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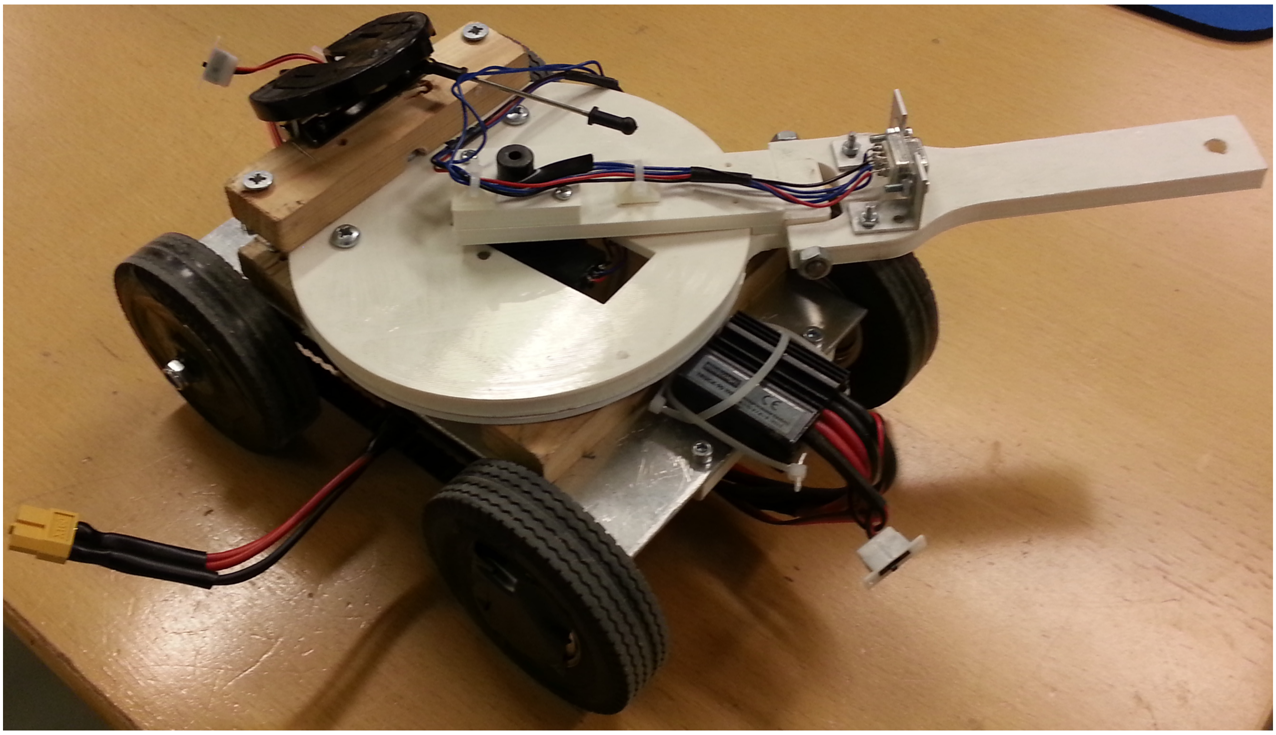

Investigation of active steering for a longer combination vehicle in scale 1:14 using a custom dolly

Master's thesis in Applied Mechanics

OLOF NORBERG

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis 2015:53
ISSN 1652-8557
Department of Applied Mechanics
Adaptive Systems Research Group
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Cover:
A picture of the active dolly used to improve the performance of a scale 1:14 longer combination vehicle.

Chalmers Reproservice
Göteborg, Sweden 2015

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Abstract

This thesis seeks to investigate the possibility of developing active steering for a dolly used in a scale 1:14 model of a longer combination vehicle. Producing some kind of active steering that makes longer combination vehicles safer and able to be used to a large extent on public roads would be of great benefit. The thesis is based on using scaled down models in an indoor laboratory, which is under development and is meant to bridge the gap between computer simulations and expensive full scale testing. The active steering is implemented with the help of an active dolly that is able to drive and steer using two motors, one for each side of the dolly. An algorithm for steering, based on an angle sensor in the dolly, is developed and tested in three different cases: two curves with different radii, and a lane change. The algorithm successfully manages to reduce lateral deviations when manoeuvring curves, but struggles to do it properly on straights. The results indicate that it should be possible to create a longer combination vehicle model that performs very well in most situations, but that some alterations in hardware might be necessary.

Keywords: Longer combination vehicle, Active steering, Dolly, Offtracking, Scale model

Acknowledgements

I would like to thank Krister Wolff, my supervisor and examiner, who gave me the opportunity to work on this thesis project, and who helped me during the project, particularly with hardware related matters. I would also like to thank Ola Benderius, who helped me with the software in the laboratory. Aside from them helping me when I needed it, discussions about the project with Krister and Ola gave me several ideas that proved useful.

Contents

1 Introduction

Recently, *longer combination vehicles* (LCVs), which are longer and heavier than normal transport vehicles and often the current legal limits, have garnered a lot of interest within the transportation industry. There would be many potential benefits to using LCVs, including significant reductions in number or trips, fuel consumption, and transportation costs [1]. However, there are downsides to using LCVs, as they can be difficult or impossible to manoeuvre on roads built for smaller vehicles. No proper statistical links have been established between road safety and the use of LCVs, but there are still many vocal opponents of LCV use [2]. The positives and negatives of LCVs mean that there is an interest within the transportation industry to develop LCVs that perform better and are safer.

At Chalmers University of Technology, research into this topic has been made, using both simulations [3] and full scale physical testing [4]. In addition to using simulations and normal testing, it is desirable to be able to perform physical testing that is scaled down. Scaled down testing, similarly to running computer simulations, is relatively cheap and not very time consuming, while retaining the advantages of being real life tests and some of the credibility that that brings. To achieve this, a scaled test track dubbed the *Intelligent Vehicles and Robots Laboratory* (IVRL) has been developed by the Adaptive systems research group at Chalmers [5]. One of the projects that are ongoing is to have a functioning scaled down LCV that can be used for testing implementations of active steering that may improve the safety of LCVs. As a part of this project, a scale 1:14 tractor-semitrailer-dolly-semitrailer combination, also known as an *A-double*, has been acquired, with the dolly having been custom built for the project [6]. The dolly, which is a wheeled unit that connects the two trailers, is fitted with motors that allow it to drive and steer.

The main purpose of this Master's thesis is to carry on the project of producing a scaled down LCV that is able to utilize active steering to help it navigate safely. As mentioned, the hardware, including an active dolly in the same scale as the LCV, already exists. Additionally, software for motion tracking and controlling vehicle models remotely also already exists in the laboratory. The remaining work to be done, and the aim of this thesis, is therefore to develop and test an active steering algorithm that controls the dolly. The hope is that this will lead to improved performance, such as a reduction in lateral deviations for the trailers, and consequently, improved road safety. Another important aspect of the purpose is to evaluate and to possibly improve the hardware, if it is found to be inadequate.

In terms of scope, the thesis is limited to what can be done in the laboratory, and what can be done with the current hardware of the LCV model. The dolly is fitted with an angle sensor, connected to the trailer in front of the dolly. The readings from the angle sensor, along with information of what the driver is doing, are the primary sources of information that the active steering algorithm may use. Although the thesis involves some minor hardware fixes and changes, major changes to the basic functionality of the dolly are only suggested rather than carried out.

2 LCV model and equipment

The development and testing of the active steering for the dolly was made possible thanks to a scaled test track, along with a scaled down model of an LCV. The LCV included a custom built dolly, and could have its position tracked using a *local positioning system* (LPS) that was set up in the laboratory containing the scaled test track. All of these things, along with the software used to run it all, are described in detail in the this chapter.

2.1 Tractor unit and trailers

In place of an actual full scale LCV, which would be quite expensive and difficult to use, a scaled down model was used instead. The three main parts of the LCV model were a tractor unit, and two trailers.

The tractor unit of the LCV was a scale 1:14 Volvo FH12 model made by Tamiya [7]. The two trailers used were scale 1:14 flatbed semi-trailers, also made by Tamiya [7]. The trailer that directly follows the tractor unit will be referred to as the *first trailer*, and the trailer at the end of the combination will be referred to as the *second trailer*. Together with the dolly, they form a tractor-semitrailer-dolly-semitrailer combination, also known as an A-double. A picture of the entire LCV is shown in Figure 2.1. The second trailer had a custom built black wooden open-box bed with hydraulics mounted on it. This construction was used for a different project that ran at the same time as this project, and was therefore not removed, despite it having no use for the purposes of this thesis.

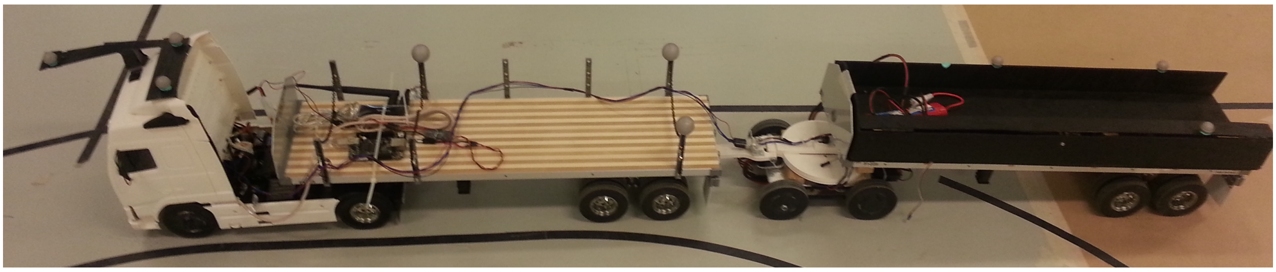

Figure 2.1: A picture of the 1:14 LCV model used in the project. The LCV consists of a Volvo FH12 tractor unit model made by Tamiya, two flatbed semi-trailers made by Tamiya, and a custom made dolly connecting the two trailers.

In the tractor unit, an Arduino Uno board [8] was installed to send signals to the motor and servos in the tractor unit, as well as any components in the dolly. The Arduino board was connected through USB to a BeagleBone Black [9], running Arch Linux. The BeagleBone Black was mounted on the first trailer, and was connected to a USB wireless network card. The purpose of the BeagleBone Black was to facilitate communication between the computer system in the laboratory and the Arduino, making the LCV remote controlled.

In total, the LCV had three different power sources. The motor and steer servo in the tractor unit were running off a 7.2 V NiMH battery mounted in the tractor unit. This battery also gave power to the BeagleBone Black and the wireless network card. To make this possible, a battery eliminator circuit had to be installed. Another 7.2 V NiMH battery was placed on the second trailer, and was used to power the motors on the dolly. The Arduino board had its own power source, consisting of four AA batteries mounted in the tractor unit.

2.2 Dolly

The dolly used in the project was custom built by Pascal A. M. Wamprecht as a Master's thesis project [6], which this project is a continuation of. A picture of the dolly is shown in Figure 2.2. Additionally, a picture of the underside of the dolly is shown in Figure 2.3.

The dolly was equipped with four wheels of the same type as those on the tractor unit and the trailers. The wheels were powered by two motors. One motor powered both wheels on the left side of the dolly, and the other motor powered both wheels on the right side of the dolly. Two wheels on the same axle could rotate independently of each other, and the motors had separate motor controllers, which meant that steering of the dolly could be achieved by giving the motors different signals. Originally, the motor controllers were not

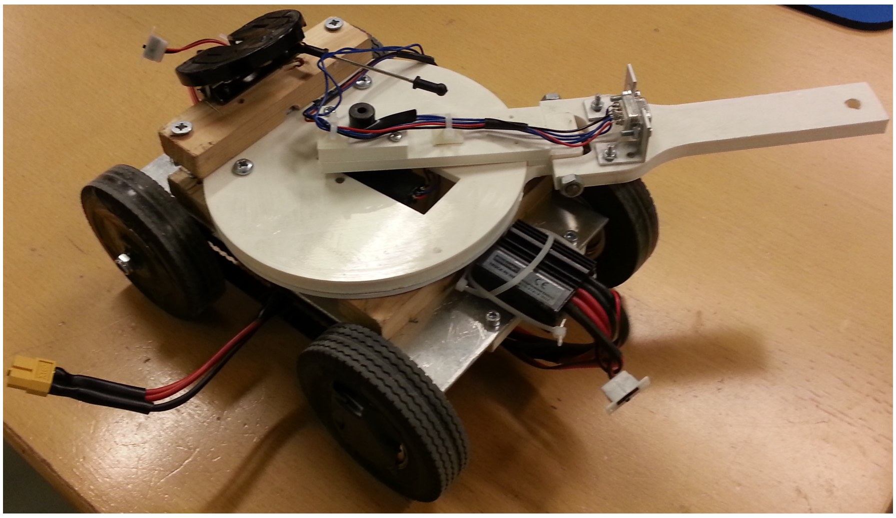

Figure 2.2: A picture of the custom built dolly used in the project, taken from the front, to the side. The long white part sticking out is connected to an angle sensor and may rotate around a vertical axis, and is used to connect the dolly to the trailer in front of it. At the back of the dolly, there is a black fifth wheel coupling that connects to the trailer behind the dolly.

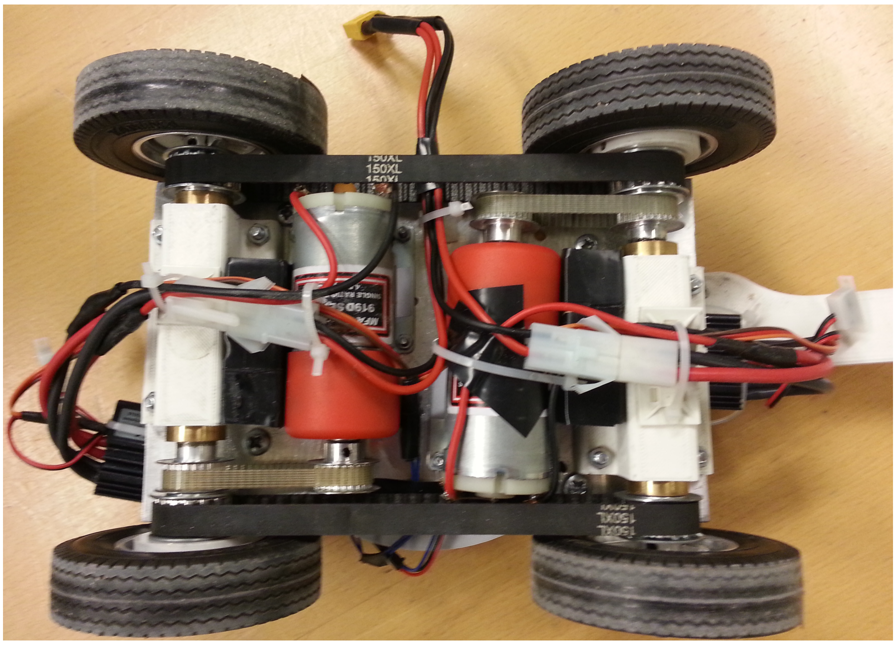

Figure 2.3: A picture of the underside of the custom built dolly used in the project. There are two motors on the dolly, each controlling a pair of wheels on the side of the dolly. The wheels on the different sides of the dolly can rotate independently of each other, even if they are on the same axle, which makes it possible to steer the dolly by controlling the motors separately.

mounted on the dolly in any way, and had long wires so that they could be placed on a trailer. During the project, the wires were shortened and the controllers were mounted to the dolly using cable ties. One motor controller was placed in the front of the dolly, and the other in the back. This made the dolly easier to handle.

On top of the dolly, there was a fifth wheel coupling that the second trailer could connect to. This meant that the second trailer could rotate around the point where it was connected. Additionally, a long piece of plastic acting as a drawbar that could connect to the first trailer was mounted on the dolly and stuck out in front of it. This drawbar could rotate around a vertical axis, and was connected to an analogue angle sensor.

The angle reading from the sensor was to be used in the active steering algorithm. While the trailers were made to be connected in the front to a fifth wheel coupling such as the one used on the dolly, they did not have any way to connect to something behind them. Therefore, the drawbar was coupled to the rearmost axle of the first trailer using cable ties. Several cable ties were used, in such a way that the drawbar of the dolly could not move forwards or backwards in relation to the trailer, and could only move a few millimetres to either side.

In total, there were six wired connections on the dolly. One cable gave both motors power, from a battery on the second trailer. Additionally, each motor controller had a signal input wire, and the angle sensor used three wires. All of these five wires connected to the Arduino in the tractor unit, which means they had to run through the first trailer. Originally, these five wires were not tied up or controlled in any way. In order to make the wires easier to handle, especially when removing the dolly from the LCV, a D-SUB connector was mounted in the front of the dolly, and all the five wires were drawn to it.

2.3 Lab environment

The testing of the scaled down LCV was done in a laboratory called the Intelligent Vehicles and Robots Laboratory, used by the Adaptive Systems Research Group. The laboratory contained a scaled test track, made up of roads marked out on an otherwise empty floor. A photograph of the laboratory can be seen in Figure 2.4.

Figure 2.4: Photograph of IVRL, the laboratory where the testing was carried out. Some roads not used in this project are marked with tape on the ground, along with pieces of paper used to mitigate reflections. The LCV model is visible in the corner of the room.

Along the walls around the scaled test track, eight ProReflex cameras made by Qualisys were mounted. A photograph of one of the cameras in the laboratory is shown in Figure 2.5. These cameras made up the LPS, and were capable of tracking small balls made of a certain reflective material in a space. Because of this, mounting such reflective balls strategically on the LCV made it possible to accurately track its position and heading. Specifically, placing several reflective balls in a unique pattern on an object, such as a trailer, made it possible for software to recognize the object by matching the ball pattern using a database of patterns. The tractor unit and both trailers were tracked separately, and each of them had three reflective balls mounted on them in L-shapes. While the shapes were the same for each part of the LCV, the distances between the reflective balls were different, which made the parts distinguishable. In Figure 2.1, it is possible to see the nine reflective balls mounted on the LCV. The tractor unit did not have any suitable place for the balls to be visibly placed in an L-shape, so an L-shaped piece of metal was made and mounted on top of the tractor unit.

Figure 2.5: Photograph of a ProReflex camera by Qualisys, taken in the laboratory. Eight of these cameras were mounted on the walls in the lab, which made it possible to track objects in the room.

The eight ProReflex cameras were not enough to be able to track objects in the entire lab. An illustration of the lab and the coverage of the LPS is shown in Figure 2.6. As can be seen in the figure, much of the room was not tracked by the LPS, due to a lack of cameras.

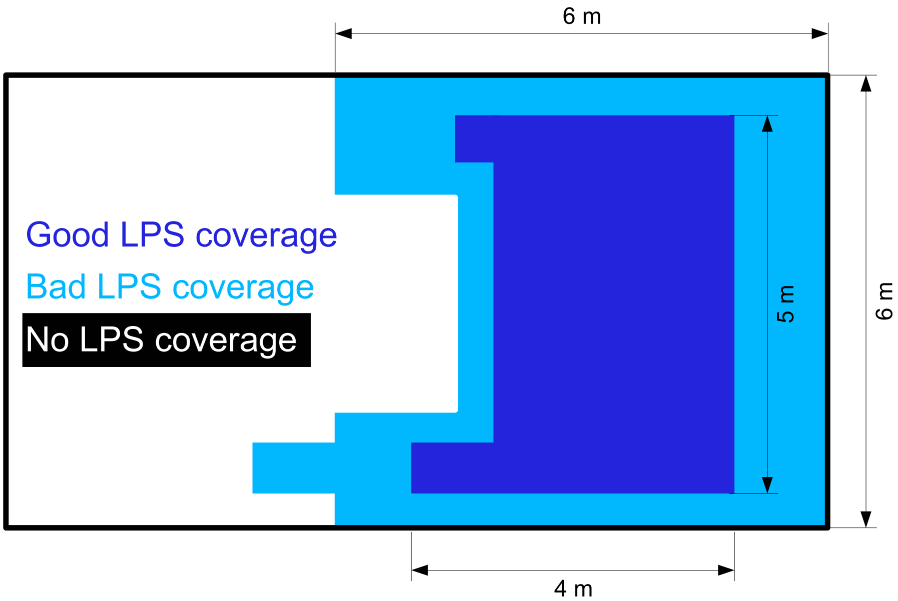

Figure 2.6: Rough illustration of the coverage of the LPS in the laboratory at floor height, not drawn to scale. In the darker blue area, objects could be tracked with very high reliability. In the lighter blue area, the LPS would frequently lose track of objects, but some data collection was still be possible. The LPS had little to no coverage over the white area, which was considered unusable.

The laboratory had several computers that could be used for various things. Two computers were particularly important for this project. The first computer was running Windows, and was used to run a software called

Qualisys Track Manager (QTM) [10], which interprets the data sent from the LPS cameras. The other computer, running Arch Linux, was used to run software that would interpret the positioning data from QTM and make decisions for the vehicle using that information, as well as a server program that facilitated communication between the two computers and the vehicle. The communication was made possible using a wireless network set up specifically for the laboratory.

2.4 Software

With the exception of QTM, produced by Qualisys, the software used in the laboratory was written in C++ by people in the research group that maintains the laboratory. The software was written before this project started, and was general enough to be able to run the LCV without any major modifications.

In addition to QTM, four programs were used during the project. A graphical user interface was supplied by a program called simply `ivrl-gui-interface`. The interface showed a map of the scaled test track, as well as any recognized objects and their positions, and also allowed for the vehicle to be controlled manually using buttons and sliders. The vehicle could also be controlled automatically, with behaviour defined by a file in the source code, called `framecontroller.cpp`. Most of the coding in this project was done within that file.

The Arduino on the LCV was running a program, `ivrl-generic`, that could take serial instructions from the USB port and give the appropriate signals to the motors and servos. The program on the Arduino also sent any sensor data from the LCV the other way. The BeagleBone Black connected to the Arduino used a program called `ivrl-vehicle`. The role of the BeagleBone Black and its program was simply to facilitate communication with the Arduino, which could not communicate wirelessly with the other computers. The BeagleBone Black was most often accessed remotely using an SSH client.

Lastly, a program called `ivrl-server` was used to handle the wireless communication between QTM, `ivrl-gui-interface`, and `ivrl-vehicle`, all running on different pieces of hardware. A flowchart showing the hardware, software, and the communication between them, is shown in Figure 2.7.

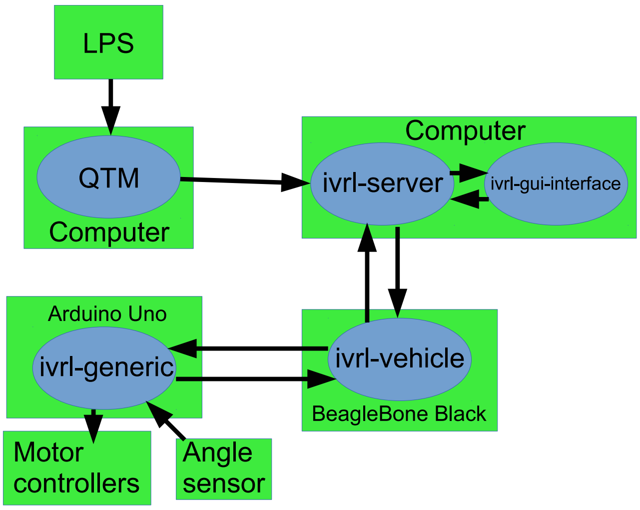

Figure 2.7: Flowchart of the software used in the laboratory. The green boxes represent hardware, the blue ellipses represent software, and the arrows represent communication. QTM processes data from the LPS and sends them to the server software, which handles communication. The other program on the same computer provides a graphical interface, does much of the calculations, and contains the control algorithms. The software on both the BeagleBone Black and the Arduino Uno are used simply to send and receive information.

When running the LCV model using these programs, a lot of data relating to the positions of the units of the LCV as well as data relating to the control algorithms was saved to a number of files. The data was then loaded into MATLAB where it was processed and analysed. All the plots shown in this report were generated with MATLAB using this data.

3 Methods and theory

This chapter describes what was done during the project, and details the methods used. This includes showing the control algorithms used, as well as the cases that were used to test them, and how the tests were organized.

3.1 Motor choice

Before the work with the active steering could begin, some hardware work had to be done in order to address some previously known shortcomings of the dolly. The most important thing to do was to replace the motors on the dolly with a pair of more suitable ones. The previous motors were quite fast, but they did not have any gear trains attached to them. This meant that, when using the motors to help drive the LCV in the lab, the motors were running at speeds far below what they were designed for. This made the motors overheat, and they performed quite badly.

The objective was to find a pair of motors that would be geared down enough to comfortably help run the LCV in a suitable interval of speeds. The motors would also have to generate torques comparable to that of the motor in the tractor unit, partly so that the motors would increase the amount of cargo that could be loaded onto the LCV, and partly so that the active steering in the dolly would be able to have a substantial effect. Finally, the motors would have to fit in the dolly, the main limiting factor being that a motor with gear train could not be longer than roughly 100 mm.

While looking for motors, *speed-torque curves* were considered, using [11] as a reference for how the curves and DC motors in general work. For a DC motor, the relationship between the speed and the torque is

$$\omega = -\frac{R_\mathrm{w}}{k^2}T + \frac{V}{k}, \tag{3.1}$$

where ω is the angular speed, R_w is called the winding resistance, k is a constant, T is the torque, and V is the voltage applied to the motor. A quantity called the *no-load speed*, denoted ω_0, is simply the speed at which $T = 0$, which means that

$$\omega_0 = \frac{V}{k}. \tag{3.2}$$

Similarly, the *stall torque*, T_S, is the torque for which $\omega = 0$, which gives

$$T_\mathrm{S} = \frac{kV}{R_\mathrm{w}}. \tag{3.3}$$

Typically, both the no-load speed and the stall torque are given in data sheets for DC motors, and these two quantities are sufficient to determine how the speed-torque curve looks.

When attaching a gear train to a motor, the speed and torque changes. When applying an input speed ω_in and an input torque T_in to a gear train with gear ratio R, the output speed ω_out and output torque T_out are simply

$$\omega_\mathrm{out} = \frac{\omega_\mathrm{in}}{R}, \tag{3.4}$$

$$T_\mathrm{out} = RT_\mathrm{in}. \tag{3.5}$$

In practice, attaching a gear train to a motor also results in a loss of efficiency, depending on the quality of the gear train. This is not always specified in data sheets, and might therefore be difficult to account for. In general, one would be wise to choose motor that seems slightly more powerful and faster than what the task needs it to be, in order to make sure that it will work despite some loss of performance that may occur.

Finding a geared motor that suited the needs of the dolly proved somewhat difficult. Only two products were found that would work well while not being overly expensive. Both products used the same kind of motor, but had different gear trains, and were part of the 919D series by manufacturer MFA Como Drills. One product had a gear ratio $R = 11$, while the other had a gear ratio $R = 50$. The main reason behind there being so few viable geared motors on the market was that the size of the combination grows with both motor power and gear ratio, and space in the dolly was limited. The combination with $R = 11$ was 101 mm long and could just about fit in the dolly, while the $R = 50$ combination at 105 mm would require some modifications of the dolly to fit.

Using the data sheet of these motors [12], as well as the data sheet for the motor in the tractor unit [13], speed-torque curves shown in Figure 3.1 were produced. Judging from the figure, it seemed that the speeds

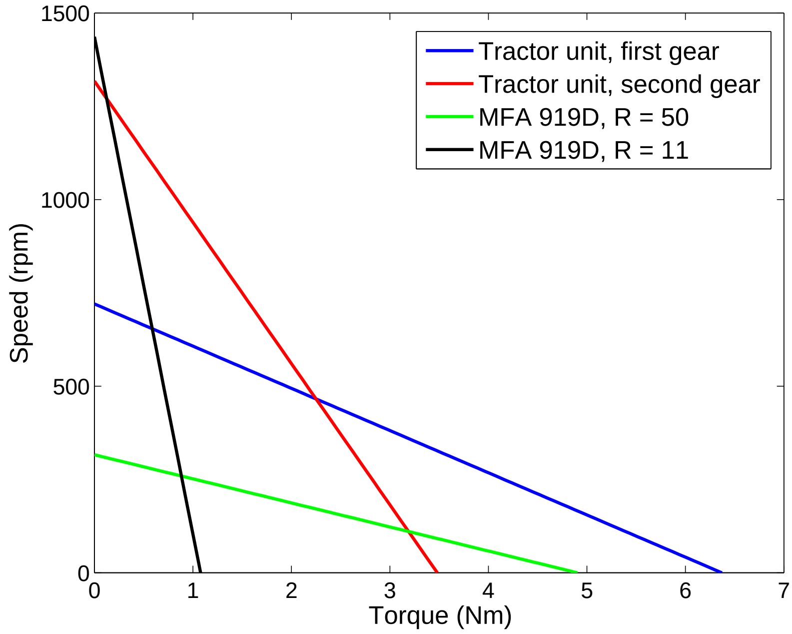

Figure 3.1: Speed-torque curves for the two geared motors considered for the dolly, as well as the motor in the tractor unit in its first and second gears. Torque at 0 rpm represents the stall torque, and the speed at 0 Nm is the no-load speed. The information used was taken from data sheets [12, 13] and by manually counting gears in the gearbox of the tractor unit. Note that 919D is data taken for 12 V, and tractor unit data is taken for 7.2 V. The dolly and tractor unit used separate power sources, so the differences are only a minor issue.

of the $R = 11$ geared motor matched up quite well with the tractor unit in its second gear. Additionally, combining two $R = 11$ geared motors would yield a total torque that is somewhat close to, but still less than, the torque of the tractor unit in its second gear. For these reasons, the $R = 11$ geared motor seemed like a good choice. The $R = 50$ geared motor, on the other hand, was less optimal. It seemed quite slow, as it was much slower than the tractor unit in its first gear, and the stall torque from two of these would be much larger than that of the tractor unit, which may have caused problems. While the $R = 50$ geared motor probably could be used for experiments in low speeds, the $R = 11$ geared motor seemed like a much better fit overall. Because of this, two $R = 11$ motors were bought and mounted to the dolly.

3.2 Measuring performance using offtracking

There are several ways of measuring the performance of a long combination vehicle. One simple and useful way of doing so is by using a property called *offtracking*. Offtracking is the lateral distance between the paths taken by the center of the front axle of the tractor unit and the center of some other point on the vehicle combination, such as the axle of a trailer [14]. An illustration of the offtracking concept is shown in Figure 3.2, with the rearmost axle of the combination used as reference. The offtracking is defined to be positive if the point that is tracked overshoots in a manoeuvre such as a curve, and negative if it undershoots. Offtracking can be represented as a graph over time or position, or as a single value, then representing the maximum offtracking obtained. In this report, the offtracking as a function is referred to simply as O, and it can be a function of either time or longitude. When analysing results, the longitude average of the absolute value of the offtracking $\overline{|O|}$ over an entire run, was frequently used. This measure was used since it says a lot about a run with just a single value: the only way to get a low average offtracking is to consistently keep a low offtracking during the entire run.

In this instance, the offtracking was measured with the help of the road segments that the tractor unit was instructed to follow. Using positioning data for the tractor unit and the trailers, corresponding longitudes and latitudes in relation to the currently traversed road segment could be calculated. If two trajectories roughly

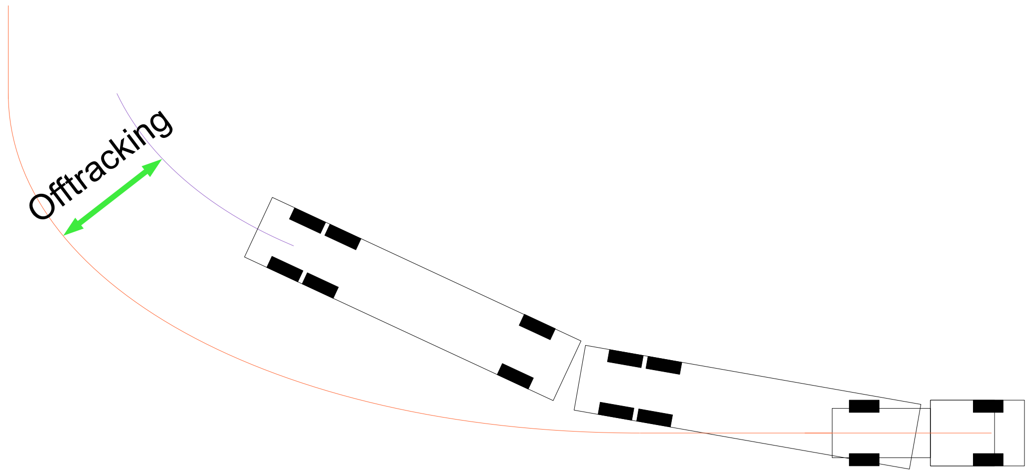

Figure 3.2: An illustration of how to define offtracking. Offtracking is the lateral distance between the paths taken by the center of the front axle of the tractor unit, and the center of another part of the LCV. In this case, the rearmost axle has been chosen.

followed a road, the offtracking could be measured where the longitudes of the trajectories in relation to the road were the same. The offtracking corresponding to a certain longitude was then found by forming the difference between the latitudes in relation to the road for the two trajectories.

3.3 Cases to study

The LCV combination and the active steering were evaluated in three different scenarios: a sharp 90 degree turn, a smoother 180 degree curve, and a single lane change. The three roads that made up these scenarios are shown in Figure 3.3. When choosing these scenarios, several things were considered. All of these manoeuvres are a natural part of driving, and it can be expected that active steering in a dolly can be quite relevant when performing them. Navigating through a curve is a particularly important case, given that it is the cause of 59.4 % of all accidents involving a heavy truck losing control [15]. Another important consideration that had to be made was the size of the lab. The entire LCV model used was roughly 1.8 m long, which is quite large in relation to the smaller than 4 m × 5 m area where data could be reliably collected (see Figure 2.6). Using scenarios that made full use of the available area was therefore a necessity. In contrast, rigorous full-scale testing may involve driving for several minutes with pseudo-random steering [14], which would not be remotely possible to do in the laboratory.

The simplest scenario is the one with the lane change. It is simply a straight road, which after a certain point is offset laterally by 0.25 m. Scaling up by a factor of 14, the scale of the LCV model, this lateral offset corresponds to $0.25 \text{ m} \cdot 14 = 3.5 \text{ m}$, the width of a lane of a normal Swedish motorway [16]. The point where the lane change happens was placed close to beginning of the road since space was severely limited, and what happens after the lane change was deemed more interesting than what happens before it.

The scenario with the 180 degree curve was to a large extent defined by the restrictions of the laboratory. The path taken in this scenario was the longest possible realistic path that the LCV model would be able to traverse in the lab without major problems with the LPS. The radius of the half-circle that defined the curve was 2.27 m, which corresponds to a radius of $2.27 \text{ m} \cdot 14 \approx 31.8 \text{ m}$ in full scale. This is equivalent of a somewhat sharp curve at a motorway interchange[1].

The final scenario, involving a sharper turn, had a curve radius of 1.56 m. This scenario does not necessarily have a common real world counterpart, as it was a much sharper turn than the previous one, and is supposed to be a more challenging alternative. Note that intersections not made for heavy traffic have turns that are even sharper than this one.

[1]For instance, such curves at interchanges may be found at Gullbergsmotet in Gothenburg, and measuring them with a map such as Google Maps gives a radius of roughly 30 m.

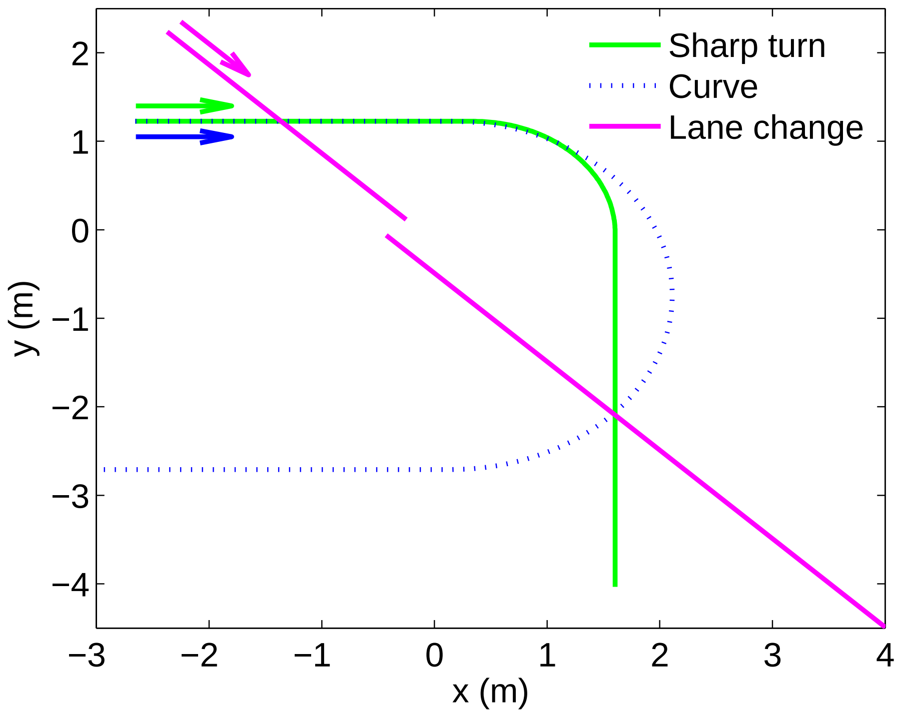

Figure 3.3: Plot showing the three different roads that were used as different test cases. All three roads start in the upper left corner of the figure, as indicated by the arrows. The cases represent a sharp turn, a smoother curve, as well as a lane change on a straight.

3.4 Control algorithms

In the LCV, two units were able to steer and to give the vehicle combination some forward momentum: the tractor unit and the dolly. The point of the project was to see how active steering in the dolly realistically could improve the performance of the LCV, so the steering algorithm of the dolly was limited to using information that was considered realistic for the dolly to have. This information included the angle read by the angle sensor on the dolly, as well as things such as the steering wheel angle and speed of the tractor unit. The high precision positioning from the LPS in the lab was not directly used by the dolly, but it was allowed to be used for the steering algorithm in the tractor unit. The tractor unit would, ideally, drive like an experienced human truck driver normally would, and the LPS was necessary to achieve that. In the following sections, the steering algorithms are described in detail.

3.4.1 Control algorithm of the tractor unit

The algorithm that controlled the tractor unit was an existing algorithm that had already been used in previous projects done in the same laboratory. While some experimentation with it was done during this project, very little was changed in the end. Instead of using sensors or any other kind of hardware on the LCV, the control algorithm in the tractor unit was entirely based on information supplied by the LPS in the lab.

The purpose of this algorithm was to make the vehicle follow a road. Roads were defined in the source code, and could consist of several smaller road segments. A road segment was defined by starting position and heading, as well as length and, if the road was curved, curvature. The roads could also have a number of lanes with different widths, but this did not affect the algorithm, which essentially just followed a line. The roads that were used to test the active steering were discussed in Section 3.3, and they were defined in this manner.

The algorithm made use of the position of the tractor unit in relation to the current road segment, in terms of lateral and longitudinal coordinates. While the software used was capable of calculating latitude and longitude to start with, a number of bugs made it necessary for the methods to be changed during the project.

Calculating latitude and longitude in relation to a straight road is rather straightforward, and can be done using a simple coordinate transformation. It is convenient to use a euclidean coordinate system $(\hat{x}', \hat{y}')$ with its origin in the starting point of the road, and with the $\hat{x}'$ axis pointing along the road. In that case, the position (x', y') of the vehicle in those coordinates are the longitude and latitude:

$$\text{longitude}_{\text{straight}} = x', \tag{3.6}$$
$$\text{latitude}_{\text{straight}} = y'. \tag{3.7}$$

The coordinates of the vehicle in the coordinate system that the LPS uses are simply denoted (x, y). The starting point of the road in that coordinate system is denoted $(x_{\text{rs}}, y_{\text{rs}})$, and the heading of the road is denoted θ_{rs}. Using these variables, the coordinate transformation can be written

$$\text{longitude}_{\text{straight}} = x' = (x - x_{\text{rs}})\cos(-\theta_{\text{rs}}) - (y - y_{\text{rs}})\sin(-\theta_{\text{rc}}), \tag{3.8}$$
$$\text{latitude}_{\text{straight}} = y' = (x - x_{\text{rs}})\sin(-\theta_{\text{rs}}) + (y - y_{\text{rs}})\cos(-\theta_{\text{rc}}). \tag{3.9}$$

Calculating the longitude and latitude for a vehicle in relation to a curved road is somewhat more tricky. A coordinate transformation is useful in this case as well. Place a coordinate system denoted $(\hat{x}'', \hat{y}'')$ in the origin of rotation, with the $\hat{x}''$ axis pointing at the starting point of the road, and the $\hat{y}''$ axis pointing at the middle point of the first half circle of the road. If the angle of the $(\hat{x}'', \hat{y}'')$ coordinate system is θ_{rc} in the coordinate system of the LPS, and the origin of rotation is at $(x_{\text{rc}}, y_{\text{rc}})$, then, as before,

$$x'' = (x - x_{\text{rc}})\cos(-\theta_{\text{rc}}) - (y - y_{\text{rc}})\sin(-\theta_{\text{rc}}), \tag{3.10}$$
$$y'' = (x - x_{\text{rc}})\sin(-\theta_{\text{rc}}) + (y - y_{\text{rc}})\cos(-\theta_{\text{rc}}), \tag{3.11}$$

where (x'', y'') is the position of the vehicle in the $(\hat{x}'', \hat{y}'')$ coordinate system. If the distance from the origin of rotation to the vehicle is not the same as the radius R of the road, then there is a lateral offset. The lateral position of the vehicle in relation to the road is then

$$\text{latitude}_{\text{curve}} = \sqrt{(x'')^2 + (y'')^2} - R. \tag{3.12}$$

To calculate the longitude of the vehicle, it is convenient to use the angle of the (x'', y'') point in relation to the $(\hat{x}'', \hat{y}'')$ coordinate system, which may be calculated using the `atan2` function commonly used in programming. If the total length of the curved road is denoted L, and the end point of the road has the angle θ_{end} in the $(\hat{x}'', \hat{y}'')$ coordinate system, then

$$\text{longitude}_{\text{curve}} = L\frac{\text{atan2}(y'', x'')}{\theta_{\text{end}}}. \tag{3.13}$$

In addition to the latitude and longitude, the yaw angle of the vehicle in the relation to the road was also used in the algorithm. This angle is simply the difference between the heading angle of the vehicle and the heading angle of the road.

If the longitude of the vehicle, in relation to a road segment, was between zero and the length of the road, then the vehicle was said to be traversing that particular road segment, given also that the lateral position of the vehicle in relation to the road was not very large.

The algorithm that controlled the tractor unit essentially boiled down to calculating the desired steering wheel angle. The steering wheel angle of the vehicle, denoted ϕ, was determined by a weighted sum consisting of three terms, called *errors*: the yaw e_{yaw} of the vehicle, the lateral offset e_{lat} of the vehicle, and the lateral offset of a point at a fixed distance in front of the vehicle $e_{\text{p,lat}}$, all taken for the tractor unit in relation to the road. The point in front of the vehicle is called a *preview point*. The steering wheel angle of the vehicle was defined on $[0, 1]$, where $\phi_0 \approx 0.5$ represented straight driving. The algorithm was then simply

$$\phi = \phi_0 + e_{\text{yaw}} \cdot C_{\text{yaw}} + e_{\text{lat}} \cdot C_{\text{lat}} + e_{\text{p,lat}} \cdot C_{\text{p,lat}}, \tag{3.14}$$

where $C_{\text{yaw}}, C_{\text{lat}}, C_{\text{p,lat}}$ were constants. The values used in the results section of this report were $C_{\text{yaw}} = 0.5, C_{\text{lat}} = 0.3, C_{\text{p,lat}} = 1.0$, and the preview distance was 0.55 m.

The speed of the tractor unit was not regulated actively, with the signal to the motor being a constant, denoted M_{c}. Any floating point number in $[0, 1]$ was a valid signal, with 0.5 representing the motor doing nothing, and 1.0 representing full speed forwards. For the runs in the results section, $M_{\text{c}} = 0.875$, except when driving on the straight road with a lane change, then $M_{\text{c}} = 0.8$.

3.4.2 Active steering algorithm for the dolly

The active steering algorithm for the dolly was created during the project, in an attempt to improve the performance and safety of the LCV when driving. The dolly was driven and steered using two motors, one for each side of the dolly. The algorithm is written in pseudo code below, with explanations following after the code. The algorithm is a result of over 100 tests made with the LCV model, in a trial and error fashion.

Before the pseudo code, let's remind ourselves that ϕ denotes the steering wheel angle used by the tractor unit. Introduce ψ to denote the angle measured by the angle sensor on the dolly, which essentially represented the position of the dolly in relation to the trailer in front of it. Let W denote a weight used in a sum, and let C denote a constant. D represents values given to the motor controllers for the dolly, with D_{L} being the value that controls the left motor, and D_{R} being the value that controls the right motor. As with the motor in the tractor unit, the motor signals were taken from $[0, 1]$, with 0.5 representing a standstill, and 1.0 representing full speed forwards.

Algorithm 1 Dolly steering

$\phi_N \leftarrow$ unweighted average of N last values of ϕ, $N = 10$ was used
$\phi_0 \leftarrow$ default value, corresponding to straight driving, $\phi_0 = 0.475$ was used
$C_\phi \leftarrow$ constant, $C_\phi = 0.25$ was used
$C_{W\phi} \leftarrow$ constant, $C_{W\phi} = 0.5$ was used
$\phi_\delta \leftarrow \phi_0 - \phi_N$
$W_\phi \leftarrow C_{W\phi} \cdot |\phi_\delta| / C_\phi$
Ensure: $W_\phi \leq C_{W\phi}$
$C_{W\psi a} \leftarrow$ constant, $C_{W\psi a} = 0.5$ was used
$C_{W\psi b} \leftarrow$ constant, $C_{W\psi b} = 1.3$ was used
$W_\psi \leftarrow C_{W\psi a} + C_{W\psi b} \cdot (C_\phi - |\phi_\delta|)/C_\phi$
Ensure: $W_\psi \geq C_{W\psi a}$
$\psi_0 \leftarrow$ default value, given from angle sensor when there is no angle, $\psi_0 = 500$ was used
$\psi_{\max} \leftarrow$ high reading from angle sensor, $\psi_{\max} = 740$ was used, representing a 45° deviation to the right
$\psi_{\min} \leftarrow$ low reading from angle sensor, $\psi_{\min} = 310$ was used, representing a 45° deviation to the left
if $\psi \geq \psi_0$ **then**
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_{\max} - \psi_0)$
else
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_0 - \psi_{\min})$
end if
Ensure: $-0.5 \leq \psi_\delta \leq 0.5$
$S \leftarrow \psi_\delta \cdot W_\psi + \phi_\delta \cdot W_\phi$
Ensure: $-0.5 \leq S \leq 0.5$
$D_{\mathrm{c}} \leftarrow$ value used as normal driving speed, $D_{\mathrm{c}} = 0.625$ was used
$D_{\min} \leftarrow$ lowest motor signal to be used, $D_{\min} = 0.4$ was used
$D_\delta \leftarrow S \cdot (D_{\mathrm{c}} - D_{\min})/0.5$
$D_{\mathrm{L}} \leftarrow D_{\mathrm{c}} + D_\delta$
$D_{\mathrm{R}} \leftarrow D_{\mathrm{c}} - D_\delta$
Ensure: $D_{\min} \leq D_{\mathrm{L}} \leq D_{\mathrm{c}}$, $D_{\min} \leq D_{\mathrm{R}} \leq D_{\mathrm{c}}$
$C_{\mathrm{D}} \leftarrow$ constant, $C_{\mathrm{D}} = 2$ was used
if $D_{\mathrm{R}} < 0.5$ **then**
    $D_{\mathrm{L}} \leftarrow D_{\mathrm{c}} + C_{\mathrm{D}} \cdot (0.5 - D_{\mathrm{R}})$
end if
if $D_{\mathrm{L}} < 0.5$ **then**
    $D_{\mathrm{R}} \leftarrow D_{\mathrm{c}} + C_{\mathrm{D}} \cdot (0.5 - D_{\mathrm{L}})$
end if

In short, the algorithm uses a weighted sum of the angle from the angle sensor, as well as the steering wheel angle of the tractor unit, to give different signals to the motors, which determines how the dolly drives. The recent history of the steering wheel angle of the tractor unit determines the weights of the weighted sum, so that the dolly can react differently depending on if the LCV seems to be in a curve or on a straight. Normally, both motors run at a cruising speed D_{c}, and if it needs to turn slightly, the signal sent to one of the motors is reduced. When the signal sent to one motor goes below the standstill point of 0.5, that motor starts to brake. When that happens, the signal to the other motor is increased, partly to make the dolly turn more, and partly to help the LCV retain its speed despite the fact that one side of the dolly is braking. In Section 3.4.3, the algorithm and the process of its development are explained in greater detail.

It should be noted that in the code that was used during testing, line 11 of Algorithm 1 had an error in it, causing W_ϕ to update instead of W_ψ. Due to this, $W_\psi \geq C_{W\psi a}$ was not ensured, and W_ϕ took the same value as W_ψ. This changes the algorithm slightly, but not by much. The deviation of the steering wheel angle was generally quite small, so the effect on W_ψ was negligible, since the ensure statement rarely would have done anything. The effect on W_ϕ was not negligible, but since it was later multiplied by the small steering wheel angle deviation, the effect on the important value S was still not very significant. The end result was, generally, that the dolly steered slightly more than intended. This bug was unfortunately discovered some time after work in the laboratory had concluded, so it could not be fixed in time. Every version of the algorithm that ever existed has been saved, and it has been verified that this bug was in the code for quite a long time. This means that the bug was present in all the runs presented in the results section, and it also means that the parameters in the algorithm were adapted to compensate for the bug during development. It is very likely that, had the bug not existed, the parameters in the algorithm would have been slightly different, but the results would largely have been the same.

3.4.3 Explanation of dolly steering

The complete algorithm used for steering the dolly can be seen in Section 3.4.2. The algorithm was developed by taking a very simple algorithm, testing it, and then adding features and tweaking parameters accordingly. There are two main steps involved in the algorithm: Calculating a weighted sum S based on the available data, and then using S to determine the signals to be sent to the motors. In the final algorithm, the latter part was the following:

Algorithm 2 Dolly steering, use of weighted sum

$S \leftarrow$ weighted sum
Ensure: $-0.5 \leq S \leq 0.5$
$D_\mathrm{c} \leftarrow$ value used as normal driving speed, $D_\mathrm{c} = 0.625$ was used
$D_\mathrm{min} \leftarrow$ lowest motor signal to be used, $D_\mathrm{min} = 0.4$ was used
$D_\delta \leftarrow S \cdot (D_\mathrm{c} - D_\mathrm{min})/0.5$
$D_\mathrm{L} \leftarrow D_\mathrm{c} + D_\delta$
$D_\mathrm{R} \leftarrow D_\mathrm{c} - D_\delta$
Ensure: $D_\mathrm{min} \leq D_\mathrm{L} \leq D_\mathrm{c}$, $D_\mathrm{min} \leq D_\mathrm{R} \leq D_\mathrm{c}$
$C_\mathrm{D} \leftarrow$ constant, $C_\mathrm{D} = 2$ was used
if $D_\mathrm{R} < 0.5$ **then**
    $D_\mathrm{L} \leftarrow D_\mathrm{c} + C_\mathrm{D} \cdot (0.5 - D_\mathrm{R})$
end if
if $D_\mathrm{L} < 0.5$ **then**
    $D_\mathrm{R} \leftarrow D_\mathrm{c} + C_\mathrm{D} \cdot (0.5 - D_\mathrm{L})$
end if

There are several things that should be noted here. $D_\mathrm{min} < 0.5$ meant that the motors on the dolly could not only slow down, but they could also brake. Using values such as $D_\mathrm{min} = 0.5$ was tested, but that was not enough to keep the second trailer from overshooting in curves; braking was necessary. The value of 0.4 was chosen, because near that value, the braking went from being barely noticeable to almost completely stopping the entire LCV. Due to this, $D_\mathrm{min} = 0.4$ seemed to be the sweet spot during testing. The value of D_c mostly affected the driving speed of the LCV. The value was chosen along with the signal sent to the motor in the tractor unit, such that the LCV would drive as fast as it could without losing control due to the software and steering servo in the tractor unit being too slow.

This part of the algorithm made it so that the dolly would start to slow down with one motor, while not changing the signal to the other motor, at first. This was because it was difficult to increase the speed of one motor without causing the LCV to go too fast, and it did not seem to help the dolly turn much. However, when one motor was slowed down so much that it started to brake, the speed of the other motor was increased. If this had not been the case, the LCV would have slowed down significantly while one motor was braking, which was undesirable. The value $C_{\mathrm{D}} = 2$ was chosen because it performed well in testing, with the speed of the LCV remaining somewhat consistent.

The first part of the algorithm, which ends with a weighted sum S being calculated, originally looked like the following algorithm:

Algorithm 3 Dolly steering, calculating S, simple version

$W_\psi \leftarrow$ constant
$\psi_0 \leftarrow$ default value, given from angle sensor when there is no angle
$\psi_{\max} \leftarrow$ high reading from angle sensor
$\psi_{\min} \leftarrow$ low reading from angle sensor
if $\psi \geq \psi_0$ **then**
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_{\max} - \psi_0)$
else
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_0 - \psi_{\min})$
end if
Ensure: $-0.5 \leq \psi_\delta \leq 0.5$
$S \leftarrow \psi_\delta \cdot W_\psi$
Ensure: $-0.5 \leq S \leq 0.5$

In this case, the amount that the dolly tried to steer was determined by the deviation indicated by the angle sensor, multiplied by a constant. This algorithm had a couple of flaws. First of all, this algorithm treated every possible case exactly the same, which was problematic. A moderate deviation in angle was actually desirable when in a sharp turn, but was strictly bad when driving on a straight, for instance. Therefore, the algorithm was changed to be able to distinguish between different events, in some sense. Another potential problem with this algorithm was that it was incapable of knowing when a turn was about to come. The tractor unit could be a decently long way into a curve before the last trailer entered the curve, and the last trailer may itself have been some way into a curve before the angle read by the sensor started to deviate significantly.

Both of the mentioned issues could be resolved by making S depend on the steering wheel angle ϕ of the tractor unit. To make the dolly capable of turning a bit in anticipation of a turn,

$$S = \psi_\delta \cdot W_\psi + \phi_\delta \cdot W_\phi \tag{3.15}$$

was a reasonable form for the weighted sum S, given a ϕ_δ that represented the deviation in steering wheel angle. The tractor unit, along with the algorithm controlling it, had a little bit of trouble following a straight road, and it would often turn back and forth across the road, instead of just driving straight. This problem was amplified a lot when driving at high speeds, but the problem still existed at low speeds as well. Due to this, it was not wise to simply include the steering wheel angle in the dolly steering algorithm, since the dolly would be influenced by the fluctuations. Therefore, an average of the 10 latest values was used instead of just the latest value. The number 10 was tested along with other numbers, but 10 seemed to give the best results, as including more values made the dolly algorithm slow to react when entering and exiting curves.

In order to make the dolly able to react differently to being in different situations, the weights W_ψ, W_ϕ were made dependent on the steering wheel angle deviation ϕ_δ of the tractor unit. Specifically, the weights were determined by

$$W_\phi = C_{W\phi} \cdot |\phi_\delta|/C_\phi, \tag{3.16}$$

$$W_\psi = C_{W\psi a} + C_{W\psi b} \cdot (C_\phi - |\phi_\delta|)/C_\phi, \tag{3.17}$$

where constants were denoted by C. This form and the constants were determined using a lot of test runs with the LCV model. In the end, the part of the algorithm that determined S became:

Algorithm 4 Dolly steering, calculating S

$\phi_N \leftarrow$ unweighted average of N last values of ϕ, $N = 10$ was used
$\phi_0 \leftarrow$ default value, corresponding to straight driving, $\phi_0 = 0.475$ was used
$C_\phi \leftarrow$ constant, $C_\phi = 0.25$ was used
$C_{W\phi} \leftarrow$ constant, $C_{W\phi} = 0.5$ was used
$\phi_\delta \leftarrow \phi_0 - \phi_N$
$W_\phi \leftarrow C_{W\phi} \cdot |\phi_\delta|/C_\phi$
Ensure: $W_\phi \leq C_{W\phi}$
$C_{W\psi a} \leftarrow$ constant, $C_{W\psi a} = 0.5$ was used
$C_{W\psi b} \leftarrow$ constant, $C_{W\psi b} = 1.3$ was used
$W_\psi \leftarrow C_{W\psi a} + C_{W\psi b} \cdot (C_\phi - |\phi_\delta|)/C_\phi$
Ensure: $W_\psi \geq C_{W\psi a}$
$\psi_0 \leftarrow$ default value, given from angle sensor when there is no angle, $\psi_0 = 500$ was used
$\psi_{\max} \leftarrow$ high reading from angle sensor, $\psi_{\max} = 740$ was used, representing a 45° deviation to the right
$\psi_{\min} \leftarrow$ low reading from angle sensor, $\psi_{\max} = 310$ was used, representing a 45° deviation to the left
if $\psi \geq \psi_0$ **then**
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_{\max} - \psi_0)$
else
    $\psi_\delta \leftarrow 0.5 \cdot (\psi - \psi_0)/(\psi_0 - \psi_{\min})$
end if
Ensure: $-0.5 \leq \psi_\delta \leq 0.5$
$S \leftarrow \psi_\delta \cdot W_\psi + \phi_\delta \cdot W_\phi$
Ensure: $-0.5 \leq S \leq 0.5$

Together, Algorithm 4 and Algorithm 2 formed Algorithm 1, which was the algorithm used for the final testing.

3.5 Performing runs and getting reference data

Doing a run with the LCV model was a reasonably simple process. If there had been any changes to the source code, such as a change of what road that was to be driven, the programs used had to be recompiled. Then, all the hardware had to be started, such as the LPS, the motor controllers, the Arduino, and the BeagleBone Black. After then starting all the software, the starting position of the LCV model could be set with precision using positioning data from the LPS. When an acceptable starting position had been achieved, the run was started using a tick box in the graphical interface on the computer. From that point, the runs were completely automatic. The tractor unit and the dolly where driven by algorithms, and the LCV would automatically stop after some stop condition had been fulfilled. The stop conditions were written into the source code, and stopped the run when a certain position had been reached. This process was repeated a number of times for each test case, using the algorithm described in Section 3.4.2. During the testing, no additional load was added to the LCV, which in itself weighed around 10 kg.

In addition to the runs made using the active steering algorithm, a number of reference runs were also made. In the reference runs, the dolly was passive, meaning that no steering was performed, and the motors were entirely inactive. Additionally, in order to reduce resistance from the motors, the timing belts connecting the motors to the wheels were dismounted from the dolly. To compensate for the dolly no longer contributing any forward momentum, the signal sent to the motor in the tractor unit was increased, so that the speed of the LCV would be roughly the same as in the tests with the dolly active. Two types of reference runs were made: one where the angle of the drawbar that connects to the first trailer was unrestricted, as in the active case, and one where the angle was restricted to the default position. These two cases will be referred to as having a *free drawbar angle* or a *locked drawbar angle*, respectively. The case with the locked drawbar angle roughly corresponds to how passive dollies normally function, which makes it particularly interesting as a reference.

While the active steering was tested multiple times per test case, the reference runs were generally not repeated. There did not seem to be any need to repeat them, as they were so consistent that they could rarely be told apart.

4 Results for the active steering

For each of the test cases described in Section 3.3, a number of runs using the active steering algorithm for the dolly was made. As a reference, a few runs with a passive dolly were made as well, with and without a restriction on the angle between the dolly and the trailer in front of it. The results were analysed mainly with the help of the offtracking concept, described in Section 3.2.

4.1 Performance on curved road

The active steering was tested on a road with a short straight, leading into a 180 degree curve, into another short straight. Six runs were made using the active steering, under almost identical conditions, along with two reference runs. The trajectories for the LCV units when using a passive dolly with a free drawbar angle are shown in Figure 4.1, and the corresponding trajectories for the case with the locked drawbar angle are shown in Figure 4.2. In Figure 4.3, the trajectories for one of the runs with active steering are shown, and it is clear that the second trailer follows the path of the tractor unit more precisely in this case.

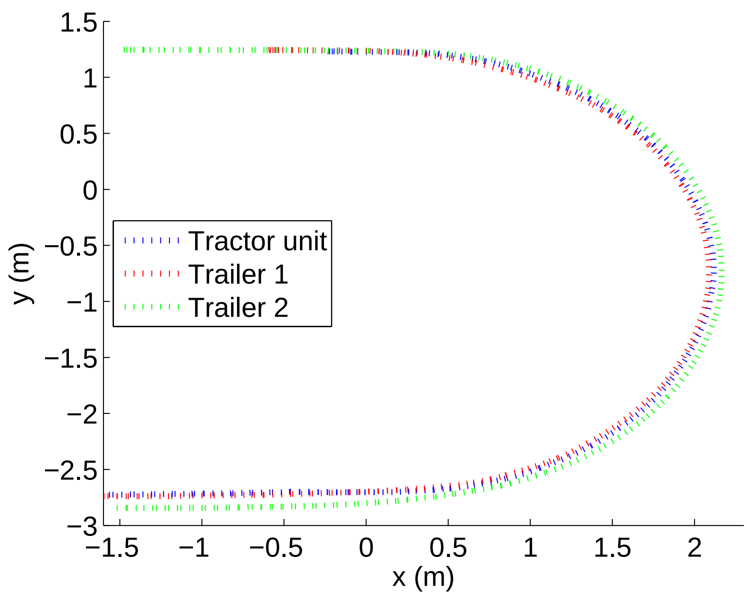

Figure 4.1: Trajectories for the three LCV units when driving on a road with a 180 degree curve, using a passive dolly with its drawbar angle free. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer is consistently on the outside of the proper path.

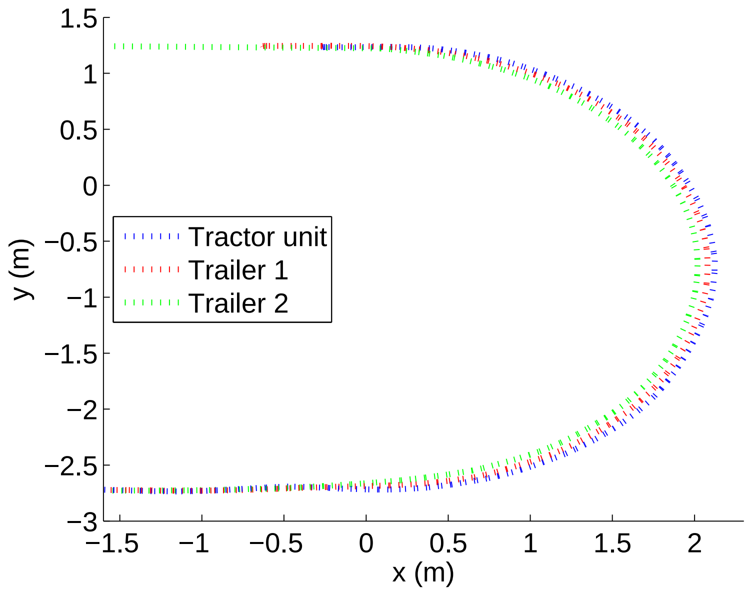

Figure 4.2: Trajectories for the three LCV units when driving on a road with a 180 degree curve, using a passive dolly with its drawbar angle locked in the default position. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer is consistently on the inside of the proper path.

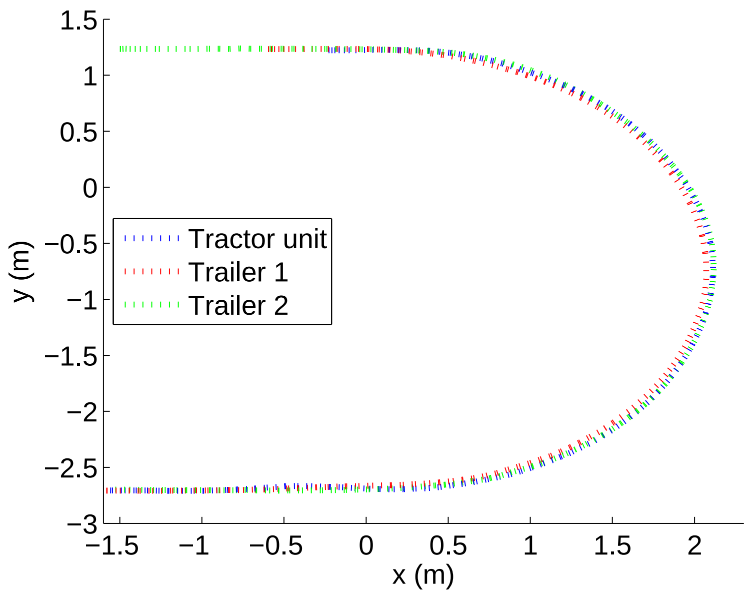

Figure 4.3: Trajectories for the three LCV units when driving on a road with a 180 degree curve, using the active dolly. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer follows the intended path well.

The offtracking with the midpoint of the second trailer as reference, as a function of the longitude, is plotted in Figure 4.4. It is quite clear in the figure that, while the reference runs with a passive dolly overshoots or undershoots depending on whether or not the drawbar angle is locked, the runs with the active steering perform quite well. However, even with the active steering, some deviations from zero are seen just after both the beginning and end of the curve. The only run that did not spike in those places is the reference run with the drawbar angle locked, which makes sense since the locked angle prevents the dolly from shifting laterally relative to the first trailer. One downside of having the angle free is that on a straight, the dolly might never recover from a lateral deviation. The active steering could make the recovery possible, but a dolly with a locked angle will still perform better in that situation.

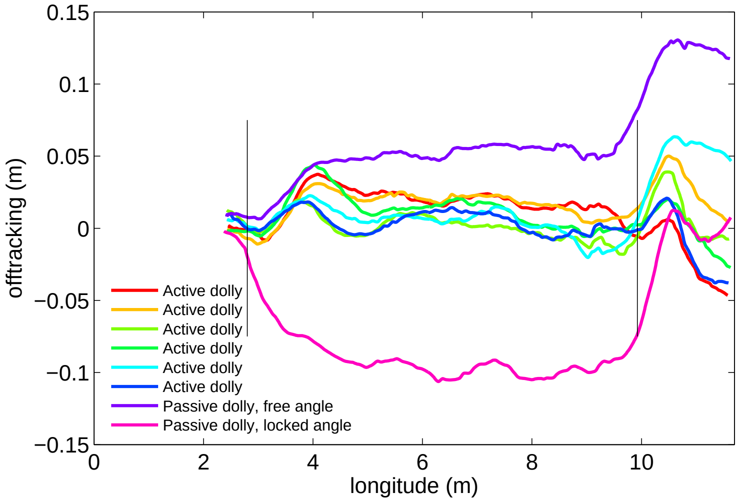

Figure 4.4: Offtracking measured on road with a 180 degree curve, with the midpoint of the second trailer as the reference point. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical lines indicate the start and end of the curve.

In Figure 4.5, where the offtracking reference points are the front of the second trailer and the back axle of the trailer, the results are quite similar. Once again, the active steering runs are in between the reference runs, but the front of the second trailer does consistently deviate a bit from the zero offtracking mark.

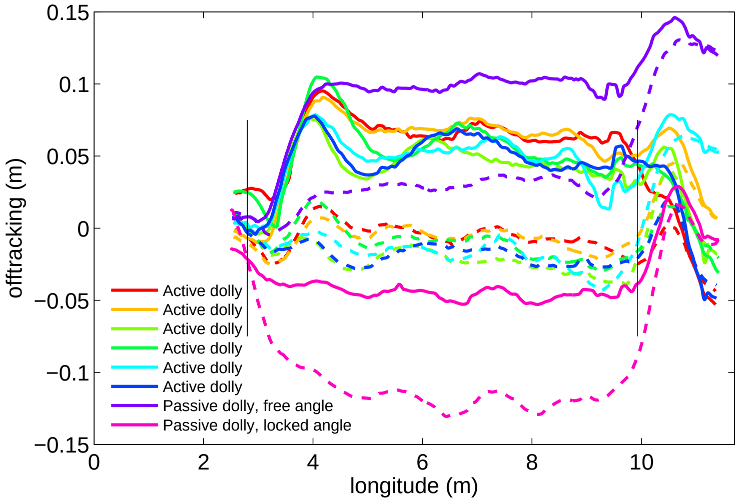

Figure 4.5: Offtracking measured on road with a 180 degree curve. The solid lines use the front of the second trailer as reference point, the dashed lines use the back axle of the second trailer. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical lines indicate the start and end of the curve.

The data shown in Figures 4.4 and 4.5 is shown in another way in Table 4.1. The most deviating offtracking values are shown, along with longitude averages of the absolute values of the offtracking. The active dolly outperforms the reference runs in almost every column, with the only exceptions coming from the fact that the front of the second trailer performs very well when the dolly is passive and the drawbar angle is locked. The last column, where the averages of the offtracking at the front and back axle of the second trailer are added, is the most significant one. This is because it is the only column that practically requires the entire trailer to have a good trajectory for the value to be low. Taking the average of the values for the active dolly in this column, and dividing that with the values for the passive dolly, one gets 0.48 for the free drawbar angle, and 0.5 for the locked drawbar angle. This means that, in some sense, the offtracking is roughly halved when using the active steering algorithm over a passive dolly.

Table 4.1: Offtracking values in metres from tests on a road with a 180 degree curve. The first three columns with data contain the offtracking values that deviate the most from zero in the corresponding runs. Columns four through seven contain averages of the absolute values of the offtracking, with the seventh column being the sum of the fifth and sixth columns. Mid, front, and back axle refers to the reference points on the second trailer that were used to calculate the offtracking. The rows are ordered as in the legends of Figures 4.4, 4.5, and the data is from the same runs.

Dolly status	$\max(O)$ (mid)	$\max(O)$ (front)	$\max(O)$ (back axle)	$\overline{\lvert O\rvert}$ (mid)	$\overline{\lvert O\rvert}$ (front)	$\overline{\lvert O\rvert}$ (back axle)	$\overline{\lvert O\rvert}$ (front + back axle)
Active	-0.0465	0.0952	-0.0437	0.0357	0.1129	0.0199	0.1328
Active	0.0500	0.0907	0.0463	0.0372	0.1154	0.0222	0.1376
Active	0.0390	0.0770	0.0402	0.0164	0.0815	0.0417	0.1232
Active	0.0439	0.1048	-0.0309	0.0250	0.0985	0.0250	0.1236
Active	0.0634	0.0786	0.0642	0.0327	0.0966	0.0437	0.1403
Active	-0.0379	0.0777	-0.0396	0.0180	0.0903	0.0360	0.1263
Passive (free)	0.1306	0.1460	0.1305	0.1190	0.1884	0.0828	0.2711
Passive (locked)	-0.1063	-0.0529	-0.1306	0.1447	0.0766	0.1850	0.2616

The speeds of the tractor unit in all the different runs on this road are shown in Figure 4.6. Overall, the speed is consistent in most of the runs. The runs that use the active dolly do fluctuate a bit though, likely because of how the dolly steering involves going slower or faster with the dolly motors.

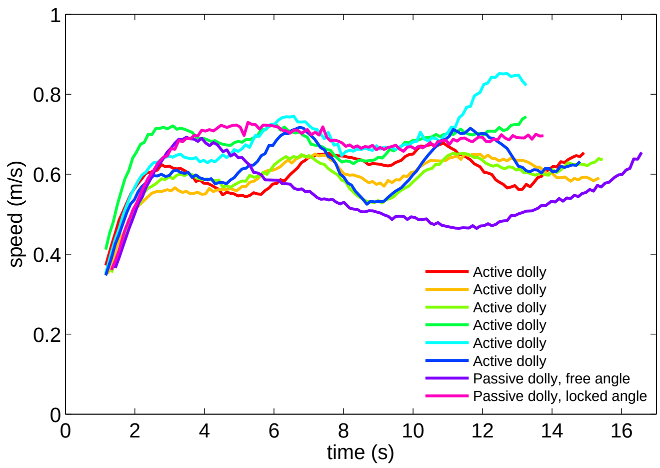

Figure 4.6: The speed of the tractor unit over several runs when driving on a road with a 180 degree curve, plotted over time. The curves have been smoothed out with averaging, which is why there seems to be data missing in the beginning. The speed is quite consistent between runs, but those using the active dolly have some fluctuations.

4.2 Performance on road with sharp turn

The same testing and analysis as in the previous section was also done on another similar road, but with a sharper 90 degree turn instead of a 180 degree turn. Figures 4.7 and 4.8 show the trajectories for the reference runs with the passive dolly, with the drawbar angle free and locked, respectively. Figure 4.9 shows the trajectories for the LCV units from one of the runs where active steering was used. This time, the passive dolly with its drawbar angle free performed well in the turn, but ended up on the outside of the correct path after the turn. The passive dolly with its drawbar angle locked once again took the inside in the turn, but was in the correct position on the final straight. The trajectory of the active dolly was the best one overall, since it followed the tractor unit consistently.

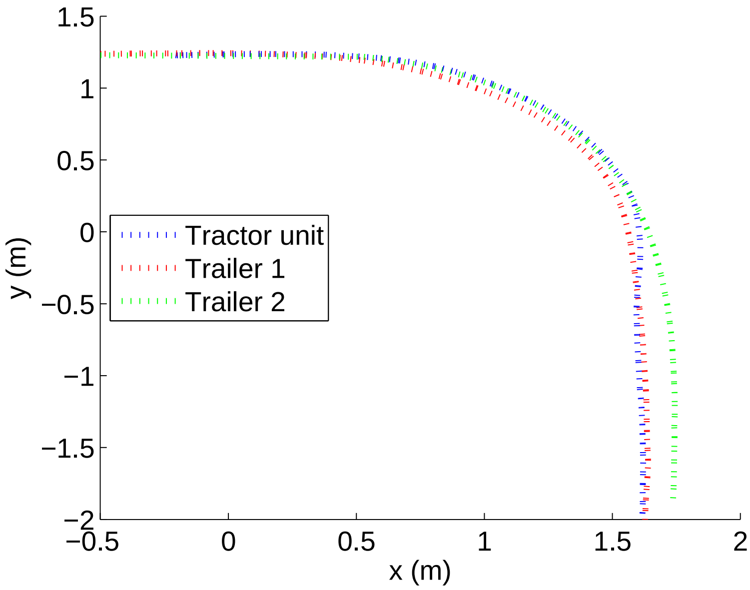

Figure 4.7: Trajectories for the three LCV units when driving on a road with a sharp 90 degree turn, using a passive dolly with its drawbar angle free. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer is on the outside of the proper path on the final straight.

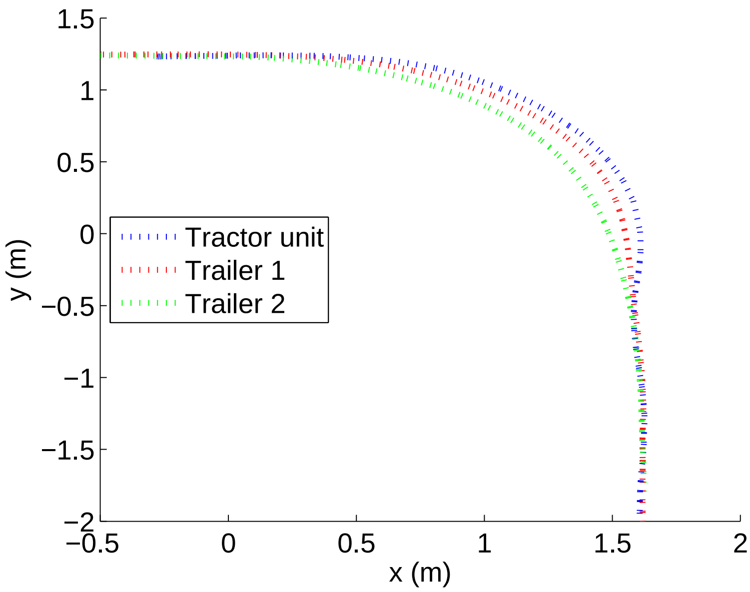

Figure 4.8: Trajectories for the three LCV units when driving on a road with a sharp 90 degree turn, using a passive dolly with its drawbar angle locked in the default position. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer is on the inside of the proper path when turning.

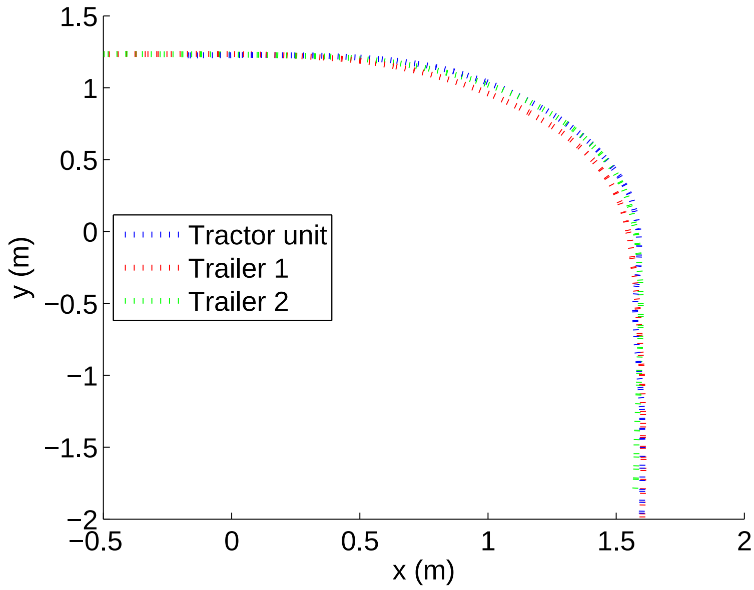

Figure 4.9: Trajectories for the three LCV units when driving on a road with a sharp 90 degree turn, using the active dolly. The trajectories are tracked at the midpoints of the LCV units. The path of the second trailer follows the intended path well.

The offtracking with the midpoint of the second trailer as reference is plotted in Figure 4.10. The results are somewhat different to those on the previous road. Once again, the active steering keeps the trailer on a good trajectory throughout the turn, but in most of the runs, the dolly turned too much, which made the trailer deviate a lot laterally on the straight that followed the turn. The passive dolly with a free drawbar angle performed similarly to the active dolly, but it deviated laterally to the other side in the end.

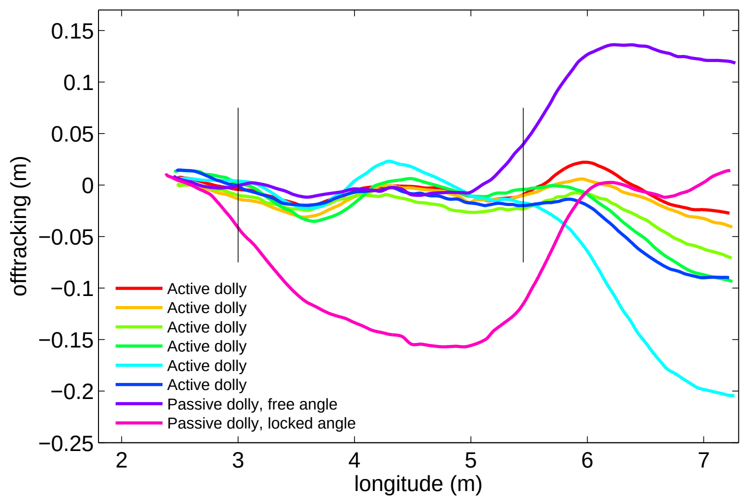

Figure 4.10: Offtracking measured on road with a sharp 90 degree turn, with the midpoint of the second trailer as the reference point. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical lines indicate the start and end of the curve.

Figure 4.11, where the offtracking is shown using the front and back axle of the second trailer as reference points, shows that with the active steering, the front and back of the trailer were on either side of the road throughout the turn. To achieve a perfect trajectory, the trailer would have to turn more in the turn, since the front ended up overshooting, and the back ended up undershooting. This goes somewhat against the conclusion that the dolly turned too much which caused the large deviations after the turn.

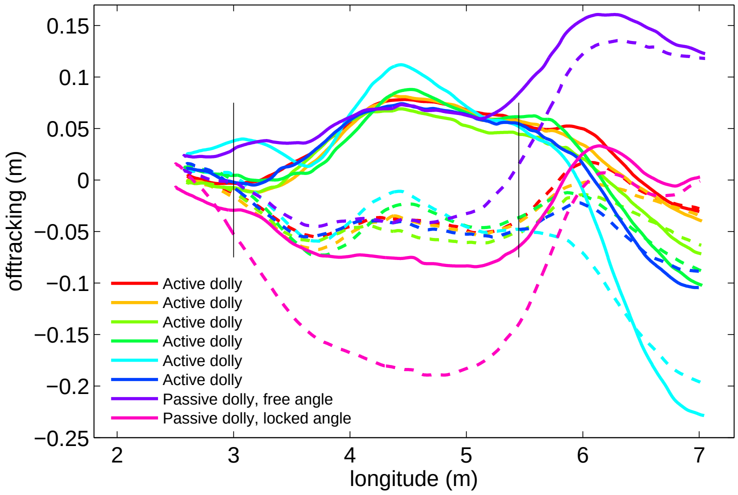

Figure 4.11: Offtracking measured on road with a sharp 90 degree turn. The solid lines use the front of the second trailer as reference point, the dashed lines use the back axle of the second trailer. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical lines indicate the start and end of the curve.

Table 4.2 shows additional information about the results. It's worth noting that almost all maximum offtracking values for the active dolly are negative values, coming from the large lateral deviations that happened on the straight after the sharp turn. Despite the poor performance at the end of the road, the values for the active dolly were still consistently better than those of the passive dolly. Once again, adding the average offtracking for the front and back axle of the second trailer gives perhaps the best general measure of performance. Averaging this value over the runs with the active dolly, and dividing with the value for the reference runs gives 0.63 for the free drawbar angle and 0.60 for the locked drawbar angle, meaning that the offtracking is reduced by roughly 40 % in this case.

Table 4.2: Offtracking values in metres from tests on a road with a sharp 90 degree turn. The first three columns with data contain the offtracking values that deviate the most from zero in the corresponding runs. Columns four through seven contain averages of the absolute values of the offtracking, with the seventh column being the sum of the fifth and sixth columns. Mid, front, and back axle refers to the reference points on the second trailer that were used to calculate the offtracking. The rows are ordered as in the legends of Figures 4.10, 4.11, and the data is from the same runs.

Dolly status	$\max(O)$ (mid)	$\max(O)$ (front)	$\max(O)$ (back axle)	$\overline{\lvert O\rvert}$ (mid)	$\overline{\lvert O\rvert}$ (front)	$\overline{\lvert O\rvert}$ (back axle)	$\overline{\lvert O\rvert}$ (front + back axle)
Active	-0.0273	0.0782	-0.0551	0.0210	0.0788	0.0587	0.1375
Active	-0.0407	0.0822	-0.0676	0.0265	0.0749	0.0658	0.1407
Active	-0.0706	-0.0716	-0.0632	0.0439	0.0724	0.0808	0.1532
Active	-0.0935	-0.1023	-0.0887	0.0464	0.0884	0.0772	0.1656
Active	-0.2044	-0.2285	-0.1976	0.1045	0.1499	0.1214	0.2713
Active	-0.0900	-0.1044	-0.0886	0.0529	0.0896	0.0877	0.1773
Passive (free)	0.1362	0.1607	0.1354	0.0958	0.1650	0.1123	0.2773
Passive (locked)	-0.1570	-0.0841	-0.1893	0.1469	0.0930	0.1939	0.2869

The speeds of the tractor unit in all the different runs on this road are shown in Figure 4.12. In this case, the speeds seem to fluctuate less than in the previous case. The speed seems very consistent overall, and a slight slowdown is seen in the turn. After the turn, the speed increases again.

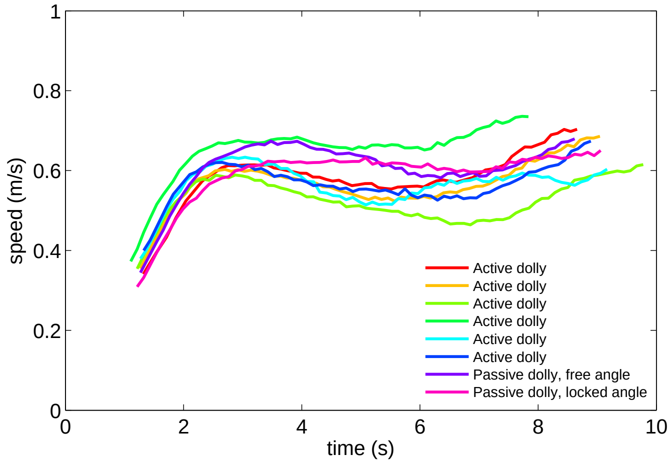

Figure 4.12: The speed of the tractor unit over several runs when driving on a road with a sharp 90 degree turn, plotted over time. The curves have been smoothed out with averaging, which is why there seems to be data missing in the beginning. The speed is quite consistent between runs. The LCV seems to slow down a bit in the turn, and then pick up speed again.

4.3 Performance while changing lane on a straight road

The performance of the active steering was also tested on a straight road, with a lane change quite early on. Trajectories for the passive dolly using a free drawbar angle are shown in Figure 4.13. The second trailer does not change lane, and keeps going on the original path. In Figure 4.14, the passive dolly is using a locked drawbar angle, and the results are quite good. Both trailers follow the tractor unit perfectly. When using the active dolly, the performance is somewhere in between, as seen in Figure 4.15. At first, the second trailer does not change lane when it should. The effects of the active steering kick in after a while, but the trailer ends up at bit off on the other side of the road.

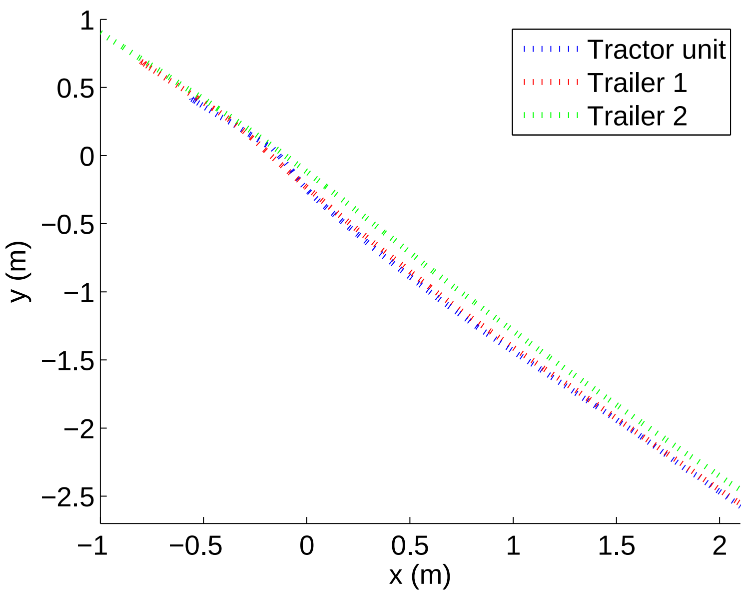

Figure 4.13: Trajectories for the three LCV units when driving on a straight road with a lane change, using a passive dolly with its drawbar angle free. The trajectories are tracked at the midpoints of the LCV units. The second trailer does not follow the rest of the LCV when the lane change happens.

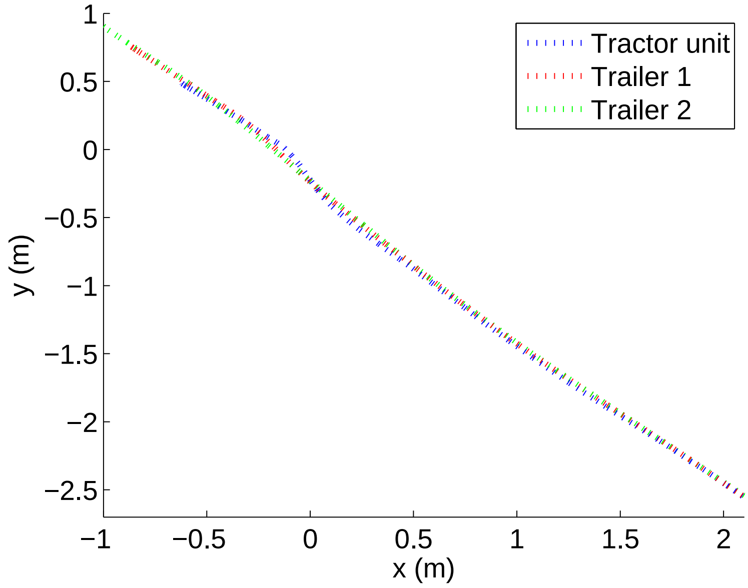

Figure 4.14: Trajectories for the three LCV units when driving on a straight road with a lane change, using a passive dolly with its drawbar angle locked in the default position. The trajectories are tracked at the midpoints of the LCV units. The second trailer follows the tractor unit very well.

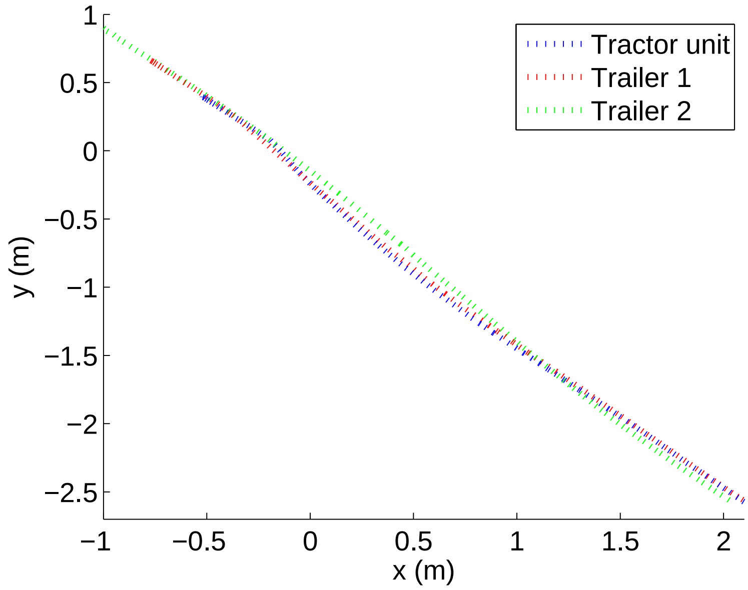

Figure 4.15: Trajectories for the three LCV units when driving on a straight road with a lane change, using the active dolly. The trajectories are tracked at the midpoints of the LCV units. The second trailer does not follow the rest of the LCV to the other lane at first, but does eventually.

The offtracking with the midpoint of the second trailer is plotted in Figure 4.16. This case is different from the earlier ones, in that the active steering is quite clearly outperformed by the passive dolly with a locked drawbar angle. For all other runs, the offtracking grows rapidly right after the lane change, and they then struggle to recover. The active dolly makes an attempt to recover, but overshoots and is still heavily out of position when the road ends, while the passive dolly with a free drawbar angle barely recovers at all.

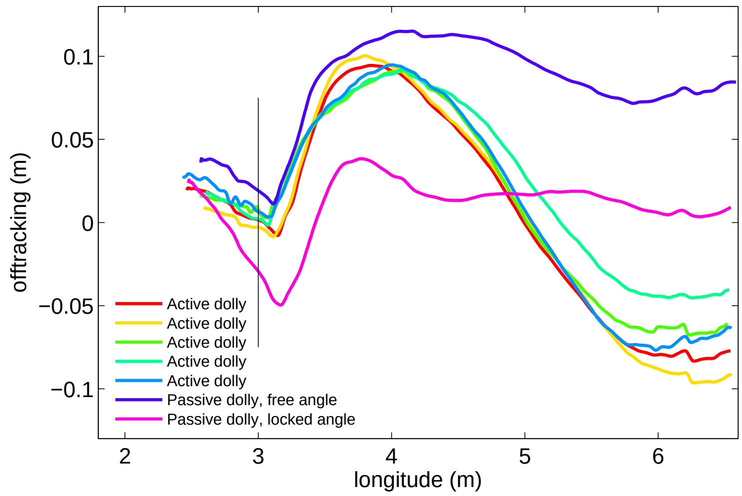

Figure 4.16: Offtracking measured on a straight road with a lane change, with the midpoint of the second trailer as the reference point. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical line indicates the where the lane change is.

Figure 4.17 shows the offtracking with reference points at the back axle and front of the second trailer. One thing to note is that the two curves for each run are quite close in this case compared to the others, which is expected since the LCV was mostly driving in a straight line.

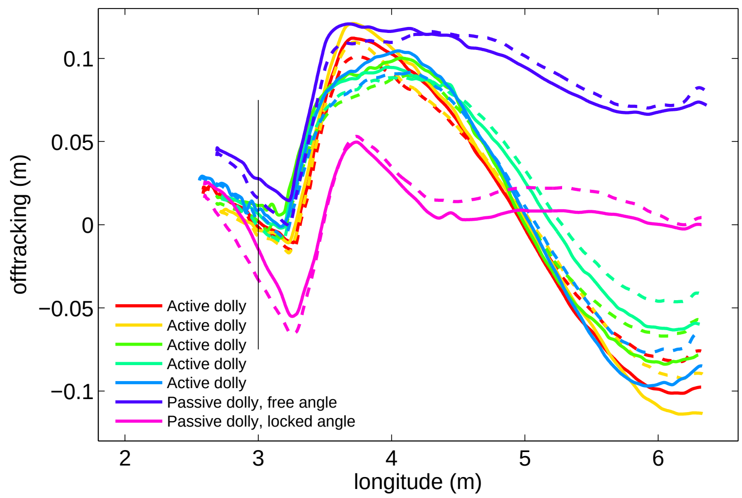

Figure 4.17: Offtracking measured on a straight road with a lane change. The solid lines use the front of the second trailer as reference point, the dashed lines use the back axle of the second trailer. The runs with the active dolly all use the algorithm in Section 3.4.2. The reference runs use a passive dolly, with the motors disconnected from the wheels. The black vertical line indicates the where the lane change is.

The maximum offtracking and the longitudinal averages of the offtracking are shown in Table 4.3. In this case, the active dolly performs consistently better than the passive dolly with a free drawbar angle, but much worse than the passive dolly with a locked drawbar angle. The last column is again the one that says the most, and averaging the values for the active dolly and dividing the result with that of the locked passive dolly gives 2.83, which means that offtracking is almost tripled in the active case compared to the locked case. The less relevant comparison with the free passive dolly gives a value of 0.66. The poor performance compared to the locked passive dolly highlights a major issue for the active dolly: using a free drawbar angle makes it difficult to recover from a lateral deviation.

Table 4.3: Offtracking values in metres from tests on a straight road with a lane change. The first three columns with data contain the offtracking values that deviate the most from zero in the corresponding runs. Columns four through seven contain averages of the absolute values of the offtracking, with the seventh column being the sum of the fifth and sixth columns. Mid, front, and back axle refers to the reference points on the second trailer that were used to calculate the offtracking. The rows are ordered as in the legends of Figures 4.16, 4.17, and the data is from the same runs.

Dolly status	$\max(O)$ (mid)	$\max(O)$ (front)	$\max(O)$ (back axle)	$\overline{\lvert O\rvert}$ (mid)	$\overline{\lvert O\rvert}$ (front)	$\overline{\lvert O\rvert}$ (back axle)	$\overline{\lvert O\rvert}$ (front + back axle)
Active	0.0944	0.1122	0.1010	0.1024	0.1160	0.1004	0.2163
Active	0.1003	0.1210	0.1098	0.1107	0.1244	0.1075	0.2319
Active	0.0911	0.1002	0.0898	0.0992	0.1158	0.0968	0.2126
Active	0.0924	0.0947	0.0884	0.0903	0.1027	0.0926	0.1953
Active	0.0948	0.1045	0.0916	0.1050	0.1206	0.1026	0.2232
Passive (free)	0.1151	0.1207	0.1161	0.1627	0.1649	0.1627	0.3275
Passive (locked)	-0.0497	-0.0552	-0.0659	0.0364	0.0305	0.0457	0.0763

The speed data calculated from the shown runs is shown in Figure 4.18. It is clear from the figure that the speed setting for the reference runs should have been lower, although it is unlikely that it affected the results much. The runs with the active dolly are reasonably consistent, and they all have a spike in the middle. The spike is likely caused by the active steering of the dolly.

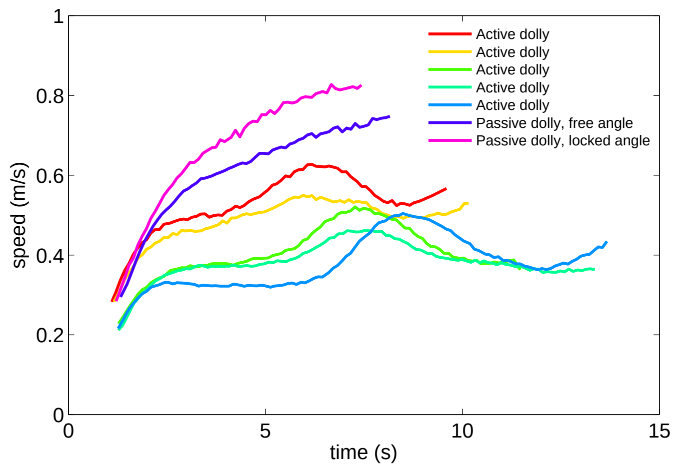

Figure 4.18: The speed of the tractor unit over several runs when driving on a straight road with a lane change, plotted over time. The curves have been smoothed out with averaging, which is why there seems to be data missing in the beginning. The reference runs seem to have been done using a speed that was a bit too high. The runs with the active dolly are somewhat consistent, and have a spike where the active steering kicks in.

5 Discussion

In this chapter, the results will be discussed and evaluated in depth, particularly with regards to potential errors and inconsistencies during testing.

5.1 Overall performance of the active steering

The active steering algorithm that was tested has clear advantages over the traditional passive dolly in some aspects, but turned out to be worse in others. The most notable improvement coming from the active steering is the ability to stay on the road when navigating a curve. The passive dolly with a locked drawbar angle, which is used on LCVs currently, would tend to go on the inside of a curve, deviating laterally from the proper path by as much as 0.1 m to 0.15 m. Meanwhile, the passive dolly with the drawbar angle free could deviate as much, but on the other side of the road. The active steering, which was implemented using a free drawbar angle, performed quite well in the curves, and would not deviate nearly as much. Averaging the offtracking over the entire road, taking into account both the front and back of the second trailer, suggested that the lateral deviation of the second trailer was reduced by up to as much as 50 %.

Contrary to the good results achieved when navigating a curve, the active dolly struggles severely when recovering from a lateral deviation when on a straight. This is a big problem for the passive dolly with an unlocked drawbar angle, so much so that it is very difficult to rectify with active steering, at least with the dolly that was used. The problem is evident in the results, particularly looking at what happens right after completing a turn, or at the results from the lane change case. During experimentation and testing, it seemed as if the dolly was almost completely incapable of recovering from a lateral offset in a satisfactory manner. Manoeuvres not involving hard braking on one side of the dolly would make the trailer recover so slowly that there was not enough room in the laboratory to test it, which is a major downgrade compared to the results from the passive dolly with a locked drawbar angle. Using hard braking, on the other hand, would often cause the dolly to very quickly turn too much, which made the trailer recover but then end up with a large deviation on the other side of the road. This behaviour is evident in Figures 4.16 and 4.17.

When looking at the results, one could keep in mind that a full size lane that is 3.5 metres wide corresponds to a lane width of 0.25 metres at the scale used in this report. The tractor unit and the trailers all had a width of 0.2 metres. This means that, when driving in the middle of the road, the distance between a wheel and the edge of the lane is (width of lane)/2 − (width of vehicle)/2 = $0.25/2\,\mathrm{m} - 0.2/2\,\mathrm{m} = 0.025\,\mathrm{m}$. Not a single run presented among the results achieved a maximum offtracking less than this value, and it could be argued that no run even came close. It has to be noted that, when scaling down physical testing of something, not everything scales as one might expect. The fact that the length of the LCV is scaled down 1:14, does not necessarily imply that the offtracking scales 1:14 as well. Therefore, it is more useful to look at the relative improvement over the reference runs, and to interpret the results qualitatively rather than quantitatively.

The motors, with gear ratio $R = 11$, that were chosen for the dolly seemed to work well overall. They were able to clearly contribute to pushing the LCV forward, even though they were generally not very close to running at their maximum capacity. The speed graphs showed that the speed of the LCV was sometimes a bit inconsistent, and one particular issue was that the speed could fluctuate. These issues were likely not related to the motors, though. The fluctuations very likely arose because of the active steering algorithm causing one side of the dolly to go faster and the other to brake. Attempts to find a balance were made, but that only shows in the case with the sharp turn.

5.2 Potential errors and their sources

During the testing, a lot of hardware and software had to come together, and with that there were many things that could go wrong, and things that to some extent did go wrong. These things will be discussed in the following subsections.

5.2.1 Problems with the angle sensor

The angle sensor measuring the angle of the drawbar connecting the dolly to the trailer in front of it had a number of issues that caused some problems with the experiments. First of all, the signal given by the sensor did not seem to depend linearly on the actual angle. When the drawbar was in its default position, pointing straight forwards, the reading given by the angle sensor and Arduino was 500. Rotating the drawbar 45 degrees to the right from the default position increased the reading by 240, while rotating it 45 degrees to the left from the default position only decreased the reading by 190. This did not impact the results significantly, since parameters in the algorithm were optimized with regard to how the dolly behaved. Furthermore, all the test cases involved right turns, but no left turns. This was a conscious decision made in an attempt to mitigate any problems arising from asymmetries in the hardware. If one were to use this hardware setup to test manoeuvres where turns both ways are involved, a proper reading to angle mapping would have to be determined first.

Another problem relating to reading the drawbar angle was in the inconsistency of how quickly the readings were processed. Usually, the readings would seem reasonable, but sometimes they would lag behind the actual angle a lot. An example of this is seen in Figure 5.1. The data in the figure is from the second to last run with the active dolly shown in figures 4.10 and 4.11, and this explains why that particular run was so much worse than the others. When the second trailer appears to be right behind the first trailer, with roughly the same heading, the angle reading of 604 suggests that the drawbar angle is in the region of 20 degrees, which seems quite improbable. Not until 0.55 seconds later does the angle sensor give a reading close to 500 suggesting that the drawbar is in the default position. However, as can be seen in the figure, at that point, the trailers have already moved quite a bit and a reading significantly less than 500 is definitely to be expected. It should be noted that it is unlikely that this problem was caused by the angle sensor itself, and that it seems more likely that the problem stemmed from the Arduino or its software. Because of these faulty readings, the active steering algorithm was lead to believe that the trailer was in a bad position when it really was not. This lead to the dolly compensating a lot for an error that was not there, and the problems were compounded further when the slow angle readings caused the algorithm to not react to the mistake in time.

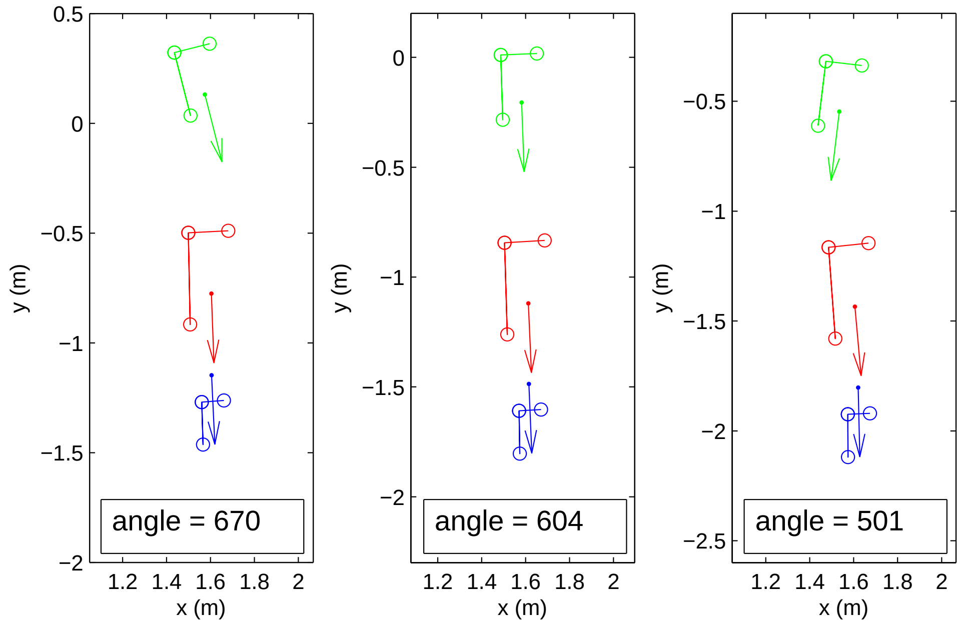

Figure 5.1: LPS and angle sensor data at three different times from the same run, showing that the angle sensor is not always reliable. The circles correspond to the markers placed on the LCV for the LPS to use, while the arrows show the headings of the LCV units. The blue arrow and circles represent the tractor unit, red represents the first trailer, and green represents the second trailer. The arrows originate at the midpoint of their respective unit. An angle reading of 500 corresponds to the drawbar being in the default position, which it looks to be in in the middle plot.

5.2.2 Tractor unit not driving exactly as intended

The algorithm used to control the tractor unit was not developed as part of this project. Instead, a pre-existing algorithm was used, and tweaked slightly. While the algorithm generally did an acceptable job following the roads that had been defined, the tractor unit would struggle quite a bit with driving on straight roads after going through a curve or after changing lane. Figure 5.2, taken from a run on the road with a lane change, shows this happening quite clearly. The data in the figure is taken from a run that used an earlier version of the active steering algorithm for the dolly, and which also used a higher speed. After completing the lane change, the tractor unit very clearly oscillates around the intended trajectory, which has a lateral position of 0.05 m. These oscillations clearly affect the first trailer as well, as it is also oscillating. The second trailer, however, appears relatively unaffected.

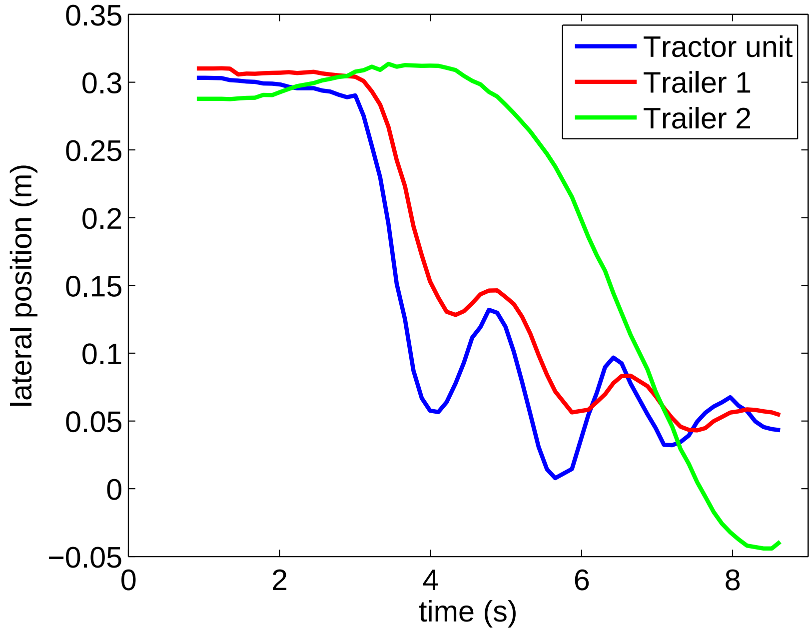

Figure 5.2: Lateral positions relative to the road for the tractor unit and the two trailers, showing the oscillations done by the tractor unit after changing lane. The intended path is to maintain a lateral offset of 0.3 m, and then to change it to 0.05 m. This run did not use the final active steering algorithm for the dolly, and used a higher driving speed than the one used for the other runs shown in the report.

It's difficult to say exactly what caused these oscillations, but possible explanations include the steering servo being slow, and the steering algorithm for the tractor unit simply not being very good in these situations. Lowering the speed of the LCV reduced this problem greatly, and a lower speed was used after that discovery, including in the runs presented among the results. The problem was still present, though, and an example of it from one of the runs presented among the results is shown in Figure 5.3. In the figure, the tractor unit is seen oversteering when coming out of the curve. While the tractor unit does manage to recover, the behaviour is still undesirable. While it seems that the second trailer was not affected much by the tractor unit deviating from the intended path at times, it is possible that it might have affected the offtracking measurements. One thing to note is that offtracking is measured relative to the path of the tractor unit, rather than the intended path. In the particular run shown, the maximum offtracking occured at the incident shown in the figure, with the tractor unit going off-road while the second trailer was positioned almost perfectly.

Unexpected behaviour from the tractor unit can be a somewhat major concern, as it affects the results in many ways. This is especially true since the active steering algorithm for the dolly depended a lot on the steering wheel angle of the tractor unit, which is one of the reasons behind using an average of several past steering wheel angles in the algorithm. Attempts were made to fix the issue by changing parameters in the steering algorithm for the tractor unit, and by creating special cases for different road types. The changes did not seem to help a lot though, and in the end the speed of the LCV had to be lowered. A potential alternative fix that was not tested is to let the tractor unit steer in a more pre-defined manner. For instance, the tractor

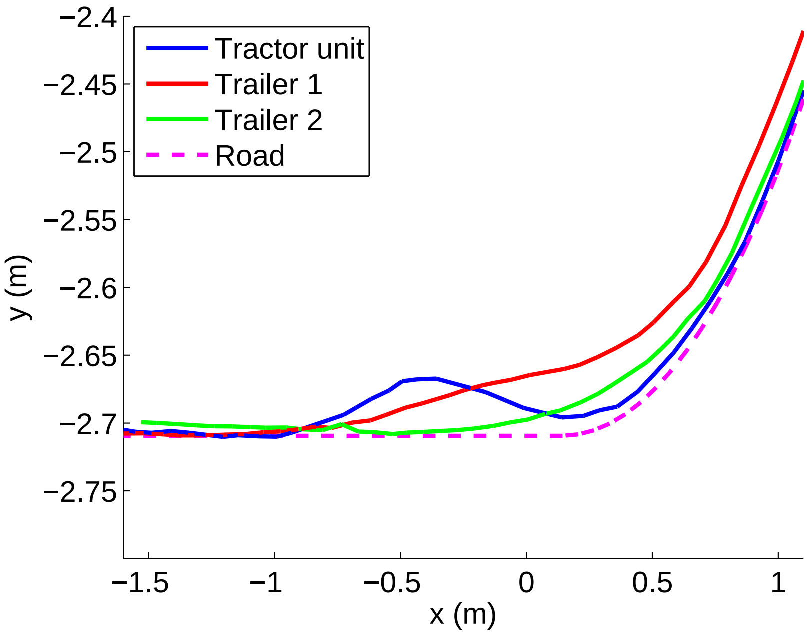

Figure 5.3: Trajectories for the tractor unit and the two trailers when driving on the road with a 180 degree curve. This is data from the third run with the active dolly shown in Figures 4.4 and 4.5. This figure only shows the ending straight of the road, and a little bit of the curve. After coming out of the curve, the tractor unit oversteers and goes a bit off the road, but recovers in the end.

unit would be ordered to go straight for a certain amount of time, then turn a certain amount for a certain amount of time, and so on. This method would eliminate the problem of the tractor unit going back and forth across the road, but it has some other issues. The main problem would be that the path of the tractor unit would depend on starting position and battery levels. Given that space in the laboratory was limited, and that the test cases were constructed to make as much use of the useful space as possible, small inconsistencies would cause a lot of problems.

5.2.3 Issues with LCV hardware

The dolly was seemingly not built with very high precision, which mainly caused issues with the drivetrain. First of all, there was a significant amount of friction in the drivetrain, which caused the wheels to not rotate as easily as they should have. As a result, the motors had to work harder unnecessarily. The resistance in the drivetrain was also not consistent between the wheel pairs, which meant that one motor would have to work more than the other in order to achieve the same output at the wheels. Additionally, the wheels on the left side of the dolly were supposed to be independent from those on the right side, but that was not really the case. When rotating the wheels on one side, the wheels on the other side would be clearly affected and would rotate slightly in the same direction. By applying some grease and by loosening some nuts to the point where they would sometimes fall off, these problems were mostly alleviated, but not entirely.

The drivetrain of the dolly had one other major issue, in that the timing belts used were not stretched enough. In total, there were four timing belts on the dolly: one from each motor leading to a wheel, and one from each of those wheels leading to the other wheels on the same sides. All of them were somewhat loose, and would frequently skip some cogs, particularly when braking. It's difficult to say how much a timing belt skipping some cogs affected any results, but those events were easily noticeable due to a distinct sound being made every time they happened. Modifications to the dolly were made in an attempt to fix the problems. Screw holes were widened to allow motors and axles to be moved slightly, and a couple of wooden objects were sawn out and placed in between the motors and the axles, to ensure that a certain distance was kept between them. The four timing belts, as well as the two wooden objects covered in black electrical tape, can be seen in Figure 2.3. The attempts to fix the problem of the timing belts skipping cogs were somewhat successful. During the final testing, which resulted in the runs presented in the results, this was largely not an issue. There was a period after an attempt to fix the problem was made, where no cog skipping could be heard for a few weeks, with many dozens of runs. Towards the end of the project, however, the problem came back slowly, and some runs in the results section were affected by a small number of cog skips.

A problem that may have affected both the dolly and the tractor unit was that the tyres did not seem to get a lot of grip on the floor of the laboratory. While the results never seemed to indicate that any unit of the LCV ever skidded off the road, it is possible that some manoeuvres, such as braking with the dolly, may have been affected. The floor in the laboratory had a surface that was quite smooth. Using a different floor with more friction would mitigate the slipping, and it would more closely resemble asphalt, making the tests more credible.

5.2.4 Software and LPS

Both the data collection and the steering of the tractor unit relied upon the LPS in the lab as well as a lot of software in order to function. The LPS generally did its job fairly well when the LCV was in a certain area (see Figure 2.6), but that area was rather limited. Because of the area where the LPS was effective being so small, choice of roads and scenarios to test became limited. Even though the test cases used were thought out with this in mind, the LPS still caused some trouble. The area of the room where the LCV started most of the time did not have perfect LPS coverage, and the LPS would frequently lose track of LCV units. Data of the second trailer on the early parts of the roads was consistently lost due to the LPS losing track of the marker balls. Since this was on straight roads where nothing special happened, the lost data could be recovered through interpolation of the data that still remained. Another problem with the LPS was that it would sometimes report positions that did not seem entirely accurate. The deviations would however only be on a centimetre scale, and they would not happen very often, so it is unlikely that the results were affected in any qualitative sense.

One factor that did not affect the results directly but that still had an impact was bugs in the software. The parts of the code that recognized objects from a set of marker positions given by the LPS hade a few significant bugs that had to be fixed for the data to be considered reliable. The same can be said for the code that calculated where the LCV units were located in relation to the road. These bugs were fixed during the project, but finding them and fixing them did take some time that would otherwise have been spent optimizing the active steering.

5.2.5 Varying conditions and inconsistencies

When testing algorithms and performance, it could be difficult to keep the testing conditions as consistent as possible. When developing the active steering algorithm, the conditions would often change on a week-to-week basis, due to frequent changes in the software and hardware, such as bug fixing and the tightening of the timing belts already mentioned. Constantly adjusting to these changes, along with the time it took to actually make the changes, caused the algorithm development to slow down significantly. The plan was for all hardware work to happen in the beginning of the project, but the problems that had to be addressed were not all apparent from the start.

When doing the final testing, and producing the data presented in this report, no changes to the hardware and software were consciously made. It is however inevitable that some degradation in hardware happened, as evidenced by the timing belts skipping cogs. Another inconsistency that has also already been mentioned is that of the angle readings from the sensor sometimes being slow.

There were also other, more predictable, factors that caused inconsistencies between the runs made. The starting position of the LCV had to be carefully set before each run, but some variance was present. The only tool that was used to help setting the starting position was the LPS, and the software was changed so that it would print out current lateral and longitudinal positions relative to the current road segment before the run had started. Using the LPS and software, it was realistic to get the errors in position down to less than centimetre level, but not better than that given that the project had a time constraint. The inconsistencies in starting positions were probably not a large problem, as it can not be expected that a real life LCV will enter every curve or lane change perfectly positioned. Additionally, the runs with the active dolly in the results section are overall quite consistent.

Another inconsistency that is important to consider is that of the battery levels. The LCV used three power sources in total, two of which had an impact on how the LCV was driven. One of those power sources powered the motor and steer servo in the tractor unit as well as the BeagleBone Black, and the other power source powered the motors in the dolly. After charging the batteries, it would generally only take a few runs with the LCV before the motors became noticeably weaker, resulting in lower speeds. To keep this problem from causing major inconsistencies, the batteries were charged quite frequently. While it is possible that the speed of the LCV varied slightly between runs, as well as the power balance between the dolly and the tractor unit, there are no indications that these factors would have ruined any results.

6 Conclusions and considerations for future work

By using active steering in a dolly, the lateral performance of an LCV model was improved in some aspects, particularly when navigating through curves. However, the design of the dolly made it difficult for it to quickly recover from lateral offsets, caused for instance by a lane change. The results were still encouraging enough to say that it certainly seems possible to create and program a scaled down LCV model with active steering that performs well in most realistic situations. In order to do so, it might however be necessary to change several things relating to hardware and testing environment.

The size of the laboratory, along with the small size of the area where the LPS coverage was acceptable, was a major issue throughout the project. Proper analysis of performance was made near impossible, and an increase in space has to be considered before resuming the project. The laboratory did have a significant amount of space that was useless because of a lack of LPS cameras, and increasing the number of cameras to extend coverage in the existing laboratory would go a long way. Use of computer simulations is also something that could be considered for testing algorithms before testing them in the laboratory, since hardware issues and restrictions on available space would not be problems.

Different situations require somewhat different algorithms for optimal performance. A sharp turn is not the same as a long curve, which is not the same as a straight. In the algorithm used in this report, this was solved by letting weights in a sum be functions of the recent history of the steering wheel angle in the tractor unit. Implementing that feature did improve the algorithm, but it was far from perfect. It was particularly difficult finding a balance that allowed the dolly to navigate both the sharp turn and the curve properly. In the end the algorithm could have performed better in the sharp turn instead of oversteering, but that would have come at the cost of performance in the curve case. Different parameters and formulas for producing the weights were tested, including the use of discrete states, but finding something that worked better proved too difficult. The best way to fix this would probably be to add more sensors to the LCV, as the angle sensor and steering wheel angle did not produce enough information for a good decision to be made. A very simple suggestion would be to actually use the LPS, and have it emulate a GPS. It is possible that an artificial neural networks approach, or something similar, would be able to get by using only the currently available information, which makes it worth considering as well.

The hardware design of the dolly had some drawbacks that should be addressed. The most glaring problem with the results of this report was how the dolly struggled to recover from a lateral offset. Steering the 'just right' amount, that would allow the dolly to recover relatively quickly without turning far too much, seemed very difficult to achieve. The only way to make the dolly react quickly was to break significantly with one side of the dolly. Not only did that make algorithm development tough, it also seems quite unsafe and too unpredictable to use in a real traffic situation. It seems likely that a braking system more sophisticated than asking the motor to reverse would perform better, as it would allow for braking with much better precision. A solution that might be even more promising would be if the dolly had steered by turning its wheels instead of using separate motors for each side. Rebuilding the dolly to use Ackermann steering would likely be tricky, but almost certainly worth the effort. Looking at other similar papers, it would seem that steering through wheel turning is a more common solution. In [17], a truck-dolly-semitrailer combination utilizes this type of steering on both axles on the dolly, as well as all three axles located at the back of the semitrailer. Another example is [18], where a 1:14 scale model very similar to the one used in this project successfully uses active steering through turning of wheels on several axles.

When optimizing the performance of the active steering, very little thought went into the performance of the first trailer, with all of the focus being on the second trailer. The first trailer also had some offtracking and some trajectories that were not optimal. The main reason behind not considering the first trailer was that, given the hardware, it would be very hard to make the dolly affect the trailer in any useful way. The free angle of the drawbar that connects the dolly and the first trailer means that most manoeuvres made by the dolly will not affect the first trailer at all. If hardware is changed, however, the performance of the first trailer should be taken into consideration, if possible.

It was intended originally for testing and optimization of the algorithm to involve using different loads and different speeds. Due to the time constraints and the time lost fixing flaws in hardware and software, however, this could not be done. For an active steering solution to be seriously considered as viable, it would have to be shown to work in many different speeds, and with many different loads.

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