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Payload Monitoring as One Basis for Commercial Vehicles Dynamics

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ABSTRACT

The paper gives a survey over recent developments in the field of driver support under particular consideration of the requirements of commercial vehicles. These research activities have been carried out by MAN Nutzfahrzeuge AG.

The paper mainly deals with on-line identification of the payload and its position as important parameters with respect to the vehicle's driving behaviour.

Firstly, the basic correlations between the stability limits due to braking potential, lane keeping and rolling over are discussed. Thus, in contrast to passenger cars, the full three-dimensional stability problem can be shown. The available input quantities for proper vehicle handling are summarized, as well as the influence of active or semiactive subsystems to these properties.

In principle, the driver is responsible for keeping the correct payload according to the legal limitation. For proper vehicle handling of trucks and truck/trailer combinations respectively, the driver also has to fit the driving speed with respect to the current payload and the suitable lateral acceleration. Additionally, the height of CG of payload above ground is a further important safety parameter for roll over warnings. Particularly vehicles with air suspension offer appropriate possibilities to estimate these parameters in a very accurate manner. Furthermore, the amount and position of payload represent additional input suitable for any safety-relevant active subsystem, such as Electronic Brake Systems and Vehicle Stability Controllers.

1. INTRODUCTION

The transportation sector tends to require continuously vehicles with higher technical performance and more and more sophisticated solutions for increasing transportation efficiency and quality. One basic reason for this tendency is the increasing amount of high-valued goods and the high time constraints in transportation, which are beside others due to just-in-time and system-supplying production concepts in the manufactoring world.
Modern truck development takes this into account by introducing optimized vehicles with best handling characteristics and additional comfort and safety features like ABS, improved air suspensions (ECAS), Electronic Damper Control (EFR), Electronic Brake Control and Anti Slip Devices (EBS,ASR), Electronic Power Steering (Servotronic), Adaptive Cruise Control (ACC) and so on.
On the other hand accident statistics are showing that most of all accidents happen because of drivers errors. Looking at accident analysises related to the lateral dynamic of commercial vehicles one will find the following main reasons for leaving the road:

- sudden course deviation, often in combination with braking and a too high initial speed
- too high curve speed
- getting on the unfortified banquet
- wrong estimation of the actual road condition and friction value
- drivers falling asleep
- a moving load

Each of these reasons may be sufficient for causing an accident but in many cases there will occure a combination of them.
To improve driving stability one of the basic information for the driver and subsequent control systems is the knowledge of the actual loading condition with the full three-dimensional position of the centre of gravity.
The following paper gives a survey over recent developments in this field carried out by MAN Nutzfahrzeuge AG during the last years.

1.1 Range of Vehicle Parameters

Looking at commercial vehicles one is faced with a numerous amount of different vehicle types like tractor/trailer and tractor/semitrailer combinations, vehicles with cargo decks, boxbody vehicles, container carriers, tippers, cus-

tomer built assemblies, bonetrucks and so on optimized for special transportation needs. Beside this large amount of vehicle variations even the parameters of one vehicle can vary very much. Between unloaded and loaded vehicle there is for example a band width from 7,5 to 40 t gross vehicle weight for semi-trailer combinations or 9 to 26 t for container carriers.
In comparison to passenger cars, where the payload is at maximum 30% of total vehicle weight, the wide range of loading conditions will result in heavy changes in vehicle driving behaviour and stability characteristics which may not be quite obvious for the driver at the beginning of a ride.

Changes in total mass will result in different longitudinal dynamics of the truck and therefore be discernible and within limits evident for the driver. But even looking at actual axle loads and the margin to their legal limits it becomes quite difficult for the driver to calculate the correct values. So much the more it will be more difficult for him to rate the complete loading status with respect to the height of the centre of gravity, which may vary between 1,1 meter for a partly loaded vehicle and may end up at 2 meters or more under worst case conditions for the fully loaded truck.

Especially with the increasing number of container transports the relevance and need of additional information and warnings for the driver may rise due to the lack of information on the stacking of the goods inside.

1.2 Loading of Commercial Vehicles

The following types of loading can be distinguished:

- mixed goods without additional fixation
- paletted goods
- dispatch boxes (ready made, fixed or loose)
- lying or stacked goods without fixation
- stacked goods with fixation (single or double level trailers)
- hanging goods
- containers with unknown load distribution
- bulk material
- fluids or gas in tanks
- moving goods (concrete mixers, animals, etc.)

All these different kinds of vehicle loading can't normally be influenced by the driver and make it necessary for him to adapt his speed and driving style.

Concerning the influence on the vehicle dynamics we have to distinguish the following basic characteristics:

1. Limit of maximum tolerable lateral acceleration determined by danger of load damage or loss of goods
2. Risk of rollover due to exceeded lateral acceleration determined by maximum lateral vehicle stability and actual road conditions (friction limits)
3. Latent risk of rollover triggered by inherent dynamics of loading

As regards item 2, the rollover stability of the vehicle can be described by the following vehicle parameters which are also given in figure 2 and will be discussed later on:

- Wheel base and roll centre height
- roll stiffness
- spring and damper tuning

and load dependent values like:

- total mass and centre of gravity
- momentum of inertia of loading.

Figure 1 shows the bandwidth of possible positions of the centre of gravity (CG) due to tolerable front and rear axle loads.

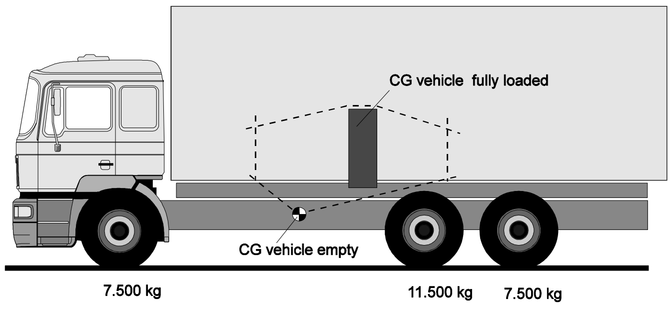


Figure 1: Range of tolerable CG

Beside this tolerable range there exists a wider range as a result of daily loading reality depending on loading and unloading stops.

The limits of maximum tolerable lateral accelerations vary between 2-3 m/s^2 with respect to not fixed goods, 3-4 m/s^2 for bulk goods up to 6-6,5 m/s^2 as rollover limit for modern truck/trailer combinations with low to normal height of centre of gravity and nearly stationary longitudinal and lateral acceleration conditions. Exceptional cases result particularly for higher CGs and moving goods with limits between 3-5 m/s^2. In these special cases, where vehicle reactions may occur quite suddenly and unexpected for the driver, information on loading conditions, warnings and in some cases active controller reactions are to be aspired in time before critical situations occur. On the other hand this leads to high demands on the quality of the payload monitoring system.

1.3 Driver Responsibilities

Before starting the ride the driver has the responsibility to check the proper vehicle condition (brakes, lights, tyre pressures, engine status etc.). Moreover, he is obliged to check the payload, the total weight and has to ensure that the maximum axle loads are not exceeded.
For this duty he can make use of the freight papers and weight declarations and if available he may drive on a weighbridge.

For estimating the vehicle´s dynamics he will get some information out of the handling characteristics while driving which gives him an idea of the loading condition, especially the eccentricy and height of the centre of gravity.

All these informations will help the driver to adapt his speed to the road and traffic conditions with respect to vehicle handling limits and braking potential.

1.4 Driving Stability

The term "driving stability" is usually defined as a general characteristic of a driver-vehicle-road system, where "the vehicle is to stay within a given driving state at any time". The borders of this area are given by the lane itself and by the road users, as well as by possible obstacles. The vehicle's dynamical state **x**(t) is described by its current position and velocities.

For commercial vehicles, particularly for heavily loaded trucks, there exists a further stability failure in terms of overturning. This reason of stability loss is closely related to the remaining longitudinal and lateral motions of the vehicle so that *all* motions have to be taken into account at the same time. Due to this fact any simplified investigations in pure lateral dynamics are no longer useful. Contrary to the efforts in passenger car's dynamics the full spherical consideration and modelling of trucks is required for advanced driving dynamics.

Hence, any early information and advice on safety-margin-related issues may help the driver to start the appropriate driving operations to maintain the stability and controllability of the truck at any time.

The input quantities necessary for a successful and predicting driving stability evaluation can in principle be classified as

a) Vehicle motions **x**(t)
b) Friction μ(s)
c) Geometrical road properties

where a fixed relation between the time t and the distance s exists.

Generally, the vehicle's motions depend on the vehicle's dynamical parameters in addition to the disturbation and control inputs.

Typically of commercial vehicles, the payload mass m_L and its position vector $\mathbf{p}_L$ (particularly its height coordinate h_L) have a strong influence on the stability margin. This is why a reliable driving state estimator requires in practice the automatical identification of payload at the beginning of each drive.

ad a) Vehicle motions
Concerning the motions of a commercial vehicle we have to distinguish between

- variables with direct influence on stability margin and
- additional dynamical variables as input into the observer (for state observation use only).

Not all of these time dependent quantities can be measured under practical (serial) conditions. However, the following signals are well qualified for a reliable on-board monitoring:

Wheel speeds ω_i , i=1, 2 ... N_{wh} (available from ABS signal)

Longitudinal and lateral chassis acceleration a_x', a_y',
where ' refers to chassis fixed coordinates

Relative roll angles $\Delta\phi_f$, $\Delta\phi_r$ between axles and frame
where f stands for front, r is for rear

Yaw velocity ω_z
Steering wheel angle δ_S

The remaining properties of interest such as the

Dynamical wheel loads F_{zi} , i=1, 2 ... N_{wh}

are hardly measurable. Therefore they better are estimated by means of a dynamical state observer.

Any autonomous on-board monitoring/estimation system operating by the observation of the vehicle's **dynamical reactions** can only perform a short term prediction of the ongoing dynamical process.

ad b) Friction monitoring
Autonomous friction monitoring systems provide at best a **snap-shot-information** on the current road-tire contact. Any further predetermination of friction-related warnings needs an input from an external host (environmental service).

However, the latter must be considered as a longterm goal of realization due to the necessary fine degree of resolution of fast changing friction data over all the supported roads. One can resume that the only realistic alternative in friction detection is restricted to an autonomously working friction monitoring system (or a combination of existing systems) in the near future.

ad c) Geometrical road properties
The predictive information on the geometrical lane trends

Road slope $\beta(s)$
Road inclination $\alpha(s)$
Road curvature $R(s)$

are important input quantities for any correct information on a proper driving mode (also see below). This information can be available from a digital road map, which is nowadays common for in-vehicle navigation systems.

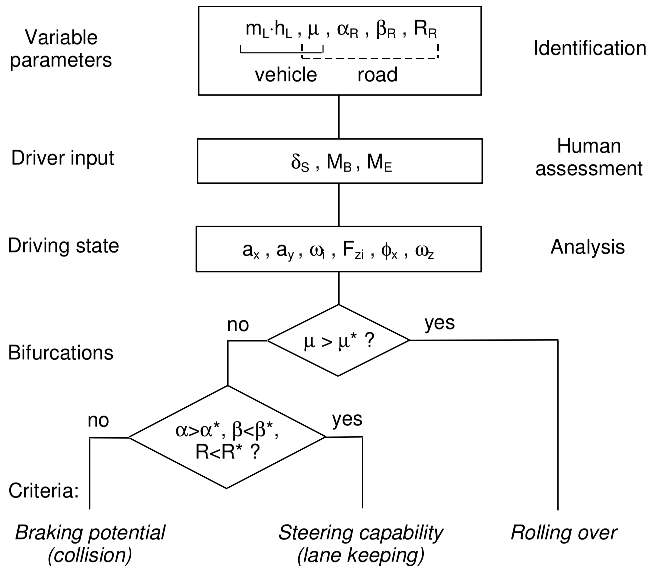


Figure 2: Basic scheme of the driving stability of commercial vehicles

Notations:

m_L	mass of payload	a_x	longitud. acceleration
h_L	height of payload	a_y	lateral acceleration
μ	road-tyre friction	ω_i	angular wheel speeds
α_R	lateral road inclination	F_{zi}	dynamic wheel loads
β_R	longitudinal road slope	ϕ_x	roll angle
R_R	curve radius	ω_z	yaw rate
δ_S	steering angle		
M_E	engine torque		
M_B	braking torque		

Figure 2 shows the discrimination of the basic driving stability modes for commercial vehicles. In opposite to passenger cars commercial vehicles will roll-over at high lateral speeds due to the height of the CG and the characteristics of their tyres. The roll-over thresholds will generally lay between 4 and 6,5 m/s^2. Not exceeding this maximun lateral acceleration the next criteria for losing stability will be the maximum deliverable forces at the tyre splitted between longitudinal and lateral demand. This leads to the distinctions between braking potential and steering capability.

All future vehicle stabilization systems for commercial vehicles will have to provide this discrimination between the above mentioned stability criteria.

2. DRIVER ASSESSMENT FOR SAFE TRANSPORT

The transport of heavy loads transfers a high amount of responsibility to the driver. As already pointed out, the driver has to adapt his driving behaviour particularly with regard to the actual payload *and* the current road conditions. In order to fulfil this task, the driver makes use of the following main input quantities:

- Visual:

- Vehicle speed
  - Roll and yaw angle
  - Vehicle position and distance
  - Road geometry

- Audio-visual:

- Texture of road and weather
  - External and internal warnings

- Haptic:

- Steering angle and steering torque needed

- Kinaesthetic:

- Longitudinal, lateral and vertical acceleration
  - Yaw acceleration.

In contrast to the assessment of the road and weather conditions, there is no direct sensor for the actual magnitude and position of the payload except some a priori informations (if available so far). Thus, the experience of the driver allows the more or less good estimation of the payload and its position based upon the above listed observations.

On the other hand, more and more improvements of the vehicle's components and active subsystems will influence the subjective driver feeling, as there are:

Component	influences:	implies :
• Tyre	Straight driving behaviour	Safety feeling
• Chassis	Frame stiffness	Good ground contact, riding comfort
• Servo steering	Steering feedback	Good ground contact
• Suspension control	Roll angle, static wheel travel	No change of payload

Hence, an electronic on-board payload monitoring system may be very helpful

1. as supportive driver information and
2. as additional input for any safety relevant active system(s).

3. IDENTIFICATION OF PAYLOAD

3.1 Levels of Payload Identification

In particular, vehicles with air spring suspension offer some appropriate possibilities to estimate the magnitude of the payload, as well as the position of its centre of gravity (CG) in a very accurate manner. In relation to the available vehicle configuration, three different levels of payload monitoring can be defined:

a) Axle load monitoring and longitudinal position of CG,

b) Wheel load monitoring and longitudinal and lateral position of CG,

c) Wheel load monitoring and full three-dimensional position of CG.

The following table focusses on these levels of payload monitoring systems.

Level	System requirements	Payload monitoring
a)	Simple air spring system for front, rear and trailer axles, semitrailer: only for tractor rear and trailer axles.	Static: Payload and longitudinal CG information and warnings while loading.
b)	Same as a), but independent left/right air spring system for rear axle(s) .	Static: Payload and 2-dim CG information and warnings while loading.
c)	Same as b)	Static: Same as b). Dynamic: Payload CG height.

Table 3.1: Basic scheme of payload monitoring

Typically of the payload identification, the highest level c) requires a dynamic solution in monitoring the payload height. Therefore, the identification process needs a definite, more or less long time period for the computation of the current CG height. This means, the driver will receive this information earliest *after* starting the drive. However, this should be sufficient in order to prevent roll over during the current transport.

The features of an air spring based payload identification system are shown and discussed in the following section.

3.2 Testing Results

The linearity of the relation between air spring pressure and the weighed axle load is shown in **figure 3.1** . The curves result from a static loading test on a tractor-semitrailer combination, where FA and RA denote the front and rear axle of the tractor, and TA denotes all the three axles of the trailer. The loading was done stepwise from empty to 14 test weights of 1.73 tons each, followed by stepwise unloading. Thus, the numbers given on the test weights denote the loading/unloading sequence. The diagram shows the quite good linearity of the pneumatic spring stiffnesses, which can advantageously be applied in the identification process. Furthermore, due to the air spring regulation system the hysteresis (caused by internal friction in the suspension system) is quite small.

The identification results of this loading test are shown in **figure 3.2** . As compared with the measured axle loads, the on-board identification provides quite

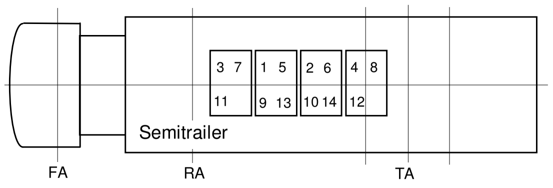
accurate values within a range of 100 kg RMS. However, the possible deviations due to serial production have not been taken into consideration in the described basic results.

Next, the second level of payload monitoring is considered, which deals with the estimation of the wheel loads left/right in order to identify any lateral vehicle load. There is an important condition for solving this task: the vehicle must be equipped with an *independent* air spring system on the axle to be identified (that is mainly the vehicle's rear axle). In the following, some validations of a 19t MAN 4x2 truck are discussed.

When the load testings were performed, the test loads of 1 ton each were stepwise loaded accordingly to the figure, where the given numbers again denote the sequence of loading. The load is situated in a lateral right distance of 0.5 m off centre. **Figure 3.3** shows the air pressure - wheel load relation for this case of lateral load. In contrast to the central load, a remarkable hysteresis can be detected, caused by the angular distortion of the suspension system. However, this load/unload hysteresis can partially be compensated when using the air pressure *differences* in order to make an identification design. Furthermore, the overload of the right rear wheel is clearly seen on the diagram, where the axle reaches the bump stops.

The results of this test are shown in the **figures 3.4.** In spite of the above mentioned hysteresis, the axle load identification remains very accurate. Again the accuracy of the identification is within 1 percent of the payload weight, however, in the area of bumper contact (overloading) the estimation has failed. Anyway, the reach of maximum air spring pressure is a clear indicator for a warning signal against lateral overload.

The single wheel identification of the rear axle is done by an extended algorithm. Thus, the procedure is qualified to estimate the wheel load within a range of 3 percent of actual payload. The identification fails in the range of the bumper contact again.



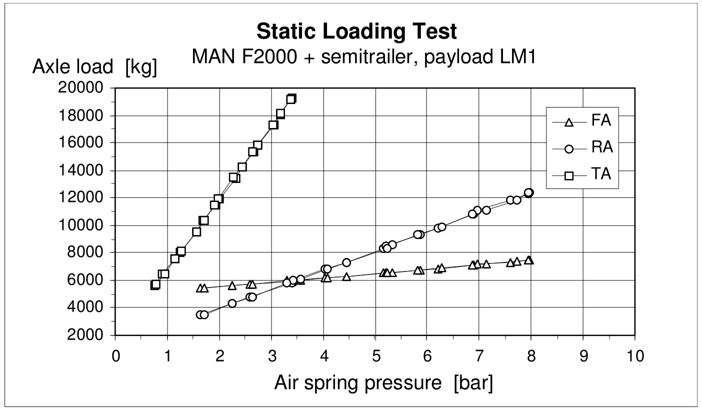


Figure 3.1: Pneumatic stiffness of the air springs

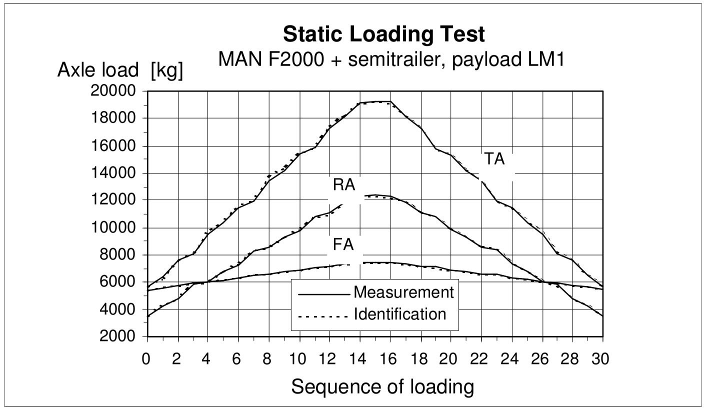
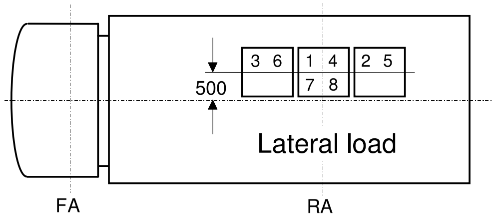


Figure 3.2: Comparison of axle loads: approach - measurement



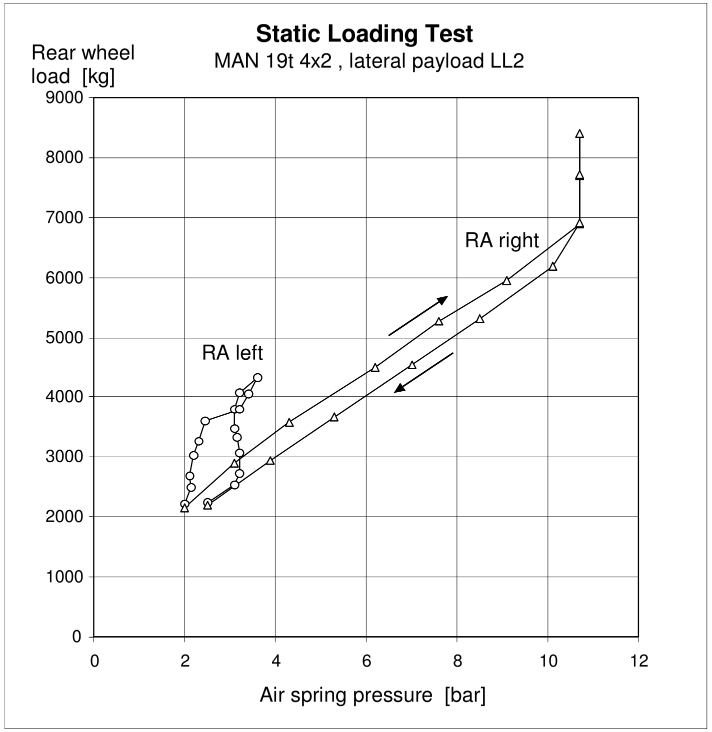
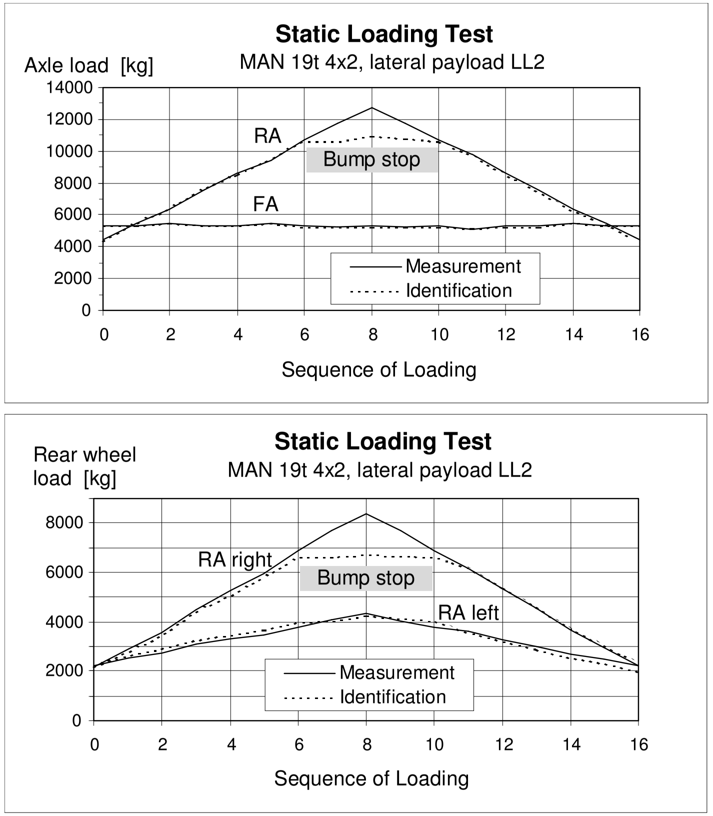


Figure 3.3: Pneumatic spring stiffness at lateral load



Figures 3.4: Comparison of axle/wheel loads: approach - measurement

Finally, the third level of payload identification - the detection of the load height - is described. As remarked above, this information is a very important one for a protective driver information as well as for an input quantity into safety relevant active subsystems.

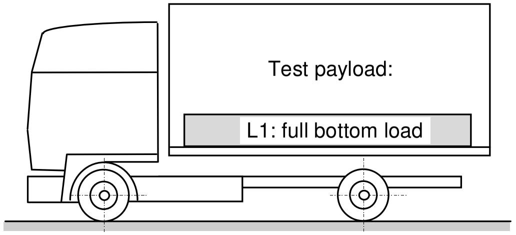
The dynamic equilibrium between any applied roll torque and the torsional axle stabilization identifies the current state of the vehicle's roll motion. Therefore, the acting roll torque can be observed by the difference of the air spring pressures left/right. The disturbing rolling torque is caused by the product of load mass, its height above the roll centre and the lateral acceleration with respect to the load-fixed axis system. Hence, the rolling torque includes the disturbations due to the centripetal acceleration while cornering as well as the side inclinations of the road.

When using the air pressure differences for the observation of the acting rolling torque, there is one basic problem to be handled, see **figures 3.5** . The example shows the result from an accelerated/decelerated cornering test with a heavy 4x2 truck under full load. Due to the acting pneumatic stabilization control, the air pressure difference is continuously increasing while cornering. This control influence must be carefully compensated in order to perform a reliable identification of the payload height, see the second diagram. Thus, the constant value of payload height can be identified after a few seconds time of cornering.

Figure 3.6 shows a comparison of different load positions at the same test truck. The following three testing loads have been considered:

- Truck with empty cargo deck,
- Full load at the bottom of the cargo deck,
- Full load in high position.

First, the diagram shows a quite sufficient result of the payload identification process for the above mentioned variants. There remains a short period of convergence in the start up phase of cornering. Second, the typical behaviour of an experienced driver can be seen in the way he has been adjusting the lateral acceleration to the actual limits. Thus, the additional information about the magnitude of the load and its height may be a valuable support for the driver, either directly displayed or as input into any supportive active subsystem.



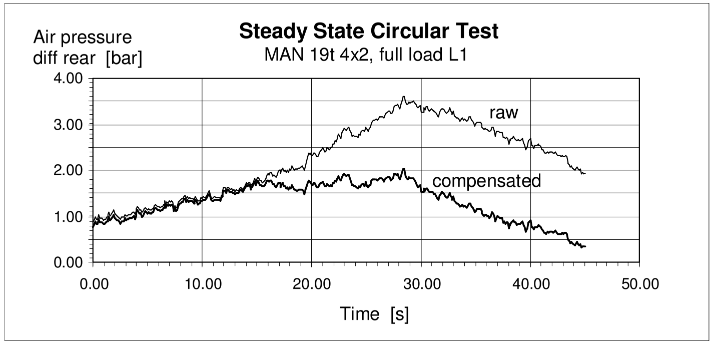


Figure 3.5 a: Compensation of roll stabilization control

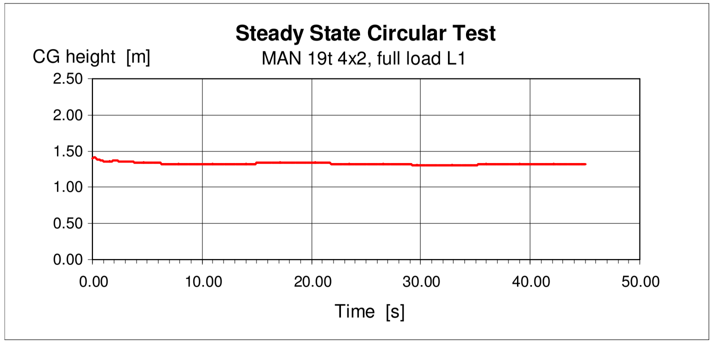
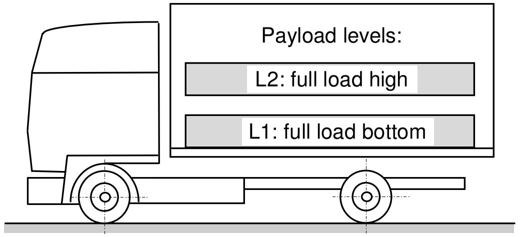


Figure 3.5 b: Identification of payload height



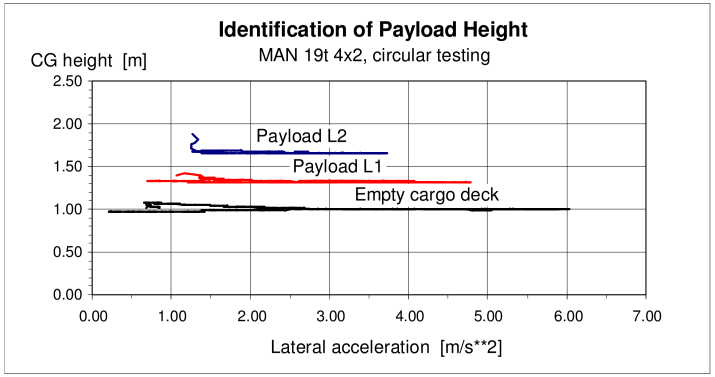


Figure 3.6: Identification of payload height

3.3 Remaining Problems

Even thought there are interesting ways for an effective and accurate monitoring of the current payload, some remaining problems have to be indicated. These problems, which are listed below, should be discussed with regard to appropriate solutions for the further serial application.

- Accurate payload and CG monitoring have had restricted to air sprung vehicles or vehicle-trailer combinations respectively. The corresponding monitoring systems for leaf sprung vehicles need total different identification methods, where particularly the accuracy and the robustness should be taken into account.
- Static tenseness of the chassis and suspension system may cause wrong identification results. This can be observed during loading a truck under locked hand brake. Due to some kinematic effects, the vehicle becomes tensed, see **figure 3.7** . Once the vehicle's brake is being unlocked, the right position of equilibrium is reached immediately. Further effects of tenseness may occur due to uneven stands, which cause internal distortions of the chassis frame (**figure 3.8**).

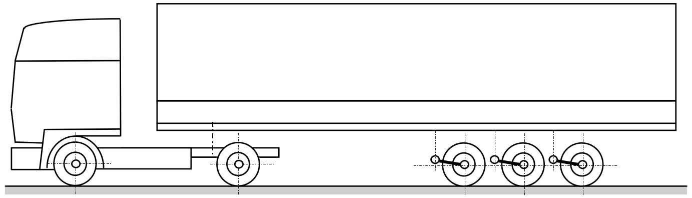


Figure 3.7: Semitrailer with inclined trailing links

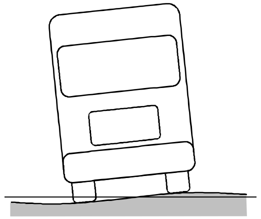


Figure 3.8: Truck distortion on uneven road surface

- The multitude of tractor - trailer/semitrailer combinations requires that each vehicle unit must *autonomously* identify and pass on its axle loads.
- Finally, it should be mentioned that the on-board identification of movable payloads (e.g. oscillating or fluid loads) has not fully been considered yet.

4. CONCLUSIONS

Due to the increasing motorization and the permanent improvements in chassis and suspension design of commercial vehicles, as well as the improved suspensions of the driver's cabins, the additional driver information concerning the actual loading state becomes relevant to an increasing degree. These information are particularly useful, if they are already available during the period of loading. Furthermore, additional information about the magnitude and the position of the payload during the transport can be used as input quantities into any safety relevant, electronic subsystem.

First, the present paper deals with some general aspects of the payload in commercial vehicles and its identification by the driver. In accordance to that, it focusses to different levels of supportive payload monitoring:

- Axle loads and longitudinal position of CG,
- Wheel loads and longitudinal and lateral position of CG,
- Wheel loads and full three-dimensional position of the payload.

Based on some recent testing results, the effectiveness and accuracy of the selected methods can be shown. However, there remain some problems which need further researches for getting solved. In particular, for the successful introduction of payload monitoring systems, it will be necessary to define the interfaces between both the autonomous systems at tractor and trailer.

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