration sensors measuring the movement of the vehicle are fitted at each wheel, all four corners of the chassis, the cabin and the seat. They are used to deliver data for the control algorithm as well as for measuring the driving comfort. Pressure sensors at the hydraulic cylinders of the chassis suspension are used to determine the resulting force at each cylinder. The force was added to the inertial force of each wheel to determine the wheel load and the wheel load fluctuations.

Different road profiles were tested using a four-post-hydraulic test stand. In Figure 5 a measured step response (front left corner of the vehicle) is shown for a passive chassis suspension and a skyhook-controlled chassis suspension. The root mean square value of the acceleration can be reduced by 6 % with the semi-active system.

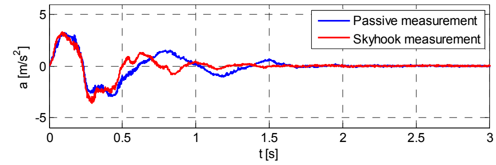

Figure 5: Step response for passive and skyhook-controlled chassis suspension.

Tests on the smoother track with the proposed combined control of skyhook and groundhook were performed. However, a combined improvement could not be shown due to the limited dynamics of the proportional valves used. More experiments with faster acting valves will be conducted in the future.

Figure 6 shows the actuator current during a test on the smoother track where both suspensions (cabin and chassis) have been set to perform the skyhook algorithm. The values of the damping and therefore the electric current are according to Equation 4 a function of the suspension velocities. The current values range between 23 % and 100 %. High values represent an open valve while the value zero represents a closed valve. Passive tests have shown that at 23 % the suspension is nearly blocked and excitations are transmitted almost directly from the wheel to the chassis.

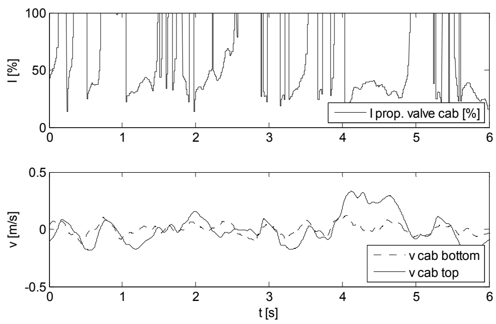

Figure 6: Actuator current and cabin suspension velocities

First tests have shown that the skyhook algorithm can reduce suspension travel compared to the soft passive setup. The comfort levels reached by the algorithm are similar to those of the soft passive setup but could not be further improved. However, as the simulations have shown, the soft damping values of a passive suspension would result in a contact of the spring deflection limiters. Therefore the soft passive setup is not suitable for all driving situations and profiles.

6 OUTLOOK ON FULL SUSPENSION TRACTORS WITH REAR MOUNTED IMPLEMENT

6.1 Different Implement Mounting Options

The advantages of the full suspended vehicle in terms of driving comfort and safety based on the dynamic behaviour of the vehicle on different road surfaces could be shown for a passive, semi-active chassis suspension and combined chassis-cab suspensions. The good dynamic characteristics also depend on the relatively small axle mass. The low mass is attributed to the fact, that the rear-mounted three-point linkage of the TUB-Trac test vehicle is attached to the suspended chassis. Today's standard tractors have an unsprung rear axle and therefore an unsprung assembly of the axle, the chassis and the three-point linkage. On tractors with a suspended rear axle like the JCB FASTRAC the rear linkage is connected directly to the rear axle, whereby the rear attached mass is more or less isolated from the sprung structure of the chassis (see Figure 7).

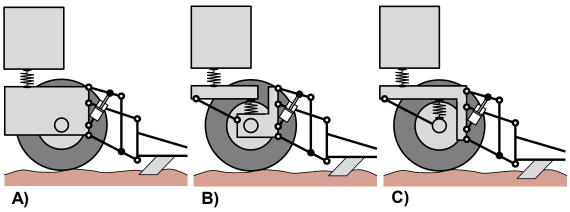

Figure 7 : Three different options to connect the rear-mounted three-point linkage to the tractor. A: directly to the unsuspended chassis, B: to the sprung rear axle, C: to the suspended chassis (TUB-Trac).

By attaching the rear mass to the sprung structure of the TUB-Trac, the entire mass forces of the attachment are acting through the chassis one the front and rear suspension and the wheels. This leads to a different dynamic behaviour of the TUB-Trac compared to standard tractors.

In addition to the mass distribution the forces that act on a rear implement like ploughs affect the vibration behaviour of the vehicle. The dynamics of the tractor-implement combination in turn affect the transferable drive power from the wheel to the ground and the operation of the attachment. Therefore the behaviour of the full suspension TUB-Trac in combination with a rear mounted implement is investigated.

The purpose is to evaluate the suitability of the current suspension design for the manifold tasks of the tractor-implement combinations. On one hand this should be done by a direct evaluation of the dynamic behaviour and on the other hand by a comparison of the characteristics with those of standard tractors. To determine the system behaviour of the tractor further laboratory test on the TUB-Trac with rear implement will be performed and calculation results of a one trac vehicle model will be evaluated.

To perform these tests the TUB-Trac was extended with an electronical controllable hydraulic system to control the rear linkage. Furthermore an "implement-simulator" was designed and built to simulate the mass characteristics of a mounted plough for the tests.

The one-trac simulation model provides the TUB-Trac with additional mass attachments as a multibody system in which the kinematic relations are described by a linear differential equation system. The kinematics of the rear linkage, the hydraulic and the hydro-pneumatic suspension system were taken into account by nonlinear relations. Furthermore, the model of a mounted plough has been incorporated and an approach was used to consider the forces that act on the plough through the depth depending ground contact.

The simulation model was validated with results of laboratory tests, so that the numerical estimation of the vehicle dynamics of the TUB-Trac is possible.

6.2 Eigenmodes with Unsprung and Sprung Axles and with and without Implement

Based on the results of first simulations the fundamental differences between the system behaviour of the tractor with an unsprung and a sprung rear axle can be shown. One approach to do this is an analysis of the natural vibration behaviour of the multibody system. Figure 8 and Figure 9 show the first three natural modes of the tractor with sprung rear axle and the tractor with an unsprung rear axle. All other eigenmodes of this model mainly relate to the movement of the cabin and the driver's seat and will not be considered due to their low impact on the dynamics of the chassis and the axles. Both models only differ by a "blocking" of the rear axle suspension. The mass distribution, the stiffness and damping characteristics are equal and represent the characteristics of the TUB-Trac.

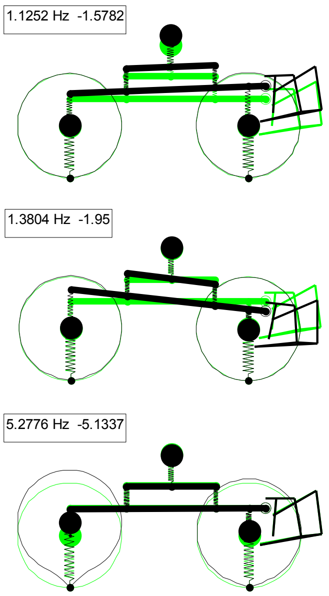

Figure 8: First three calculated eigenmodes of the tractor model with a sprung rear axle.

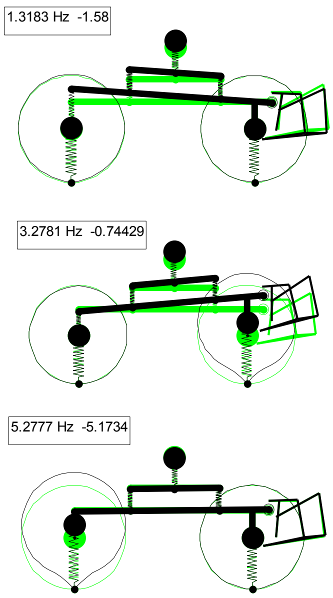

Figure 9: First three calculated eigenmodes of the tractor model with an unsprung rear axle.

The first three eigenmodes of both, the tractor with sprung and unsprung rear axle, basically show similar mode shapes. The first eigenmode of the tractor with an unsprung rear axle essentially describes the deflection of the front part of the tractor. For the vehicle with a sprung rear axle, the first natural mode comprises a synchronous up and down movement of the tractors front and the rear. The corresponding natural frequency in case of an unsprung rear axle is, as expected, somewhat higher than that of the full-suspended vehicle. The second eigenmode of the tractor with an unsprung rear axle describes the rebound of the tail with a slight deflection of the front, which can be considered as pitching eigenmode. The second eigenmode of the full suspended tractor also shows such a pitching motion.

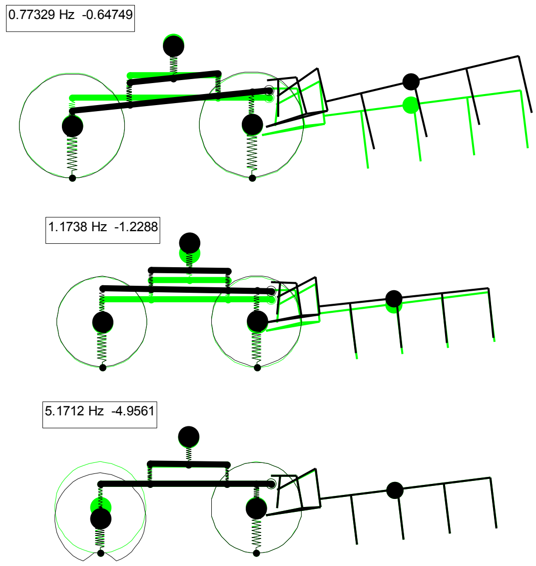

Figure 10: First three calculated eigenmodes of the tractor model with a sprung rear axle and rear mounted mass.

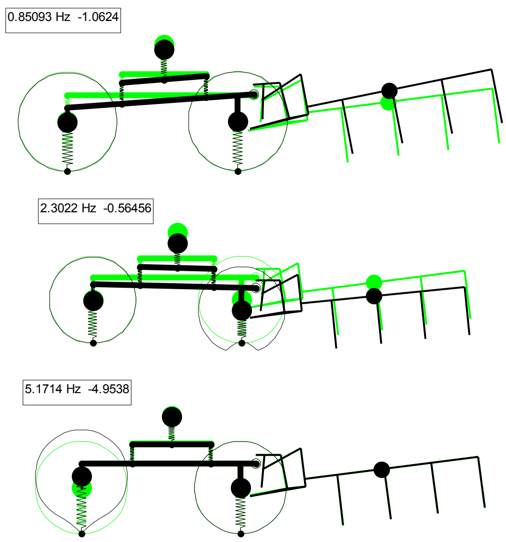

Figure 11: First three calculated eigenmodes of the tractor model with an unsprung rear axle and rear mounted mass.

The natural frequencies of the second mode differ strongly from each other, since the chassis of the unsprung rear axle tractor only uses the tyre suspension for the tail motion, whereas the natural frequency of this mode is significant higher than for the suspended axle.

The third mode mainly represents the dynamics of the front wheels. The natural frequencies of these eigenmodes hardly differ from each other.

Essential on these results is that the unsprung rear axle basically affects the second mode of the vehicle and that the natural frequency increases for a tractor with an unsprung axle. All other eigenmodes remain nearly unaffected.

By extending the tractor model with a rear-linked mass it can be observed that the natural frequencies of the first eigenmodes will reduce (see Figure 10 and 11). The percentage decrease of the first and second frequencies, based on the vehicle without mounted mass, is nearly similar for both systems. The frequency of the third eigenmode remains approximately unchanged.

Figure 12 shows the first three (four) calculated natural frequencies of the tractor with an unsprung and a sprung rear axle and with and without a rear-linked mass. The fourth eigenmode only occurs with a sprung rear axle and includes the natural vibration of the rear axle.

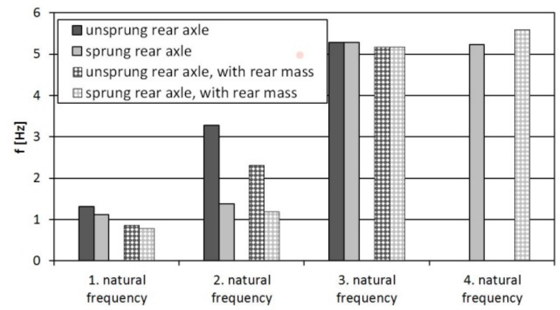

Figure 12: Overview of the first three (four) calculated natural frequencies of the tractor model showing the influence of the rear axle suspension and a rear-mounted mass.

6.3 Influence of Rear Axle Suspension and Implement on Driving Safety

To show the basic influence of both an unsprung and a sprung rear axle in combination with the attachment of a rear mass on the driving safety, the dynamic wheel load factor was calculated as a function of the vehicle speed for three different road profiles. For that the ISO 5008 rougher and smoother tracks and the numerically generated profile of a smooth highway were used to reproduce the spectrum of relevant roadways for tractors. Figure 13 and Figure 14 show the results for the tractor with a sprung and an unsprung rear axle without a rear-mounted mass.

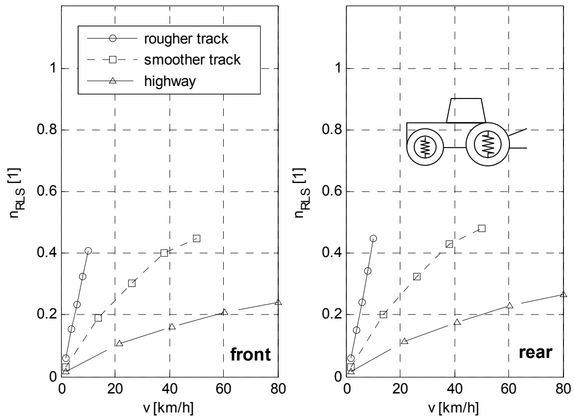

Figure 13: Calculated dynamic wheel load factor of the tractor model with sprung rear axle, without rear-mounted mass.

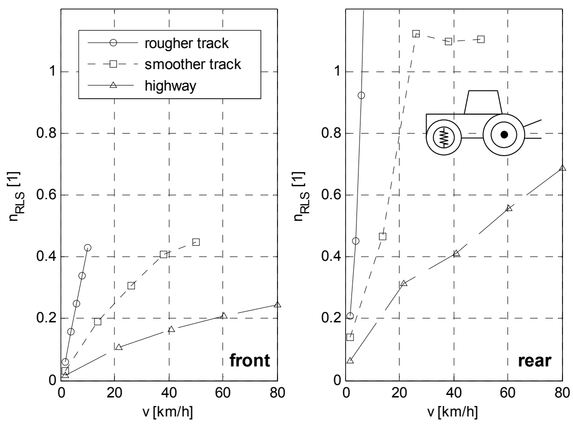

Figure 14: Calculated dynamic wheel load factor of the tractor model with unsprung rear axle, without rear-mounted mass.

The comparison of the dynamic wheel loads illustrated in Figure 13 and Figure 14 shows that the dynamic wheel load factor for the rear wheels of the tractor with an unsprung axle is significantly higher than with a sprung rear axle. In contrast, the dynamic wheel load factors for the front wheels do not differ significantly. As it was shown above, by considering the natural frequencies the type of rear axle connection does not influence the dynamic behaviour of the front chassis and the front wheel significantly. The attachment of a rear mass to the fully suspended tractor leads to a higher dynamic wheel load factor for the front wheels and a lower factor for the rear wheels (see Figure 15 and Figure 16). This can simply be attributed to the higher static load on the rear wheels and the smaller static loads on the front wheels.

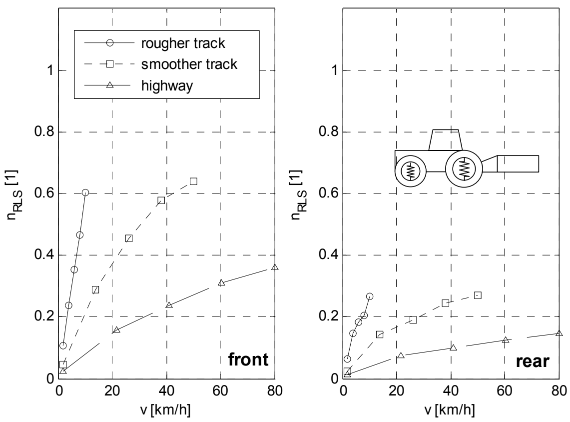

Figure 15: Calculated dynamic wheel load factor of the tractor model with sprung rear axle and rear-mounted mass.

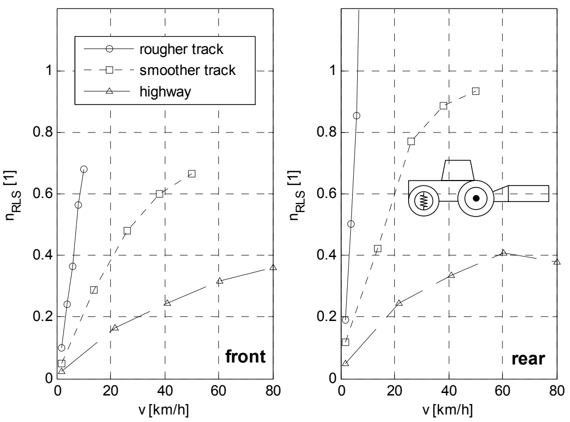

Figure 16: Calculated dynamic wheel load factor of the tractor model with an unsprung rear axle and rear-mounted mass.

Even if the calculated models only roughly reproduce the dynamic properties of real tractors, due to the clear results it can be concluded that the driving safety - on a basis of the dynamic wheel load factor - of tractors with a rear suspension is generally higher than for tractors with unsprung rear axles, regardless if a rear mass is attached or not. The same results can be seen for smooth roads like highways and for roads with very rough profiles like dirt roads.

As could be demonstrated the full suspension tractor even with an implement, has better drivability - with respect to the wheel-ground contact at constant speeds - than a tractor with an unsprung rear axle. The assessment of the suitability of the sprung rear-axle for the performance of work in agriculture is part of the current work.

7 CONCLUSIONS

As the simulations have demonstrated a semi-active suspension using skyhook or groundhook control can improve either comfort or driving safety. While passive suspensions have to be set to rather firm damping values to avoid excessive spring deflection the experiments with the skyhook controlled suspension have shown a reduction of suspension travel in combination with high comfort for the driver. The combination of two suspensions combining both strategies can help to fulfil both objectives at the same time provided that fast actuators are available. As the advantages of the fully suspended tractor can only be used if the work with an implement is not affected first investigations have been made on the influence of an implement on a tractor with rear axle suspension. As the traction efficiency of the rear wheels is dependent on a constant contact force with the ground rear axle suspensions can help to improve overall efficiency and driving safety of tractors.

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