DEVELOPMENT AND EVALUATION OF AN EXPERIMENTAL PLATFORM FOR STEERED AXLES OF LONG COMBINATION VEHICLES


M. HOFMANN
Chalmers University of Technology, Sweden

S. FRANZ
Chalmers University of Technology, Sweden


MM. ISLAM
Chalmers University of Technology, Sweden

L. LAINE
Chalmers University of Technology, Sweden

Abstract
Long Combination Vehicles (LCVs) can benefit from advanced strategies in controlling lateral dynamics of the combinations to ensure optimal motion by the trailers. Steering more than the towing units first axle has been developed in previous works and now needs to be verified in real vehicle tests. This work thus developed an experimentation platform incorporating a rapid-prototyping system to provide the possibility of evaluating these algorithms on vehicle level. In this paper the solution is detailed as a Hardware-in-the- Loop (HiL)-platform linking a vehicle dynamics frame-work with two steered axles. In accordance with the V-model development process, this allows to safely verify the functioning of both software and hardware before performing track-tests of the fully integrated system with all units of a LCV. This paper outlines the development and capabilities of the resulting experimental platform and gives a short example of its performance in a standard-maneuver, which is also used to proof the validity between simulation and HiL-environment enabling full system testing on vehicle level.

Abstrait
Pour contrôler la dynamique latérale des combinaison longues camion-remorques (mega-camions), il faut différentes stratégies pour assurer le suivi d'une trajectoire optimale par les remorques. Le contrôle de plus d'un essieu directeur de la combinaison a été développé et simulé lors de travaux précédents, et cette stratégie doit maintenant être vérifiée en conditions réelles. Cette publication présente donc le développement d'une plateforme d'expérimentation intégrant un système de prototypage rapide, qui offre la possibilité d'évaluer facilement ces algorithmes sur véhicule. Dans cette publication, la solution est décrite comme une plateforme de test Hardware-In-the-Loop (HiL), qui crée un lien entre un modèle calculant les dynamiques du véhicule, et deux essieux directeurs. En accord avec le cycle de développement en V, cette méthode permet de tester indépendamment, et de façon sûre, le logiciel et les partie mécaniques, avant d'effectuer des tests sur piste avec le système totalement intégré sur une combinaison camion-remorque complète. Cet article décrit le développement et les capacités de la plateforme de tests obtenue, et donne un exemple de ses performances lors d'une manœuvre standard. Cette manœuvre est également utilisée pour prouver la corrélation des résultats entre simulation et environnement HIL, autorisant les tests du système complet sur véhicule.

Keywords: Long Combination Vehicle, Active Steering System, Hardware-in-the-loop testing, Truck dynamics, Rapid-Prototyping

1. Introduction

The driving behaviour of Long Combination Vehicles (LCVs) is in many ways different to that of single unit trucks and needs to be researched in great detail to gain an understanding of the vehicle's dynamic properties, which is equally detailed as it is for other vehicle classes. This will lead to development of better safety and assistance systems and thus reduce threat potential, accidents and fatalities involving this emerging mode of transportation [1]. The research project in which this work is embedded aims to develop an active dolly [2, 3], meaning that steering of two axles in a LCV will be autonomously conducted based on the driving situation at hand and various vehicle parameters (e.g. speed, steering wheel angle). This control algorithm is a result of previous works and shall now be executed on a rapid-prototyping system which controls two axles. To supply this connection between the hardware and control-algorithm implemented in the modeling-environment Simulink is the main-contribution of this work. This leads to lateral control over all units on vehicle level in a LCV. The platform developed in this work can be used to add steering for any two axles in a LCV.

The following points will be covered in this paper:

- outline of the development process of the experimental platform and presentation of the utilized hard- and software systems
- evaluation of existing hardware characteristics and delays and implemented measures to eliminate them
- discussion of a standard driving maneuver of a combination executed on the developed Hardware-in-the-Loop (HiL)-system
- a comparison between these HiL-maneuver and simulation results, which proofs the validity of the platform

1.1 Limitations

The limitations of for this work are:

- HiL-applications of the system are covered only
- all measurements in this work were undertaken with the axles being raised which eliminates friction. However, the axle loads are correctly simulated during the HiL-testing and are accounted for.

2. System Components

2.1 Base Vehicle Unit

The vehicle unit is a dolly manufactured by Parator Industri AB [4]. The steering system is based around the Electronically-controlled hydraulic Trailer Steering (ETS) developed and built by V.S.E. Vehicle Systems Engineering B.V. (VSE) [5] with two hydraulically steerable axles. The dolly's steerable axles were designed to be used in trailer steering as an after-market system and thus do not tie in with any of the truck's communication networks or sensor data. This makes it manufacturer independent and very robust. The ETS solely relies on the articulation angle between the leading and the unit with the steerable axle, and the speed of the combination. The articulation angle is obtained via a dedicated sensor mounted on the king-pin of the respective unit, the speed-signal is gathered from the ISO-11992 Controller Area Network (CAN).

2.2 Rapid-Prototyping System

To execute the previously developed algorithms, that govern the steering of the LCV-combination, they needed to be ported to a platform, capable of interacting with the dolly and the tractor, while ensuring robust behavior during run-time. It was decided to incorporate the MicroAutoBox II (MABII) [6] by dSPACE [7]. This real-time platform was chosen for its advantages in automotive environments with a vast selection of in- and outputs for interfacing with vehicular communications systems (CAN, Ethernet, FlexRay). Furthermore, it conveniently ties in with Simulink, which was used for algorithm development, code-generation and compilation. The tool-chain furthermore comes with the supporting tool ControlDesk to easily provide logging and monitoring during run-time as well as control over the simulation variables' states.

2.3 Vehicle Dynamics Simulation

To evaluate the dynamic performance of the LCV on vehicle level Volvo Group Truck Technology's Virtual Truck Model (VTM) [8] library came to use. It is a library developed in and for Simulink environment and permits the simulation of truck dynamics based on a multi-body model for the kinematic relation and a parametrized tire model using the magic formula. It is a state-of-the-art tool validated in many real vehicle tests. The safety margins for the supervisor system were also determined in the VTM environment.

3. Architecture

3.1 Modification to Base System

The articulation sensor described in section 2.1 were discarded and replaced by an artificial signal emulating the original message structure. By using the inverse function of the original mapping of articulation angle to steering angle, it was possible to command the desired steering angle. The base system has one CAN for both axles, resulting in one common steering angle for the both of them. By splitting this CAN into two separate networks, it is possible to actuate the axles independently.

3.2 Track Testing Setup

On-track the setup of the developed system will be partitioned as illustrated in Figure 1. The MABII runs the steering controllers (and supporting safety functions) and is located on the dolly. Two separate CAN-connection with the two hydraulic ECUs controlling one axle each are used to command the steering. Closed-loop feedback is also handled via these CANs.

To provide relevant vehicle parameters (e.g. yaw-rates, accelerations) to the steering controller the MABII is also connected to the tractor's CANs.

Logging and monitoring is possible via a laptop ("Host-PC") connected to the MABII via Ethernet. This laptop is located in the tractor cabin.

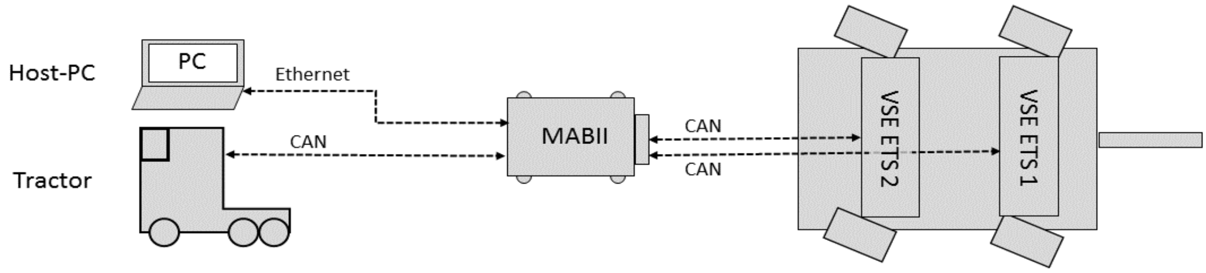

Figure 1 – Test-track Configuration of Active Steering Dolly in a LCV

3.3 HiL Verification Setup

In accordance with the process of the V-model [9] it was deemed necessary and safest to verify both hardware, software, and the integrated algorithm in cooperation with the system in a HiL-test. To evaluate the performance of the active dolly in a lab environment the target system described in section 3.2 was modified. The CAN-connection coming from the truck which provides vehicular parameters to the steering controller was replaced with corresponding data from a real-time simulation in VTM. In this simulation the dynamic behavior of the whole LCV was simulated excluding the steered active dolly which ran on the actual dolly. The resulting (delayed, damped) steering on the dolly was fed back in real-time into the simulation via an additional feedback loop as depicted in Figure 2.

Furthermore, the VTM library includes a lot of processing-intensive sub-models (tire models, vehicle parameter sets) which lead to processing power not sufficing to allow for VTM's easy execution in the dSPACE environment on the MABII. To perform HiL-testing it was thus advisable to split the computational load and accomplish real-time data exchange between the hardware controlling-system on the MABII and the rest of the simulation which will be run simultaneously in Simulink in real-time on a standard PC. Though there are dedicated real-time platforms available to achieve real-time execution it was decided to rely on a standard PC to minimize costs. Figure 2 illustrates the distribution of the HiL-setup's different components according to the Volvo Group Technology functionality model [10] over two computers, the MABII and the actual hardware (axles, hydraulic control system).

The Vehicle Motion Management (VMM) which contains the actuator coordination for realizing the desired global forces and moments on the combination vehicle consists of the previously developed controller which is executed on the simulation PC and the steering interface executed on the MABII. For track-testing it is necessary to also port the controller for execution on the MABII to have one closed off system. Running the actual steering controller on the MABII will further increase the dynamic performance so running it in the simulation environment is a conservative estimate and was mainly done for convenience reasons. All controllers were designed to run and verified on the MABII (i.e. no special tool kits, real-time capable).

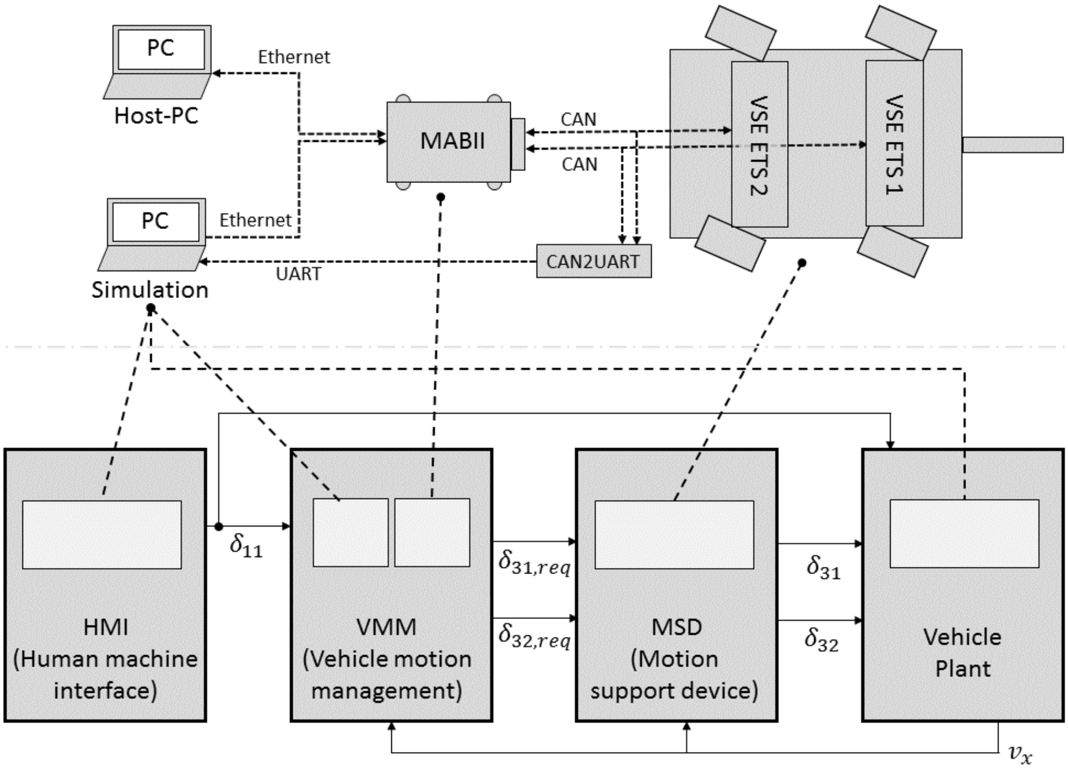

Figure 2 – Overview of Hil-Simulation, Distribution of Sub-Functions over Different Physical Platforms (Top) And Correlation to Vehicle Functionality Architecture (Bottom)

4. Characteristics and Implemented Measures

Three characteristics mainly influence the behaviour of the system:

1) If a constant steering-angle is requested over a certain period, the hydraulic system will slowly fall back to the middle position. This needs to be eliminated because turning maneuvers or shunting situations often require maximum articulation for longer timespan.
2) Around the middle-position the steering does not react towards small changes. The legacy system has a dead band for commanded articulations between ±2 degrees. For the original application this is useful to ensure a straight path of the vehicle. For this experimental platform however consistent control over the complete range is desirable. This is to also enable small articulations of the axles which is especially called for at higher speeds, where steering angles are a lot smaller (compare section 5).
3) The steering system has a response time, composed of the normal inertias of the hydraulic system and an additional delay introduced by filtering and noise-canceling in the legacy system. This delays can be gathered from Figure 3.

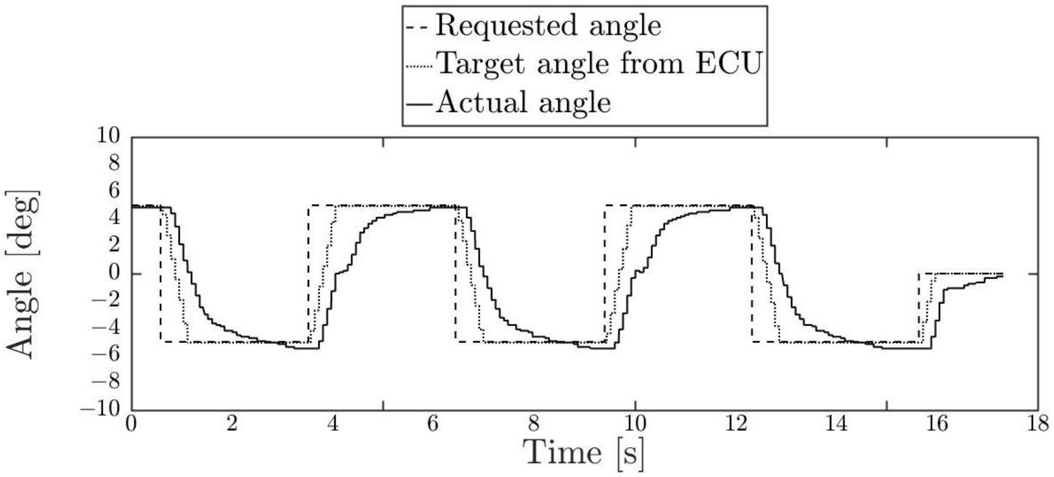

Figure 3 – Delay between requested angle and actual angle

Measures to address these issues were:

1) To avoid the decline for constant requests, a periodic rectangular function with a small amplitude is added to the requested value and then fed forward to the Electronic Control Unit (ECU).
2) A Pulse Width Modulation (PWM) around the zero articulation position reaching out of the dead-band was implemented for requested angles lying within this range. Figure 4 shows the working principle of this measure. The mean value of the request to the ECU equals the desired request from the steering algorithm. The pulse function oscillates between specified amplitudes outside the dead band. Through the inertia in the hydraulic system smaller angles can be accomplished, too.
3) Exactly determining the delay period made it possible to account for it in the calculations for initial open-loop testing at sufficiently low speeds. A value of 0.26 s for the front axle's reaction time and 0.30 s for the back axle's respectively were measured.

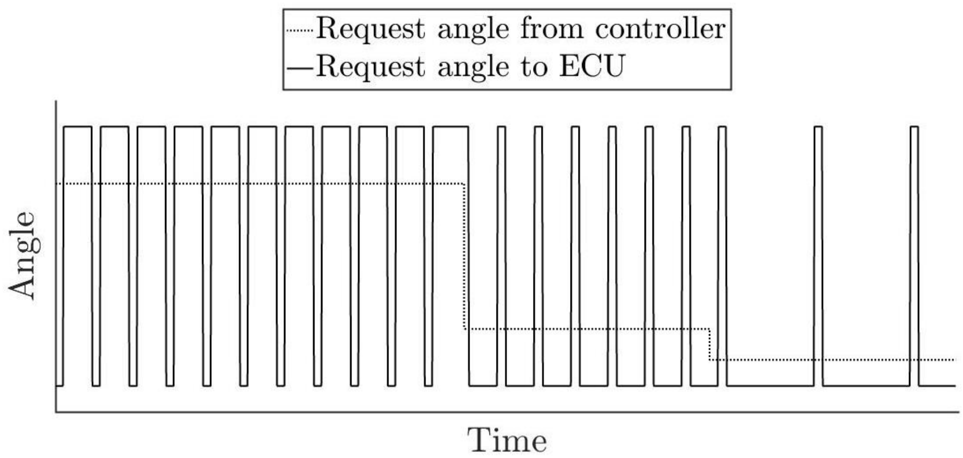

Figure 4 – Sketch of working principle of the implemented PWM to circumvent dead band

4.1 Supervisor Functionality

Figure 5 illustrates the dataflow in the control system. The steering algorithm bases its calculation on the actual steered angle of the dolly (and various other vehicle parameters). The computed request is limited by supervising functions and then handed over to signal conditionig functions further outlined in section 4. From here the requested steering angle is send to the hydraulic ECU, which in return provides the actual steering angle completing the feedback loop.

The supervisor block limits the steering angle and steering rate. Limts are based on the maximum articulation of the steering system (± 26°) for low speeds (≤ 20 km/h). With higher speeds the supervisor gradually decreases limits of the steering angles based on vehicle simulations priviously conducted in VTM. This prevents unsafe driving situation of the combination. The determination of the maximum steering angle at the dolly was based on limiting the vertical acceleration of that unit at 0.25 g.

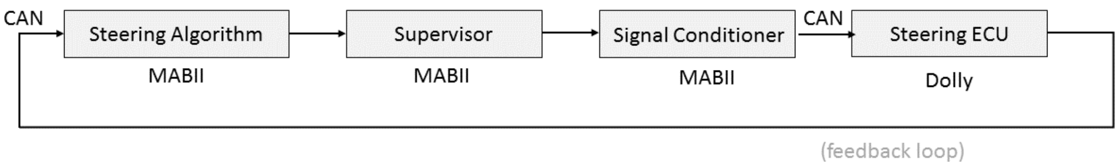

Figure 5 – Dataflow in Steering Controller system

5. Showcase Maneuver

To show the capabilities of the designed active dolly and demonstrate the validity of the developed HiL-system two maneuvers at low and high speeds are presented. These two cases have entirely different demands towards the system.

5.1 Low-speed U-Turn

To briefly show the general functioning and to give the reader insight into a practical application of the project, a standard driving maneuver was performed on the platform in the outlined HiL configuration. As an example the U-turn was chosen for its relevance in everyday driving and the fact that it shows some of the characteristics of LCVs distinctively. It was executed at a longitudinal velocity of 2 m/s, thus resulting in a turning radius of approx. 16 m. To ensure consistent behaviour over all measurements, the steering-angles of the truck were pre-programmed. As visible from

Figure 6, the truck does not leave the turn in a perfectly straight path. However, this is not relevant to this verification, as discussed further on only matching between the two environments is called for.

Figure 6 shows the behaviour of two different units in the combination both for the developed platform in its HiL configuration as well as the performance in the simulation environment. This gives the opportunity to compare between the two different stages of abstraction in the V-model, thus verifying the correct functioning of the actuated axles before executing further testing in the V-model: What clearly shows in

Figure **6** is the phenomenon, that the second trailer does not follow the tractors path exactly. This is called off-tracking and minimizing it with an adequate actuation strategy is one of the major points within this research project.

However, this shall only be a brief mention in this publication. The main point of Figure **6** however is, to show the congruence of the resulting trajectories of the simulated environment and the HiL setup.

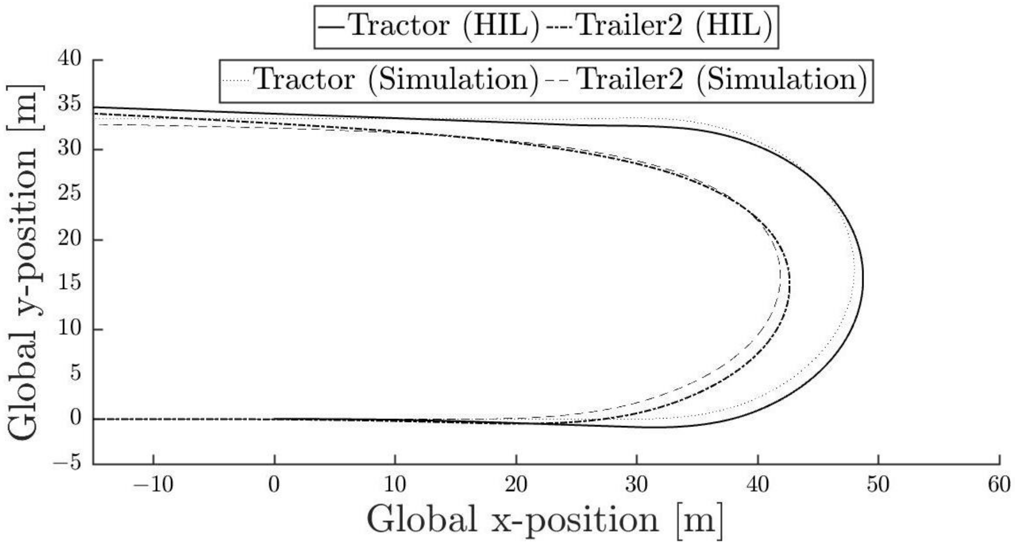

Figure 6 – Path of Tractor and Second Trailer for HiL and Simulation

5.2 High-Speed Single Sine-Input

To evaluate the performance of the active steering dolly at higher speeds, a single sine input (amplitude of 0.025 rad, frequency of $0.4 \times 2 \times \pi$ rad/s) at the speed of 20 m/s was conducted at the steering wheel. The steering algorithm for the active steering was designed after [1].

Figure 7 shows the yaw rates of the first and last unit during this maneuver both for pure simulation environment and the HiL setup. Again results match very well between the two environments and produce congruent dynamic behavior.

The yaw rates of the last unit in the combination are a good indicator for the off-tracking of the last unit, which is one of the prime target of optimization in LCVs. As becomes evident from Figure 7, the yaw-rates at the last unit are considerably higher than for the first unit. This is due to the fact, that the tested controller was an early version to verify the platform early on during development. Its performance to optimize trajectories is of little relevance here. The main point is to compare the performance between the two environments (HiL and simulation) and ensure the correct interfacing of the control algorithm with the platform.

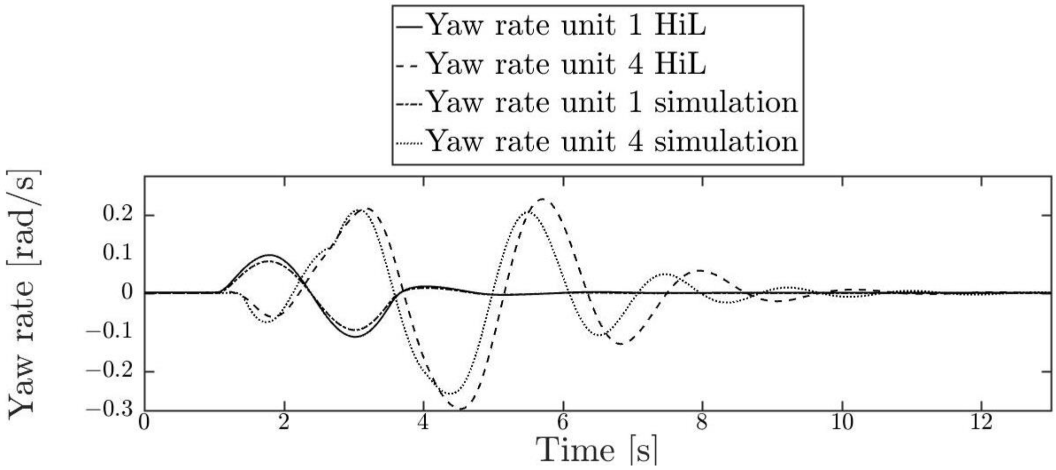

Figure 7 – Comparison of Vehicle Yaw Rates between Simulation and HiL-testing

Figure 8 again shows the distinctive behaviours of the hydraulic system (slow rising) and the delay between requested and actual steering angle at the axles in the HiL described in section 4. Furthermore the actions of the supervisor are visible as the requests are cut off (plateau at 4 °) for this high speed maneuver.

The main-point however again is the matching between the simulation and the HiL setup. The promising conformity between the environment suggests further tests in real vehicle application.

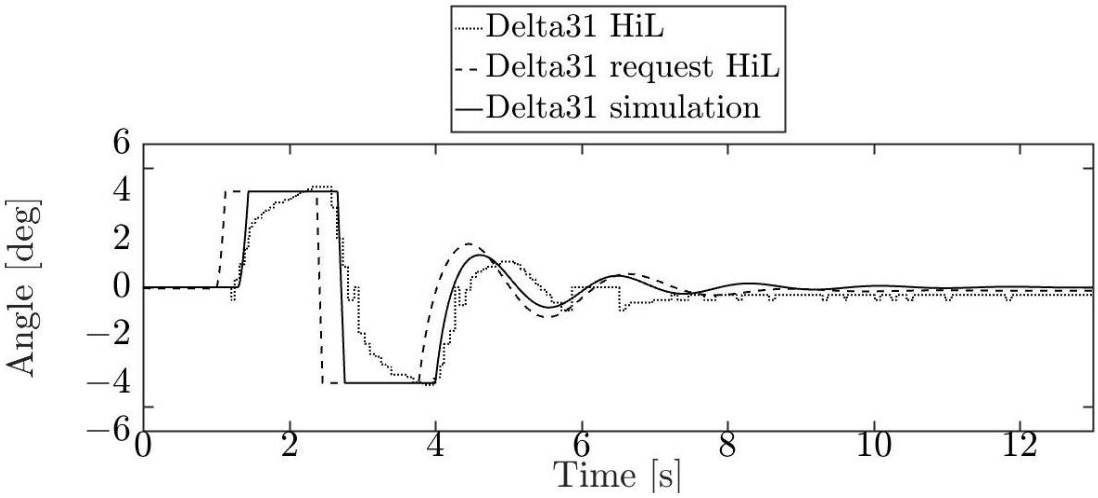

Figure 8 – Articulation of the First Axle on the Dolly in Simulation and HiL-testing

6. Conclusion

A platform which provides steering of two axles in a truck-combination was developed. Both axles can be steered independently. A compact software interface for the algorithm development process was created, enabling access to the platform's hardware in the native Simulink environment. This interface already includes first safety functions to limit undesired inputs. Based on experience from simulations or practical limitations, further rules can be conveniently implemented. This platform enables rapid-prototyping of steering algorithms and functions on an abstract level without the need to consider lower level hardware issues. The experimental platform was linked with a vehicle dynamics framework to form a HiL system, which enables safe evaluation of a whole combination on vehicle level with two axles as hardware in the lab. Safely locating deficits and peculiarities before deploying the whole combination to the track is the main benefit of the developed system. The correlation between the simulation results and the HiL tests was achieved accurately enough to continue with track testing.

7. Future Work

Matching the platforms performance in HiL configuration and the actual LCV on the track will need fine-tuning in the future. Practical experience during the deployment of the steering algorithms to the system will be very beneficial in enhancing the benefit of this tool further. Cutting out the legacy ECU by directly controlling the hydraulic steering could further decrease the delay in the system and thus the dynamic performance.

8. Acknowledgements

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