

CHALMERS



REAR AXLE STEERING FOR HEAVY TRUCKS EVALUATION AND IMPROVEMENT OF MAXIMUM STEERING ANGLE OF TAG AXLES FOR VOLVO TRIDEM TRUCKS

Bachelor thesis in Mechatronics

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PREFACE

The result of this thesis report is created based on many people's efforts and their passion for their jobs and to help. This bachelor thesis is the final course of our education in mechatronics (180 credits) at Chalmers University of Technology. The project has been conducted during April to June 2013 and comprises 15 credits. It has been conducted at ÅF Technology and Volvo Group Trucks Technology (GTT) in Gothenburg.

First we would like to thank Anna Josefsson who helped us to get in touch with Volvo Group Trucks and ÅF and Lena Larsson, Volvo GTT for starting the project, spreading energy and guiding us along the way.

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...and many more.

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SAMMANFATTNING

Styrsystemet för bakaxelstyrning som Volvo använder ger en otillräcklig maximal styrvinkel mot vad som efterfrågas på tridem lastbilar, lastbilar med tre bakaxlar. Styrningen på bakaxeln är "steer by wire". På grund av det strikta säkerhetstänket ges restriktioner på den maximala styrvinkeln. Det finns eftermarknads servicekit till Volvo lastbilar som tillåter ökad maximal styrvinkel. Examensrapporten är gjord i uppdrag från Volvo Group Trucks Technology (GTT) och utreder Volvos styrsystem samt ett fåtal konkurrenters. Ett antal förbättringar och rekommendationer till Volvos styrsystem föreslås. Det upptäcktes att det inte går att göra någon snabblösning för att få en större styrvinkel på grund av hårdvarubegränsningarna, det går dock att göra några förbättringar med en liten ansträngning. Fordonet måste uppträda säkert i alla situationer, tester och beräkningar på slirvinkeln är därför att rekommendera innan större styrvinklar tillåts.

Nyckelord: Bakaxel styrning, Tag axelstyrning, Löpaxel styrning, Styrbar bakaxel, Styrbar löpaxel, Styrbar tag axel, Elektro-hydraulisk styrning, Ackerman vinkel

ABSTRACT

Volvos steer system for rear axle steering provides too small maximum steering angle for optimal function on tridem trucks, trucks with three rear axles. The control system for the rear axle steering is a "steer by wire" and the reason for the restriction in steering angle is a strict safety approach in the event that the control system fails or sends out false control signals. There is an aftermarket service kit allowing greater steering angles that can be retrofitted on Volvo trucks. This thesis ordered by Volvo Group Trucks Technology (GTT) evaluates these steering systems as well as competitors systems and presenting a number of improvement concepts and recommendations. It was found that due to hardware limitations, increased maximum steering angles is not a quick fix. However, some improvements can be done with small efforts. The vehicle must behave safely in every possible situation, a number of tests and calculations concerning slip angles are therefore recommended to be performed before considering allow greater steering angles.

Keywords: Rear axle steering, Tag axle steering, Steerable rear axle, Steerable tag axle, electro-hydraulic steering, Ackerman angle.

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NOMENCLATURE

ÅF – The ÅF group is a leader in technical consulting.

FH - Front High. Volvo model name for a heavy truck mostly used for long distant and heavy transports.

8x4 - 8 wheels of which 4 are driven wheels

8x2 - 8 wheels of which 2 are driven wheels

6x2 - 6 wheels of which 2 are driven wheels

6x4 – 6 wheels of which 4 are driven wheels

Tag axle – Axle placed behind the drive axle(s).

Push axle – Axle placed in front of the drive axle(s).

Bogie – A truck with two rear axles, normally 6x2 or 6x4.

Tridem - A truck with three rear axles, normally 8x4 or 8x2.

Steer by wire - No mechanical connections between the driver and the wheel. Instead the information is transferred via electrical wires.

ECU – Electronic Control Unit, microcontroller to control electrical component by information from sensors.

PWM – Pulse Width Modulation

PI – A proportional part and an integral part

1 INTRODUCTION

1.1 Background

Volvo's system for rear axle steering provides too small maximum steering angle for optimal function. The control system for the rear axle steering is a "steer by wire" and the reason for the restriction in steering angle is a strict safety approach in the event that the control system fails or sends out false control signals. For example an external magnetic field generated around power lines can possibly disturb the control signal. Even if the control system fails, the vehicle must behave safely in every possible situation.

There is an aftermarket service kit allowing greater steering angles that can be installed on Volvo trucks. So far as it is known it works without issues. Furthermore, other truck manufacturers have systems that allow greater steering angles.

1.2 Purpose

The purpose of the project is to improve the steering during sharp turns, especially at low speeds.

1.3 Restrictions

The project is aimed to investigate the steering function for steerable rear axles in heavy trucks as well as their control systems. The rear axle itself will not be investigated or improved.

Calculations in vehicle dynamics are not included in the project.

Since a variety of configurations of wheelbases and wheel dimensions exist, the thesis will primarily include 8x4 tridem vehicles with steerable tag axle.

The improvement proposed in this thesis is optimized for an 8x4 tridem vehicle with steerable tag axle and a wheelbase of 4100mm.

1.4 Clarification of the question

Is Volvo's steering system for rear axle steering safe enough to allow greater steering angles without compromising safety?

Is the aftermarket service kit for Volvo trucks safe and good enough to implement from the start in the production of the truck?

Is there a better solution?

2 TECHNICAL BACKGROUND

2.1 Introduction

Transport by trucks account for the main part of transports in Sweden and around the world. The competition is high and to bring down the cost of transportation, the trend is to build larger and heavier vehicles. In order to avoid heavier load on the roads than permitted, the solution is to build trucks with additional axles. The advantage by using heavier trucks is improved fuel efficiency [ton km/liter] (1).

The disadvantage with heavier trucks and more axles is that tire wear increase and the vehicle will be clumsier to maneuver, especially in sharp turns when the fixed rear axles strive to go straight ahead. To improve maneuverability, the automotive industry has multiple solutions, which all somehow involve making several axles steerable. Many different axle configurations exist. What axle configuration that suits a certain vehicle depends on what transport sector the vehicle is specialized in and in what geographical area the vehicle is supposed to be used. However, the control systems developed for these vehicles is not very different from each other. Today there are basically two technologies for rear axle steering on the market. There are pure hydraulic systems and electro-hydraulic systems (“Steer by wire”).

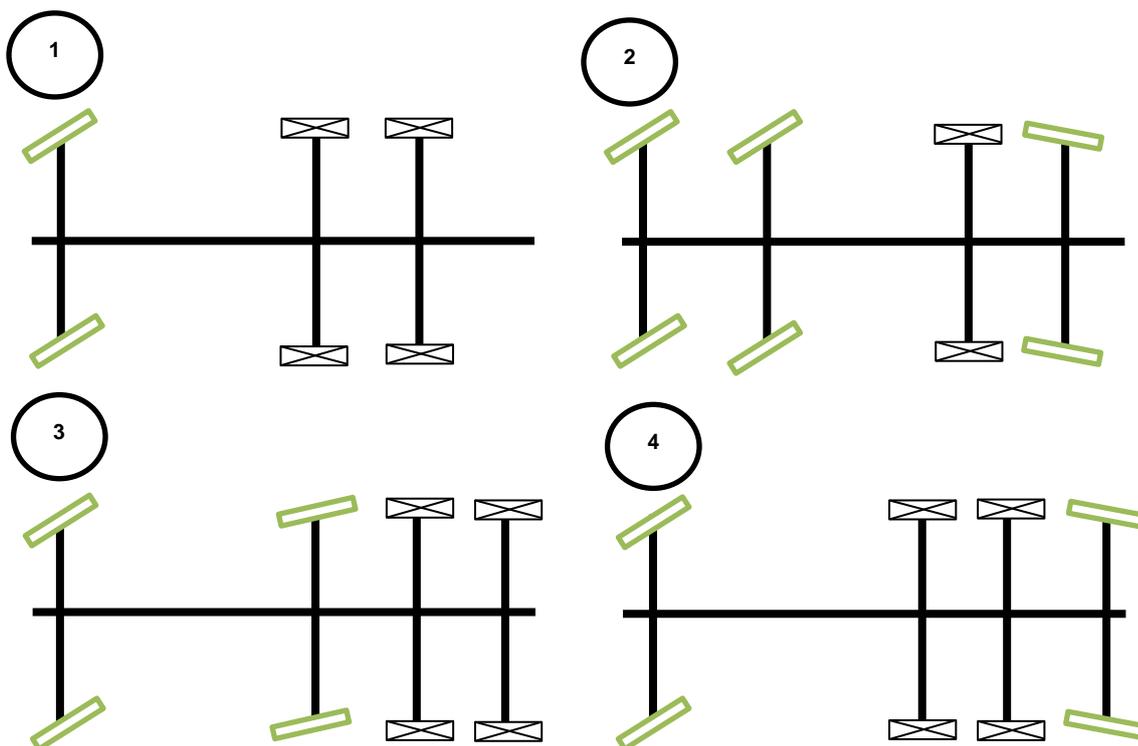


Figure 1. Popular axle configurations for trucks with three and four axles. 1. Bogie truck with two fixed drive axles (6x4). 2. Truck with double front axle, one fixed drive axle and steerable tag axle (8x2). 3. Truck with double front axle, two fixed driven axles (8x4). 4. Tridem truck with two fixed drive axles and steerable tag axle (8x4).

Trucks with three axles have been the standard in the 90s and early 00s. However, the annual sales of trucks with four axles, especially Volvo tridem trucks, which are the target trucks in this project, have increased the last years (Figure 2).

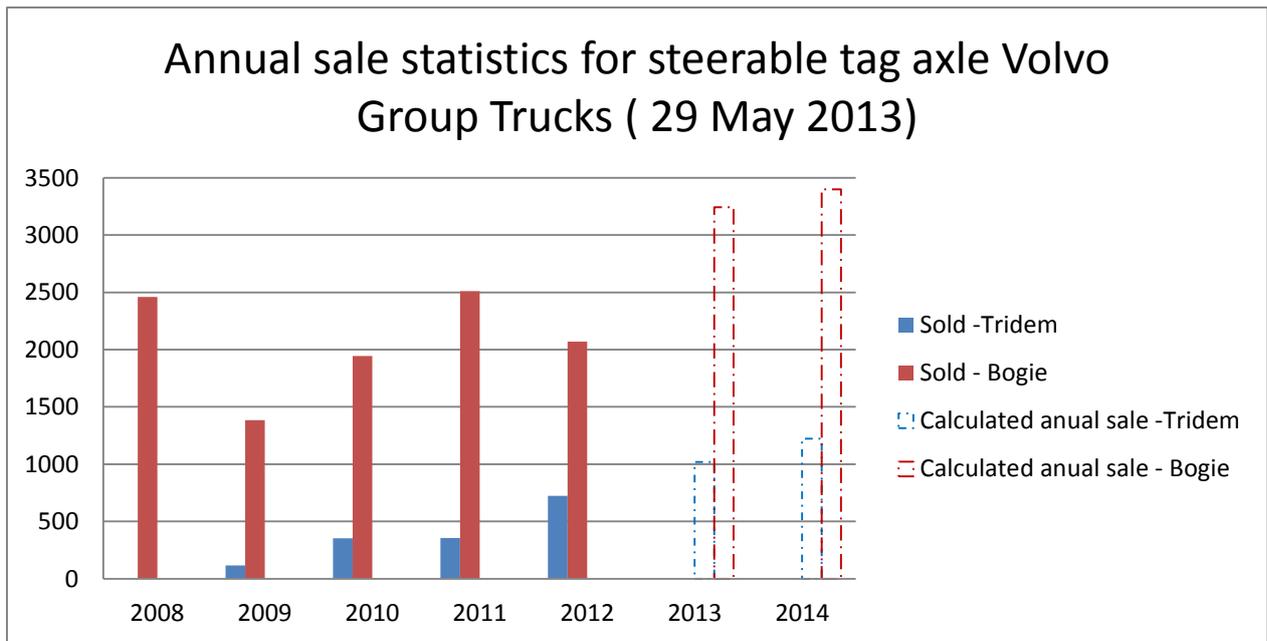


Figure 2. Annual sales statistics of Volvo Group Trucks globally. The statistics was collected the 29th of May 2013. The statistics for 2013 and 2014 is therefore just calculated from sale statistic. It shows that the sales of tridem is increasing.

Volvo's present steering system for rear axle steering is a "steer by wire" and was first introduced in 2004 (2). The system is used in all Volvo truck models with steerable rear axles. Today software optimized for bogie trucks (6x2) is used in tridem trucks, in other words the system is not optimized for these trucks.

Today legislative proposals about increasing the maximum weight allowed from 60 tons to 74 tons (SWE) and 76 tons (FIN) are in progress. If these proposals are approved, the sales of tridem trucks will for sure increase greatly (3).

2.2 Desired Steering geometry

The desirable steering geometry on a vehicle is called "Ackerman geometry" (4). This geometry is when a line perpendicular to the vehicle through a point on the truck called the center of rotation coincident with a line perpendicular to every steerable wheel, in a single point (Figure 3). On a tridem truck this geometry is achieved when the truck's center of rotation is positioned right between the fixed drive axles (Appendix A). This geometry minimizes tire wear and geometrically gives the truck equal turning radius to a bogie truck with the same wheelbase.

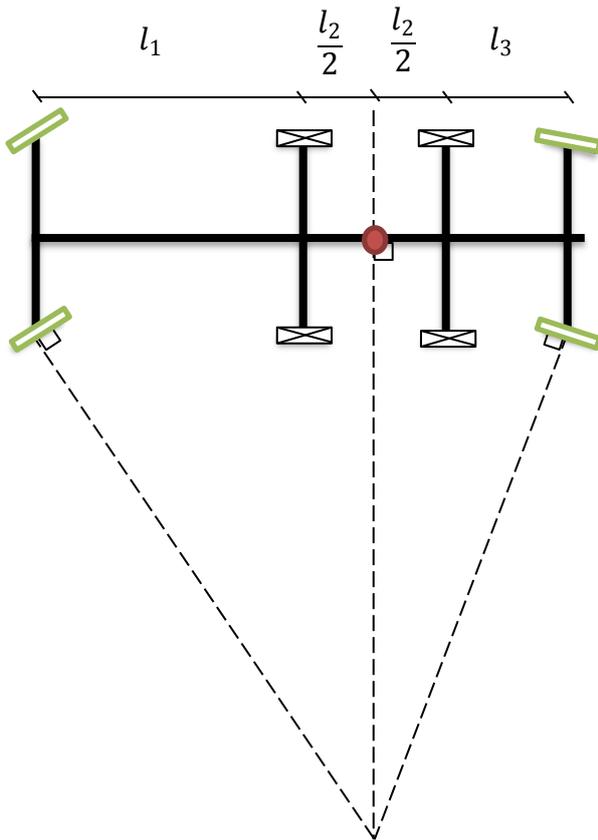


Figure 3. Desirable function. Centre of rotation (red spot) in the middle of the drive axles.

When including the fact that the tag axle offloads the stiff drive axles and also loads the front axle, which lead to more traction (Figure 4) the turning performance compared to the mentioned bogie truck should be considerably improved and tire wear on drive axles decreased.

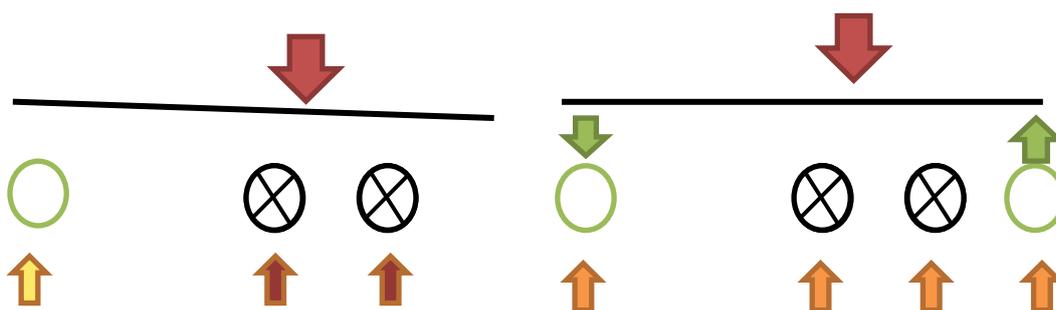


Figure 4. On a tridem truck (right) the tag axle offloads the driving wheels and loads the front wheel. This leads to less tire wear on the driving wheels and more traction for the front wheels.

2.3 Volvo tag axle steering system

2.3.1 Introduction

On the Volvo original steering system the tag axle does not have a sufficient steering angle. Neither in wide, nor in sharp turns (Figure 5) (Appendix A).

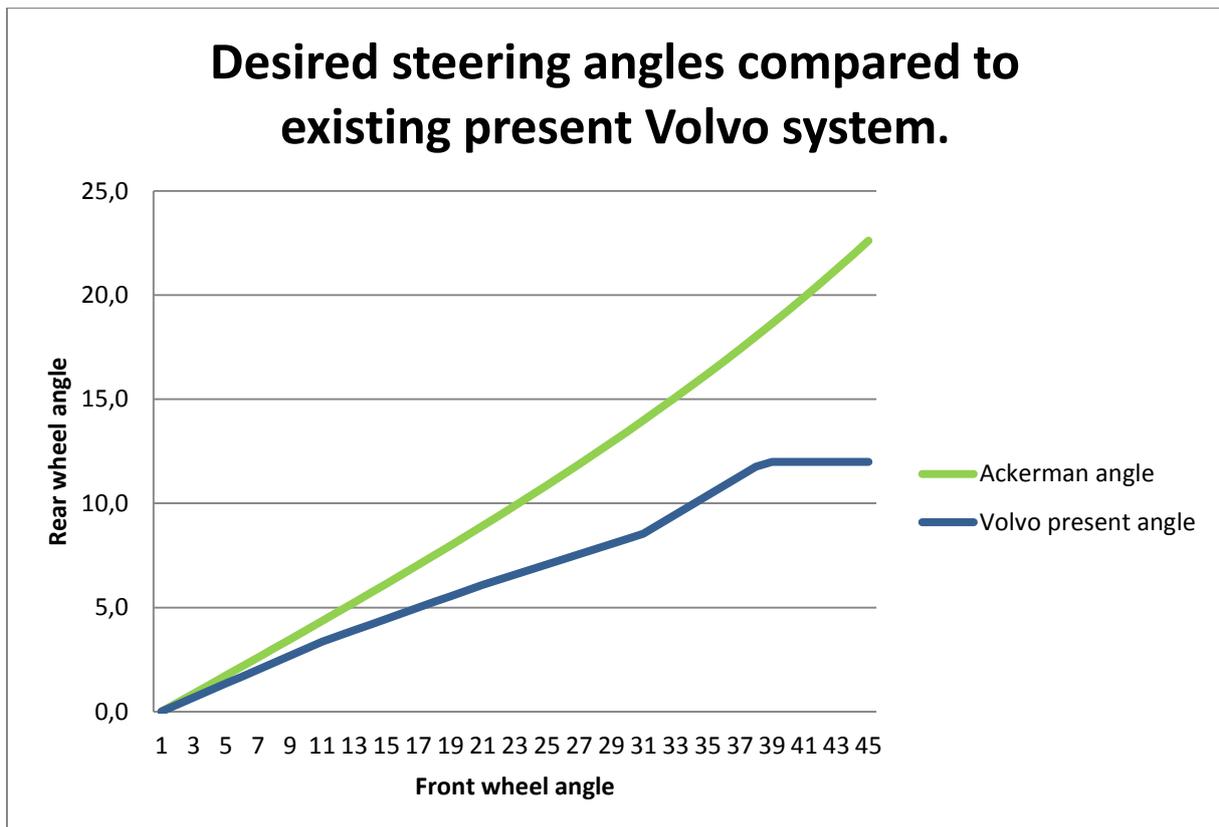


Figure 5. Desired steering angle (Ackerman) compared to in the existing Volvo system. Especially in sharp turns when the Volvo software limits the angle to a maximum of 12° there is a great difference between the desired angle and performed angle. This leads to increased tire wear and decreased turning performance.

The result of the insufficient steering is that the “center of rotation” moves towards the rear of the truck. This leads to an increased turning radius, greater friction forces on the driven wheels and uneven tire wear (Figure 6) (5) (Appendix D).

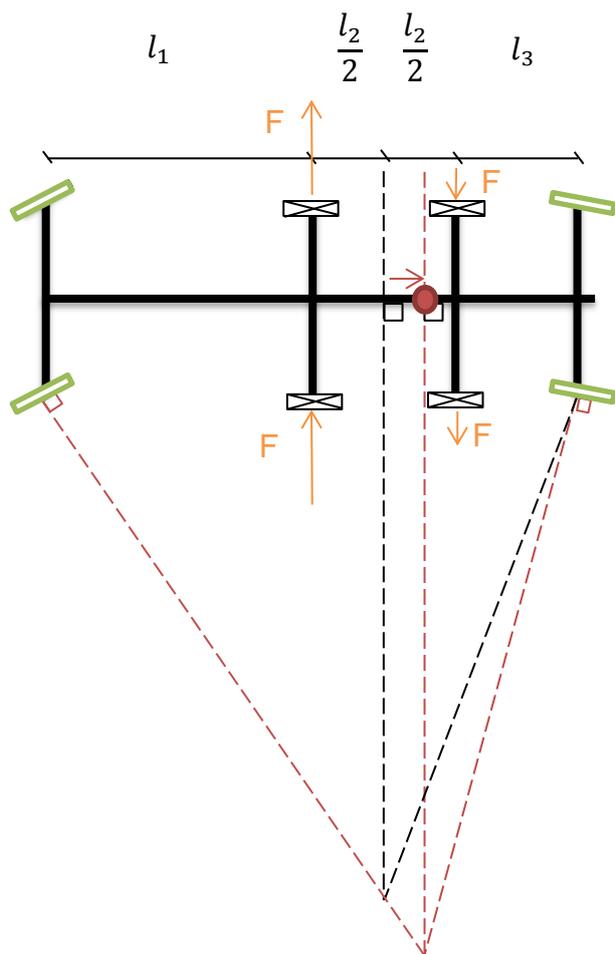


Figure 6. Too a small tag axle turning angle leads to increased turning radius and uneven tire wear. The orange arrows show the friction forces affecting the driven tires.

2.3.2 Original Volvo truck system

The tag axle steer system for Volvo tridem trucks is a “steer by wire”. The system and it’s components originally is developed by the German company ZF Lenksysteme. In the new series of FH introduced 2013, Volvo introduced an own developed software. The new software have the same functions and limitations as the ZF software. The hardware is unchanged. An ECU (Electronic Control Unit) recives information from sensors reading the position of the steering wheel, the steer cylinder steering the tag, vehicle speed and weight information. A PWM (Pulse Width modulated) control signal is then sent to an hydraulic control valve that manouvers the steer cylinder which is connected to the tie rod arm (6).

2.3.2.1 Hardware

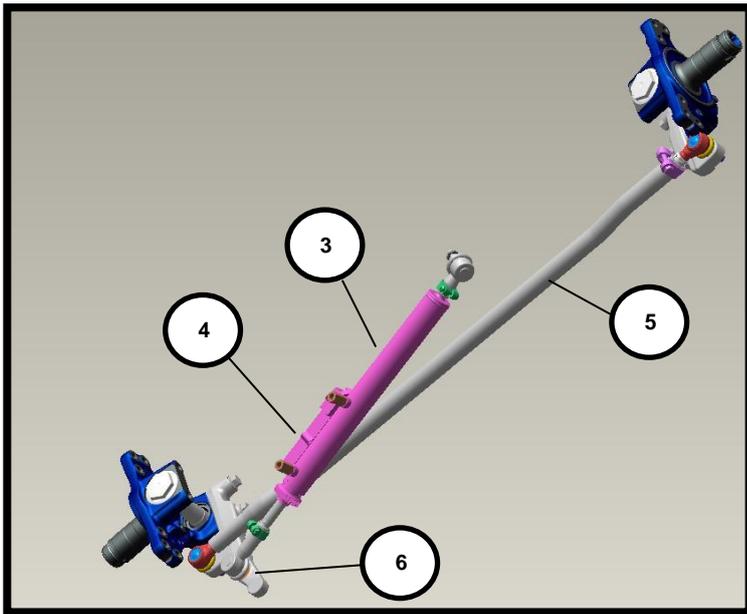


Figure 9. Overview tag axle steer system.

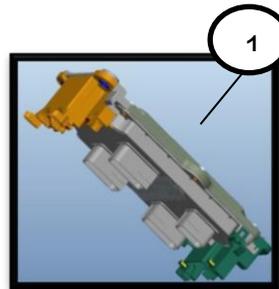


Figure 7. ECU

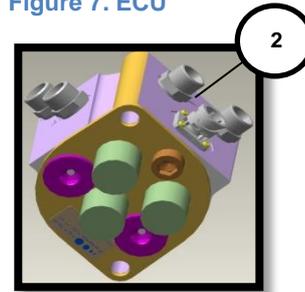


Figure 8. Control valve

The components involved in the tag axle steering system.

1. ECU
2. Hydraulic control valve
3. Steering cylinder
4. Steering cylinder sensor
5. Tie rod
6. Tie rod arms

2.3.2.2 Software

The brain of the tag axle steering system is a centrally located ECU. The primary functions of the program are given below:

- A “target” steer angle based on the vehicle speed and the steering wheel angle is decided.
- The system then controls the hydraulic flow to the steering cylinder by open and close the control valve with a PWM signal. The controller is a PI (Proportional and Integrating) controller.

Due to hardware limitations in terms of maximum stroke of the steering cylinder and sensor range limitations a software steer angle limit of 12° is programmed into the system (7).

When using ECU: s to control critical functions, as in this case, it’s very important to make sure that the system is safe. Failures have to be detected fast, so that the vehicle behaves safely in every possible situation.

Volvo tag axle steering system has two different fail modes, passive fail mode and active fail mode. The passive fail mode “releases” the control of the axle so that the tag axle is just trailing. The tag axle is constructed so that it steers straight forward when no lateral forces are applied to the vehicle, but when turning the wheels follow. In other words, the steering system is disabled and it is possible to keep on driving (8). The passive fail mode is entered when for example a sensor failure on the steer cylinder, a shortcut or a malfunction of the hydraulic control valve is detected. The active fail mode sets the target steer angle to zero and is applied for example when information from the steering wheel sensor is lost (7).

2.3.3 Modified Volvo truck system

As a result of complaints from drivers about tire wear and poor maneuverability of the original rear axle steering, an aftermarket service kit was developed by Volvo market Nordic. The service kit consists of a new tie rod arm. The new tie rod arm has a shorter lever, which gives a greater steering angle compared to the original tie rod arm when turning the steering wheel. Due to the shorter lever the modified solution has around 20% decreased steering power (Appendix C).

The modified Volvo system provides a maximum steering angle of about 15° (Appendix C).

2.4 Scania tag axle steering system

Scania decided to use a pure hydraulic system for their steerable tag axles (Appendix C). The system is similar to a former Volvo system used in trucks before 2005 (2). Basically, a master cylinder in the front of the truck steers the front wheels and distributes a certain rate of the total flow to a slave cylinder steering the rear wheels. In the slave cylinder there is also a centering function included. This centering device is powered by a pressure accumulator and strives to center the cylinder. The centering device’s job is to make the rear axle fix (straight) as long as the steering wheels doesn’t exceed about 5° (9).

According to Scania their rear axle steering system provides a maximum steering angle of 13-14° (Appendix C).

2.5 MAN tag axle steering system

The MAN rear axle steer system is similar to the Scania system. According to MAN they achieve a maximum steering angle of 19°, depending on the wheelbase (10).

3 METHODOLOGY

3.1 Collection of data

To find out how original, service, and competitor's systems work tests and interviews have been conducted and drawings and datasheets have been examined. The tests have been performed on trucks operating in daily service on Volvo demo tracks or in the field. The interviews were conducted with the owners of the trucks, drivers and mechanics at Volvo service centers, hardware developers, software developers and project leaders.

3.1.1 Simulation

To see how the geometry changes, the angles have been analyzed in 3D, the CAD-program Pro Engineer. Pro Engineer has also been used to visualize the new concepts.

3.1.2 Tests

The tests had to be as accurate and simple as possible, partly because they were carried out under varying circumstances and partly because the trucks are used for daily jobs. The tests were therefore designed so they could be performed during breaks or on other times when the driver had time to assist or when the truck was not in use. A test takes about 30 min to perform for the driver and then it takes about 30 min to do measurements and get the data from the tests (Appendix D).

3.1.3 Meetings

A large portion of the data has been collected from meetings with people that have knowledge of the subject. Protocols from the meetings are saved on a database at ÅF.

3.1.4 Documentation

Since much data has been collected throughout the work, it's important to deal with it properly and to categorize the data in order to make it possible to get a good overview of the data during the analysis work. Much of the data collection was done with the help of cameras, GoPro action cameras and standard cameras have been used. During field tests GoPro:s where mounted on the trucks to get the small details as well as to capture data (Appendix G).

To get all the measurements during field tests, forms have been developed to document information such as axle weights and numbers from the physical measurements (Appendix E).

3.2 Specification

In order to make a new system, a specification was created. A specification contains subjects like security, desired function and desired performance.

From material from the tests and meetings, a specification was developed to create an improved system, this is added in order to create a specification. The tests and meetings must be interpreted in an impartial way (Appendix A-F).

3.2.1 Steering

- Improved steering from 12°, as close to 22°-23° as possible
- The system will stop steering when the speed is greater than 38km/h
- The system will ramp from 25km/h to 38km/h
- The system will be as strong as the original rear axle steering
- The system must keep up with the front steering, so when the front wheel is turned to max deflection, the rear wheel must do the same.

3.2.2 Safety

- The design must ensure that the steering system won't turn when the speed is too high
- Some kind of hardware lock for the system when the speed is greater than 38-40 km/h
- Maybe use the existing ABS sensors as a back-up

3.2.3 Modeling

- The system must be very solid in order to avoid malfunction due to weather and harsh environmental conditions.

4 RESULT

4.1 Present solution

The desired steering geometry at low speed is called Ackerman Geometry. Volvo has no software for rear axle steering optimized for tridem trucks. Instead they use the software optimized for bogie trucks with the same wheelbase. The consequence of this is that tridem vehicle tag axles do not steer enough, neither in wide or sharp turns (Figure 10). This leads to poor maneuverability and increased tire wear.

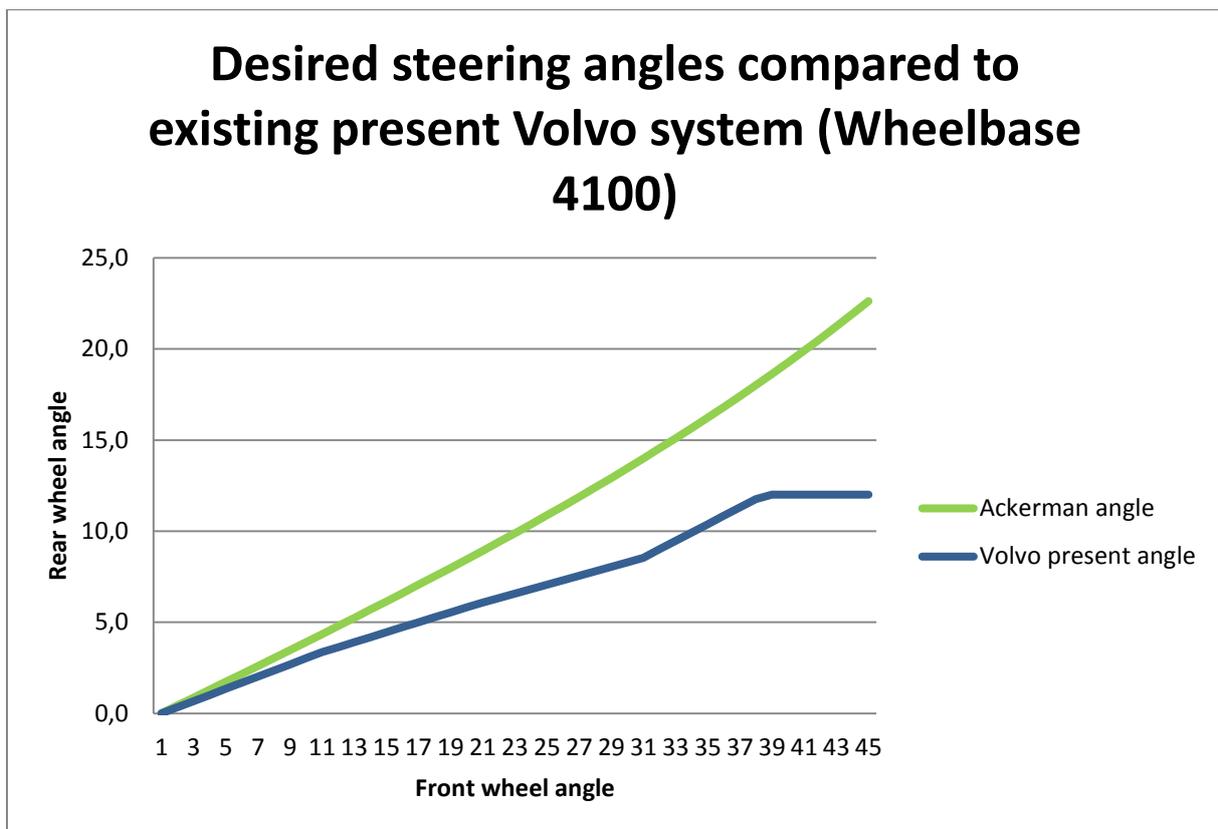


Figure 10. Desired steering angle (Ackerman) compared to the steering angle in the present Volvo system on truck with a wheelbase of 4100 mm. Especially in sharp turns when the Volvo software limits the angle to a maximum of 12° there is a great difference between the desired angle and performed angle. This leads to increased tire wear and decreased turning performance.

4.2 Before increasing steering angles

Due to hardware limitations in terms of maximum stroke of the steer cylinder and sensor range, a software limited steering angle of 12° is programmed into the system. Optimization of steering angles above 12° is because the hardware limits is not a quick fix. However, some improvements can be done with small efforts. Before permitting an increased steering angle on the tag axle, serious precautions concerning safety have to be applied. Safety approach is the main reason for the limits in today's hardware. The biggest concern is that the position sensor fails and sends out false position to the ECU (7). This can, in the worst-case scenario, lead to

max steering in one direction and a very unpleasant experience for the driver or even an accident. To prevent this from happen multiple fail-detect functions are included in the software (Appendix B) and tests have been performed to examine the effects of different kinds of malfunctions. No test allowing the wheels to reach their maximum angle have been performed, it's therefore not known at what angle the wheels loose traction and starts to slip. No accidents caused by rear axle mal function are known.

4.3 Concepts

In this section, improvement concepts for True Ackerman geometry and increased maximum steering angle are presented in order of engagement necessary for realization. An overview of the concepts are shown in Figure 11.

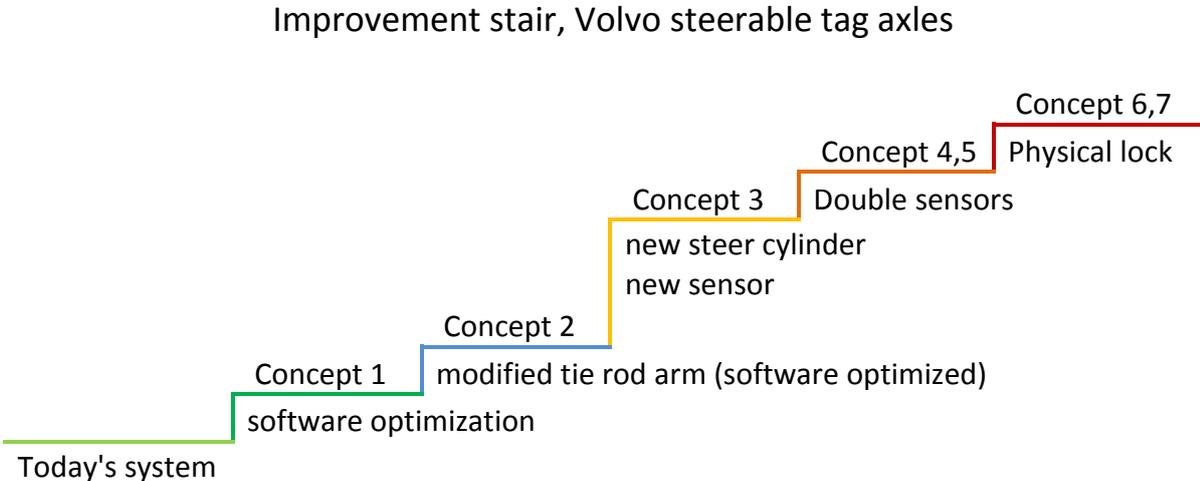


Figure 11. Graph for suggested improvements , Volvo system for steerable tag axles. Improvements are shown in order of engagement necessary to improve.

4.3.1 Concept 1: Software optimization for true Ackerman angles up to 12°

A software update optimizing steering angles up to 12° is easy to implement, very cheap and it will decrease tire ware in wide turns. This software update won't affect any safety aspects. The result of an optimization like this is shown in Figure 12 (Appendix A). This concept is a “quick fix” and can be implemented in production without any further delays.

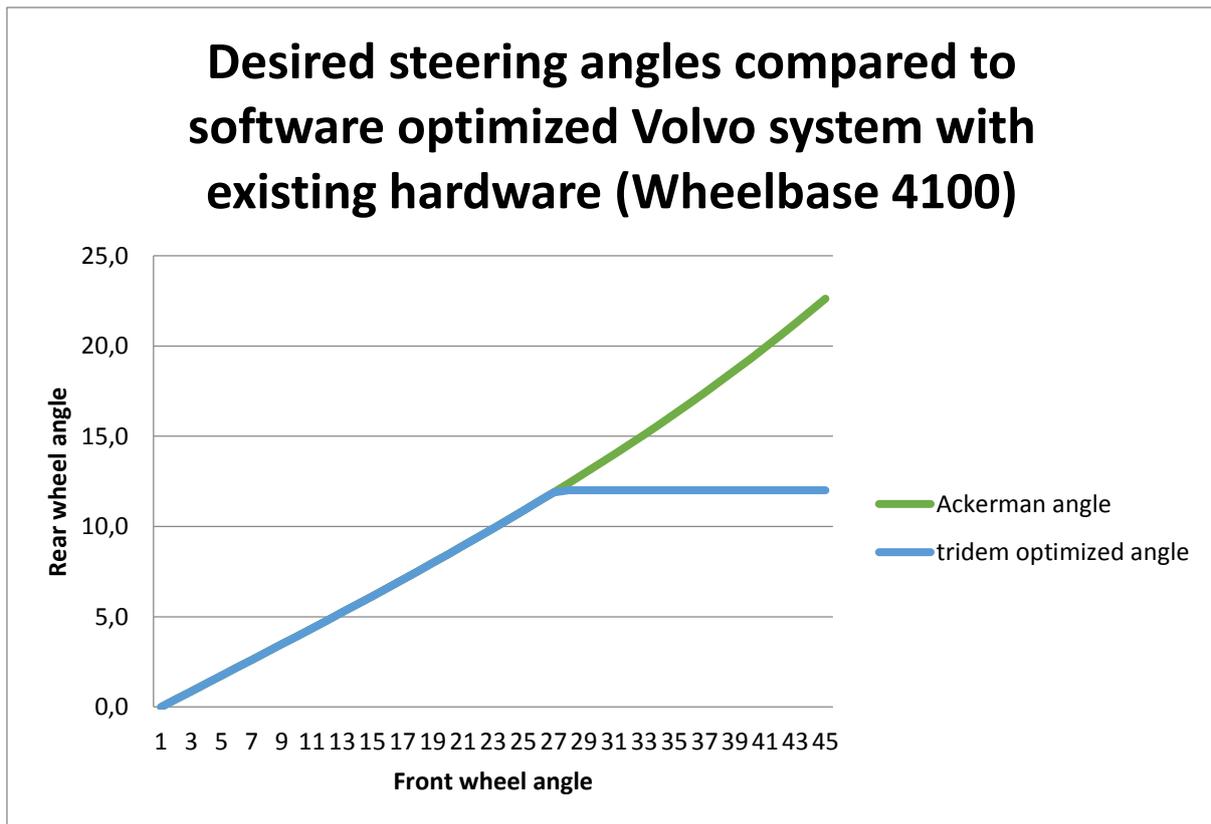


Figure 12. Desired steering angle (Ackerman) compared to software optimized Volvo system with existing hardware. Tire wear is minimized and turning performance maximized until the maximum steering angle of 12° is reached.

4.3.2 Concept 2: Modified tie rod arm for increased steer angle to 15°.

The tie rod arm can be shortened so that a certain movement of the cylinder causes a greater steering angle on the wheels. This solution is already realized as an aftermarket service kit and can be retrofitted in Volvo Service centers. More than 250 vehicles in Nordic countries have installed this kit since 2006 (11). According to drivers the service kit is working very well. Concept 2 is a short term solution ready for production until a long term solution is developed.

The advantage is that the maximum steering angle is increased to about 15° (Appendix B).

There are three main concerns with the existing modified tie rod arm in the service kit.

1. The first is that it's not software optimized according to Ackerman. This can easily be solved and even if not, calculations show that the modified tie rod arm is closer to Ackerman than the original system (Appendix B).
2. The second concern is that the modified tie rod arm, due to the shorter lever, may provide insufficient steering power. The steering power is decreased with 20% compared to the original system and it may affect for example the ability to keep the tag axle steering straight forward when lateral forces are applied in high speed (12). No tests have been performed on this matter. Another thought is that the lifetime of the components can be decreased when loading them more than they are originally designed for.
3. The third important concern is safety when allowing greater steering angles. No tests have been performed to examine the effects of a malfunction with the modified tie rod arm installed.

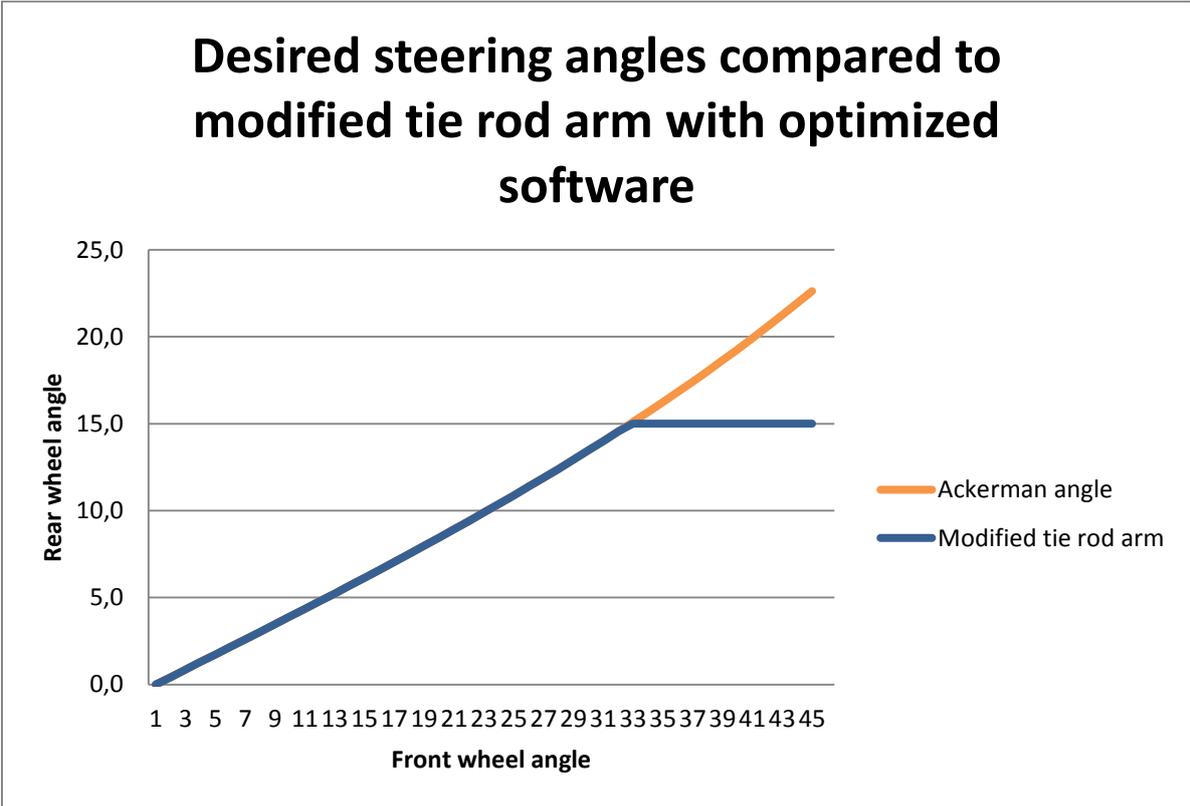


Figure 13. Desired steering angle (Ackerman) compared to software optimized Volvo system with modified tie rod arm. Tire wear is minimized and turning performance maximized until the maximum steering angle of 15° is reached.

4.3.3 Concept 3: New steer cylinder with longer stroke and new position sensor.

A steer cylinder with 60-70% increase of stroke is sufficient for true Ackerman angle in full steering lock if using the original tie rod arm. (Appendix B).



Figure 14. Hydraulic cylinder with integrated position sensor. The picture is picked from manufacturer MTS Sensors webpage (7).

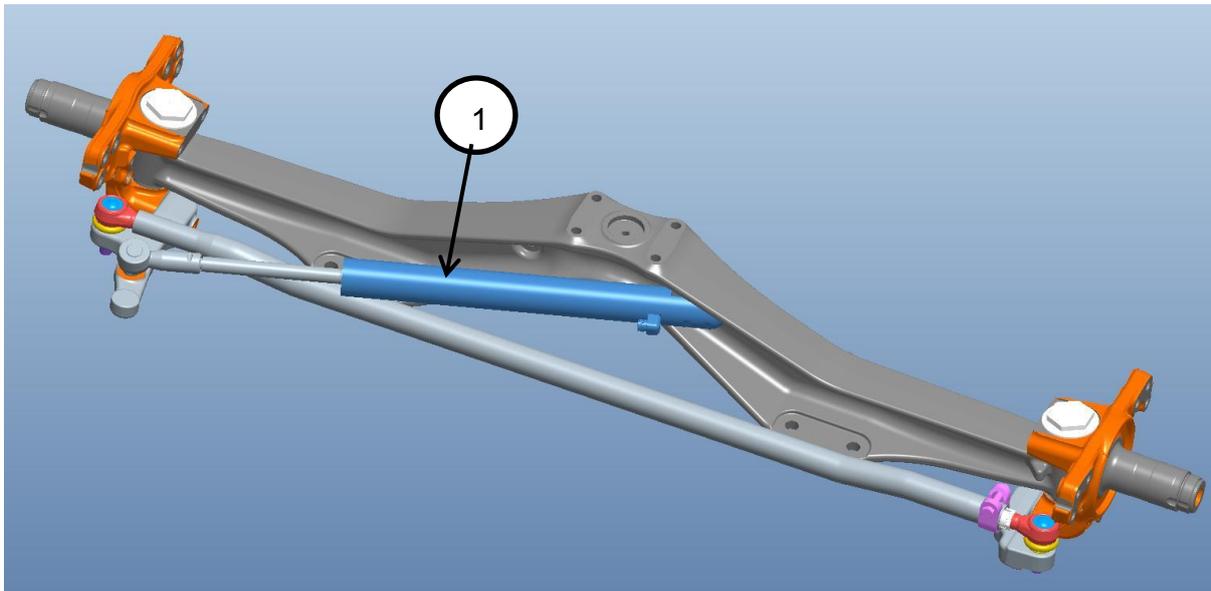


Figure 15. Rear axle steering system with a new steering cylinder 1. This allows a longer stroke and is fitted with a built-in position sensor.

4.3.4 Concept 4: New steer cylinder with longer stroke and kingpin sensor.

The kingpin sensor has no angle limits and is cheaper than the existing linear sensor. The cylinder in today's design has a dead stroke and can be redesigned for a longer stroke.

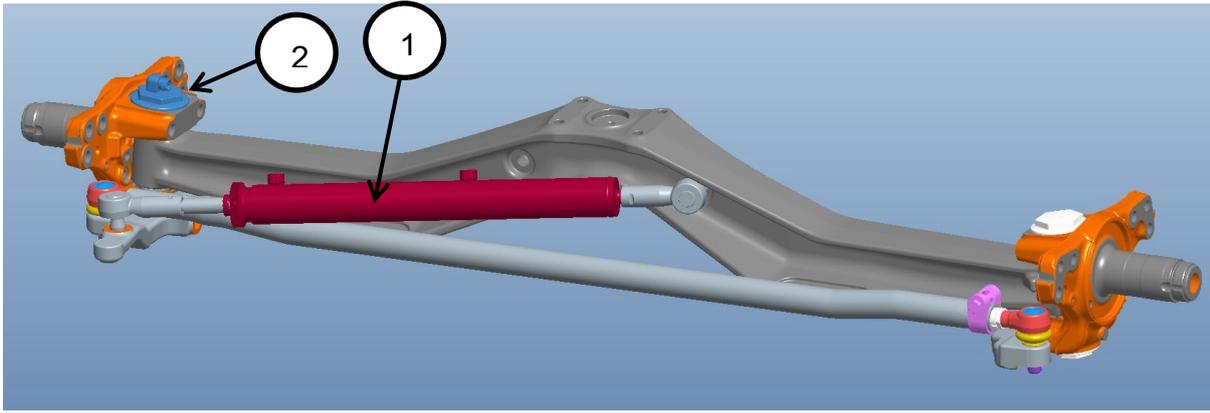


Figure 16. Rear axle steer system with new steering cylinder providing a longer stroke 1. A position sensor is mounted on the kingpin 2.

4.3.5 Concept 5: New steer cylinder with longer stroke and double sensors.

One possibility is to redesign the cylinder like in concept 4 and add a second sensor to cover the full stroke.

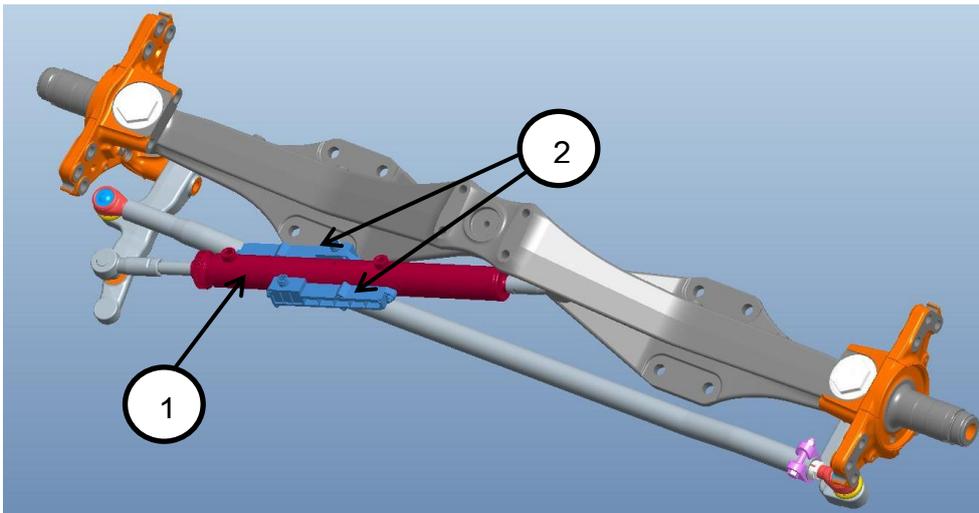


Figure 17. Rear axle steering system with new steering cylinder providing longer stroke 1 and an extra sensor to cover the stroke length 2.

4.3.6 Concept 6: New steer cylinder with longer stroke and hydraulic lock.

For extra safety a hydraulic lock that cuts off the hydraulic flow can be added to the system between the hydraulic control valve and the cylinder.

4.3.7 Concept 7: New steering cylinder with longer stroke and mechanical locking.

A mechanical locking is the absolute safest and robust way to make sure that the tag axle steers straight at speeds exceeding 38km/h. This concept can be combined with all cylinder and sensor concepts. In this concept the cylinder in concept 3 is used.

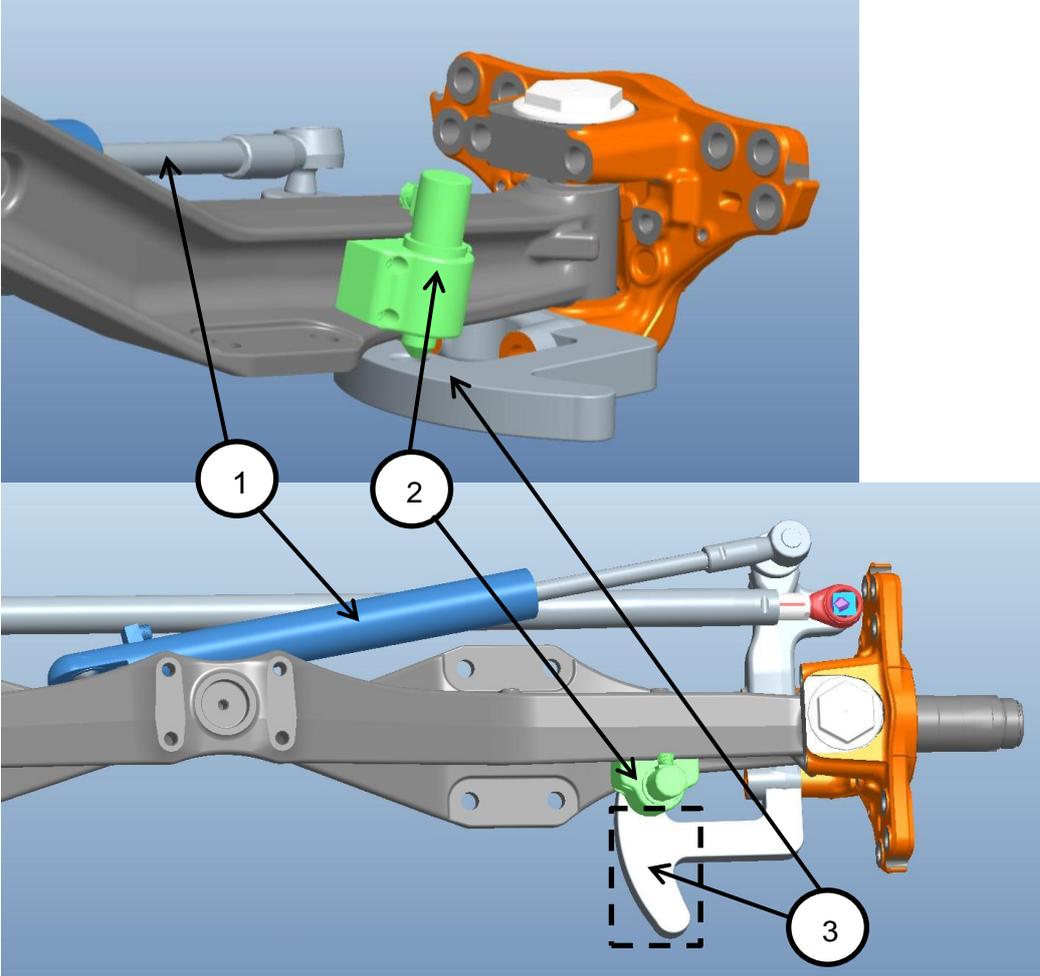


Figure 18. Rear axle steer system with new steer cylinder providing longer stroke 1, a built in position sensor and a mechanical lock 2. The tie rod arm is modified so that it can be locked with the lock mechanism. Surface 3 is a surface where the lock pin can slide and makes sure that the tie rod arm only can be locked in the straight forward position.

5 CONCEPT EVALUATION

To decide which / what concept is good enough to go ahead with such a concept evaluation has been made (15). Importance (Imp.) has been picked from Appendix F.

5.1 Selection Matrix

Selection Criteria	Concepts								
	Imp.	(Reference)	Concept						
		Original	1	2	3	4	5	6	7
Improved steering from 12°	5	0	0	+	+	+	+	0	0
Stop steering >38km/h	4	0	0	0	0	0	0	+	+
Ramp 15km/h -> 38km/h	3	0	0	0	0	0	0	0	0
Strong as the original	3	0	0	-	0	0	0	0	0
Fast as the original	4	0	0	+	0	0	0	0	0
Insurance from failure	5	0	0	0	0	0	0	+	+
Physical lock	4	0	0	0	0	0	0	+	+
Rough enough	5	0	0	0	0	0	0	+	+
Price	3	0	0	0	0	+	-	-	-
Sum +'s		0	0	2	1	2	1	4	4
Sum 0's		9	9	6	7	6	6	4	4
Sum -'s		0	0	1	0	0	1	1	1
Net Score		0	0	1	1	2	0	3	3
Rank		4	4	3	3	2	4	1	1
Continue?		Revise	Combine	Yes	Yes	Yes	No	Combine	Combine

From this selection we can see that Concept 5 will no longer be interesting because of the low net score. All other concepts will be investigated in a concept-scoring matrix. Working on concept 1, 6 and 7 a combination must be done with some other concepts. Concept 1 will be investigated because of low cost to implement.

5.2 Concept-scoring Matrix

		(Reference) Original		Concept 2		Concept 3		Concept 4	
Metric	Imp.	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Improved steering from 12°	5	3	15	4	20	5	25	5	25
Stop steering >38km/h	4	3	12	3	12	3	12	3	12
Ramp 15km/h -> 38km/h	3	3	9	3	9	3	9	3	9
Strong as the original	3	3	9	2	6	3	9	3	9
Fast as the original	4	3	12	4	16	3	12	3	12
Insurance from failure	5	3	15	3	15	3	15	3	15
Rough enough	5	3	15	3	15	3	15	3	15
Price	5	3	15	3	15	3	15	4	20
		REF	102		108		112		117
Rank		4		3		2		1	

Rating	Relative performance
5	Much better than reference
4	Better than reference
3	Same as reference
2	Worse than reference
1	Much worse than reference

From the concept-scoring matrix the concept 3 and 4 became the two best alternatives.

6 CONCLUSION

Volvo rear axle steering system achieves smaller steering angles than desired and what their competitors offer. Especially on tridem trucks with a steered tag axle, this results in poor maneuverability, increased and uneven tire wear. An aftermarket service kit consists of a new tie rod arm is developed by Volvo Market Nordic. The modified tie rod arm is highly appreciated by customers, but not blessed by system owners at Volvo, and is not to be found in Volvo's database.

No evidence that an increased maximum steering angle results in decreased safety was found. No tests with maximum steering angle in high speeds were done. The failure tests performed have instead focused on how quickly the software has to find errors and enter a failure mode. This means that a cylinder with increased stroke but equal cylinder diameter (Concept 3-7) should pass these tests with the same result. A system with the modified tie rod arm (Concept 2) should due to the shorter lever move a little quicker. No accidents caused by rear axle malfunction are known, the system is considered safe.

A number of concepts improving steering geometry have been generated. Concept 1 is a very simple and cheap improvement which update the software in the present system so that the target steering angles calculated by the ECU complies with the Ackerman geometry. This concept does not increase the maximum steering angle but will improve steering in wide turns. This concept is recommended as a short term solution. Concept 3 includes a new steering cylinder with longer stroke and a built in position sensor. This concept allows the, according to Ackerman, maximum desired steering angle ($22,6^\circ$ for the target vehicle in this project). Concepts 3 got high points in the concept evaluation process and are recommended as a long term solution after some testing. Concept 4 won the concept rating and has great potential both according to price and functionality. Concepts 6 & 7 consist of a physical locking mechanism which can take safety to another level. Unfortunately this kind of mechanisms does not exist today and would be expensive.

This project's main contribution to Volvo trucks is that the problem with insufficient rear axle steering now is on the decision makers' agenda. It was known that there is a problem, but it was not a high priority for all of the different stakeholders. Today a strategy to solve the problem, including a short term- and a long term solution is under progress.

6.1.1 Recommendations, further work

- Calculate in what slip angle the tag axle on tridem trucks creates maximum lateral forces (have best traction) and when it loses grip. These calculations can show if there should be any concern to allow greater steering angles.
- Test if an increased maximum steering angle on the rear axle really affects the safety negatively. This can be done by carry out the same test on a truck fitted with concept e.g. Concept 3 as carried out with the original system.
- Create and use tridem optimized software in all new vehicles. (Original and modified tie rod arm). Calculations with target angles are find in Appendix A.
- Develop installation instructions for the modified tie rod arm for the 7,5ton axle.

- Realize concept 3 in a test vehicle. Log data about tire wear and ask for driver experiences when allowing different maximum steering angles in the range 15 - 22,6°.

7 DISCUSSION

Before the project begun, nobody was quite prepared for what had to be investigated in order to introduce an improved rear axle steering and the existing system seemed pretty simple. Because of the size of the project we knew that we had to come up with a good method to obtain information and then create a specification of what we want that the control system should be able to cope.

Later we found out that the system where more advanced than first said, this made that the expected results have not been quite achieved.

The result out of the thesis is a number of concepts were all of them have advantages and disadvantages in different areas. In the beginning the goal was to develop a concrete concept, which could be tested in a field test truck later this year. After a few weeks we realized that the time wasn't enough for this so we focused on creating concept that our successor can continue working with. The thesis has instead led to a good description of that something should be done and in which direction the new solution should have. There have been both practical and safety aspects of what is possible.

One of the best parts of the work has been people's reactions to the project because no one has done such a complete investigation before, the reaction where very positive and it was noticeable that our methods were appreciated. Especially our test documentation with cameras was very important in this matter (Appendix G). We were able to show the effects of the insufficient steering directly on our laptop, which we are sure made difference on meetings with decision makers on Volvo that usually doesn't have the luxury to actually see the problem with their own eyes. Since the reactions have been very positive, we have been able to find out all the relevant information during the project.

What we can tell the successor who will continue with this project is to try to make clear restrictions which are easy to follow. We think it's important to get input from all directions, i.e. of them working with the system or who use it, we recommend our successor to work in the same direction. What is important when taking input from all sides is to be critical and do not believe everything that is said. In our project, we found out some info in the beginning as we gradually been able to prove incorrect. All we have done in this project will be archived and stored on ÅF's database and also in a binder.

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APPENDIX A – Desired steering geometry

The desirable steering geometry on a vehicle is called “Ackerman geometry”. This geometry is when line perpendicular to the vehicle through a point on the truck called the center of rotation coincident with a line perpendicular to every steerable wheel in a single point (figure X). On a tridem truck this geometry is achieved when the trucks center of rotation is placed right between the fixed drive axles (14). This geometry minimizes tire wear and geometrically gives the truck equal turning radius to a bogie truck with the same wheelbase.

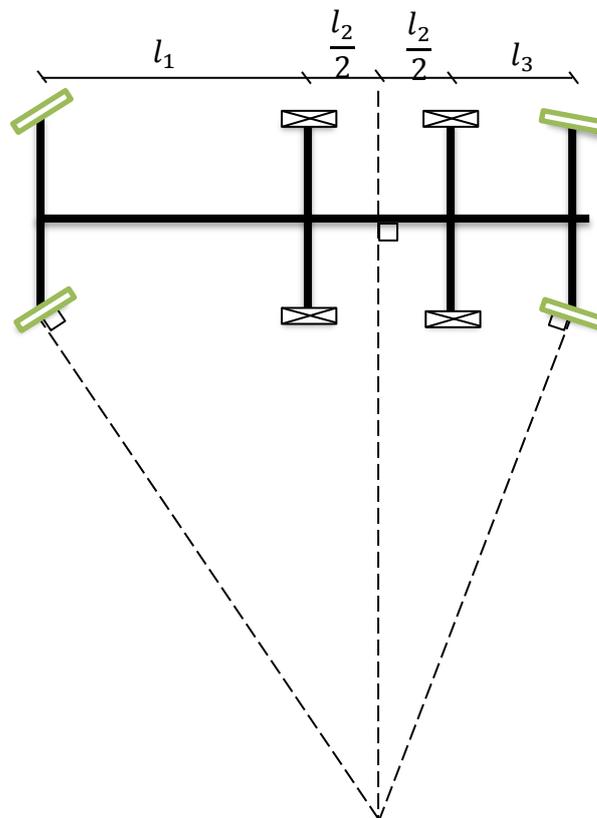


Figure 19. Desirable function. Centre of rotation in the middle of the drive axles.

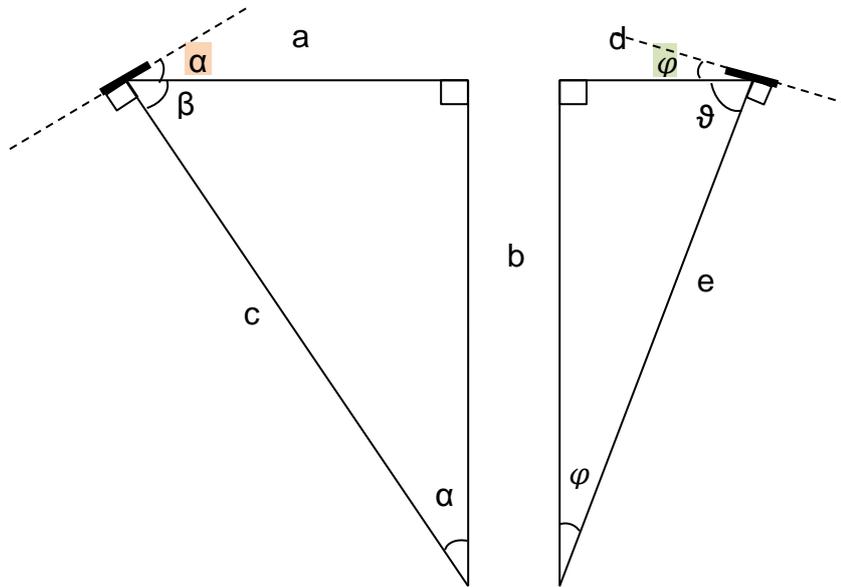


Figure 20. Geometric sketch, desirable steering angle

When the maximum steering angle (front wheel) α is known:

$$\tan \alpha = \frac{a}{b} \rightarrow b = \frac{a}{\tan \alpha}$$

$$\tan \varphi = \frac{d}{b} \rightarrow \varphi = \tan^{-1} \left(\frac{d}{b} \right)$$

$$b = l_1 + \frac{l_2}{2}$$

$$d = l_3 + \frac{l_2}{2}$$

$$\varphi = \tan^{-1} \left(\frac{l_3 + \frac{l_2}{2}}{l_1 + \frac{l_2}{2}} \cdot \tan(\alpha) \right)$$

APPENDIX B – Volvo tag axle steering system

Tag axle steer system for Volvo tridem trucks

The tag axle steer system for Volvo tridem trucks is a “steer by wire”. The system and its components originally are developed by the German company ZF Lenksysteme. In the new series of FH introduced 2013, Volvo introduced a software of their own. The new software have the same functions and limitations as the ZF software. The hardware is not altered. An ECU receives information from sensors reading the position of the steering wheel, the steering cylinder steering the tag, vehicle speed and weight information. A PWM control signal is sent to an hydraulic control valve that maneuvers the steering cylinder that is connected to the tie rod arm.

Hardware

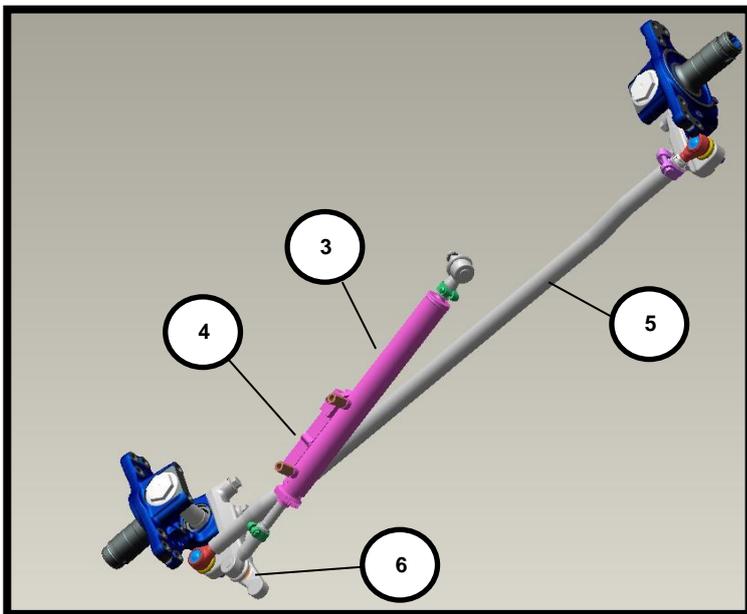


Figure 23. Overview tag axle steer system.

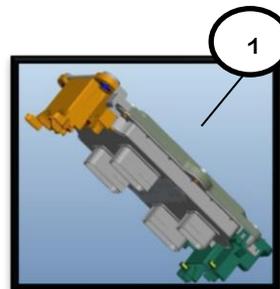


Figure 21. ECU

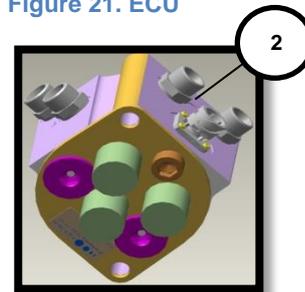


Figure 22. Control valve

The components involved in the tag axle steering system.

1. ECU
2. Hydraulic control valve
3. Steering cylinder
4. Steering cylinder sensor
5. Tie rod
6. Tie rod arms

ECU

The ECU controlling the tag axle steer system is shared with the break system. It communicates with sensors around the truck receiving 4-20mA current. The output of the ECU is a PWM signal controlling the hydraulic valve connected to the steer cylinder.

Hydraulic valve

In the hydraulic valve a PWM control signal from the ECU controls the hydraulic pressure to the steering cylinder.

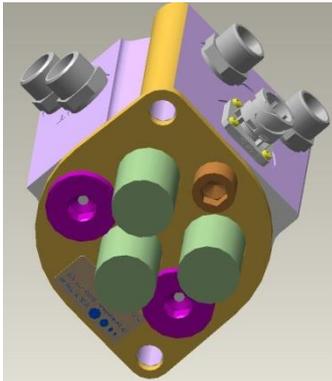


Figure 24. Hydraulic valve.

Steering cylinder

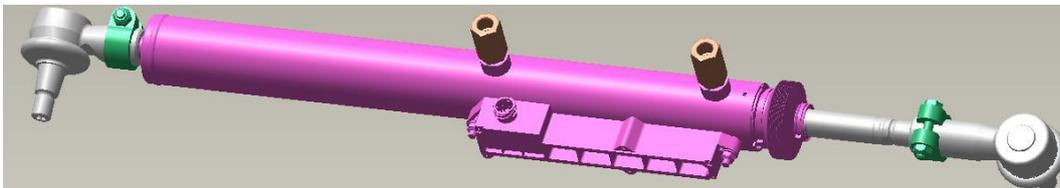


Figure 25. Steering cylinder

To perform greater steering angles the steer cylinder can be modified to achieve greater stroke. In Figure 29 maximum steering angles with different strokes is shown. The result is produced using a dynamic CAD model over the steering system.

Maximum steering angles when extending stroke	
Maximum stroke (mm)	Maximum angle [°] possible
75 (original)	13,5
100	18,2
110	20,2
120	22,2
130	24,3
140	26,2
150	28
160	30

Figure 26. Maximum steering angle possible with different strokes.

Steering cylinder sensor

The steering cylinder sensor is placed on the steering cylinder and it's job is to keep track of the cylinder piston position. The problem is solved with a magnetic sensor that detects the piston position. Depending on the position the sensor induces a voltage in the range of 0,5-4,5v. Two "inverted" signals are transmitted from the sensor.

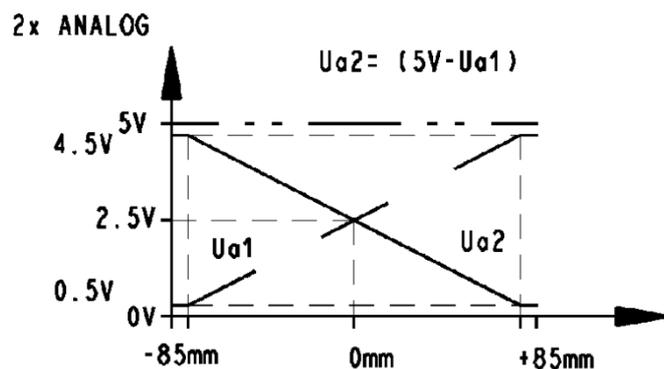


Figure 27. Characteristic for the magnetic sensor placed on the steering cylinder.

Tie rod arm

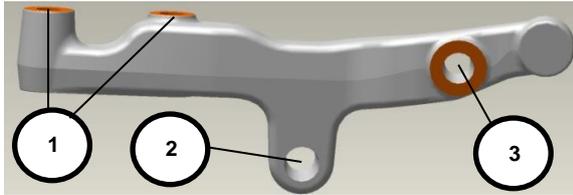


Figure 28. Left wheels tie rod arm on the tag axle. The tie rod arm is mounted in the hub in (1), the steer cylinder is connected in (3), the tie rod connecting right and left wheel in (2).

Software

The brain of the tag axle steering system is a centrally located ECU. The primary functions of the program are given below::

- A “target” steer angle based on the vehicle speed and the steering wheel angle is decided.
- The system then controls the hydraulic flow to the steering cylinder by open and close the control valve with a PWM signal. The controller is a PI controller.

Due to hardware limitations in terms of maximum stroke of the steering cylinder and sensor range limitations a software steer angle limit of 12° is programmed into the system (7).

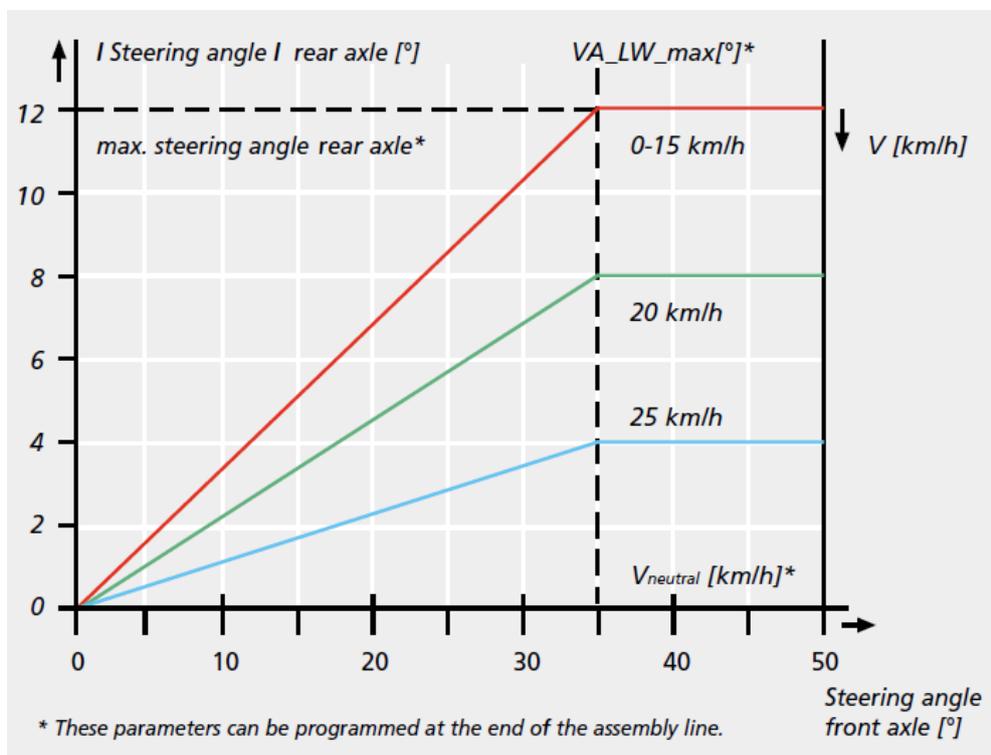


Figure 29. Shows how the target angle is based by vehicle speed and steering wheel angle. (figure, ZF Lenkysteme)

When using ECUs to control critical functions as in this case it's very important to make sure that the system is safe. Failures have to be detected fast, so that the vehicle behaves safely in every possible situation.

Volvo tag axle steering system has two different fail modes, passive fail mode and active fail mode. The passive fail mode "releases" the control of the axle so that the tag axle is just trailing. The tag axle is constructed so that it steers straight forward when no lateral forces are applied to the vehicle, but when turning the wheels follow. In other words, the steering system is disabled and it is possible to keep on driving (8). The passive fail mode is entered when for example a sensor failure on the steer cylinder, a shortcut or a malfunction of the hydraulic control valve is detected. The active fail mode sets the target steer angle to zero and is applied for example when information from the steering wheel sensor is lost (7).

Modified tie rod arm

The modified tie rod arm has a ca20% shorter lever which results in ca20% decreased steering power (figure 32). The measurements are performed in CAD-environment.

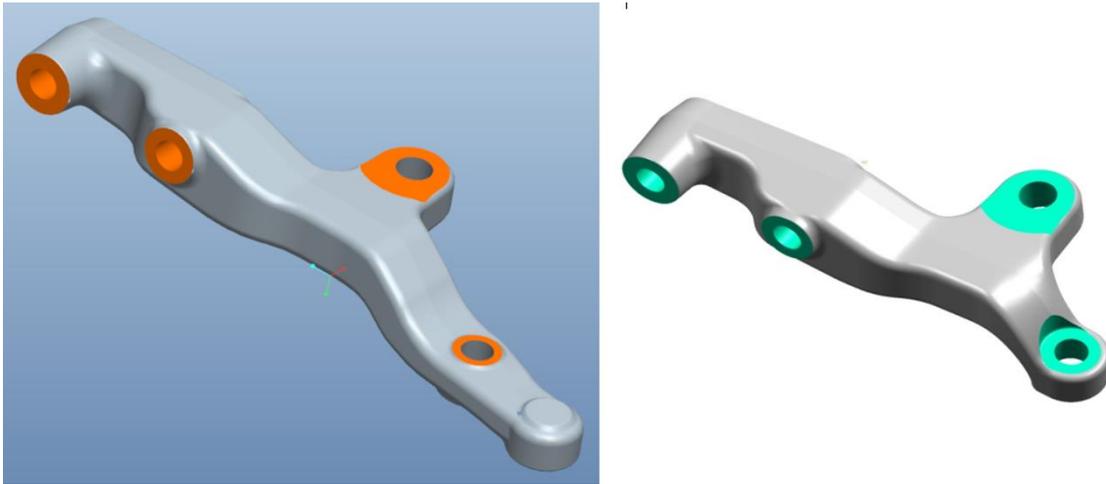


Figure 30. Original (left) and modified (right) tie rod arm.

No documentation about the modified tie rod arm exist in Volvo's database. A CAD-model of the modified tie rod arm was sent from Bharat Forge Kilsta AB, the producer of the component. To examine the steering geometry with the modified tie rod arm a dynamic 3D model with the components of the steering system was assembled and measurements were taken.

Original tie rod arm	
angle [°]	Cylinder movement (from center position)
0	0
1	6
2	11
3	17
4	22
5	28
6	33
7	39
8	44
9	50
10	55
11	61
12	66
13	72
13,5	74

Modified tie rodarm	
angle [°]	Cylinder movement (from center position)
0	0
1	4
2	9
3	13
4	17
5	22
6	26
7	31
8	35
9	39
10	44
11	48
12	52
13	57
14	61
15	65
16	69
17	74

Figure 31. Cylinder movement required for certain steering angles for the tie rod arms.

Following calculations give the difference in steering angle achieved with the original and modified tie rod arm.

$$\text{angle mod. tie rod arm} = \frac{\text{Angle orig. tie rod arm}}{\frac{\text{movement mod. tie rod arm}}{\text{Movement orig. tie rod arm}}}$$

Angle Orig. tie rod arm [°]	Angle mod. Tie rod arm [°]
0	0
1	1,50
2	2,44
3	3,92
4	5,18
5	6,36
6	7,62
7	8,81
8	10,06
9	11,54
10	12,50
11	13,98
12	15,23

Figure 32. Difference in steering angle achieved with the two tie rod arms.

APPENDIX C – Concurrent analysis Scania & MAN

Scania tag axle steering system for tridem trucks



Scania has chosen to use a pure hydraulic system for their steerable tag axles. The System is similar to a former Volvo system used in trucks before 2005 (2). Basically a master cylinder at the front of the truck steers the front wheels and distributes a certain rate of the total flow to a slave cylinder steering the rear wheels. In the slave cylinder there is also a centering function included. This centering device is powered by a pressure accumulator and strives to center the cylinder. The centering device job is to keep the axle in a fixed forward position as long as the steering wheel doesn't exceed about 5° (6).

According to Scania their rear axle steering system provides a maximum steering angle of 13-14° (16).

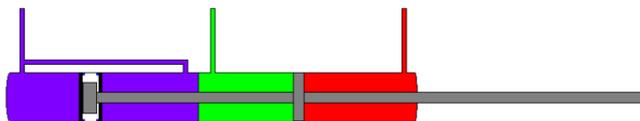


Figure 33. Slave cylinder with centering function. The purple hose is connected to the accumulator and works as a centering device. Green and red areas are controlled by the master cylinder and used for turning.

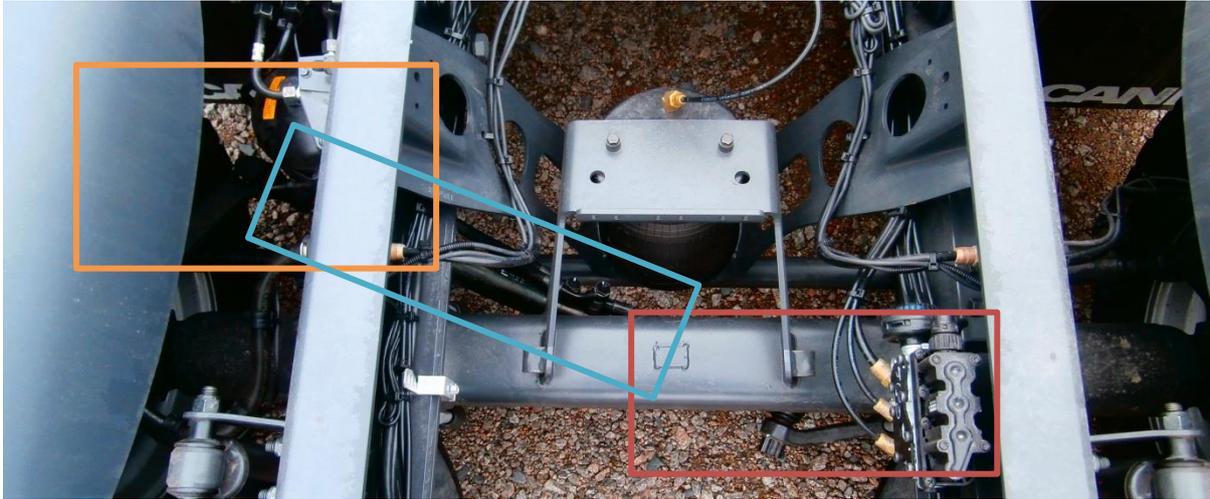


Figure 34. Tag axle steering system for Scania tridem trucks.



Figure 35. Connection steering cylinder - Tie Rod arm.



Figure 36. Cylinder attachment.



Figure 37. Slave cylinder hose connections

Discussion

This system is proven to work well and has previously been used by Volvo. The hydraulic system is known to be one. A negative thing with the system is that it cannot be switched off. The rear axle is always steering, even if the axle is hoisted.

MAN tag axle steering system for tridem trucks



MAN also uses pure hydraulic systems for their steerable tag axles. The steering systems are similar to Scania's. According to MAN they achieve a maximum steering angle of 19° , depending on wheelbase (9).

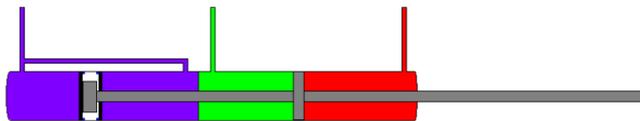


Figure 38. Slave cylinder with centering function. Purple hose is connected to the accumulator and work as a centering device. Green and red areas is controlled by the master cylinder and used for turning.



Figure 39. Steering cylinder

From previous photos we can see that the MAN truck have a larger cylinder rash for the rear axle steering than the original Volvo rear axle steering.

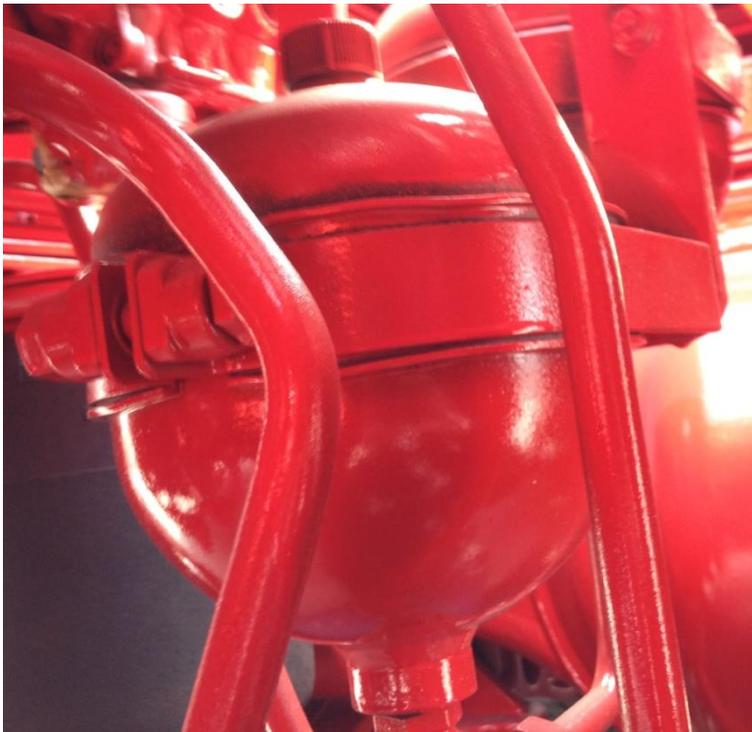


Figure 40. Accumulator

Discussion

This system is proven to work well and has previously been used by Volvo. The hydraulic system is known to be a solid one. A negative thing with the system is that it cannot be switched off. The rear axle is always steering, even if the axle is hoisted.

APPENDIX D – How the measurements were carried out

Turning radius

The turning test was carried out on a smooth plane asphalt surface. It has been discovered that these test rips very much on the tires.



Figure 41. Test circle for turning diameter. Green arrows - front wheel, Red arrows - front drive wheel, Blue arrows - rear drive wheel. Here can also be seen how much tire wear during a test

The driver turned the steering wheel to its limit and drove 360° at low speed. During the turn the position of the tire was marked regularly on the ground. The diameter of the front wheel and the driving wheels was then measured. The test was done twice, the first time maximum load on the tag axle was applied and the second time the tag axle was hoisted. Factors that affects how far up the tag axle can be hoisted are mainly how much the truck is loaded. The tests were carried out with fully loaded trucks. The pressure on the axles is determined by the logic of the air springs, therefore it's not even possible to lift the tag axel so high it won't touch the ground. Weight applied on each axle was documented (Appendix E).

Maximum steering angle



Figure 42. The marks show the maximum steering angle of the tag axle.

To measure the maximum steering angle of the tag axle the driver turned the steering wheel to its limit while the truck was in motion. When the tire was considered reached its limit the truck stopped and measurements of the relation between the tag axle and driving axle was taken. By trigonometric calculations the angles were identified. Measurements were taken on the left and on the right wheel when the truck were first turning to the left and then to the right. A long ruler was used to obtain the steering angle more accurately.

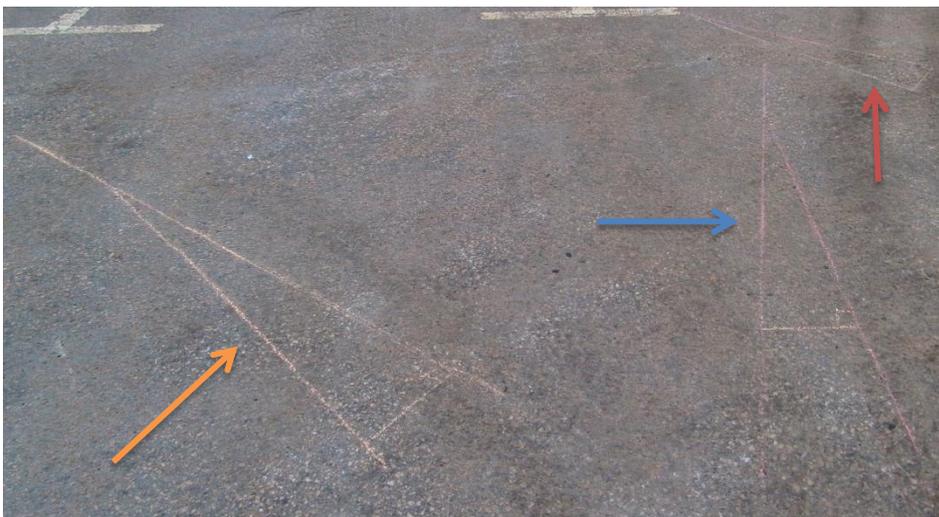


Figure 43. Steer angle measurements. Green arrow - Left turn right wheel, Red arrow - Left turn left wheel, Blue arrow - Right turn, left wheel

Index and information of the trucks being tested

Truck id	NEB319	NAS408	SXA217	-	DOB467	NSH778	DPS029
Mark	Volvo FH	Volvo FH	Volvo FH	Scania	New Volvo FH	Volvo FH	MAN
Tie rod	Original	Original	Modified	Original	Modified	Modified	Original
Wheelbase [mm]	4100	4100	4100	4200	3700	3700	3600
Type	Timber Truck	Timber Truck	Timber Truck	Chassie	Hook	Gravel Truck	Hook
Rear steer angle [°]	12,54	11	13,5	12,55	14,4	12,55	17
Weight [tons]	29,3 - 29,7	31,1	32,1 - 32,6	10,6 - 11	31,6	32-33	13
Turning diameter front wheel [m]	16,33	16,25	15,1	14,78	14,33	13,56	-
Turning diameter front drive wheel [m]	13,53	13,17	12,01	11,33	11,25	10,61	-
Turning diameter rear drive wheel [m]	13,4	12,91	11,78	11,17	10,97	10,43	-
Condition on the road	Dry asphalt with little gravel	Dry asphalt	Dry asphalt	Dry asphalt	Dry asphalt	Dry asphalt with little gravel	Dry asphalt
Other	-	-	-	-	-	Modified front steering	-

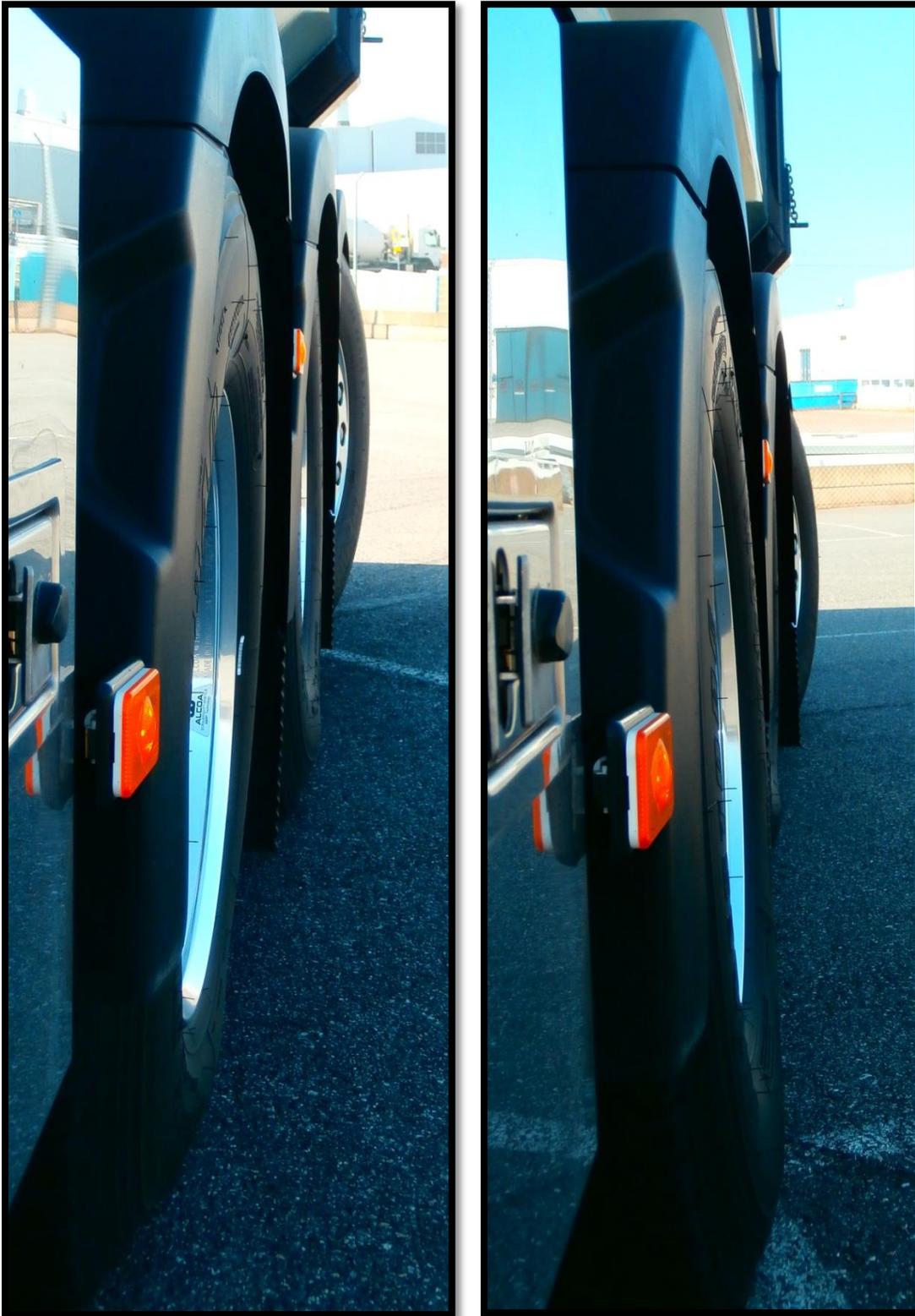


Figure 44 & 45. Here it shows how the forces in the wheels changes when first drive forward and then backward. This can be compared by turning to the left and then to the right.

APPENDIX E – Measurement data

VOLVO ORIGINAL

ST-KRAN 1-5

REGNR: NEB319



Summary

Timber truck with additional height and timber crane.

Volvo name: ST-KRAN 1-5.

8X4*

Total weight 29,3 – 29,7 t

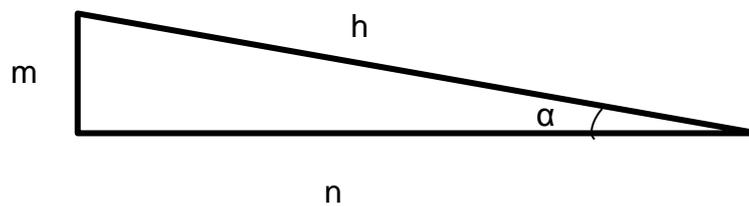
Conditions: Plane dry asphalt surface with a little gravel

Maximal steering angle

	Cosine [°]	Sine [°]	Tangent [°]	Average angle [°]
Right turn, left wheel	11,56	12,39	12,35	12,1
Right turn, Right wheel	10,14	14,29	14,07	12,83
Left turn, left wheel	14,4	13,32	13,38	12,37
Left turn, Right wheel	12,77	12,87	12,87	12,84

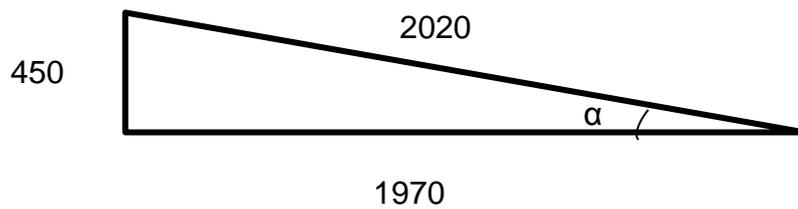
Average of all: 12,54°

Calculations - Maximum steering angle



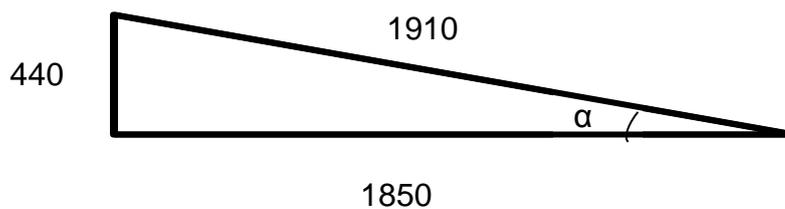
Rear

Left turn, right wheel



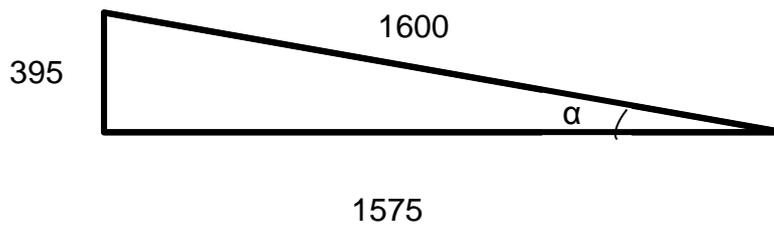
$$\begin{aligned}\cos \alpha_1 &= \frac{n}{h} \Rightarrow \cos^{-1} \frac{1970}{2020} = \alpha_1 = 12,77^\circ \\ \sin \alpha_1 &= \frac{m}{h} \Rightarrow \sin^{-1} \frac{450}{2020} = \alpha_1 = 12,87^\circ \\ \tan \alpha_1 &= \frac{m}{n} \Rightarrow \tan^{-1} \frac{450}{1970} = \alpha_1 = 12,87^\circ \\ \alpha_{1,average} &= \frac{12,77 + 12,87 + 12,87}{3} = 12,84^\circ\end{aligned}$$

Left turn, left wheel



$$\begin{aligned}\cos \alpha_2 &= \frac{n}{h} \Rightarrow \cos^{-1} \frac{1850}{1910} = \alpha_2 = 14,4^\circ \\ \sin \alpha_2 &= \frac{m}{h} \Rightarrow \sin^{-1} \frac{440}{1910} = \alpha_2 = 13,32^\circ \\ \tan \alpha_2 &= \frac{m}{n} \Rightarrow \tan^{-1} \frac{440}{1910} = \alpha_2 = 13,38^\circ \\ \alpha_{2,average} &= \frac{14,4 + 13,32 + 13,38}{3} = 12,37^\circ\end{aligned}$$

Right turn, right wheel



$$\cos \alpha_3 = \frac{n}{h} \Rightarrow \cos^{-1} \frac{1575}{1600} = \alpha_3 = 10,14^\circ$$

$$\sin \alpha_3 = \frac{m}{h} \Rightarrow \sin^{-1} \frac{395}{1600} = \alpha_3 = 14,29^\circ$$

$$\tan \alpha_3 = \frac{m}{n} \Rightarrow \tan^{-1} \frac{395}{1575} = \alpha_3 = 14,07^\circ$$

$$\alpha_{3,average} = \frac{10,14 + 14,29 + 14,07}{3} = 12,83^\circ$$

Right turn, left wheel



$$\cos \alpha_4 = \frac{n}{h} \Rightarrow \cos^{-1} \frac{1725}{1690} = \alpha_4 = 11,56^\circ$$

$$\sin \alpha_4 = \frac{m}{h} \Rightarrow \sin^{-1} \frac{370}{1690} = \alpha_4 = 12,39^\circ$$

$$\tan \alpha_4 = \frac{m}{n} \Rightarrow \tan^{-1} \frac{370}{1690} = \alpha_4 = 12,35^\circ$$

$$\alpha_{4,average} = \frac{11,56 + 12,39 + 12,35}{3} = 12,1^\circ$$

	Average angle [°]
Left turn, right wheel	12,84
Left turn, left wheel	12,37
Right turn, right wheel	12,83
Right turn, left wheel	12,1

Average of all: 12,54°

TURNING RADIUS

Turning diameter

Wheelbase:

	(maximal) wheelbase [mm]
1-2	4100
2-3	1370
3-4	1380

Wheel dimensions

Axle	Wheel diameter (tire + rim) [mm]
1	1072
2	1013
3	1013
4	1072

Test 1: tag axle full load

Weight: [tons]

- Total 29,7
- Tagaxle 6,6
- Front wheel 7,7
- Front drivingwheel 7,8
- Rear drivingwheel 7,7

	Measurement 1 [m]	Measurement 2 [m]	Average [m]
Turn diameter front wheel	16,45	16,20	16,33
Turn diameter front driving wheel	13,80	13,25	13,53
Turn diameter rear driving wheel	13,69	13,10	13,40

Test 2: tag axle minimum load. (Still touching ground)

Weight: [tons]

- Total 29,7
- Tagaxle 3,2
- Front wheel 6,4
- Front driving wheel 10
- Rear driving wheel 10,1

	Measurement 1 [m]	Measurement 2 [m]	Average [m]
Turn diameter front wheel	16,98	16,94	16,96
Turn diameter front driving wheel	14,28	14,02	14,15
Turn diameter rear driving wheel	14,10	13,90	14,00

Test 3: tag axle raised from ground. (After removal of timber crane)

Weight: [tons]

- Total 25,9
- Tagaxle 0
- Front wheel 6,7
- Front driving wheel 9,7
- Rear driving wheel 9,5

	Measurement 1 [m]	Measurement 2 [m]	Average [m]
Turn diameter front wheel	15,80	15,82	15,81
Turn diameter front driving wheel	13,21	13,36	13,29
Turn diameter rear driving wheel	13,05	13,23	13,14

3/4-13

Volvo
OriginalProvtagningsmallLastbil:

Timmerbil ST-KRAN 1-5

Regnummer: NEB314	Chassinummer:			
	Total vikt:		29,3 - 29,7	
Test 1	Beskrivning av inställning av tagaxel			
	Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	16,45	16,20	16,33	6,4
Axel 2	13,80	13,25	13,53	10,0
Axel 3	13,69	13,10	13,4	10,1
Axel 4				3,2

Test 2	Beskrivning av inställning av tagaxel			
	Uppre (Nästam)			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	16,98	16,94	16,96	6,2
Axel 2	14,28	14,02	14,15	10,1
Axel 3	14,10	13,90	14	10,6
Axel 4				2,6

Test 3	Beskrivning av inställning av tagaxel			
	Uppre - Ny total vikt: 25,9 (KRAN BORTMONTERAD)			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	15,80	15,82	15,81	6,7
Axel 2	13,21	13,36	13,29	9,7
Axel 3	13,05	13,23	13,14	9,5
Axel 4				0

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2				
Axel 3				
Axel 4				

Max vinkel tagaxel

Högersväng	Vänster bak			Vänster fram		
Hypo. [cm]	172,5			/		
Närl. katet [cm]	169					
Mots. katet [cm]	37					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	11,56	12,39	12,35			
Medelvinkel [°]						
	Höger bak			Höger fram		
Hypo. [cm]	160			/		
Närl. katet [cm]	157,5					
Mots. katet [cm]	39,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	10,14	14,29	14,07			
Medelvinkel [°]						
Vänstersväng	Vänster bak			Vänster fram		
Hypo. [cm]	191			/		
Närl. katet [cm]	185					
Mots. katet [cm]	44					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	14,4	13,32	13,38			
Medelvinkel [°]						
	Höger bak			Höger fram		
Hypo. [cm]	207			/		
Närl. katet [cm]	197					
Mots. katet [cm]	45					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	12,77	12,87	12,87			
Medelvinkel [°]						

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	4100	1370	1380

	Tagaxel	Framaxel
Total Medelvinkel [°]	12,54	/

Rådande underlag	Torr asfalt, lite grus
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SCANIA

CHASSISNR: 02084541



Summary

Chassis

8X4*

Total weight 10,6 – 11,1 tons

Conditions: Plane dry asphalt surface with a little gravel

Steers all by hydraulics

11/4-13

Provtagningsmall

Lastbil: *

Scania Chassie

Regnummer:		Chassinummer:	02084541	
Art.nr. Ch	426 858	Total vikt:	10,6-11	
Test 1	Beskrivning av inställning av tagaxel			
	Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1 Vit	14,58	14,98	14,78	5,4
Axel 2 Blå	11,18	11,48	11,33	2,7
Axel 3 grön	11,03	11,31	11,17	1,7
Axel 4				1,3

Test 2	Beskrivning av inställning av tagaxel			
	Uppre			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1 Blå	14,06	14,16	14,11	5,0
Axel 2	10,68	10,87	10,78	2,8
Axel 3	10,57	10,77	10,67	3,0
Axel 4				0

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1				
Axel 2				
Axel 3				
Axel 4				

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1				
Axel 2				
Axel 3				
Axel 4				

Max vinkel tagaxelHögersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	123					
Närl. katet [cm]	119					
Mots. katet [cm]	28					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	14,7	13,2	13,2			
Medelvinkel [°]			13,7			
	Höger bak			Höger fram		
Hypo. [cm]	160					
Närl. katet [cm]	157					
Mots. katet [cm]	30					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	11,1	10,8	10,8			
Medelvinkel [°]			10,9			

Vänstersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	155			100		
Närl. katet [cm]	151			68		
Mots. katet [cm]	34			70		
	cos	sin	tan	cos	sin	tan
Vinkel [°]	13,0	12,7	12,7	47,2	44,43	45,83
Medelvinkel [°]			12,8			45,83
	Höger bak			Höger fram		
Hypo. [cm]	134					
Närl. katet [cm]	130					
Mots. katet [cm]	28					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	14,0	12,2	12,2			
Medelvinkel [°]			12,8			

Hjulbas

Axel [mm]	1 - 2	2 - 3	3 - 4
	4100	1350	1300

	Tagaxel	Framaxel
Total Medelvinkel [°]	12,55	45,83

Rådande underlag	Torr asfalt, lite grus
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VOLVO SERVICE LÖSNING

REGNR: NSH778

Summary

Gravel truck with modification on steerable tag axle

The front axle has been modified as well

8X4*

Total weight 32-33 t

Conditions: Plane dry asphalt surface with a little gravel

11/4-13

Volvo
Service lösningProvtagningsmallLastbil:

Grusbil, blad fjädring

Regnummer: NSH 778	Chassinummer:	
	Total vikt:	32-33

Test 1	Beskrivning av inställning av tagaxel			
	Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	13,53	13,58	13,56	/
Axel 2	10,62	10,60	10,61	
Axel 3	10,42	10,44	10,43	
Axel 4				

Test 2	Beskrivning av inställning av tagaxel			
	Uppre (Nästom)			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	14,24	14,13	14,2	/
Axel 2	11,60	11,49	11,55	
Axel 3	11,45	11,29	11,37	
Axel 4				

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Max vinkel tagaxel

Högersväng	Vänster bak			Vänster fram		
Hypo. [cm]	/			/		
Närl. katet [cm]	/			/		
Mots. katet [cm]	/			/		
	cos	sin	tan	cos	sin	tan
Vinkel [°]						
Medelvinkel [°]						
	Höger bak			Höger fram		
Hypo. [cm]	/			/		
Närl. katet [cm]	/			/		
Mots. katet [cm]	/			/		
	cos	sin	tan	cos	sin	tan
Vinkel [°]						
Medelvinkel [°]						
Vänstersväng	Vänster bak			Vänster fram		
Hypo. [cm]	148			/		
Närl. katet [cm]	142			/		
Mots. katet [cm]	35,5			/		
	cos	sin	tan	cos	sin	tan
Vinkel [°]	16,37	13,88	14,04			
Medelvinkel [°]			14,76			
	Höger bak			Höger fram		
Hypo. [cm]	152			/		
Närl. katet [cm]	144			/		
Mots. katet [cm]	42			/		
	cos	sin	tan	cos	sin	tan
Vinkel [°]	18,67	16,04	16,26			
Medelvinkel [°]			16,99			

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	3700	1370	1380

	Tagaxel	Framaxel
Total Medelvinkel [°]	15,88	/

Rådande underlag	Torr asfalt, lite grus
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MAN

REGNR: DPS029



Summary

Chassis

8X4*

Total weight 13,8 tons

Conditions: Plane dry asphalt surface with a little gravel

Steers all by hydraulics

22/4-13

ProvtagningsmallLastbil:

MAN, Försädd med lyftdragkrok

Regnummer:	DPS029	Chassinummer:	
		Total vikt:	13 ton

Test 1	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 2	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Max vinkel tagaxelHögersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	122			/		
Närl. katet [cm]	110,5					
Mots. katet [cm]	35,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	25,1	17	18			
Medelvinkel [°]	20					
	Höger bak			Höger fram		
Hypo. [cm]	150			/		
Närl. katet [cm]	143					
Mots. katet [cm]	51					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	18	20	20			
Medelvinkel [°]	19					

Vänstersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	166,5			168,5		
Närl. katet [cm]	161			124		
Mots. katet [cm]	50			116		
	cos	sin	tan	cos	sin	tan
Vinkel [°]	15	17	17	42,6	43,5	43,1
Medelvinkel [°]	16					43
	Höger bak			Höger fram		
Hypo. [cm]	142			166		
Närl. katet [cm]	139			143		
Mots. katet [cm]	33			83,5		
	cos	sin	tan	cos	sin	tan
Vinkel [°]	12	13	13	30,5	30,2	30,3
Medelvinkel [°]	13					30,3

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	3600	1350	1450

	Tagaxel	Framaxel
Total Medelvinkel [°]	17	37

Rådande underlag	Torr, asfalt
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VOLVO SEVICELÖSNING

REGNR: SXA217



Summary

Timber truck with additional height and timber crane.

Volvo name: ST-KRAN 1-1.

8X4*

Total weight 32,6 t

Conditions: Plane dry asphalt surface

2/5-13

Volvo
Service lösningProvtagningsmallLastbil:

Timmerbil ST-KRAN 1-1

Regnummer:	SXA 217	Chassinummer:		
		Total vikt:	32,1-32,6	
Test 1	Beskrivning av inställning av tagaxel			
	Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	15,10	15,10	15,10	8,8
Axel 2	12,02	12,00	12,01	} 23,3
Axel 3	11,79	11,76	11,78	
Axel 4				

Test 2	Beskrivning av inställning av tagaxel			
	Uppe (Nästan)			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	15,84	15,65	15,77	6,3
Axel 2	12,90	12,69	12,80	} 26,3
Axel 3	12,66	12,46	12,56	
Axel 4				

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Max vinkel tagaxelHögersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	144,5			/		
Närl. katet [cm]	140,5					
Mots. katet [cm]	34,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	13,5	13,8	13,8			
Medelvinkel [°]			13,7	/		
	Höger bak			Höger fram		
Hypo. [cm]	120			/		
Närl. katet [cm]	117					
Mots. katet [cm]	28					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	12,8	13,5	13,5			
Medelvinkel [°]			13,3	/		

Vänstersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	163,5					
Närl. katet [cm]	159					
Mots. katet [cm]	36,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	13,5	12,9	12,9			
Medelvinkel [°]			13,1			
	Höger bak			Höger fram		
Hypo. [cm]	136,5					
Närl. katet [cm]	132,5					
Mots. katet [cm]	33					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	13,9	14,0	14,0			
Medelvinkel [°]			14,0			

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	4100	1370	1380

	Tagaxel	Framaxel
Total Medelvinkel [°]	13,5	/

Rådande underlag	Torr asfalt
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VOLVO SERVICELÖSNING

REGNR: DOB467



Summary

Gravel Truck with modification on steerable tag axle

8X4*

Total weight 31,6 t

Conditions: Plane dry asphalt surface

7/5-13

ProvtagningsmålLastbil: Ny FH med service lösning

Regnummer:	DOB 467	Chassinummer:		
		Total vikt:	31,6	
Test 1	Beskrivning av inställning av tagaxel Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	14,43	14,23	14,33	8,2
Axel 2	11,35	11,15	11,25	} 23,4
Axel 3	11,06	10,88	10,97	
Axel 4				

Test 2	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2	/	/		/
Axel 3	/	/		/
Axel 4	/	/		/

Max vinkel tagaxelHögersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	176			/		
Närl. katet [cm]	170,5					
Mots. katet [cm]	45					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	14,4	15,8	14,8			
Medelvinkel [°]				14,7		
	Höger bak			Höger fram		
Hypo. [cm]	146,5			/		
Närl. katet [cm]	140,5					
Mots. katet [cm]	41					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	16,5	16,3	16,3			
Medelvinkel [°]				16,4		

Vänstersväng

	Vänster bak			Vänster fram		
Hypo. [cm]	168,5			/		
Närl. katet [cm]	163,5					
Mots. katet [cm]	41					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	14,0	14,1	14,1			
Medelvinkel [°]				14,1		
	Höger bak			Höger fram		
Hypo. [cm]	193,5			/		
Närl. katet [cm]	189					
Mots. katet [cm]	41					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	12,4	12,2	12,2			
Medelvinkel [°]				12,3		

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	3700	1370	1380

	Tagaxel	Framaxel
Total Medelvinkel [°]	14,4	/

Rådande underlag	torr asfalt
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VOLVO ORIGINAL

REGNR: NAS408



Summary

Timber truck with additional height and timber crane.

Volvo name: ST-KRAN 1-4.

8X4*

Total weight 31,1 t

Conditions: Plane dry asphalt surface

16/5-13

Volvo
OriginalProvtagningsmallLastbil:

Timmerbil ST KRAN 1-4

Regnummer: NAS 408	Chassinummer:			
	Total vikt:		31,1	
Test 1	Beskrivning av inställning av tagaxel			
	Nere			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	16,25	16,24	16,25	8,3
Axel 2	13,17	13,17	13,17	7,9
Axel 3	12,90	12,91	12,91	7,7
Axel 4				7,3

Test 2	Beskrivning av inställning av tagaxel			
	Uppre (Nästare)			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	16,45	16,39	16,42	6,0
Axel 2	13,67	13,68	13,68	12,3
Axel 3	13,45	13,45	13,45	12,3
Axel 4				0,4

Test 3	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2				
Axel 3				
Axel 4				

Test 4	Beskrivning av inställning av tagaxel			
	Diameter 1 [m]	Diameter 2 [m]	Med.	Vikt på axel [ton]
Axel 1	/	/		/
Axel 2				
Axel 3				
Axel 4				

Max vinkel tagaxel

<u>Högersväng</u>	Vänster bak			Vänster fram		
Hypo. [cm]	162,5			/		
Närl. katet [cm]	159					
Mots. katet [cm]	31,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	11,9	11,2	11,2			
Medelvinkel [°]			11,4			
	Höger bak			Höger fram		
Hypo. [cm]	160,5			/		
Närl. katet [cm]	157,5					
Mots. katet [cm]	32,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	11,1	11,7	11,4			
Medelvinkel [°]			11,4			
<u>Vänstersväng</u>	Vänster bak			Vänster fram		
Hypo. [cm]	157,5			/		
Närl. katet [cm]	155					
Mots. katet [cm]	32,5					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	10,2	11,5	11,5			
Medelvinkel [°]			11,1			
	Höger bak			Höger fram		
Hypo. [cm]	146,5			/		
Närl. katet [cm]	144					
Mots. katet [cm]	24					
	cos	sin	tan	cos	sin	tan
Vinkel [°]	10,6	9,5	9,5			
Medelvinkel [°]			9,9			

Hjulbas

Axel	1 - 2	2 - 3	3 - 4
	4100	1370	1380

	Tagaxel	Framaxel
Total Medelvinkel [°]	11,0	/

Rådande underlag	Torr asfalt
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APPENDIX F – Specification

ÅF/VOLVO	Document	Specification				
	Project	Bachelor Thesis				
Issuers: Olof Bengtsson and Martin Holmgren		Created: 21 may 2013				
	Subject: Tridem timber truck 4100mm wheel base with tag axle	Modified:				
	Criteria	Target	D/W	Weight	Verification Method	Referens (Specifier)
1.	Functional					
	1.2	Improved steering from 12°, as close to 22°-23° as possible	D/W	5	Teoretical/practical maesurments	
	1.3	The system will stop steering when the speed is greater than 38km/h	D/W	4	Tests	Volvo Trucks Corporation
	1.4	The system will ramp from 25km/h to 38km/h	W	3	Tests	Volvo Trucks Corporation
2.	Performance					
	2.1	The system will be as strong as the original rear axle steering	W	3	Teoretical measurments and tests	
	2.2	The system must keep up with the front steering, so when the front wheel is turned to max deflection, the rear wheel must do the same.	W	4	Tests	
3.	Safety					
	3.1	The design must ensure that the steering system won't turn when the speed is to high	D/W	5	Tests	Volvo Trucks Corporation
	3.2	Some kind of hard ware lock for the system when the speed is greater than 38-40 km/h	W	4	Tests	
4.	Modeling					
	4.1	The system must be very solid in order to avoid malfunction due to weather and harsh environmental conditions.	D	5	Tests	Volvo Trucks Corporation

APPENDIX G – Camera documentation



Figure 46. Shows how the GoPro camera has been placed on the truck



Figure 45. Shows the view from the GoPro camera