# "FORCE-SENSING KINGPIN" FOR INTELLIGENT, TRACTOR-INDEPENDENT CONTROL OF SEMI-TRAILER E-AXLES





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**Abstract**
Driven by the European Green Deal, the road-freight sector is hybridizing its fleet. However, at present, trailing units do not possess any form of powertrain, a missed opportunity. By introducing electrically driven axles, these units may reduce fuel consumption and emissions substantially. Nevertheless, swift integration of these vehicles is challenging. One of the dominating ones is the intelligent control of the E-axle without receiving information from the towing vehicle to ensure interoperability & interchangeability, a must in the logistics sector. A new type of coupling system appears as a relevant and necessary solution, a Force-Sensing Kingpin. Such a system measures the longitudinal force, representing the supplied tractor power, which can be used to control the E-axle. This paper discusses the development and testing of this system, including modelling and simulation, lab-environmental tests and analysis of the signal's suitability for control. The outcomes will be used in another project, CHANGE, which further explores the control strategies using the "Force-Sensing Kingpin".

**Keywords:** Trailer Electrification, E-trailer, Kingpin, Heavy Vehicles, Hybrid Propulsion

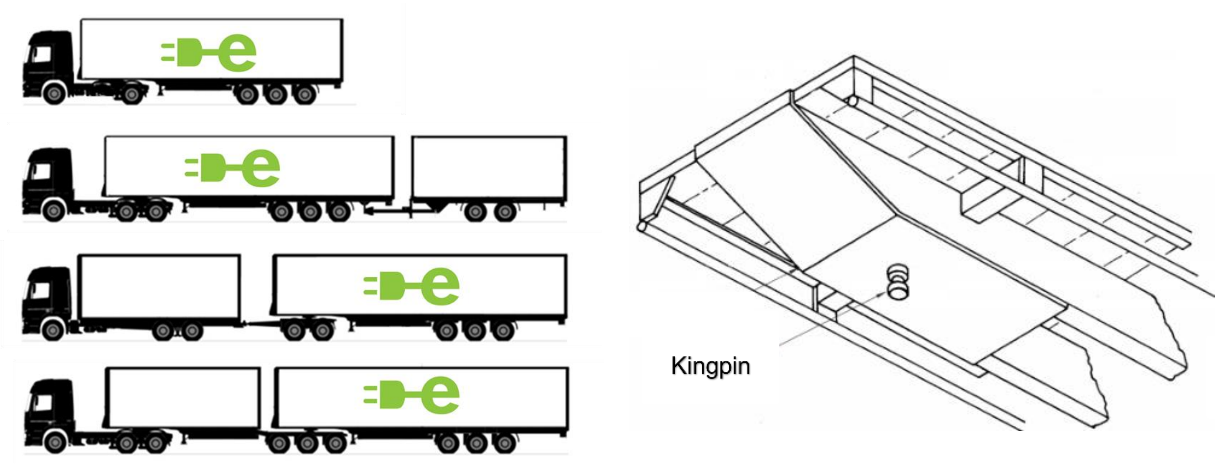
## 1. Introduction

To reach the European Green Deal by 2050, the target for the road transport sector is set at 45% less CO2 emissions by 2030 [1]. Given the fact that heavy-duty commercial vehicles throughout Europe are driven nowadays almost exclusively on fossil fuels it is obvious that transition towards reduced emission targets needs to happen seamlessly by hybridization of the existing fleet, with a growing share of Zero Emission vehicles. Along with this, On May 13, 2024, the Council of the European Union ratified the agreement on the revision of the CO2 standards for heavy-duty vehicles. In addition to the stricter rules for trucks also trailers have been added, which must reduce their emissions by 7.5% for trailers and 10% for semitrailers [1]. And even though trailers generally do not emit any CO2 emissions, they can significantly contribute in reducing the emissions from the motorized trucks that tow them. SHIFT (Serving Heavy vehicle Intelligence in Future Transport) aims to address the transport sector emissions, to reach the European Green Deal.

At present, trailing units do not possess any form of powertrain, being a missed opportunity. By introducing electrically driven axles into these units, fuel consumption and emissions may reduce substantially (in the order of 15 – 20 % [2]), since part of the propulsion forces is supplied on emission-free basis. Furthermore, trailer electrification enables recuperation of the kinetic energy while braking. This electrification of trailers is apparent in many research projects and different prototypes have been developed, like the Kraker E-Force E-Trailer demonstrator as discussed in [2] and depicted in Figure 1.


**Figure 1 – KRAKER E-Force E-Trailer Demonstrator.**

Nevertheless, a number of challenges still exist preventing swift integration of these vehicles to daily operation. One of the dominating ones is the intelligent control of the E-axle so it delivers right amount of propulsion / braking power at the right time without receiving detailed information from the towing vehicle. This is required to ensure interoperability and interchangeability of E-Trailers with different tractors / towing vehicles in the fleets, which is a must in the logistics sector nowadays. With the current trailers being 'dummy' and without powertrain, this interoperability is obviously guaranteed. For an E-Trailer, where optimal fuel reduction is pursued, this is not straightforward. Additionally, the E-Trailer may also be engaged in different combinations of vehicles, as shown in Figure 2 (a), which influences the control algorithms and inter-vehicle communication. Therefore, robust and efficient control of E-trailer independent of derailed information from coupled vehicle units is of special interest.




(a) (b)

**Figure 2 – (a) Possible E-Trailer Applications for Hybrid Drive and (b) Semitrailer Bottom view with Kingpin.**

### 1.1 Research Objective

To deal with the above mentioned challenges, a new type of coupling of E-trailer to other vehicle units appears as a relevant and necessary solution, being the focal point of this research. Normal coupling of a semitrailer to other vehicles is realized by the kingpin, depicted in Figure 2 (b), which clicks into the jaws of the fifth wheel that is permanently attached to the towing vehicle. Within SHIFT, this new type of coupling system is intended to be developed, a "**FORCE-SENSING KINGPIN**". This system combines the connecting purposes of the kingpin and measures the longitudinal reaction force between the kingpin and the fifth wheel. Such a signal, when rightly measured and processed would represent the power transferred from tractor to trailer, which in its turn will represent the supplied tractor power. This can be used as an input to control the E-axle, including both recuperation through braking and propulsion during acceleration.

The initiative of this new coupling system comes from Van Klink Engineering [3], who has partnered with HAN University of Applied Sciences and Pavonodum [4] in this project.

Along with the proof of concept of the "Force-Sensing Kingpin", effort has been given in designing an E-axle control approach, based on the measured (longitudinal) kingpin force. The paper, described by Pauwelussen, [5] discusses this control approach.

### 1.2 Paper Structure

This paper discusses the development and testing of the "Force-Sensing Kingpin", including modelling and simulation, lab-environmental tests and analysis of the signal's suitability for control. At first, some brief words will be given to the state-of-the art of E-trailer initiatives. Next, the modelling and simulations with the use of advanced Multibody Simscape models, to get an understanding of the longitudinal reaction force(s) acting on the kingpin, will be explained. Results of the simulations are shown, followed by the testing of the Force-Sensing Kingpin main sensor in a lab-environment, including results. The paper is concluded with a discussion of the systems suitability and a research outlook.

## 2. State of the Art

The European Green Deal and the stricter regulations on CO2 reductions for (semi-) trailers have led to various E-trailers initiatives, like the Kraker E-Force E-Trailer as discussed in [2] and depicted in Figure 1. The developed controller, which delivers the torque request, uses inputs from the tractor (FMS data). Other initiatives show similar approaches [6], by using a fixed communication line between tractor and trailer. The need for tractor data makes these systems unsuitable for trailer interchangeability. Next to this, such an approach requires regular updates when new tractor types are deployed.

Needless to say, that an E-trailer control, independent of the tractor, is necessary, and WABCO[1] / ZF have addressed this issue. The first generation E-trailer was developed by WABCO in 2019 and the second, and newest, generation was introduced in 2021 [7]. This model has a more compact layout than the first generation and all components are integrated on the trailer, including the controlling. To control the E-axle, integration with the trailer EBS (Electronic Braking System) is required, and the controller will receive all necessary inputs from this integration. This makes it possible to control the E-trailer independently of the tractor. However, the required signals from the trailer EBS to control the E-axle are not widely available and accessible. Only a limited number of data messages is, specified by the ISO 11992-2:2023 standard [8] (specifying data messages for electronically controlled braking systems ensuring the interchange of digital information between road vehicles and their towed vehicles, including communication between towed vehicles). Since ZF uses their own EBS modulators (developed by WABCO) it is possible to access all the required data. Compliance with the EBS manufacturer, in this case WABCO / ZF, is therefore required.

Another E-trailer project tents to overcome the usage of tractor data with a kingpin invention that has an integrated measuring device. This kingpin invention[2] [9] is developed by Trailer Dynamics [10] and according to the invention the system can detect driving-dynamic reaction forces. These reaction forces tell something about the tractor power and are used for E-axle control. This approach has many similarities to the approach of SHIFT. Nevertheless, it is unclear what other data signals are used by Trailer Dynamics to control the E-trailer, and therefore it is uncertain whether the controller is constrained to OEM specific devices, similar to the ZF E-trailer. Next to this, this invention works on the kingpin itself [9], a component that operates in harsh conditions. Excessive forces, heavy metal on metal connections and greasy environments are very common. It is uncertain how robust such a system will be and what the consequences for its lifespan will be.

As can be seen various initiatives on E-trailers are present, as well as various control strategies. Numerous are depended on a direct communication connection with the truck or are constrained by (EBS) data accessibility. New initiatives using reaction forces measured in the kingpin seem promising. Still a combination with other data signals is required and the lifetime of systems operating directly in / on the kingpin is unknown.

Within SHIFT it is therefore intended to develop a force-sensing kingpin that can measure the longitudinal reaction force, without harming the regular operation of the kingpin. The controller design is part of a larger project, CHANGE, which aims to develop an E-trailer controller based on this force-sensing kingpin in combination with limited accessible data signals, as reported by Kural [11].

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[1] *ZF bought WABCO in May 2020 (https://press.zf.com/press/en/releases/release_16832.html 29th of May 2020*

[2] *Trailer Dynamics has a patent WIPO: WO 2024/056430 [9]*

## 3. Modelling & Simulation Using Advanced Multi-Body Models

The focal point of this research, and therefore this paper, is the development of a new type of coupling system between E-trailer and other vehicle units, a "force-sensing kingpin". This system will combine the connecting purpose of the kingpin and measures the longitudinal reaction force between the kingpin and the fifth wheel. However, before designing the "force-sensing kingpin," it is important to understand the (longitudinal) reaction force(s) acting on the kingpin. This is done using modelling and simulations, where a truck-trailer model takes driving scenarios as input (accelerating, braking, cornering, etc.) and outputs the longitudinal reaction force acting on the kingpin. This gives insights in the longitudinal kingpin force's magnitude (min / max values) and direction (positive / negative). Next to this it provides insights into the force's behaviour as a control input signal, aiding the controller design.

Modelling is done by using Simscape Multibody of MathWorks [12]. HAN University of Applied Sciences and the Technical University of Eindhoven (TU/e) developed a commercial vehicle library, consisting of modular vehicle units, by using Simscape Multibody. These vehicle units can be combined into a heavy duty vehicle (HDV) combination, e.g. a truck semitrailer, as depicted in Figure 3. These vehicle units consist of rigid bodies, which inertias are linked to each other through joints which have varying degrees of freedom. For example, the kingpin, connecting the body of the trailer with the truck (Figure 3). The model(s) also include chassis flexibility, suspension dynamics, roll behaviour and drivelines, and they are validated by Kural [13]. In 2022 the models were updated by Ajaykumar [14], and the Pacejka Magic Formula, a nonlinear mathematical model used to describe tyre behaviour under various conditions, was implemented to simulate nonlinear tyre behaviour.

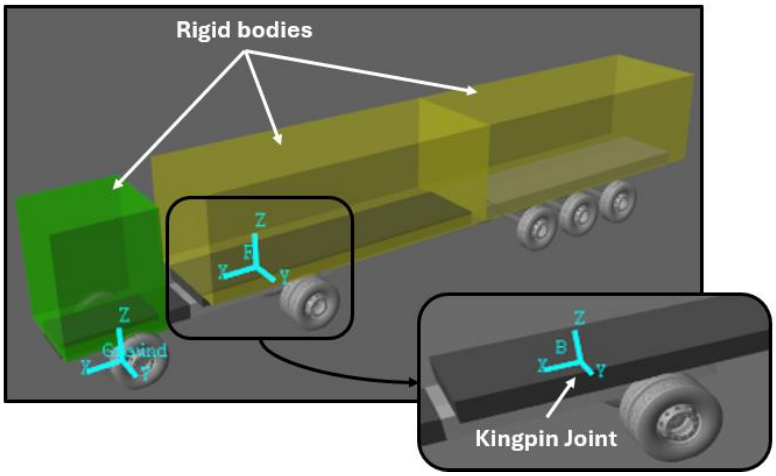



**Figure 3 – Visualisation of a classic truck semitrailer Simscape Multibody Model.**

Initial simulations showed that the brake force distribution between truck and semitrailer has a significant impact on the kingpin force. The Simscape Multibody model has a simple brake model, distributing the brake force over the axles based on a certain, constant ratio. Although this approach can be sufficient for other relevant vehicle dynamic analysis, for this research the braking system was insufficient. Therefore, a more accurate model of a truck-trailer braking system has been developed.

Truck trailer brake systems make use of pneumatic (air) brakes. By applying the brake pedal, a driver generates an air flow. This air flow, with a certain pressure, will, after passing some other elements, enter the brake chambers of the brakes. This brake chamber pressure pushes a rod, resulting in a certain force applied on the brakes. This brake force results in a certain brake torque applied on the tyres. A simplified representation of the air brake system of a truck trailer combination is represented in Figure 4.

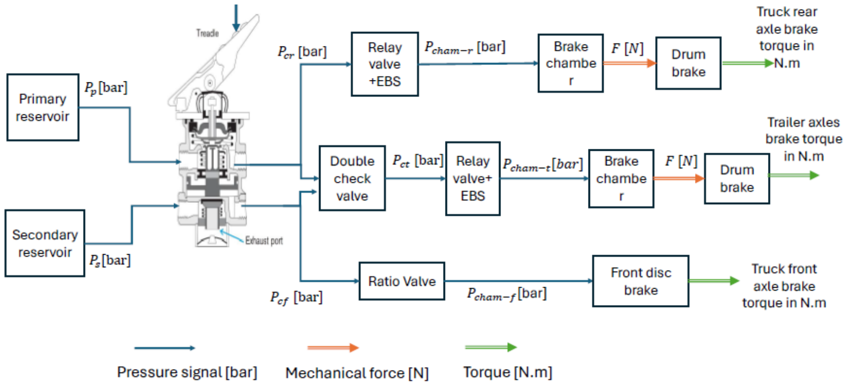
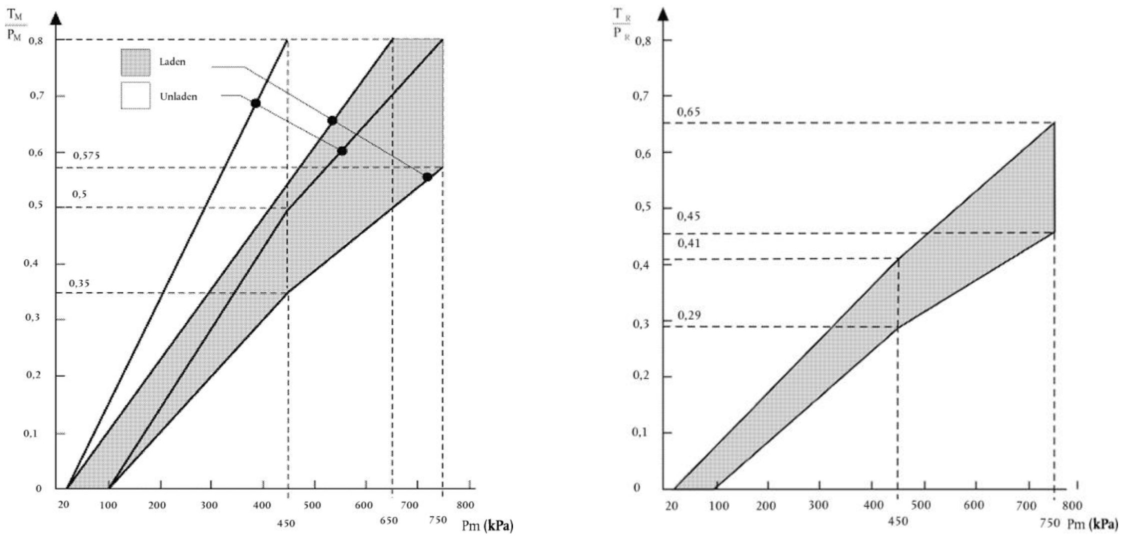



**Figure 4 – Simplified air brake system of a truck trailer combination.**

The brake chamber pressure is related to the brake force (and hence the brake torque), i.e. a higher pressure results in a higher force and vice versa. To ensure safe braking, especially for the trailer, a control unit is required to regulate the pressure. This is done by the Electronic Braking System (EBS), which regulates the brake chamber pressure, based on the axle load, to control the brake force [15]. Besides, it can improve brake performance and reduce wear.

Regulating the brake chamber pressure and hence the brake force depends on the kind of trailer. An EBS must therefore be configured specifically for a trailer type, complying with Regulation No 13 of the Economic Commission for Europe (ECE) [16]. This regulation describes the permissible relationship between the brake rate $T_{M/R}$[3] / $P_{M/R}$[4] and the pressure $p_m$ for two situations, laden and unladen states of load. This relationship shall lie within the areas derived from different diagrams, shown in Figure 5, with (a) the boundaries for the towing vehicle and (b) the boundaries of the semitrailer. As can be seen in (b), only one area is given for the semitrailer. To determine the areas corresponding to the laden and unladen conditions the upper and lower limits of the diagram are multiplied with the factors $K_c$ (laden) and $K_v$ (unladen) derived from another diagram provided in the regulation.




(a) (b)

**Figure 5 – (a) Brake boundaries of the towing vehicle and (b) the semitrailer in laden and unladen situation according to regulation No 13 [16].**

[3] $T_{M/R}$ = *the sum of braking forces at periphery of all wheels of towing vehicles (M) / of trailer (R) [16]*
[4] $P_{M/R}$ = *total normal static reaction of road surface on all wheels of trailer [16]*

The Multibody model was updated with the more advanced braking system based on the representation of Figure 4. The different components are represented by equations and look-up-tables, based on existing braking system components. The input of the braking system is pedal position, resulting in a command pressure, and the output is brake torque on the wheels. The performance of the braking system in the Multibody model is validated by complying with regulation No 13 for a truck semitrailer combination. Figure 6 shows the Multibody model brake curves for the truck (a) and semitrailer (b) respectively for the laden situation. Similar results can be obtained for the unladen situation, showing a valid brake model.

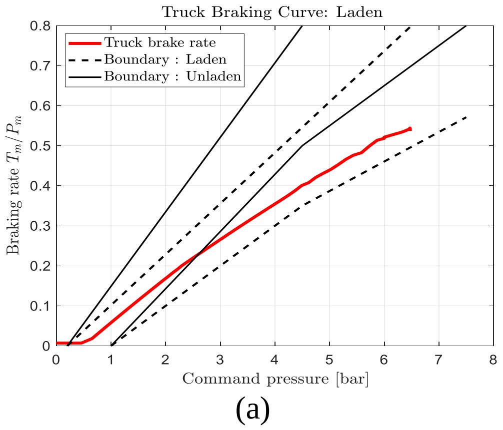



**Figure 6 – Brake curve of the Multibody model truck (a) and semitrailer (b) in the laden situation, complying with the regulation No 13 boundaries.**

To gain insights in the order of magnitude as well as the direction of the kingpin force, a realistic speed profile input is provided to the model, depicted in Figure 7 (a). At t=10 [s] full throttle is applied to the fully loaded truck semitrailer (40 tons) and at t=40 [s] the brakes are fully applied till the vehicle stops. This scenario has no steering, and the road is considered flat with ideal conditions. The throttle and braking result in certain acceleration values, which are given in Figure 7 (b). The resulting longitudinal kingpin force is provided in Figure 7 (c), which shows a positive value for acceleration and a negative value for braking. This result is of importance for E-trailer control design, where a positive kingpin force can be interpreted as support, and a negative force requires recuperation of energy. Another important aspect from the results in Figure 7 (c) is the order of magnitude of the longitudinal kingpin force. During the acceleration phase, the longitudinal force peaks above **123,600 [N]** and when full braking is applied the longitudinal force overshoots to **-83,800 [N]**. The new coupling system should be able to withstand such forces and be able to measure them, both positive and negative.

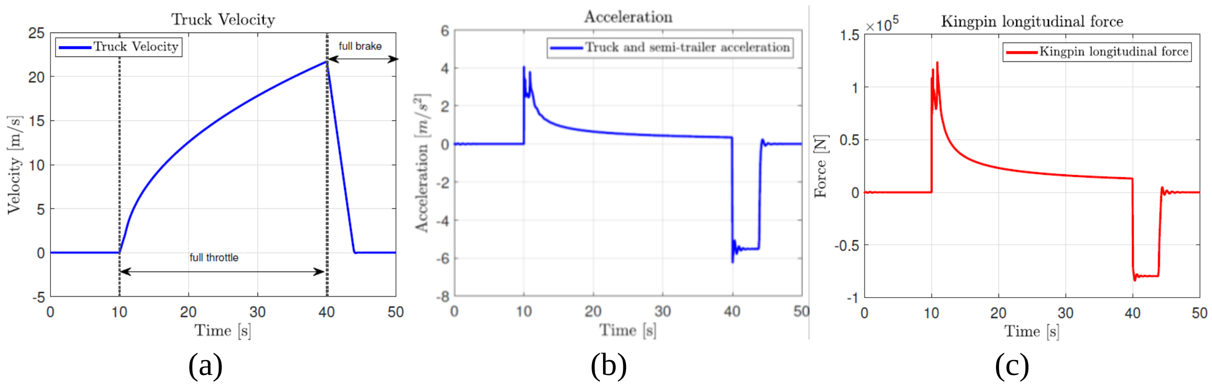
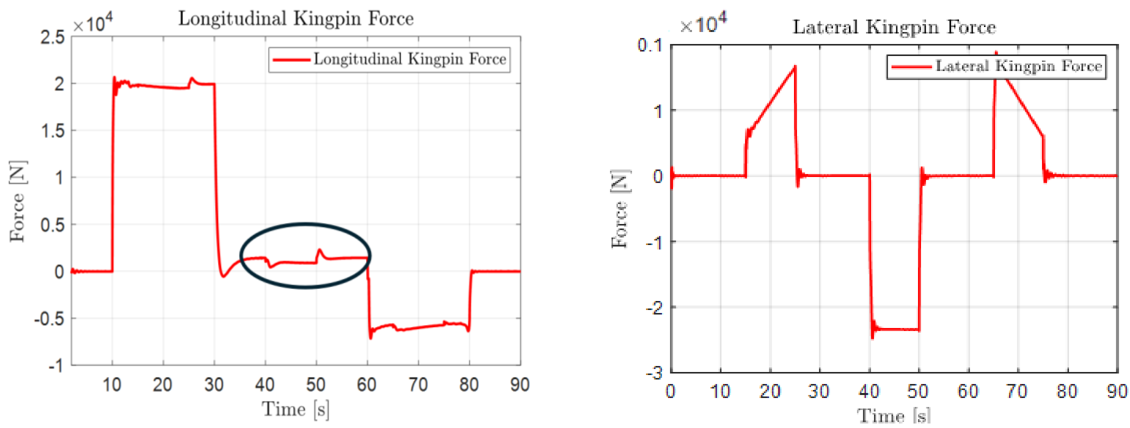



**Figure 7 – Analyses of Multibody model kingpin force with (a) speed profile input, (b) corresponding acceleration and (c) resulting longitudinal kingpin force.**

Additionally, the effect of road gradients (slopes) and cornering on the kingpin force have been studied. Various scenarios were simulated to assess the impact of slopes: full throttle uphill and full braking downhill, with varying slopes of 5%, 10%, and 15%. This resulted in an increase of the kingpin force of approximately **6.7%** for the uphill scenario whereas the downhill scenarios showed minimal change. The latter comes due to the braking system being capable of stopping the combination to a full stop since effects like temperature are not considered in the braking model. Furthermore, full braking downhill might not be the most representative scenario, whereas driving downhill with constant velocity or coasting are of more interest. Especially to see what the direction of the longitudinal kingpin force will be to make sure regeneration of energy can take place instead of regular braking.

Cornering on the other hand shows significant more impact. A scenario was simulated where the fully loaded truck trailer accelerates, drives with a constant velocity and brakes to a full stop. In every phase a steering input was given, i.e. steering, keep constant and steer back. The acceleration rates and steering inputs were considered small. Figure 8 (a) shows the effect of cornering on the longitudinal kingpin force. The effect is relatively small during the acceleration phase, whereas this is significant during the constant velocity phase (encircled). An increase in longitudinal force of more than **25**% can be noticed. An increase was expected, because the added cornering resistance forces would require more tractor power to maintain a constant speed. This results in a higher (positive) kingpin force. However, the significance of the increased force was a new insight, since an increase in positive force can be seen as an indication for E-axle assistance by a controller, even though it can be questioned whether this is desired during cornering. Similar observations can be made for braking and cornering, however more analyses are required to study the effect of cornering while braking / decelerating (e.g. coasting) on the kingpin force effectively.




(a) (b)

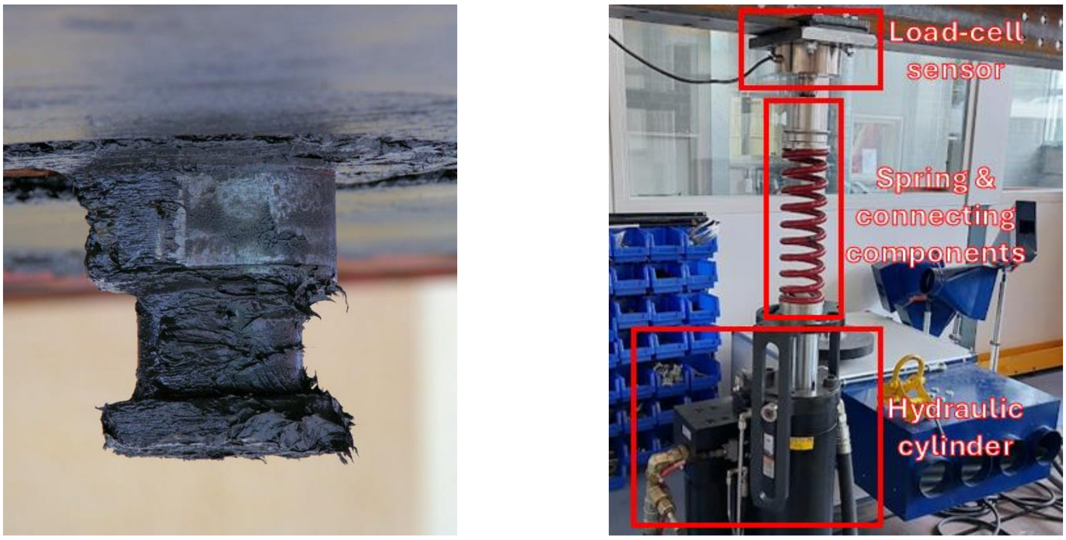
**Figure 8 – Cornering effect on the (a) longitudinal and (b) lateral kingpin force.**

It might be good to mention that the simulation model also outputs the lateral kingpin force (Figure 8 (b)), showing a higher magnitude of force during the constant velocity phase compared to the acceleration and braking phase. This confirms the effect as described above. Further analysation of the lateral kingpin force has been left out of scope since the new coupling system will not be capable of measuring forces in this direction. However, for precise control of an E-axle this kind of measurement or signal could be beneficial (as well as the vertical force). It is therefore advised to further investigate whether the lateral kingpin force can contribute to the E-axle control and whether it will be possible to integrate this in the new coupling system without change the set-up of the kingpin itself (see next section).

## 4. Lab-Environment Testing of Load-Cell Sensor

Without going into details of the mechanical construction of the new coupling system it is important to notify that such a system must operate in harsh conditions. Normal coupling systems have a purely connecting purpose and are robustly constructed. The kingpin clicks into the fifth wheel resulting in a metal on metal connection. To avoid excessive wear, grease is used, see Figure 9 (a). Besides the high forces, heavy metal on metal contact and the greasy environment, the system needs to operate in various environments (e.g. sand roads) and climates (e.g. Scandinavia or South EU). The new coupling system does therefore not change the set-up of the kingpin itself, but a construction around the kingpin is designed with the measuring sensor integrated in it. This will be beneficial for the lifetime of the system. Something that is uncertain for other initiatives as described in Section 2, State of the Art.

The intended sensor for this new coupling system will be a heavy duty Strain Gauge Load-Cell sensor, integrated in the construction enclosing the kingpin such that all the longitudinal forces are transferred to the sensor. This sensor can measure up to 20,000 [kg] with a safe overload of 30,000 [kg]. From the simulations it can be seen that the intended sensor should be able to measure the longitudinal forces, i.e. the maximum forces do not exceed the sensor measurable range. However, this does not automatically mean that outputted signal of the sensor can be used as a control input signal. The signal should be rightly measured and possible be (pre-) processed to make it a suitable signal for estimating the tractor power. It is therefore necessary to analyse the behaviour of the load-cell sensor. This has been done via a Lab-Setup, shown in Figure 9 (b)[5]. The load-cell sensor is rigidly fixated to a metal construction and a hydraulic cylinder is used to provide displacement inputs to the sensor.




(a) (b)[5]

**Figure 9 – (a) HAN Lab-Setup and (b) a Kingpin with Grease.**

Since displacement does not represent force a spring with a known (high) spring constant is placed between the cylinder and the sensor (also to prevent damage). By applying Hooke's law, the applied force can be calculated based on the displacement, Equation 1. Where $F$ is the applied force in [N], $k$ the spring constant in [N/m] and $x$ the displacement in [m].

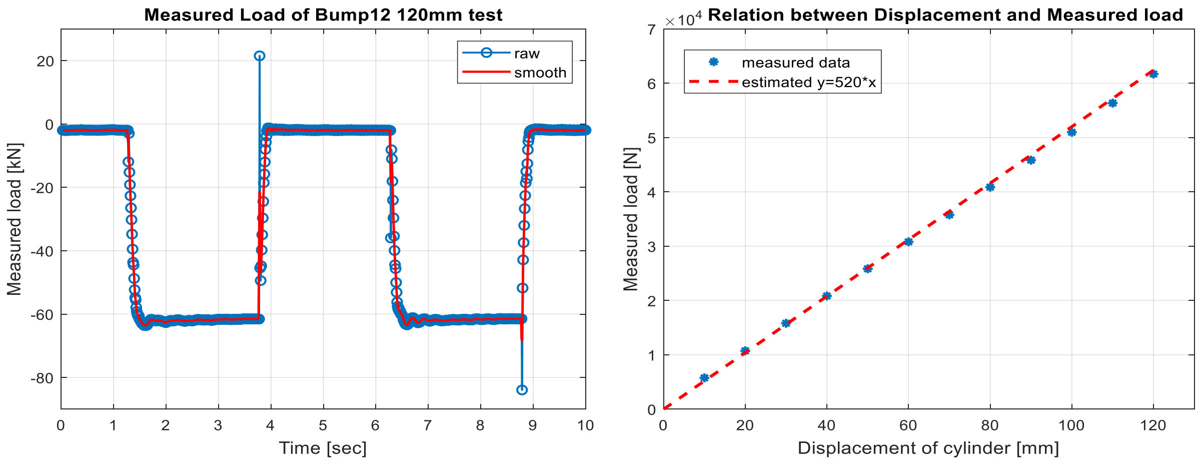
$$F = k \cdot x \quad (1)$$

[5] *The sensor is orientated in a vertical position, not longitudinal. Still the lab-setup is measuring in one direction.*

A computer system controls the displacement of the cylinder with a resolution of 0.1 [mm] and both the displacement of the cylinder as the electric signal of the load-cell sensor are logged with 100 [Hz].

The load-cell sensor is tested for two aspects 1) overshoots and delays and 2) vibrations / frequency responses, to see how suitable the sensor's output is as a control input signal. First, bump inputs (two sequent step inputs, one rising, one falling) with amplitudes ranging from 10[mm] to 120[mm] were provided, to analyse the overshoot and delay behaviour. These tests were performed such that the spring did not touch the sensor before an input was given. This simulated the effect of a sudden input due to the play between the kingpin and the fifth wheel.

Figure 10 (a) shows an example of the measured load by the sensor for a bump test with an amplitude of 120[mm]. The measured data is given in blue and in red data is shown when a moving average filter is applied. This to show how a relatively simple filtering technique can enhance the signal to make it more suitable as a control input signal, for example to filter out overshoot values. Something that can be noticed at approximately t=4[s] and t=9[s]. Besides the overshoot, the bump tests did show some measuring delay by the sensor of 0.01[s], although it is unclear whether this is delay or limitations of the test setup. And it can be questioned whether such a (small) delay has an impact when the signal is used by a controller.




(a) (b)

**Figure 10 – (a) Measured load by the load-cell sensor for a bump test with 120[mm] amplitude and (b) Linear behaviour of the load-cell sensor.**

In addition to a bump test example, Figure 10 (b) is given to validate the linearity of the sensor by showing the relation between the displacement and the (absolute) measured force. The blue points are the measured data, and the red line is representing the estimated values by applying Equation 1with the known spring constant. Little deviations, in the order of 5%, can be seen but overall good similarity, and therefore linear behaviour is observed.

Next to the bump tests, sinewave inputs with a maximum amplitude of 120[mm] and a frequency ranging from 0.1[Hz] to 6.0[Hz] were tested. These tests represent trailer vibrations, e.g. coming from the truck diesel motor or road surface disturbances. This to assess how well the sensor could measure the input and how well it could follow frequencies (and up to what frequencies). Figure 11 (a) shows an example of a sinewave test with a frequency of 1.0[Hz], with the measured data in blue and in red the moving average data. It can be seen that both this test as the bump test in Figure 10 (a) show the same maximum value for the same amplitude of 120[mm]. In addition, it can be seen that the sensor is well capable of following the provided input since a clear sine wave signal is measured.

To assess how well the sensor can follow / measure frequencies inputs Figure 11 (b) is given, showing the results of a sinewave test with an input frequency of 5.25[Hz]. Please note that the maximum force values do differ between (a) and (b). This is due to the fact that the lab-setup was not capable of delivering the maximum amplitude of 120 [mm] for frequencies > 4.0[Hz]. The amplitude was therefore lowered to 100[mm] for all tests above 4.0[Hz]. Nevertheless an amplitude of 100[mm] should result in a measured load of more than 50[kN], see Figure 10 (b), while the sensor measures a maximum of approximately 35[kN] (absolute). Besides, the sensor does not measure 0[N] anymore even though the set-up is providing 0[mm] input. This implies that the sensor is not capable of measuring frequency inputs above a certain value. By analysing the different sinewave tests, this seems to be around 5[Hz].

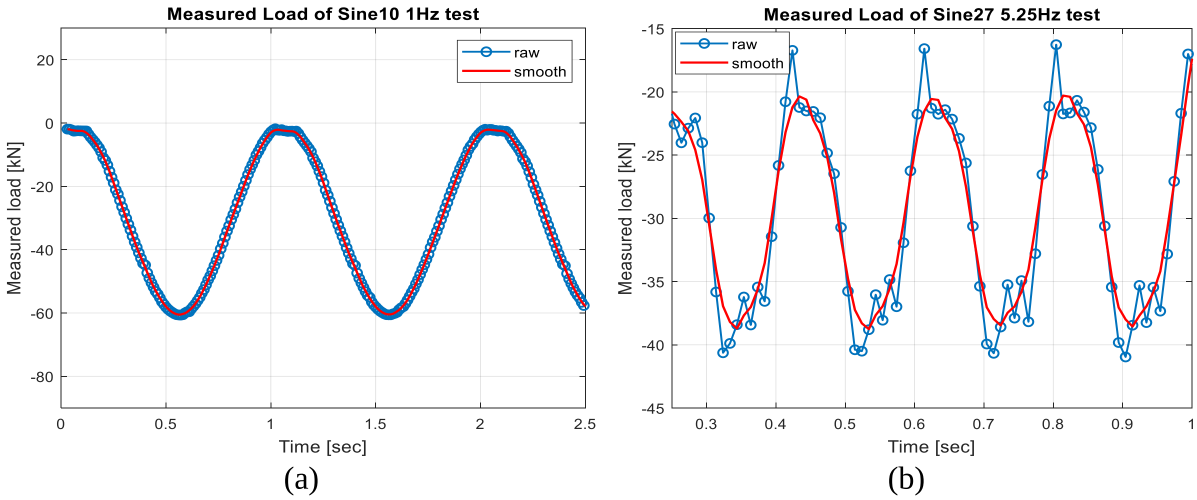



**Figure 11 – Frequency turning point for (a) 4.75[Hz] and (b) 5.25[Hz] sinewave tests.**

Figure 11 (a) and (b) do show that the load-cell sensor is capable of measuring vibration inputs, which implies that the sensor, and therefore the output signal, will be affected by vibrations. The sensor's capability of measuring frequencies has a turning point around 5[Hz], because above this threshold the sensor will not be able to measure the given input correctly anymore. It is therefore quite certain that filtering techniques are required before the signal can be used as a control input. However, from the lab-tests it is challenging to determine what techniques are suitable due to the ideal conditions. In real-world application more noise and disturbances are expected. Real-life road tests with the sensor integrated as intended should show the effect of acting vibrations, road disturbances and noise on the output signal better.

## 5. Conclusions and Future Work

This paper presented part of the work of the SHIFT project, which aims to address the transport sector emissions, by developing a new type of coupling system, to enhance E-trailer deployment. This "force-sensing kingpin" system combines the connecting purpose of the kingpin and measures the longitudinal reaction force between the kingpin and the fifth wheel, which can be used as an input to control the E-axle.

A Multibody model was updated with a validated braking system and used to gain insights in the longitudinal force(s) acting on the kingpin under several driving conditions. Maximum values were determined and furthermore it was found that the kingpin force is positive for acceleration and negative for braking. This result is of importance for E-trailer controller design. Other important findings were the effect of slopes, adding to the kingpin force, as well as the effect of cornering, which can be significant. However, there is a need to analyse the effect of cornering more thorough, especially for cornering while braking and/or coasting (no throttle or brake applied). The results show some indications that this will affect the kingpin force significantly, which can have an impact on the control approach. Also, a deeper understanding of the kingpin force for downhill scenarios while coasting are of importance.

In addition to the simulations, lab-tests have been conducted with the intended measuring sensor of the coupling system. It can be concluded that the load-cell sensor will be rigid enough to measure the (high) kingpin forces, and linear behaviour is observed. Sudden inputs are measured correctly, with high but short overshoot and neglectable delay. Furthermore, vibrations and/or disturbances can be detected by the sensor, especially with frequencies below 5[Hz]. It is therefore quite certain that filtering techniques, like Kalman, are required to make the signal more suitable as a control input. However, the lab-setup had ideal conditions, while noise and disturbances can be expected in the real-world application. Real-life road tests with the system integrated are advised to gain better insights in these effects on the output signal. Something that will be done in CHANGE, after the submission of this paper.

SHIFT is nearly finished, although is followed-up by a larger project CHANGE. Within this project it is aimed to develop and validate an E-trailer, including controller design based on this force-sensing kingpin system, reported by both Pauwelussen [5] and Kural [11].

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