Trailer Reversing Supported by Steer-by-Wire

Trailer back-up assist using Steer by Wire

Chang Liu[1,2], Jakob Roempke[1,2], Matthijs Klomp[2,3][0000−0001−5972−1660], and Lars Drugge[1][0000−0001−8928−0368]

[1] Royal Institue of Technology, Stockholm, Sweden
[2] Volvo Cars, Gothenburg, Sweden
[3] Chalmers University of Technology, Gothenburg, Sweden

Abstract

Backing up a trailer can be a daunting task, even for experienced drivers. The main challenge being the unstable property of car-trailer kinematics when reversing. With steer-by-wire systems, the mechanical connection between the steering wheel and the road wheels is replaced by an electrical connection. This means that road wheels no longer have to be directly connected to the steering wheel input. The aim of this paper is to help the driver to steer the trailer directly by stabilising the car-trailer kinematics during reversal. This is achieved by developing a steer-by-wire system coupled with a closed-loop trailer reversal control using the necessary feedback. How to obtain this feedback is further investigated in this paper as well as how to use the steering wheel input and torque feedback to interact with the backup assist function. The developed control and user interaction is subjectively and objectively evaluated using computer simulation and a physical prototype of a vehicle equipped with steer-by-wire.

The results from the simulation experiments demonstrate that drivers with and without experience of driving a trailer can do the wanted manoeuvres with higher accuracy as well as within a short time span with the controller that is developed in this work. The results from the real life experiments also appears to indicate that the system can remove stress from the driver and move the trailer in an accurate way during a parking manoeuvre.

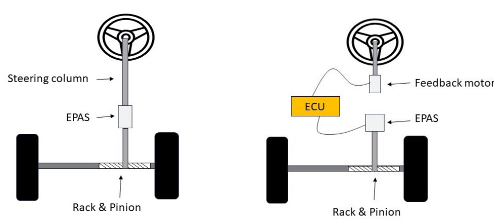
Keywords: Steer-by-Wire · Trailer · Backup Assist

1 Introduction

There are many benefits with the introduction of steer-by-wire into vehicles. There are both economic and functional reasons for this introduction, examples of economic reasons can be, fewer modifications for left- or right-hand driven vehicles, simpler axle geometry as seen in Figure 1, and weight/space reduction. The main functional reason for steer-by-wire is the possibility of having a steering ratio that changes with speed, surface, etc [1].

Reversing with a trailer is known to be a difficult manoeuvre and a lot of experience is needed for being able to do it in a good and accurate way. The main challenge lies in that the system is unstable during reversal. If you drive the car-trailer system in a straight line, sooner or later the trailer angle will diverge unless stabilised by the driver. It is also challenging from the drivers perspective since the trailer will initially move in the opposite direction of the drivers steering input due to offset between tow hitch and the rear axle of the vehicle [2].

The system developed in this project will be different to a traditional "non-steer-by-wire" car since it takes the input from the driver of what the desired car-trailer angle should be instead of what the wheel angle should be. While this manoeuvre could also be achieved in a traditional car without steer-by-wire, there are drawbacks, as noted in [3]. The primary challenge lies in the difficulty for the driver to translate their desired trailer movements through the steering wheel, which is mechanically linked to the wheels. Consequently, the steering wheel must constantly mirror the wheel angles, necessitating the use of alternative mechanisms, such as a knob, for the driver to specify the desired car-trailer angle i.e. the ϕ angle. This setup results in the steering wheel rotating during manoeuvres, sometimes at high speeds, causing discomfort for the driver and potentially posing safety risks.



(a) Conventional steering (b) Steer-by-Wire

Fig. 1: The difference between conventional steering and Steer-by-Wire.

2 Car-trailer motion and controller design

2.1 Bicycle model for the car based on geometry

The way that the kinematic model of the car-trailer system will be derived for this thesis will be based on the method that is used in [4]. This model, which is based on a bicycle model of a car-trailer system, is going to be implemented in a car-trailer system so that the angle between the car and the trailer (i.e. hitch angle) can be controlled .

There are both fixed variables such as the wheelbase, length from the tow hook to the rear axle of the car as well as the length from tow hook to the axle on the trailer, and also values that will change with time such as, actual and demanded car-trailer angle ϕ, the actual and demanded angular rate $\dot{\phi}$ as well as the speed of the car.

The angle and the angular rate of the hitch angle ϕ is defined in this thesis as seen in Equation 1 where θ_1 and θ_2 is the car and trailer global angle respectively. This can be seen in Figure 2:

$$\phi = \theta_2 - \theta_1, \qquad \dot{\phi} = \dot{\theta}_2 - \dot{\theta}_1 \tag{1}$$

The points IC_T and IC_V are the trailer and car rotational centres, respectively. These are defined as the points around which the bodies rotate.

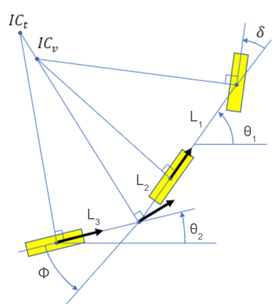


Fig. 2: An overview of the kinematic model.

Based on the bicycle model in Figure 2 equations can be derived on how the angular rate of the hitch angle ($\dot{\phi}$) depends on the hitch angle (ϕ) and the steering angle (δ) [4], which can be seen in Equation 2.

$$\dot{\phi} = -\frac{v}{L_3} \cdot \sin(\phi) - \frac{v}{L_1} \cdot \left(1 + \frac{L_2}{L_3} \cdot \cos(\phi)\right) \cdot \tan(\delta) \tag{2}$$

2.2 Stability analysis of the open-loop system

To analyse the stability of the open-loop system Equation 2 an eigenvalue analysis is performed.

In order to do so, a first-order Taylor expansion of Equation 2 is made such that:

$$\dot{\phi} = -\frac{v}{L_3} \cdot \phi - \frac{v}{L_1} \cdot \left(1 + \frac{L_2}{L_3}\right) \cdot \delta \tag{3}$$

From Equation 3 it can be seen that the car-trailer system without any backup assist, the eigenvalue of the linearised system is $-\frac{v}{L_3}$, which lies in the left-hand side of the complex plane if and only if v takes on a positive value, indicating forward driving. Conversely, we can confirm what we know from experience, namely that the system is unstable when reversing. The instability of reversing raises the need for an assist system to ensure that the eigenvalue is in the left-hand side of the complex plane.

2.3 Controller design

In this paper, the controller by solving for the steering angle, δ, from Equation 3 such that:

$$\delta_{target} = -\frac{L_1}{v} \cdot \frac{L_3 \cdot \dot{\phi}_{target} + v \cdot \phi}{L_2 + L_3} \tag{4}$$

with $\dot{\phi}_{target}$ being the control value.

The control value is based on the difference between the real-time ϕ and the target ϕ as a P-controller:

$$\dot{\phi}_{target} = k \cdot (\phi_{target} - \phi) \tag{5}$$

The value is fed to a P controller with the output as the $\dot{\phi}$ input to the steering angle, that is the target front wheels angle of the car. The value of ϕ is also given as an output from the system, which can be used as feedback to the driver in a way that the ”zero-torque” position of the steering wheel always corresponds to the angle of ϕ. A block diagram of the controller is shown in Figure 3.

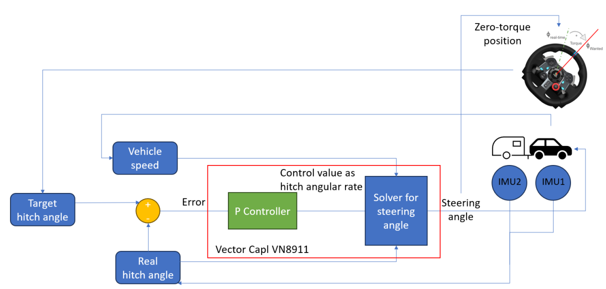


Fig. 3: The flow chart for controlling ϕ.

2.4 Stability analysis of the closed-loop system

By combining Equation 4, Equation 5 and Equation 3, the eigenvalue of the system is changed to $-k$. This means that, all that is required to ensure the stability of reversing is that k needs to be larger than zero so that the eigenvalue lies in the left-hand side of the complex plane.

3 Length estimation of trailer

For the model that is developed in this project to work, there is a need to know the length of the trailer to its wheel axle. The length of the trailer is not always known and it can also be difficult to accurately measure the length. This could be a cumbersome process if it must be done by the driver. Therefore it would be beneficial if the trailer length could be determined automatically. This could be done using a error prediction method, using a parameter value that minimises the quadratic sum of the prediction errors [3]. However, to make the system compact and more efficient, another simple yet effective way of determining the length of the trailer is created and utilised. This is by using Equation 2 to derive the length of the trailer L_3. The equation for L_3 can be seen in Equation 6.

$$L_3 = -\frac{v \cdot (\sin(\phi) \cdot L_1 + L_2 \cdot \cos(\phi) \cdot \tan(\delta))}{\dot{\phi} \cdot L_1 + v \cdot \tan(\delta)} \tag{6}$$

This equation will give the length of the trailer whenever all of the variables in the equation are steady-state. The car-hitch angle as well as its angular rate, steering angle, and car speed will be recorded during a short period when reaching steady-state and the distance between the trailer axle and the tow hook can be calculated using Equation 6. The easiest way to get stable inputs is to start the length estimation while going forward in a turn with a fixed steering angle. This means that $\dot{\phi}$ will move towards zero and the speed and ϕ will move towards steady values respectively. This will make the equation easier to solve as well as make the result more stable. If the trailer gets replaced by a different one, the system will work again to estimate the new geometry. In theory, the estimation also works during reversing if the trailer back-up assist system is not active. After the automatic length estimation, the result will be sent to the controller as input of trailer length. The driver can also choose to manually input the length.

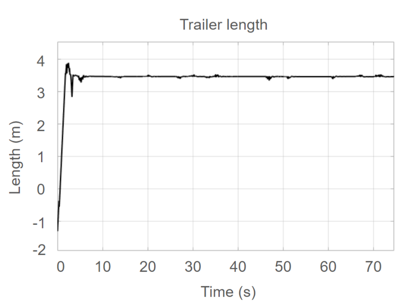


Fig. 4: Simulation results of the length estimation of a 3.5 meter long trailer.

As can be seen from Figure 4, the trailer length estimation gives reasonable values after about 5 seconds. This delay is due to the road being straight in the beginning and leads to that there is no steering angle to start with.

4 Determining the car-trailer angle

In the trailer backup assist system, estimating the hitch angle is a key for controlling the required steering during trailer reversing. This angle can be determined direct measurement or by using yaw-rate sensors, as was done in this project. This works by having one yaw-rate sensor on the car and the other on the trailer. The hitch angle is then determined by integrating the difference between the car and trailer yaw angular rate ($\dot{\theta}_1$ and $\dot{\theta}_2$) over time.

One challenge with this way of determining the trailer-car angle is that there is no way for the car and trailer to know their global angle relationship at the start of integration, therefore a calibration of what is zero degree of the hitch angle must be done. This is done by resetting the integration to zero when the yaw rate of both car and trailer has been close to zero for some time during forward driving.

Another challenge with this setup is that it is very common to have integration drift due to sensor bias. There are several more or less complicated ways to reduce the influence of the IMU drift. In this paper sensor bias is observed over time and when the car is stand still, the observed bias is removed from the yaw rate and thereby reduce the influence of the integration drift.

5 How to avoid jack-knifing

Jack-knifing is when the car-trailer angle can no longer be reduced but increases until there is contact between the car and trailer. This so-called critical angle is reached the moment the car and the trailer share the same yaw rate and the front wheels are the front wheels are steered to its maximum value [3] [5]. To find the critical hitch angle, calculations can be done to find when the car and trailer share the same instant centre of rotation when the maximum geometrical angle on the front wheels is reached.

An estimate of the critical angle $\dot{\phi}_{crit}$ can be found from Equation 3 when $\dot{\phi} = 0$ and $\delta = \delta_{max}$ such that

$$\phi_{crit} = -\frac{L_3}{L_1} \cdot \left(1 + \frac{L_2}{L_3}\right) \cdot \tan(\delta_{max}); \tag{7}$$

This means that to prevent jack-knifing from occurring, ϕ should not be allowed to pass the critical angle. The width of the car and trailer is not considered in this calculation which might lead to that the critical angle might not be reached before the car and trailer hit each other if the car or the trailer is very wide.

6 Experiments

6.1 Experimental setup

For the driving simulator studies conducted in this research, IPG CarMaker was used. Two experiments were conducted to discover if the trailer back-up assist is improving the drivers' performance to reverse with a trailer. For the straight reverse experiment, the trace of the car was recorded and compared with a reference lane that it should follow. Mean squared errors of the comparison were computed to determined the accuracy of the car-trailer system motion with or without the back-up system. Time for movement was also recorded for each of them. For the parking experiment, similarly, a reference lane was given for the driver to follow, with and without the back-up assist system. In this case the time it took to complete the manoeuvre is shown for comparisons and not mean squared errors since was found to be difficult to compare the actual trace with the reference in a good way.

For the real-world tests using a test vehicle with a trailer, steering wheel data were recorded and are plotted to show the difference between manual and assisted manoeuvres.

6.2 Experiment results - Driving Simulator

The first experiment was conducting using a Volvo XC90 demo model with user-defined steering system based on steer-by-wire with the trailer back-up assist. The experiment was made up by two parts: the straight-line reverse test and the parking into a designated parking lot on the simulated parking space test. For the straight-line reverse, the test drivers drove the trailer-car system to reverse for 80 meters on a straight road, with and without the assist system. Driving traces of the car, for three test drivers, are shown in Figure 5 to make comparisons between driving with and without the assist system.

(a) Driver 1, without assist (b) Driver 1, with assist

(c) Driver 2, without assist (d) Driver 2, with assist

(e) Driver 3, without assist (f) Driver 3, with assist

Fig. 5: Results from the straight line experiment.

In Figure 5, the blue line is the reference straight line to follow for the test driver, which starts from the left side of a figure. The red lines are the traces of the cars driven by test drivers, with a sampling rate of 2 Hz. It is clear that the drivers can follow the reference lane more accurately with the help of the assist system. Without the assist system, some drivers have to undergo several trials and errors to correct the direction of the trailer. To quantitatively show the differences of lane-following accuracy, a mean squared error based on the deviation between the trace and the reference lane is defined and computed. Results are shown in Table.1.

Table 1: Mean squared errors (MSE) of three test drivers

	Non-assisted	Assisted
Driver 1	3.005 m^2	0.0 m^2
Driver 2	3.149 m^2	0.042 m^2
Driver 3	1.308 m^2	0.037 m^2

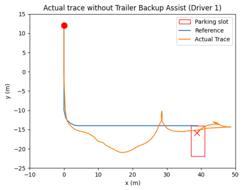
A smaller MSE value stands for a higher accuracy in following the reference lane. Without the back-up assist system, none of the drivers can easily control the car-trailer system even though driver 2 is experienced in reversing a trailer in the real world. Comparatively, with the assist system, all the drivers can follow the reference lane effortlessly.

In Table 2, time-to-reach for each driver has been recorded as well and the difference in time between being assisted and not is not as large as the difference in MSE.

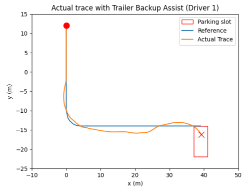
Table 2: Time for passing the distance of three test drivers

	Non-assisted	Assisted
Driver 1	187 s	31 s
Driver 2	62 s	71 s
Driver 3	169 s	109 s

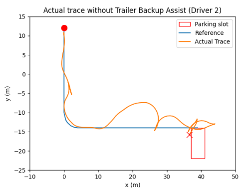
In the second experiment, the reference lane is no longer a straight road, but a path to park the trailer into a parking lot. Here, time-to-reach is the main output for evaluation shown in Table 2 and the three test drivers are put into a parking scenario. Their driving traces with and without the assist are recorded and shown in Figure 6.



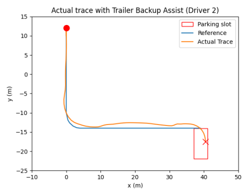
(a) Driver 1, without assist



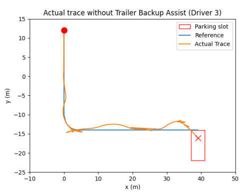
(b) Driver 1, with assist



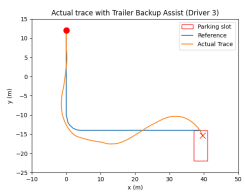
(c) Driver 2, without assist



(d) Driver 2, with assist



(e) Driver 3, without assist



(f) Driver 3, with assist

Fig. 6: Results from the parking experiment.

Table 3: Time for parking the trailer in the parking slot of 3 test drivers.

	Non-assisted	Assisted
Driver 1	192 s	43 s
Driver 2	131 s	41 s
Driver 3	170 s	46 s

It can be seen in Figure 6 that driving without the assist normally requires more correction movement and less possibility in keeping to the reference lane due to greater challenge in hitch angle control compared with having the assist. With these disadvantages, time-to-reach shows a great difference between assisted and non-assisted driving. For driver 1 and 3 who do not have much trailer parking experience, time-to-reach has been significantly reduced by 4 to 5 times. For driver 2 who is experienced, it has also been reduced by 3 times.

6.3 Experiment results - Real world

Due to lack of time the system that is implemented into a Volvo V60 was tested by any test persons other than the developers of the system. The main experiment that was conducted in the car is to study the steering wheel angle, ϕ and the velocity of the car through a parking manoeuvre. The data can be seen in Figure 7.

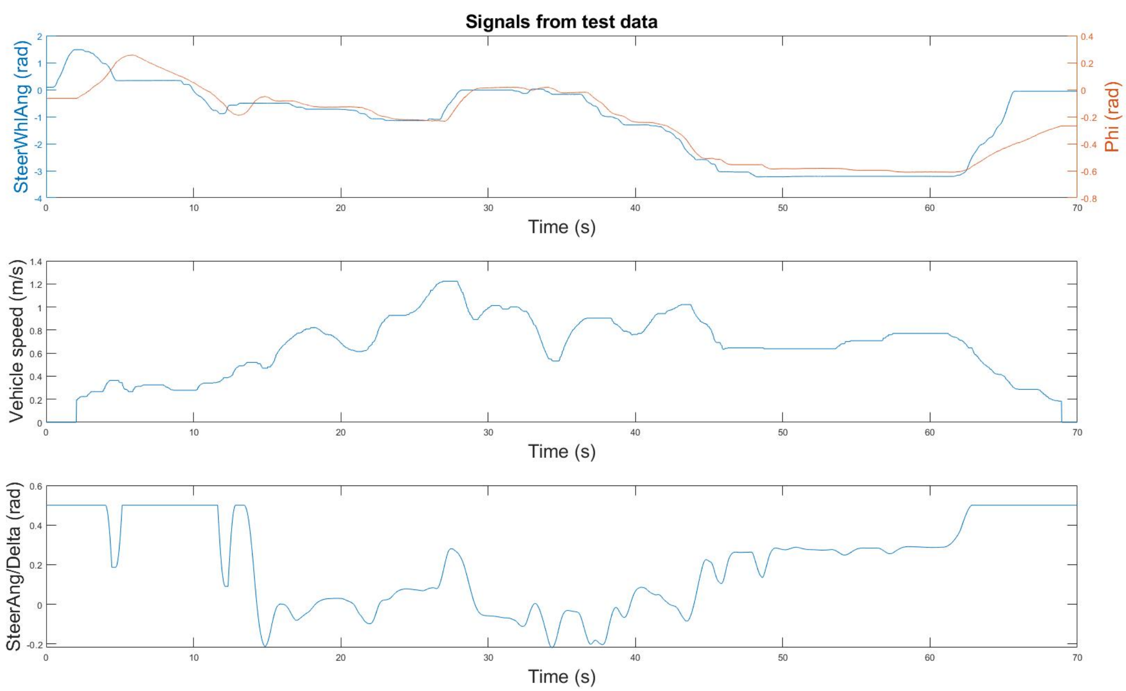


Fig. 7: Data gathered from the car in the experiment. The first graph show steering wheel angle in blue and ϕ in orange. The second graph shows how the speed is changing under time and the last graph show how δ changes with time.

As shown in Figure 7, the steering wheel angle input by the driver, the hitch angle ϕ, the steering angle δ, as well as vehicle speed from a 70-second trailer parking manoeuvre with regard to time were all recorded. The manoeuvre starts from stand-still and ends when the trailer reaches the target spot. To analyse the delay between the driver input and the hitch angle ϕ, the steering wheel angle and the hitch angle ϕ are overlaid.

The system is speed-sensitive since the steering angle δ was frozen below speeds of 0.1 m/s to reduce the stress on the steering rack at standstill. Also an amplitude limiter 0.5 rad for the steering angle δ was implemented. When the vehicle starts from stand-still, the steering angle δ was kept at 0 until the speed of the system reaches the safety limit. During this process, delay was accumulated since the system does not output required steering angle. After several seconds, the controller finishes compensating for the error and the delay is controlled under one second during the parking process. The delay also occurs during braking. Vehicle speed v controlled by the driver does not influence the delay unless it is smaller than the safety limit of 0.1 m/s. The last graph in Figure 7 shows how the steering angle δ is changing to fulfil the driver's request. A large difference can be seen between the steering wheel input in the first graph and the actual steering angle in the last graph. The steering wheel angle is changing slowly and predictable while the steering angle is more erratic. This difference is showing how much strain that has been taken off from the driver during a parking manoeuvre.

7 Discussion and Conclusion

The overall stability of the trailer back-up assist that is developed in this thesis can be considered as stable and does not seem to be restricted due to the linearisation of the equations used in the controller.

The main issue with reversing and controlling the motion of the trailer without the trailer back-up assist system that was noticed in the simulation experiments is that the driver must control the car direction in order to adjust the trailer direction in a nonlinear fashion. When the car-trailer system is moving, it is hard to predict how the trailer will react to the steering wheel input, and corrections must be made constantly. The delay in the change of trailer direction is also large. That explains for the large curves and less accuracy in the traces of the simulator experiments without the assist. When the driver becomes anxious due to lack of control over the trailer direction, the driver tends to overreact and give large inputs on the steering wheel, leading to more errors.

However, with the trailer back-up assist, the intensity of the above issues were reduced. The hitch angle follows the steering wheel input directly and ease the burden from drivers so that they had enough time to avoid obstacles and move the trailer in a stable manner. Also, since the car could react to very small changes of the angle in the car-trailer system, the driver could react before any large deviations occur in the wanted car-trailer angle and hence the stability of the system was vastly increased compared to the non-assisted system.

It can be seen from the experiments in the driving simulator that both the time to finish the manoeuvres as well as the accuracy of the manoeuvres was greatly increased using system that is developed in this work, both for experienced and non-experienced trailer drivers. The real life experiments shows that there was a large difference between the requested car-trailer angle (i.e. steering wheel angle) and the actual steering angle. This difference shows how much strain that was taken from the driver since the driver could focus on the path of the trailer instead of focusing on controlling the steering angle on the car and through that the path of the trailer. Hence, the experiments show that the trailer back-up assist can be a great help to drivers with different levels of driving skills.

One thing that is not considered in this work is the motion of the vehicle and therefore the risk of hitting obstacles with the vehicle. This means that since that the driver is mostly checking the motion of the trailer it might be so that the driver forgets to check the motion of the car and may drive into an obstacle with the car. However, this is something that can easily be avoided by using the proximity/camera sensors that are available on the car to alert the driver if the car get close to any obstacle. Another way to tackle this issue is by switching between the trailer backup assist mode and a normal driving mode.

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