

Active Safety of Self-Propelled Trailers: Proposal for Safety Requirements

Patrick Seiniger

Oliver Bartels

Maxim Bierbach

German Federal Highway Research Institute (BASt)

Paper Number 23-0269

ABSTRACT

Trailers are by definition non-propelled, towed vehicles. They pose resistance forces to the towing vehicle, resulting from e.g. rolling resistance, friction, air resistance. New concepts are proposed where trailers would be able to support the towing vehicle by reduction of the toeball forces, sometimes even pushing the towing vehicle. This would allow for higher traction of the vehicle combination, possibly even a higher overall energy efficiency when the required energy storage system would be distributed to both vehicles.

A study conducted by BASt did investigate the possible influence of driven trailers on the driving dynamic properties of the vehicle combinations.

Driving experiments with two prototype trailers (caravans) had been carried out in direct comparisons with active and inactive trailer motors. The experiments focused on possible effects on the handling (double lane change test) and lateral stability (yaw damping test). Additionally, calculations had been carried out to investigate the transferability of the results.

Based on the available data, it was shown that there is no negative impact of the propelled trailer to the stability of the towing vehicle and vehicle combination, provided that there is always a remaining towing force in the towball, and no torque vectoring between the trailer wheels. It was also found that handling benefits from a driven trailer. Theoretical calculations show that when these two conditions are met (=no torque vectoring, no pushing), propelled trailers are safe with regards to driving dynamics.

Theoretical calculations also show that torque vectoring has a potential to even further improve handling and stability, however possible faults of the drive system and control strategy could negatively influence handling and stability.

The study had been carried out with only two prototype vehicles. Calculations checked that the results can be transferred to almost all kinds of trailers. Articulated trailers that have a steering of their own, however, need to be excluded from the conclusions without further research. Trailers for single-track vehicles (motorcycles, bicycles) are still under investigation.

As a conclusion, it has been identified that propelled trailers where a towing force in the coupling remains (=the trailers compensate their driving resistance only partially, they do not push the towing vehicle) and without torque vectoring do not have negative effects on the stability of the combination and can have possible effects on the handling. This is true for non-articulated trailers, including semi-trailers and central-axle trailers. Regulations could as a next step be adapted, so that the positive effects towards traction and energy efficiency could be demonstrated. Also as a next step, the benefits and possible issues with torque vectoring should be identified.

INTRODUCTION

Motivation

Trailers are by definition non-driven vehicles designed to be attached to driven vehicles. This means that the traction required for a combination to overcome the driving resistance can only be provided by the foremost, the towing vehicle.

The question therefore arises whether, from a scientific point of view (= technical point of view and from the point of view of driving dynamics), powered trailers could make sense. This is possible in principle in that

- each trailer only drives itself (partially compensates for its driving resistance, for example air resistance, or at best fully compensates for it, so that the trailer is still towed), or
- individual trailers apply more power than is required to overcome the driving resistance (then connecting devices are also loaded in compression, individual trailers push).

The benefits of powered trailers in both cases would be an increase in the traction of the combination and thus the ability to overcome slopes even under adverse friction conditions, the ability to distribute and use energy storage more efficiently since each trailer could store its own required energy, and the ability to recuperate energy more efficiently, i.e. to make better use of braking energy. This can improve traffic flow (for example, disruptions caused by broken-down combinations on motorway gradients in winter) and energy efficiency (through higher energy recovery and through more reasonable dimensions of the towing vehicle energy storage).

To be more specific, the slope q_{\max} (typically dimensionless, equal to the sinus of the slope angle) a vehicle-trailer-combination can climb is the product of the friction coefficient μ (between horizontal tire force and tire load, $F_{\text{horizontal,max}}/F_z$) and the traction coefficient τ (between the axle load of all driven axles and the weight of the full vehicle combination, $F_{z,\text{driven axle}}/(m \cdot g)$):

$$q_{\max} = \tau \cdot \mu.$$

The traction typically becomes a problem on snowy roads (e.g. $\mu < 0.3$) with vehicle combinations with a

low traction coefficient (e.g. 1 out of 5 axles driven, $\tau = 0.2$) on highways with a slope of 6% and higher.

However, an essential prerequisite for this would be precisely controllable (typically electric) motors in the trailer.

Regulatory Background

UN ECE's special resolution R.E.3 (ECE/TRANS/WP.29/78/RE3), which defines amongst other items the vehicle categories, has a definition for trailers: "Trailer' means any non-self propelled vehicle, which is designed and constructed to be towed by a power driven vehicle and includes semi-trailers."

The definition in the European Type Approval Framework in Regulation (EC) No. 858/2018 is similar but more specific:

"Trailer' means any non-self-propelled vehicle on wheels designed and constructed to be towed by a motor vehicle, that can articulate at least around a horizontal axis perpendicular to the longitudinal median plane and around a vertical axis parallel to the longitudinal median plane of the towing motor vehicle;"

Both these definitions exclude the possibility for the trailer to be self-propelled.

State of the Art

Since the relevant regulations at least in Europe prohibit driven trailer axles, no series production vehicles are known. There are, however, a number of prototype vehicles or prototype components are known in the vehicles categories O₂ [1], O_{3/4} [2] and for bicycles [3]. In all of these examples, trailers are not pushing the vehicle combination, sometimes with the exception of low speeds.

Aims of the research

While there are advantages for traffic flow and energy efficiency, there could be new risks introduced through driven trailers. The aim of this research was to identify possible negative implications for driving dynamics, both with calculations and experiments with prototype vehicles, in order to propose requirements for driven trailers.

METHODOLOGY

The aim of the research, as discussed above, is to identify hazards to road safety from driven axles of trailers (for two-track vehicles) and, if necessary, to determine what requirements should be placed on trailers to avoid these hazards.

To do this, it is necessary to analyse the driving dynamics of trailers, describe the dependencies of the relevant physical variables and derive road safety

criteria from them. These descriptions can then be verified and supplemented by driving tests.

Self-propelled Trailer Driving Dynamics

A challenge in trailer driving dynamics is the possible destabilisation of the towing vehicle about the yaw axis due to lateral forces introduced at the trailer coupling device and longitudinal forces pushing the towing vehicle (both forces increase the yaw angle of the towing vehicle). Pulling longitudinal forces around the yaw axis stabilise the yaw movement (they reduce the yaw angle of the towing vehicle).

Thus, first of all, it is assumed that trailers in normal operation should not transmit any compressive forces to the towing vehicle; this could be ensured by the requirement to always remain in towing operation despite a driven trailer, and by appropriate safeguarding of functional safety.

In this case, it can be assumed that additional lateral forces at the coupling device are generated by the trailer drive in the following cases:

- during stationary circular travel (in this case it can be expected that the lateral force at the coupling device F_y is lower since $F_{longitudinal}$ is lower),
- during corner braking (in this case there should be no driving force on the trailer axle, so that no influence of the drive is expected here either), as well as
- dynamically due to weave mode at higher speeds.

Model for weave motion

It is assumed that weave movements at high speed are the case in which influences by driven trailers are most likely to show: In the cases of corner braking, cornering, corner acceleration, lateral forces will occur, but not more strongly than in the case of the non-driven trailer (assuming correct system function without a pushing trailer, which is then a problem of functional safety).

Due to the large number of different trailer designs, the initial aim is to describe the influence of the driving force of non-driven trailers (rigid drawbar trailers, and due to the fundamentally different driving dynamics, singletrack vehicles are excluded) on the coupling forces, with the assumption that driving safety is not impaired if the lateral force introduced with drive is lower in the respective direct comparison (with/without drive) at all times.

For the theoretical derivations, the single-wheel model is used, in which the contact patch forces at all wheels are projected onto a single wheel (Figure 1). Furthermore, the angles should be small so that the

cosine of the articulation angle becomes 1, the sine of the articulation angle then is the angle itself (in radians).

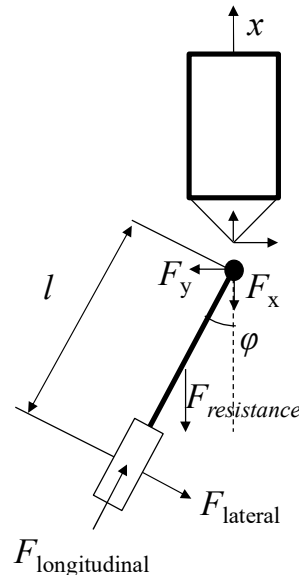


Figure 1: single-wheel model for trailer in weave motion

The lateral trailer forces for symmetric wheel torques depend only on the tire slip angle and its derivate, so no lateral force F_y is introduced specifically by the propelled trailer:

$$F_{lateral} = k_{\alpha} \cdot m \cdot g \cdot \left(\varphi + \frac{l}{\dot{x}} \cdot \dot{\varphi} \right)$$

with the lateral tire stiffness k_{α} , the sideslip angle φ (in this case of pure weave motion approximately equal to the articulation angle, speed \dot{x} and distance of wheel centers to towball l).

The longitudinal force $F_{longitudinal}$ points – for symmetric trailer design – to the towball of the towing vehicle. It does not introduce additional side forces into the towing vehicle either, and will not destabilize the towing vehicle as long as $F_{longitudinal}$ is smaller than the resistance force $F_{resistance}$.

Non-symmetric torques on both sides of the trailer have the advantage that active stabilization of the trailer becomes possible, analog to what electronic stability control can do for towing vehicles, however lateral destabilization of the towing vehicle can occur as well.

Controllability

A propelled trailer will change the driving performance of the combination. An assessment of the effect of these changes for the drivers is possible in the closed-loop test. A good test for controllability



Figure 2: Non-valid test run in double lane change test

problems for example is the closed-loop double lane change test.

Experiments

The standard test for high speed stability defined in ISO 9815:2010 “Road vehicles – Passenger-car and trailer combinations – lateral stability test” [4]. The test contains an excitation on the steering wheel with a specific speed and amplitude, after which the trailer weaves in its natural frequency. The excitation has been conducted using a driving robot, so the steering actuation has been constant between experiments with self-propelled trailer and non-self-propelled trailer. Key performance indicator is the natural frequency and damping for the trailer around the yaw axis. As long as these characteristics are similar for self-propelled and non-self-propelled trailers, no negative influence is assumed.

The test for the controllability is the double lane change according to ISO 3888-1:2018 [5] with the parameters as shown in Figure 3. Key performance indicator is the maximum speed for which the driver was able to drive through the corridor without touching one of the cones. To be more robust, three trials were available for a given test speed, and one valid trial was sufficient to qualify for the next higher speed. Speeds were selected with a spacing of 5 km/h. The test was driven with constant speed (maintained by the speed limiter device of the towing vehicle).

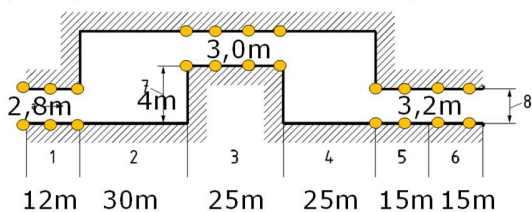


Figure 3: Characteristics of double lane change test: cones and spacing

An impression of a non-valid experiment is shown in Figure 2.

Tools

Experiments were conducted with two prototype trailers (A: mass approx. 2.1 tons, single axle, l approx.

4 m, motors fully active up to 100 km/h, symmetric torques, and B: 1.8 tons, tandem axle, l approx. 9 m, motors active up to 85 km/h, symmetric torques), towed by a large SUV (mass approx. 2.2 tons in test configuration). The towing vehicle was equipped with precise position measurements equipment and a steering robot. The trailers were equipped with precise position measurement equipment as well, trailer A was equipped to measure towball forces, allowing the verification of the single wheel model for high speed stability with regard to the forces. The test configuration can be seen in Figure 4.



Figure 4: Towing vehicle and one of the trailers on test track.

RESULTS

High-speed stability (weave mode)

A representative example of the towball forces and the articulation angle is given in Figure 5 below. Plots for experiments with self-propelled trailer are red, plots for experiments with non-self-propelled trailer black. It can be seen that the articulation angle is constant between test runs. Differences between configurations (self-propelled – non-self-propelled) in this case are hardly noticeable. This is not the case for all test runs; however, the characteristic velocity for trailer A – the speed, for which the damping ratio is calculated to become zero – is 5% lower for the self-propelled trailer (101.4 to 105.1 km/h). For trailer B, the difference for characteristic velocity is neglectable (93.4 to 93.6 km/h).

As a consequence, there is no reason to assume that propelling a trailer will negatively influence the weave mode of the vehicle combination.

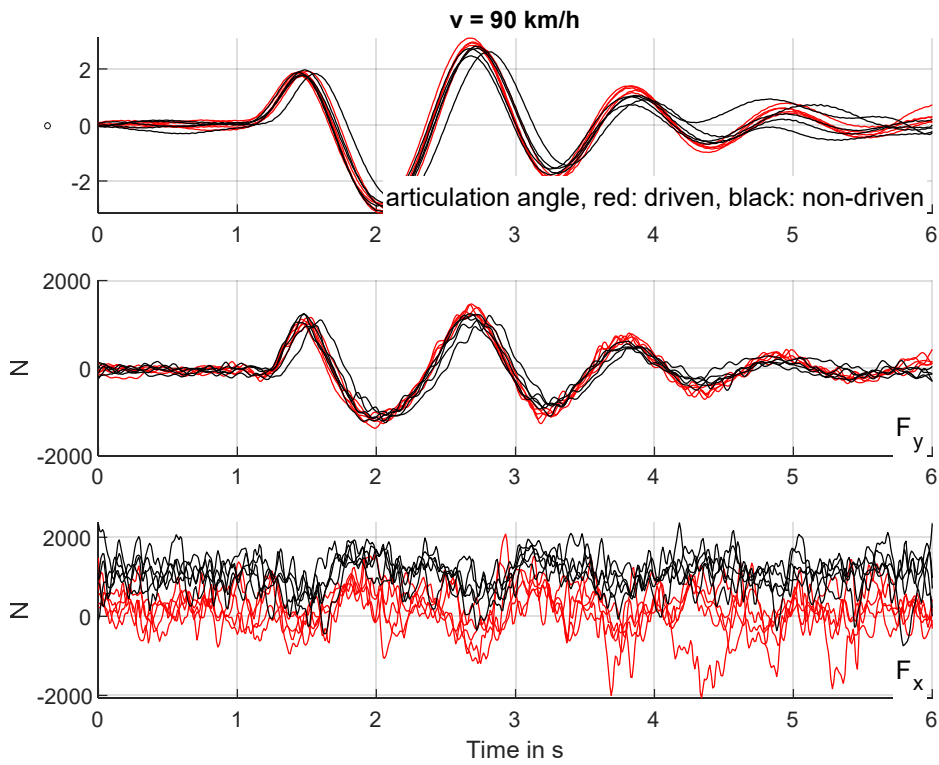


Figure 5: Example test run for trailer A

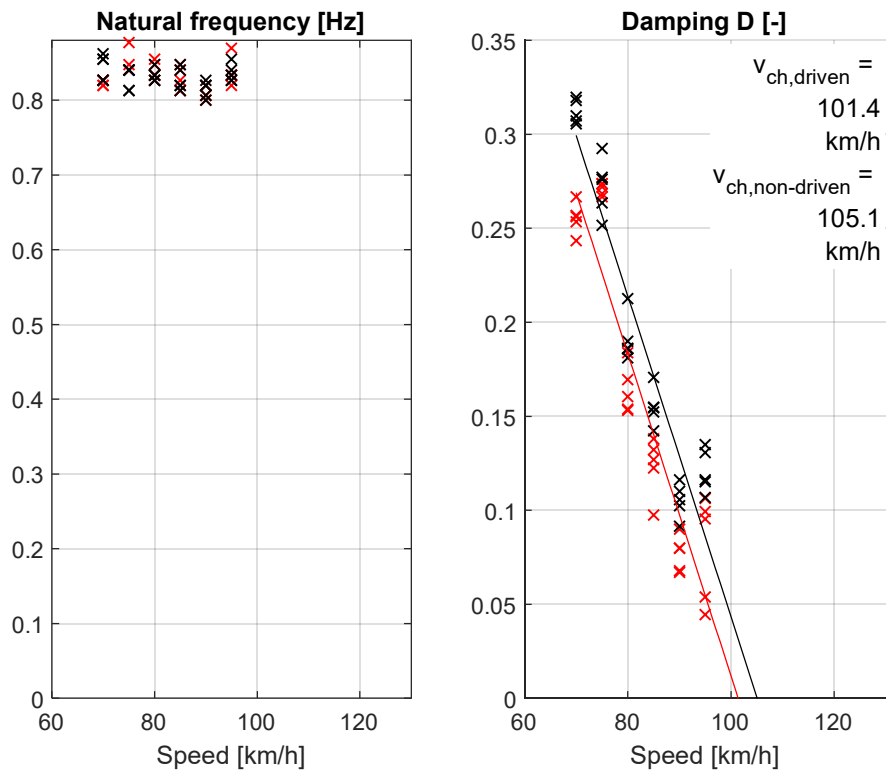


Figure 6: Natural frequency and characteristic velocity for trailer A

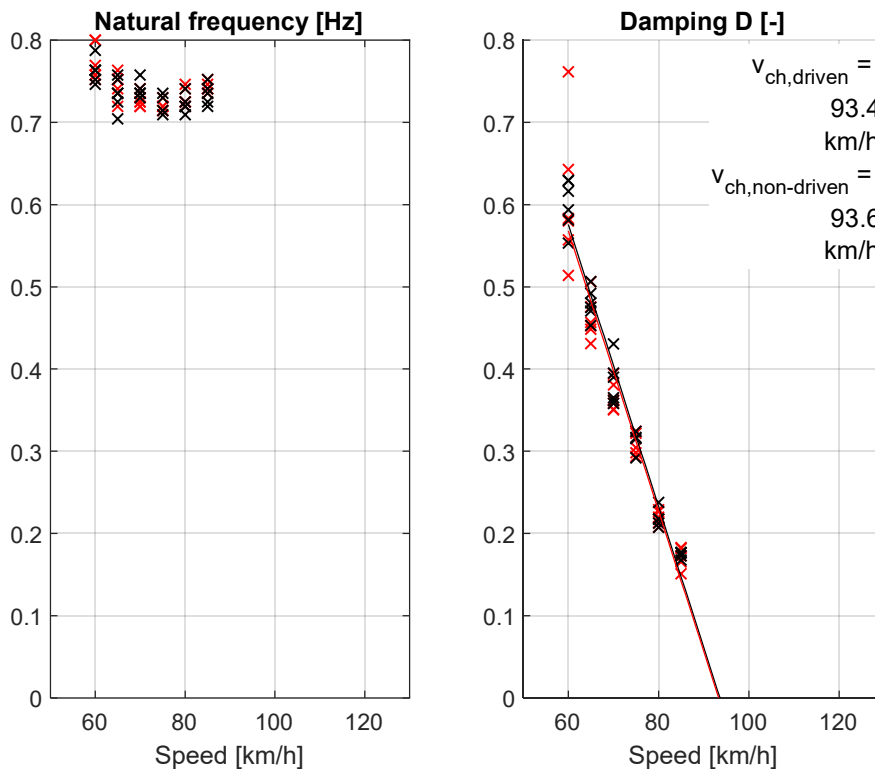


Figure 7: Natural frequency and characteristic velocity for trailer B

Double Lane Change

The double lane change results are given as number of required runs for one valid test run in the following Table 1. While the performance of the driver with trailer A is quite comparable and the final maximum speed is the same, 95 km/h (above which the test runs were stopped due to safety considerations), the performance of the driver with the much longer trailer B shows advantages for the self-propelled configuration (80 km/h with only one test run required for a valid test run, while at 70 km/h for the non-self-propelled configuration, three test runs were required for one valid test run). This means that trailer handling was obviously better with self-propelled configuration.

One remark here: it could very well be the case that trailer A also has a better handling when self-propelled, however since it is much shorter, this might not have influenced the driver’s double lane change performance.

Table 1: Required test runs for one valid test run, self-propelled (sp) and non-self-propelled (nsp)

v [km/h]	A (sp)	A (nsp)	B (sp)	B (nsp)
50	1			
60	1			3
65	1			
70	2		1	3
75	1		1	No valid run
80	1	1	1	
85	3	1	No valid run	
90	2	1		
95	3	3		

The results for the double lane change test are consistent with the weave results above in that there is no reason to assume that self-propelled trailers influence the handling negatively.

Transferability of Results

For checking the validity of the equations for the single-track weave model, in particular also for estimating the lateral force based on the articulation

angle of the combination, the measured values (forces and articulation angle) for trailer A can be used.

The following additional assumptions are required:

- Sideslip stiffness of the tires $k_{\alpha} = 0.75$ 1/rad,
- Time delay between angle measurement and force measurement constant 0.2 s (this

indicates a 5 Hz low-pass filter in the inaccessible hardware and software of the force measurement).

With these assumptions, there is apparently good agreement between measurement and calculation (Figure 8), although the calculation tends to overestimate the lateral forces at higher driving speeds (Figure 9).

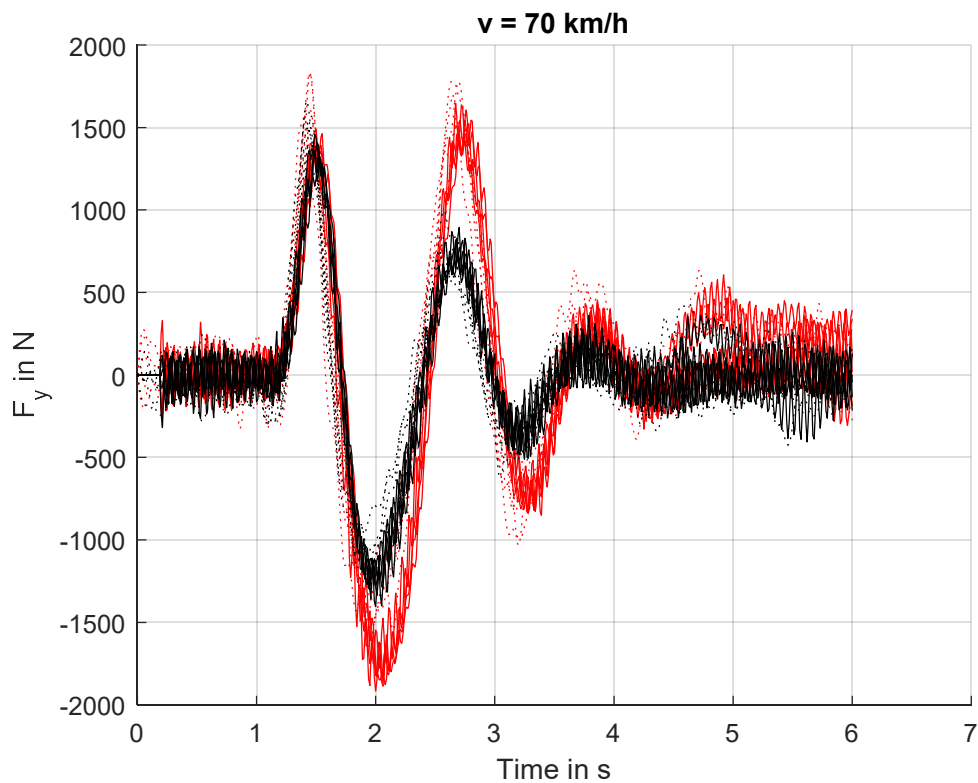


Figure 8: Comparison between measured (solid line) and calculated (dashed line) lateral forces, trailer A, 70 km/h

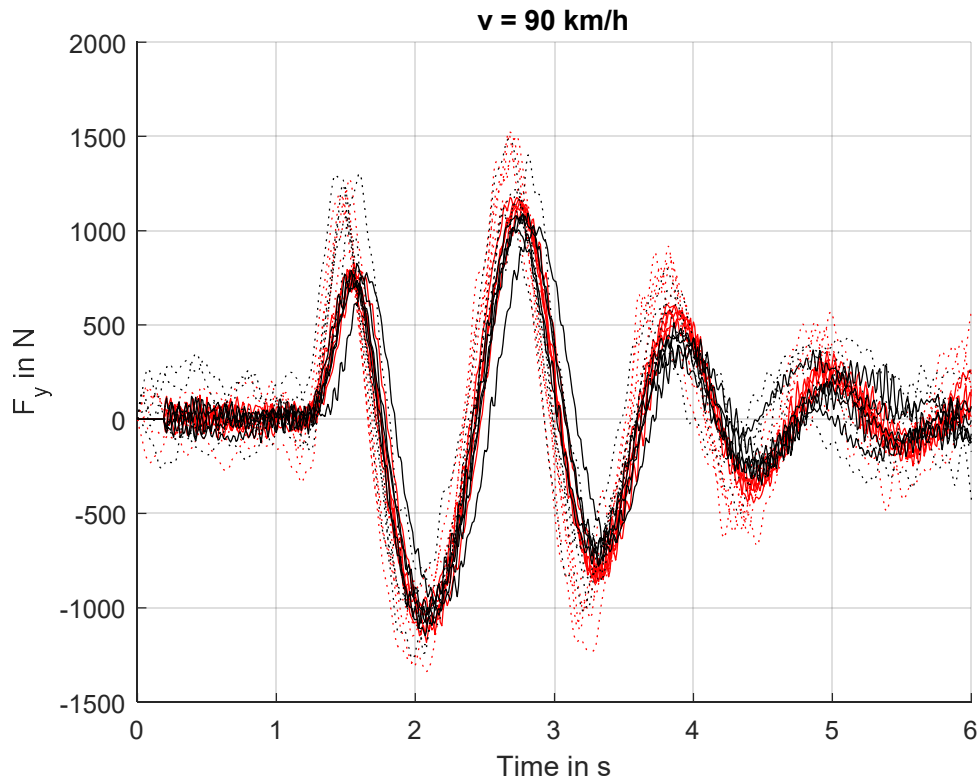


Figure 9: same as above, but for 90 km/h

Based on the fact that the driving dynamic calculations do not seem to show any fundamental differences to the measured lateral force, it is assumed that the findings are transferable at least to other trailer types that can be simplified as a single-wheel model. Trailer types for which this is not possible are those with several degrees of articulation freedom, such as turntable drawbar trailers.

CONCLUSIONS

Theoretical considerations show that trailers with symmetrical drive force which is less than the driving resistance force of the trailer are not critical with regard to the impairment of the driving dynamics of the vehicle combination. The theoretical considerations have been verified with data from high speed stability tests, and the test results show that the characteristic velocity – the velocity at which the damping could become zero – is not substantially influenced.

Driven trailers should have a positive influence on the driveability of the vehicle combination due to lower towing forces to be applied by the towing vehicle, which has been verified with double lane change tests. Based on these results, it is not assumed that there are implications to vehicle safety if self-propelled trailers

are designed so that the drive forces are distributed equally over both sides of the trailer and that the trailers do not push the towing vehicle.

Proposal for requirements

Based on the conclusions above, the following requirements for self-propelled trailers can be proposed:

- The driving force should not exceed the driving resistances so that the trailer is always towed. Then no greater – destabilising – lateral forces are expected at the trailer coupling than in the non-propelled case.
- The driving force should be applied to wheels on both sides equally in terms of magnitude and phase. This should be demonstrable by considering the functional safety of the system.

Trailers designed according to those requirements will have no negative effect on traffic safety, but might have a positive effect on traffic flow (traction on slippery highway slopes) and energy efficiency (e.g. longer ranges for electric vehicles, better brake energy recuperation). To be able to bring self-propelled trailers to the market, the type approval framework on

European level (Regulation (EC) No. 858/2018) and at UN level (R.E. 3) needs to be amended.

In a next step, trailers with non-symmetric forces on both sides could possibly assist in stabilizing the vehicle combination. Requirements for these trailers have to be defined at a later stage.

REFERENCES

[1] Erwin Hymer Gruppe: “Weltweit erster e-Caravan“. Available at <https://www.erwinhymergroup.com/de/presse/themen-highlights/dethleffs-ehome-coco>. Access August 31, 2022.

[3] Schäfer, P.: “Bosch elektrifiziert die Achse von Lkw-Sattelanhängern“. Available at <https://www.springerprofessional.de/schwere-lkw/elektrofahrzeuge/bosch-elektrifiziert-die-achse-von-lkw-sattelanhängern/16077896>. Access August 31, 2022.

[4] Wikipedia: “Schubanhänger“. Available at <https://de.wikipedia.org/wiki/Schubanh%C3%A4nger>. Access August 31, 2022.

[5] ISO 9815:2010 “Road vehicles – Passenger-car and trailer combinations – lateral stability test”. International Standardization Organisation, 2010.

[6] ISO 3888-1:2018 “passenger cars — Test track for a severe lane-change manoeuvre — Part 1: Double lane-change”. International Standardization Organization, 2018.