Simulation-based investigation of active trailer stabilization for use in utility trailers

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Abstract. In contrast to caravans, utility trailers have a high variability in geometry and weight (different loading). This is a major challenge in the development of a system for active stabilization if the trailer starts snaking. For this task, simulation is a very useful tool. The article first describes the step-by-step process of the targeted selection of trailers for the following simulations by using theoretical considerations based on the single-track model. Subsequently, the performance evaluation, carried out by means of dynamic simulations in the framework DYNA4, is explained. The study also includes a sensitivity analysis in order to identify dominant influencing parameters. Finally, some selected simulation results are presented.

Keywords: vehicle dynamics simulation, trailer stabilization, pendulum vibration, utility trailer, sensitivity analysis

1 Introduction

An increasing speed of car-trailer combinations may result in pendulum oscillations (so-called snaking), i.e. oscillations of the trailer around the coupling point. This can be triggered by a steering action or an external force, e.g. gust of wind on trailers with a large side attack area. The tires provide a self-aligning and damping torque [1]. If this oscillation does not decay, the system has reached its critical speed v_k. If the car-trailer combination is commuting at supercritical speed (see Figure 1), the situation is usually uncontrollable for the driver, as the trailer keeps rocking up and ultimately serious accidents can result.

Al-KO already developed the Al-KO Trailer Control (ATC) in 2006, which senses the lateral acceleration on the axle and actuates the Bowden cables depending on defined amplitude thresholds. By aimed slowing down the trailer, the system is stretched again and the speed is lowered below v_k. The oscillation amplitudes decay immediately, as shown in Figure 2, and the car-trailer combination is stable again.

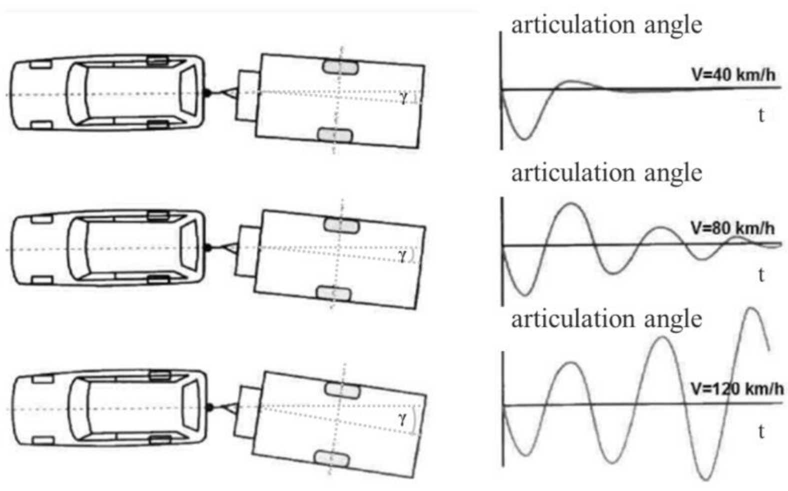

Fig. 1. Time course of the pendulum oscillation at different speeds without ATC intervention

In contrast to the much more complex ESC systems the lateral acceleration is the only input quantity of the ATC. The desired braking force is preset for different weight classes. Additional parameters or sensor signals are not necessary. If the trailer begins to oscillate (e.g. due to crosswind or ruts), the system can trigger faster than the ESC of the towing vehicle due to the detection of the oscillation directly on the trailer axle. If the lateral acceleration has fallen below a defined threshold again, the braking intervention is terminated. The ATC is currently only used in caravans, as there are additional challenges when adapting to utility trailers. On the one hand, there is a very large number of possible design variants, so that the geometric influencing variables scatter strongly. Additionally, in the case of utility trailers, a significantly larger loading delta is to be expected contrary to caravans. In the further development of the ATC for utility trailers, these questions were therefore already worked on in advance virtually via an investigation in cooperation with the TESIS GmbH and the simulation framework DYNA4, in order to be able to develop more targeted and save experiments based on these findings.

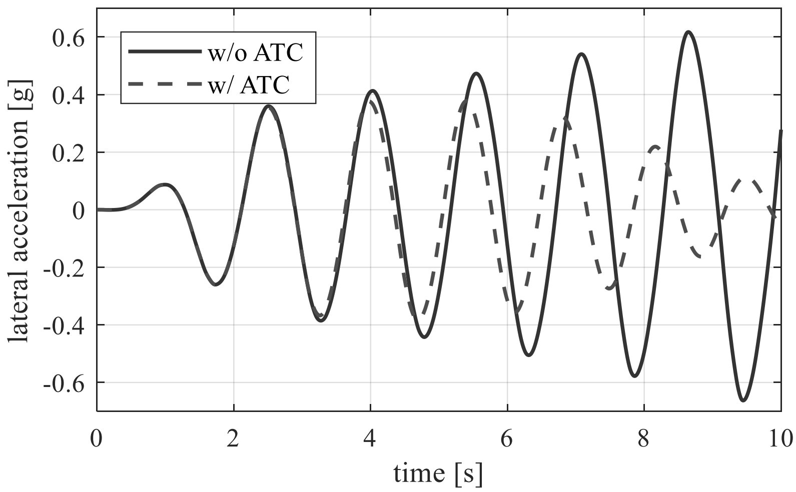

Fig. 2. Lateral acceleration with and without ATC intervention at supercritical speed

2 Challenges in the further development of the ATC for utility trailers

2.1 Variety of construction and variance of geometrical dimensions

Unlike caravans, there is an extremely high variety of variants in utility trailers, both from the chassis geometry as well as possible superstructures and thus also load distributions. These points lead to a different oscillation behavior of the trailer.

2.2 Large loading delta

Caravans have a relatively low loading delta. The customer buys the ATC approved for its weight range, where a fixed operating force is applied so that the wheels do not overbrake (i.e., the wheel does not lock and loses its cornering force). Since the actual friction coefficient is not known, the design is carried out with $\mu = 0.3$. This corresponds to a very wet to snow covered road. In simulations it has been shown that at lower traction a pendulum process at critical speed immediately merges into a transverse motion and the trailer can no longer be stabilized, regardless of the set operating force

$$F_{actuation\_max} = \frac{\mu \cdot m \cdot g}{\rho \cdot \frac{1}{r_{dyn}}} \tag{1}$$

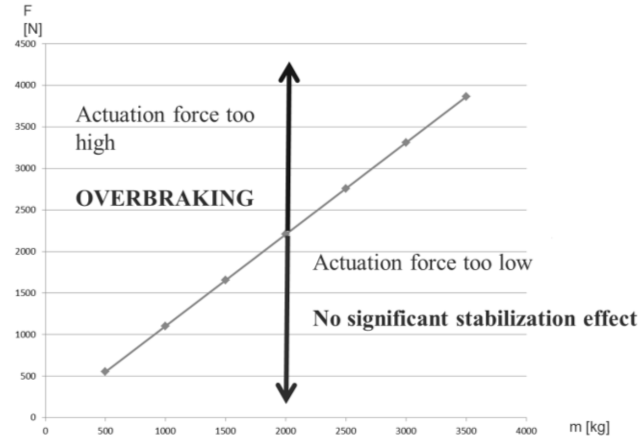

Fig. 3. Maximum permissible actuating force as a function of mass at $\mu = 0.3$

For utility trailers, there is a significantly higher loading delta, which is why a fixed set operating force is no longer effective here. In Figure 3, starting from (1), the maximum permissible actuation force is shown as a function of the trailer mass *m*. In addition to the friction coefficient μ, the brake characteristic value ρ, the dynamic tire radius r_{dyn} and the gravitational acceleration g also enter here. If an actuating force is too high, it will lead to overbraking (high critical state), whereas a low actuating force leads to a no longer sufficient stabilizing effect. The permissible deviation from this ideal line considering different trailer geometries has been investigated within the simulations.

3 Preselection of trailer variants for the simulations

In order to select from the multitude of possible trailer variants those that should be considered in the subsequent vehicle dynamics simulation, a stepwise preselection was performed.

3.1 Estimation of self-damping behavior

The simplest modeling of the pendulum oscillation represents the linear trailing model shown in Figure 4, whose system dynamics is given by

$$\left(m_A \cdot (l_D - l_A)^2 + \theta_{Z,A}\right) \ddot{\gamma} + \; c_{S,A} \, \frac{(l_D)^2}{v_K} \dot{\gamma} + c_{S,A} \cdot l_D \cdot \gamma = 0 \qquad (2)$$

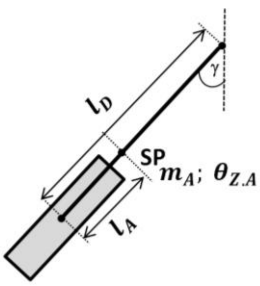

Fig. 4. Linear trailing model

A lateral deflection of the trailer results in a self-aligning and damping torque by the tire [1, 2, 3]. According to [1] the damping factor can be calculated as follows:

$$D = \frac{1}{2 \cdot v_K} \sqrt{\frac{c_{S,A} \cdot l_D{}^3}{\theta_{Z,A} + m_A \cdot l_D{}^2 - m_A \cdot l_A{}^2}} \tag{3}$$

The higher the speed v_K, the lower the damping. A large drawbar length l_D, a low yaw moment of inertia $\theta_{Z,A}$, a low mass m_A, a high cornering stiffness $c_{S,A}$ and a larger center of gravity shift l_A have a positive effect on the attenuation. If the center of gravity is very close to the wheel contact point, the formula can be simplified by setting $l_A = 0$, [2, 3]. The relatively simple model concept, however, does not take into account the coupling of the masses [2], which is why the stability limit is lower in the real system consisting of towing vehicle and trailer [1]. Nevertheless, the calculation according to (3) is well suited for a first comparative assessment of different trailer and can thus be used as the first selection criterion.

3.2 Linear single track model

For further investigations of the selected trailers in chapter 3.1, Al-KO developed a linear single track model (Figure 5) of a car-trailer combination in Matlab/Simulink. In this model also an ATC intervention can be triggered optionally. To avoid algebraic loops due to the similar velocity vectors in the coupling point of trailer and towing vehicle, the coupling was modeled as a very stiff spring-damper link [4].

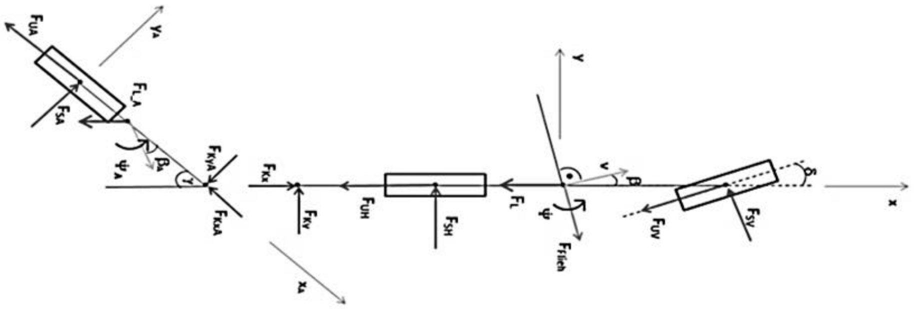

Fig. 5. Linear single track model of a car-trailer combination

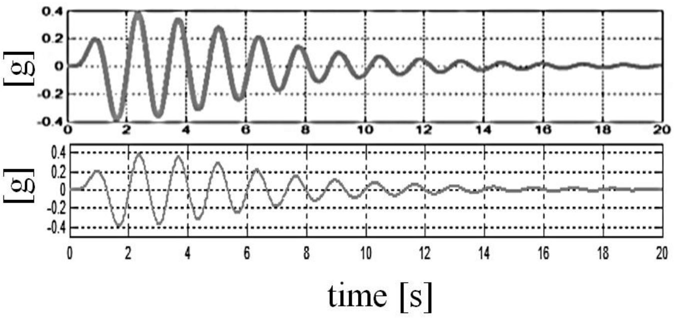

Fig. 6. Comparison of single-track model (top) and multi-body simulation (bottom) for a pendulum oscillation with ATC intervention at maximum amplitudes until 4 m/s².

As it can be seen in Figure 6, the results in this model level of detail fit, at slow pendulum processes, qualitatively good compared with the subsequent multi-body simulations [5]. Due to the linearization, the model is only reliable for slip angles up to 3° and lateral accelerations up to 4 m/s² [6, 7]. Thus, driving maneuvers with a large first amplitude of the lateral acceleration and larger steering angles can not be depicted. Therefore, lane changes as well as driving situations outside the stable range can not be assessed with this model. A further limitation is the reduction to a single track, so that effects such as wheel load shifting due to rolling motion can not be considered.

3.3 Selected trailer variants

Based on the preselection in chapter. 3.1 and 3.2, a total of 11 variants were defined for the complex trailer simulation (Figure 7 shows some variants), which differ greatly in their chassis geometry and in the superstructure and thus also in their oscillation behavior.

Fig. 7. Different trailer variants

For trailers with a loading delta, different loading variants were selected (see Figure 8), which then also have a significantly different yaw inertia and a different center of gravity.

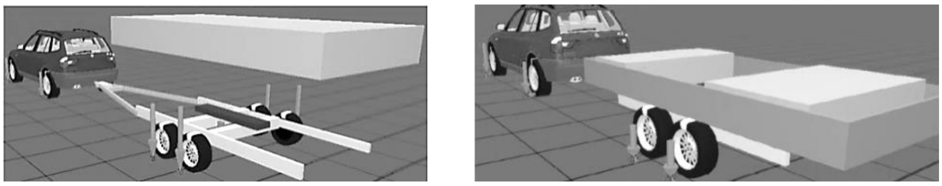

Fig. 8. Two different load variants in the simulation framework DYNA4 (left: abstracted sailboat trailer, right: high loader)

In order to determine the necessary accuracy for the mass estimation, various brake sizes were also used, which have a different brake characteristic ρ.

4 Characteristic rating by vehicle dynamics simulation

In order to identify development priorities and to avoid costly prototype tests, characteristic properties with respect to behavior in critical pendulum situations should be assessed with the help of a complex car-trailer simulation involving the ATC system. For this purpose, models for different trailer configurations must be set up in a virtual test environment, test cases defined and evaluation criteria determined.

4.1 Simulation environment

The simulation software used must provide modularity in the modeling and automated implementation of variational calculations of defined test cases with subsequent result processing and enable the visually supported examination of the system behavior. Using the simulation framework DYNA4 [8], these multi-layered requirements can be resolved. In this way, different characteristics (with regard to physics and system logic) of the electromechanical ATC system can be easily managed and exchanged in the model.

4.2 System modeling

In order to obtain meaningful results, the focus should be generally on the use of a valid overall model. This includes a correct depiction of the system dynamics with appropriate parameterization of the physical properties [9]. In the employed investigations, an SUV-typical data set was used for the towing vehicle. A partially limited data situation can be counteracted, for example, by using the tire model TMeasy [10].

An elementary part, however, is the implementation of a valid model of the electromechanical ATC actuator. In this case, a DC motor model is actuated by a PWM current controller whose power is delivered via the downstream mechanism consisting of gear, spring and Bowden cable to the brake system of the trailer. In addition to the manufacturer's specifications, a component test bench for the identification of electrical parameter values of inductance and resistance was used as data source. This allows a detailed and highly accurate mapping of the temporal force build-up behavior, which is of particular importance in the evaluation of sensitivities of individual system properties.

4.3 Test procedure

The dimension of the test scope is defined by the aforementioned trailer configurations as well as by the environmental conditions, the driving condition and the application of the ATC system. The latter is varied from an abstract angle of view by the amplitude of the brake actuation force resulting from theoretically different variations in mass based on (1). The definition of the driving task initially results from the critical speed according to ISO 9815 as a function of the lateral acceleration level for each trailer. Based on this, two basic maneuvers are defined, which differ in the type or the temporal extent of the pendulum oscillation. On the one hand, a maneuver was chosen which, when excited with a sinusoidal steering impulse and the associated moderate lateral acceleration level, leads to a slowly rising pendulum motion of the trailer and thus to a tendency for a later stabilization intervention. On the other hand, with a stronger steering pulse, and thus higher lateral acceleration amplitude, a faster braking intervention is provoked. These two driving situations are carried out at (above / below) critical speed. The environmental conditions are characterized by the friction coefficient in the contact between tire and road, which is varied in all test cases in the range of 0.3 to 1.0. Figure 9 shows the system behavior of a particular trailer configuration using the ATC system in the described driving situations and varying road friction coefficient. In particular, reducing the road friction value, effects occur that can lead to a random pendulum motion of the trailer. As a result of the combination of all test parameters, approximately 4000 simulations were finally carried out and evaluated automatically. Scalar scores help analyze the effects of various application parameters. The damping behavior or maximum values of different state variables of the trailer and towing vehicle describing the stabilization performance are decisive here.

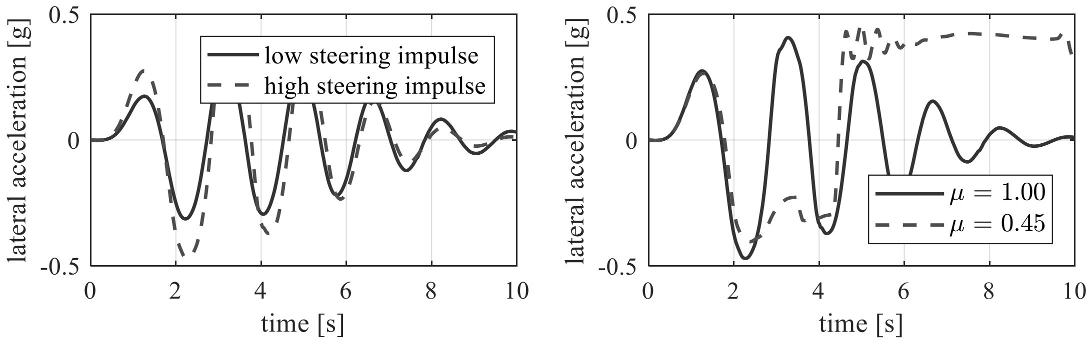

Fig. 9. Effect of different steering amplitudes (left figure) and different friction coefficients with the same trailer configuration and ATC intervention

4.4 Sensitivity analysis

Based on the results of different trailer configurations, the influence of various ATC system parameters on the characteristic values is determined in an extended analysis process. The parameter space is spanned both by the electromechanical properties such as stationary force and force build-up time as well as the system logic in the form of intervention time and braking time. A selection of the existing test cases, i.e. a combination of driving task and environment condition, is simulated with a particular set of parameter combinations. These are created depending on the choice of the method of the sensitivity measure (e.g. eFAST, Sobol). The goal is to identify dominant effects based on sensitivity measures. This task is also supported automatically by the simulation framework DYNA4. Figure 10 shows the sensitivities of the first order and the main influences as examples for a specific setup. In this case, one recognizes the clear influence of parameter B on the criterion 1, whereas parameter C exerts almost no influence on this evaluation variable. Throughout the entire range of possible setups, development priorities can be identified and the stabilization behavior targeted improved.

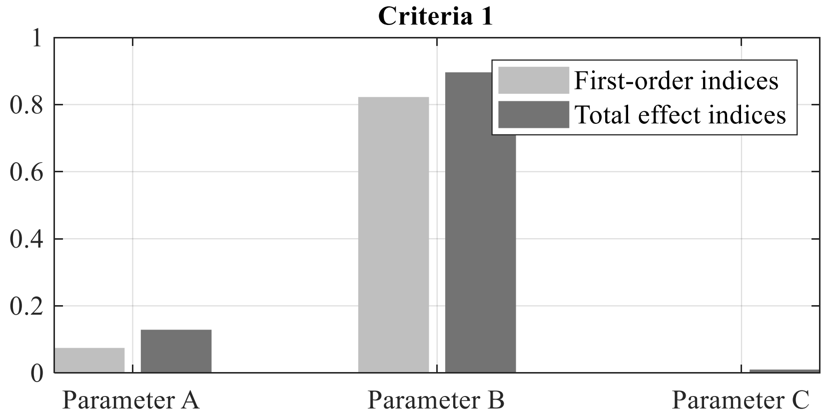

Fig. 10. Sensitivity analysis

5 Exemplary results of the driving dynamics simulation

From the numerous simulations important results for the further development of the ATC could be obtained. As an example, some results of the simulation studies are presented and explained by means of time courses.

For an ATC on utility trailers the sensing of the correct mass to calculate the appropriate operating force via (1) is fundamental. In Figure 11 you can see that the pendulum oscillation decays at ideal operating force (target intervention). However, as the operating force increases further, the amplitudes of the articulation angle increase significantly and the car-trailer combination becomes unstable.

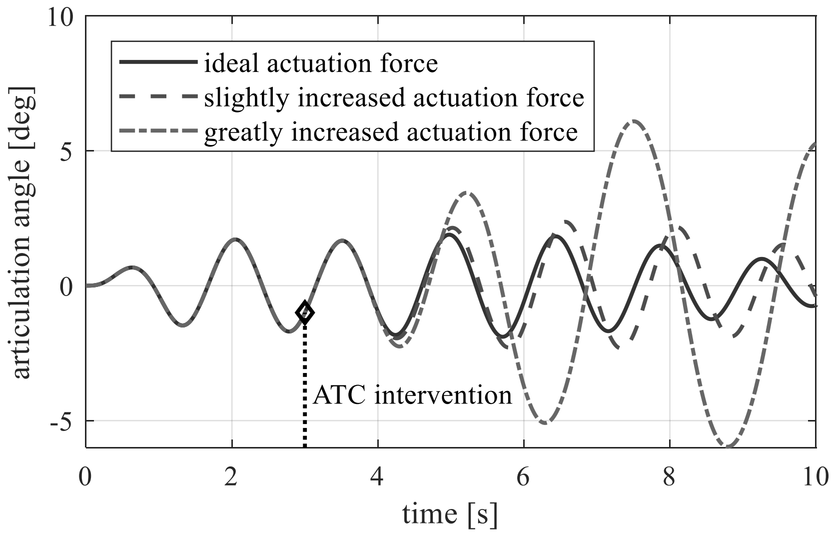

Fig. 11. Articulation angle for different actuation forces (μ = 0,45; m = 1250kg)

If one looks at the associated lateral accelerations in Figure 12, it can be seen that at the excessive actuation force a significant transverse thrust occurs, since the tire can then not build enough cornering force. By evaluating the simulations over the bandwidth of the selected trailers and loading variants, it was possible to determine the necessary accuracy of the mass determination so that an overbraking situation does not occur.

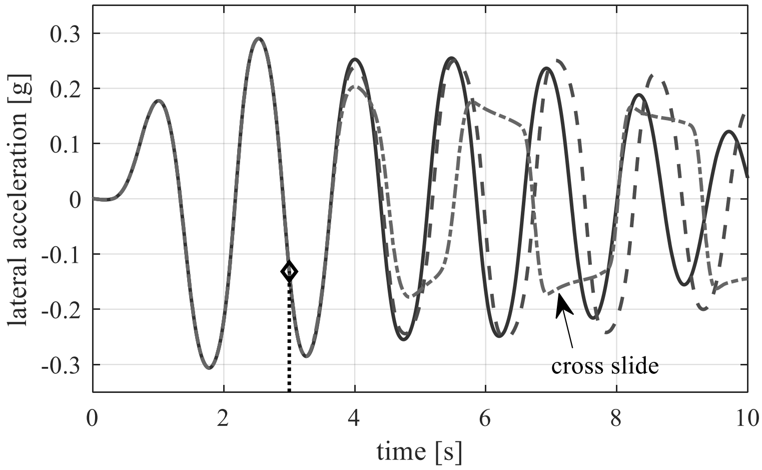

Fig. 12. Transverse movement identified by the lateral acceleration

Another important result of the simulations is the comparison of the up-swing behavior of trailers with identical mass but different geometry. In (3) it can be seen that the internal damping also depends on geometrical parameters. Since the ATC uses lateral acceleration as an input variable, the goal was to investigate whether the algorithm for detecting a critical oscillation had to be adapted for different trailers.

Figure 13 shows that two trailers, each weighing 3.5 tons, oscillated differently with identical excitation by the towing vehicle. The trailer with the shorter drawbar length swings faster and achieves higher amplitudes than the equally heavy trailer with longer drawbar length. Since the triggering algorithm should work for all utility trailers, it must be adapted according to the findings.

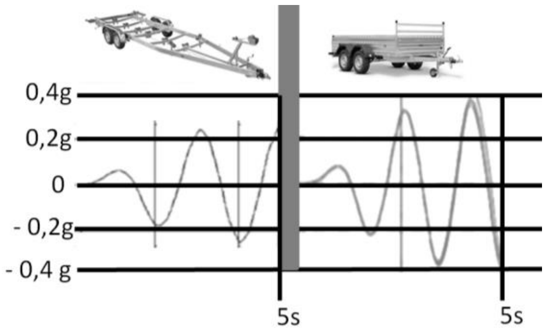

Fig. 13. Comparison of lateral acceleration during up-swing movement of a trailer with long (left) and short (right) drawbar length

6 Conclusion and outlook

Since a wide range of geometries and loading configurations could be studied and many other influencing parameters could be varied, the simulation-based assessment was a valuable tool. Based on the results, it was possible to specify the necessary accuracy for a sensor to determine the trailer mass, so that even at low friction coefficients no overbraking occurs, but a sufficiently high braking force for the stabilization is ensured. Such a sensor is currently under development. The sensitivity analysis also provided approaches for optimizing the existing detection algorithm. Due to the further developments of the ATC, for the first time for utility trailers of up to 3.5 tons, an active trailer stabilization system will be offered which adapts to the current load and thus helps to prevent accidents in critical situations in this segment as well.

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