CHALMERS

Improved rear axle steering of 8x4 tridem trucks

Enhanced tag axle steering and installation of lifting equipment for the second drive axle

Degree project in the Bachelor of Science in Engineering Programme

Mechanical Engineering

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Preface

This thesis work was conducted at ÅF Consult for Volvo Group Trucks Technology in Gothenburg, Sweden. It was the final course of the bachelor programme of mechanical engineering (180 credits) at Chalmers University of Technology, Lindholmen, Gothenburg. The thesis covered a total of 15 credits.

Thanks to both ÅF and Volvo Trucks, a lot of opportunities for new experiences and new knowledge were offered to us during the work. This thesis could not have been carried out if not for all of the valuable input and feedback from those involved. We would like to say thank you to the following people for their time and effort:

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Sammanfattning

Tag-axels styrsystem på Volvos 8x4 tridem tag lastbilar (åtta hjul varav fyra drivna, tridem står för tre bakaxlar och tag är benämningen för den bakre av dessa tre axlar) ger i dagsläget en icke optimerad styrning. De ingående komponenterna i systemet gör att hjulens styrvinklar är otillräckliga och även att däckslitaget är onödigt högt vid svängar i låg hastighet. En förbättrad styrgeometri hade minskat lastbilens svängradie och däckslitage samt sänkt bränsleförbrukningen. Dessutom hade det varit fördelaktigt om ett lyftsystem för andra drivaxeln skulle kunna installeras så att axeln kan lyftas när den körs utan gods. Färre axlar i marken gör att bränsleförbrukning minskar och lastbilen blir lättare att manövrera. Att lyfta axlar förändrar även förutsättningarna för styrgeometrin.

Arbetet utfördes på ÅF Consult mot Volvo Group Trucks Technology i Göteborg, Sverige. Rapporten är ämnad att utveckla förbättringar som åstadkommer det som är nämnt i stycket ovan.

I rapporten presenteras förslag på förbättringar av styrsystemet. En undersökning av möjligheterna för installation av lyftsystem för andra drivaxeln uppvisas dessutom. Dessa två delar sammanfogas till olika koncept som uppnår de önskade förbättringarna. Rapporten tar upp en rad olika aspekter kring de nya systemen vad gäller säkerhet, hållfasthet och påverkan av köregenskaper.

Summary

The tag axle steering system of Volvo 8x4 tridem tag (eight wheels of which four are driven, tridem stands for three rear axles, and tag is a notion for the last axle at the far end of the truck) trucks currently has an un-optimized steering. The constituent parts cause insufficient steering angles of the steered wheels. This results in a longer turning radius and unnecessarily high tire wear during low speed maneuvering. An improved steering geometry will reduce the truck's turning radius, decrease tire wear and lower the fuel consumption. In addition, it would be beneficial if a lifting system for the second drive axle could be installed to enable lifting of the axle when the trucks runs without goods. Fewer wheels in contact with the road surface mean lower fuel consumption and allows for better maneuverability. Lifting axles also influences the conditions for the steering geometry.

The work was carried out at ÅF Consult for Volvo Group Trucks Technology in Gothenburg, Sweden. The report is intended to develop improvements that achieve what is mentioned in the paragraph above.

The report presents proposals for improvements of the steering system. The feasibility of installation of lifting equipment for the second drive axle is also examined. These two segments are combined into different concepts that achieve the desired improvements. The report addresses a number of different aspects of the new systems regarding safety, structural strength and influence on driving characteristics.

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NOMENCLATURE

This section presents relevant notions of this report.

8x4 *- a four-axle truck with two mechanically driven axles, 4 out of 8 wheels are driven*
Ackermann steering geometry *- steering geometry according to Ackermann principles (explained in chapter 2.1, page 4 of this report)*
CAST *- Common Architecture Shared Technology*
ECU *- Electrical Control Unit*
ETS1 *- product name of an aftermarket tag axle steering system delivered by the company VSE*
Gross combination weight *– gross weight of a truck and trailer combination*
FEM *- Finite Element Method, method for structural analysis*
FH-1672 *- Truck ID (Front High 1672), a specific Volvo field test truck within the VETT project with a front high cabin*
HCT *- High Capacity Transport*
Hook *- a truck type with a hydraulic hook lift hoist that enables the truck to carry flatbeds and dumpster bodies (e.g.)*
Kingpin *- a rotation axle, in this case the rotation axis of the wheel knuckle*
Mesh size *- mesh grid size used in finite element method calculations, smaller mesh size often provides a more accurate calculation*
PC04 *- product class 04, notion for old Volvo products*
PC24 *- product class 24, notion for new Volvo products*
R_m *- ultimate tensile strength, how high stress the material can withstand before breaking*
$R_{p0.2}$ *- yield strength, how high stress the material can withstand without permanent deformation*
RADDT-GR *- a Volvo truck variant specification, rear axle air-suspension system*
Rigid truck *- a truck which does not have a fifth wheel (the fifth wheel links a trailer to the towing truck)*
RIH170 *- Rear Installation Height 170 [mm]*
Tag axle *- a trailing axle behind the driven axle(s)*
Tridem *- an axle group with three rear axles, also short for a four-axle truck with this rear axle configuration*
VETT *- a Volvo Trucks research project focusing on HCT timber transports (*Volvo En Trave Till, in English Volvo One More Pile)
WB4300 *- wheelbase 4300 [mm] (e.g.), measured from the center point of the front axle to the center point of the first drive axle*

1. INTRODUCTION
This section is an introduction to the underlying problem of this project.

1.1 Background
This report is part of a Volvo Trucks research project called “VETT”. The purpose of VETT is to investigate how different Volvo trucks can be improved to achieve greater transport efficiency. The research and development is done by engineers at Volvo Trucks, ÅF Consult and at several other companies. Improvements are done and tested on a wide range of different test vehicles that are in daily use.

This thesis is done at the industry department of ÅF Consult and is meant to result in improvements that could be implemented and tested on one of VETT’s test vehicles, the Volvo FH-1672, an 8x4 tridem tag truck with steerable tag axle used for transporting timber.

The steerable rear axle is used to improve the maneuverability of the truck at lower speeds. The steering angles of the tag axle are not optimal in the current design. It would be advantageous to optimize the relative steering angles between the wheels for an even better steering of the truck. The setup and components of the current design does not allow for Ackermann steering geometry, which will be explained in chapter 2.1, page 4. A proposal from the VETT-team is to investigate if turning the tag axle 180 degrees relative to the chassis could benefit the steering geometry by enabling a redesign of the components in question.

To increase maneuverability and to lower fuel consumption on tridem trucks, the tag axle is often lifted when the truck does not carry any cargo. Self-loading timber trucks usually have a crane mounted at the far end of the truck. This can be an issue when the tag axle is hoisted up due to large loads on the end of the chassis. Therefore, it would be advantageous to lift the second drive axle instead. Also, when the tag axle is hoisted up the truck loses the steering of that axle. On Volvo tridem trucks there are uncertainties regarding the spacing available for mounting of this type of lifting equipment on the second drive axle. The proposal from the VETT-team named earlier would not just enable a redesign for the steering components, but also free space for the lifting equipment.

1.2 Purpose
The purpose of this work is to investigate the advantages and disadvantages of turning the tag axle 180 degrees relative to the chassis. It is also to state if it is possible to achieve an improved steering geometry of the tag axle by turning it around to enable a redesign of the components affecting the steering. This work will also investigate if the prior will free space for lifting equipment for the second drive axle.

The project should result in a technical report that states the feasibility of the former and also how the redesign can be done.

1.3 Restrictions
This project only deals with Volvo 8x4 tridem tag trucks with steerable tag axle. There are several other restrictions that can be done to clarify what should not be addressed. The following list presents those restrictions.

- *This report will deal with an evaluation of the feasibility of turning the tag axle 180 degrees relative to the chassis*

- If the prior is achievable, this report will also focus on the redesign of the steering components to enable an enhanced steering
- FEM calculations on the redesigned components will only be done if time allows
- This report mainly deal with the components and setup of the specific Volvo FH-1672 truck
- The improvements proposed in this thesis will be optimized for a 8x4 tridem vehicle with steerable tag axle and a wheelbase of 3700 [mm]

1.4 Clarification of the question

This section contains different goals and questions aimed to clarify the underlying problem of this work. This report intends to in the end present answers to the following objectives and questions.

For a steering solution that is justified to be incorporated into Volvo's CAST range, it should meet the following requirements:
- Ackermann geometry between the tag axle wheels
- Ackermann geometry between the front and tag axle wheels
- Obtain a shorter turning radius than competitor trucks
- Reduce tire wear
- Lower fuel consumption

This work aims to answer the following questions:
- What are the advantages and disadvantages of turning the tag axle?
- What redesigns are needed?
- Is it possible to improve the steering geometry with a redesign of the steering components?
- How should the redesign of the steering components be done?
- How will the overall steering of the truck be benefitted?
- Is the proposed redesign favorable to implement?
- Will turning the tag axle give room for lifting equipment for the second drive axle?
- If the truck where to have its second drive axle hoisted up, how would it affect the Ackermann steering geometry?

2. TECHNICAL BACKGROUND

This section of the report presents important technical concepts and theories. This section is considered the pilot study of this work.

2.1 Ackermann steering geometry

In the vehicle industry, the optimal steering geometry for a given design of a vehicle is called Ackermann steering geometry. Ackermann geometry means that all of the steered wheels rotation axes intersect at the center of the turning circle. This implies that the inner wheel of a turn will have a larger steering angle than the outer wheel. If the steering components does not allow for this geometry the tire wear will increase when turning. This is due to tire slippage when the vehicle turns. A vehicle without the Ackermann steering geometry will also have a decreased maneuverability. True Ackermann allows for a shorter turning radius [5].

Ackermann geometry depends on several different factors. A vehicle with many axles and multiple steerable axles obviously has a more complex Ackermann geometry. Other parameters such as wheelbase and chassis width also have an influence on the steering geometry. Ideally, a completely optimized steering geometry would only be achieved if all the axles were steered. However, this is not the case for most of today's cars and trucks.

At lower speeds the Ackermann geometry is preferable. However, at higher speeds a more parallel steering is better in terms of tire wear and maneuverability aspects. This is due to outward drift that occurs when a vehicle corners, which in turn puts the instantaneous center further away from the vehicle than the Ackermann geometry assumes. Therefore, a vehicle's steering components are usually designed to create a steering geometry somewhere between true Ackermann and parallel steering. Parallel steering means that the left and right wheels steer at the same steering angle, see figure 2.1-3 [1].

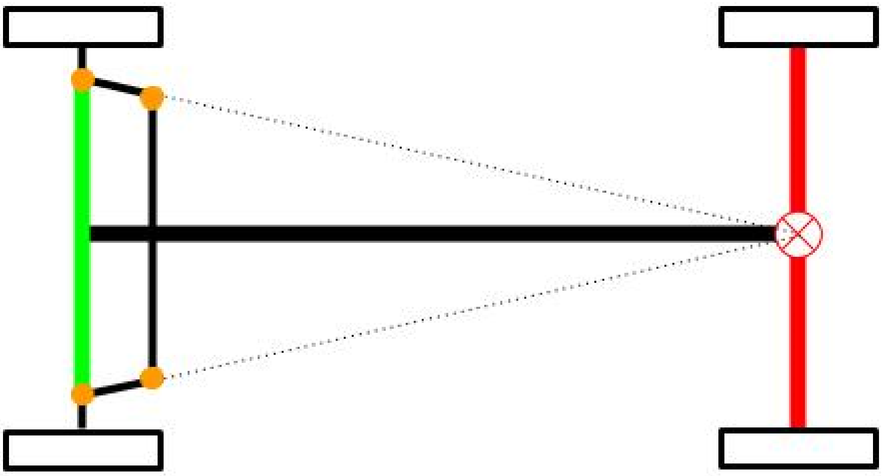

Figure 2.1-1. Principled overview of the Ackermann steering geometry of a car.

In figure 2.1-1 above, the car's front axle (with tie rod and tie rod arms) represents the steering axle and the rear axle represents the drive axle. The ring with a cross shows the position of the wanted center of rotation for Ackermann geometry. The figure 2.1-2 below shows the Ackermann geometry when the car is turning. As seen in the figure, the inner and outer wheels of the front axle have different steering angles. The inner wheel needs to steer at a greater angle than the outer wheel.

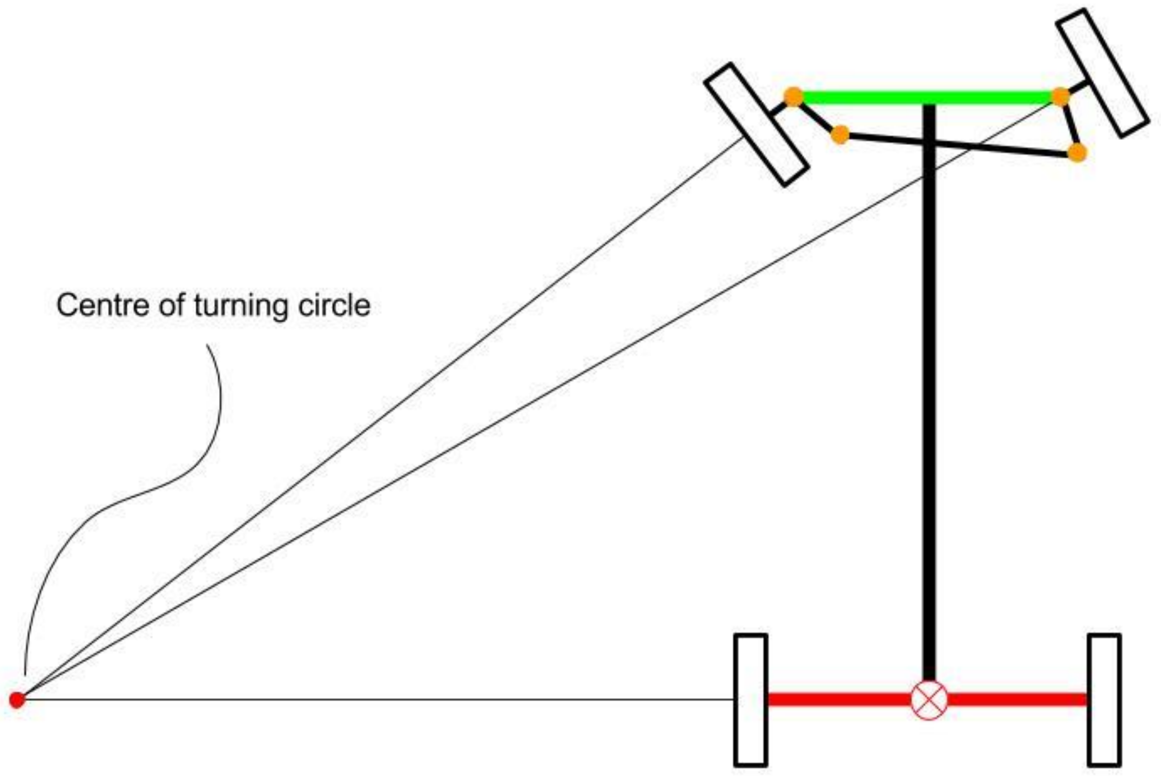

Figure 2.1-2. Principled overview of Ackermann geometry of a car during a turn.

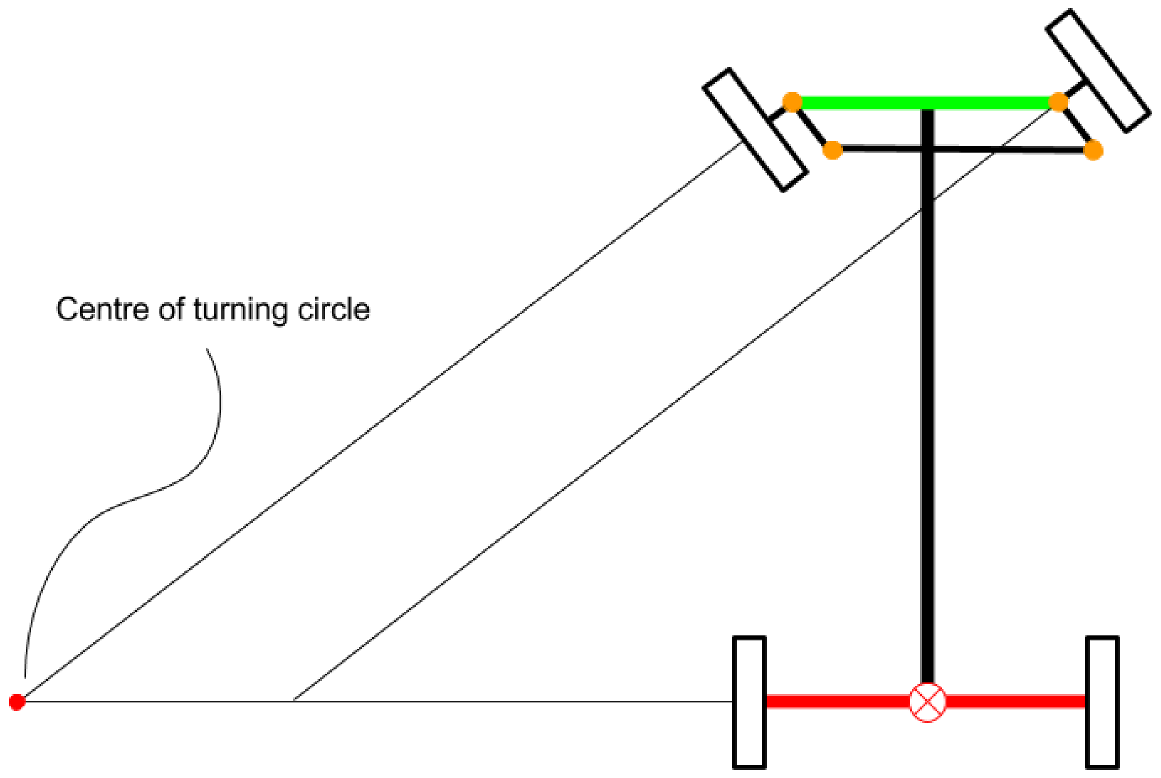

Figure 2.1-3. Principled overview of a parallel steering geometry of a car during a turn.

2.2 Volvo tridem tag truck steering and tridem tag Ackermann geometry

A Volvo tridem tag truck with a steerable tag axle has two steerable axles, the front axle and the tag axle itself. The additional steering of the tag axle greatly contributes to the truck's steering performance. For safety and performance reasons these trucks usually only steer with the front axle at higher speeds. On Volvo trucks the tag axle only steers fully at speeds under 25 [km/h]. At speeds greater than 25 [km/h] the steering software starts to ramp down the steering and when reaching 38 [km/h] the wheels are locked parallel to the truck's chassis. Volvo's standard RADDT-GR system has a maximum steering angle of about 12 degrees. An ECU in the truck processes measured steering angles of the front wheels and then computes which angles the tag axle wheels should be positioned to. There are sensors located in both the front and rear wheels that measures the mean steering angles in real-time. This steering system is equipped with a software safety mechanism that turns the tag axle wheels to their initial position if the computer loses sensor signals [2].

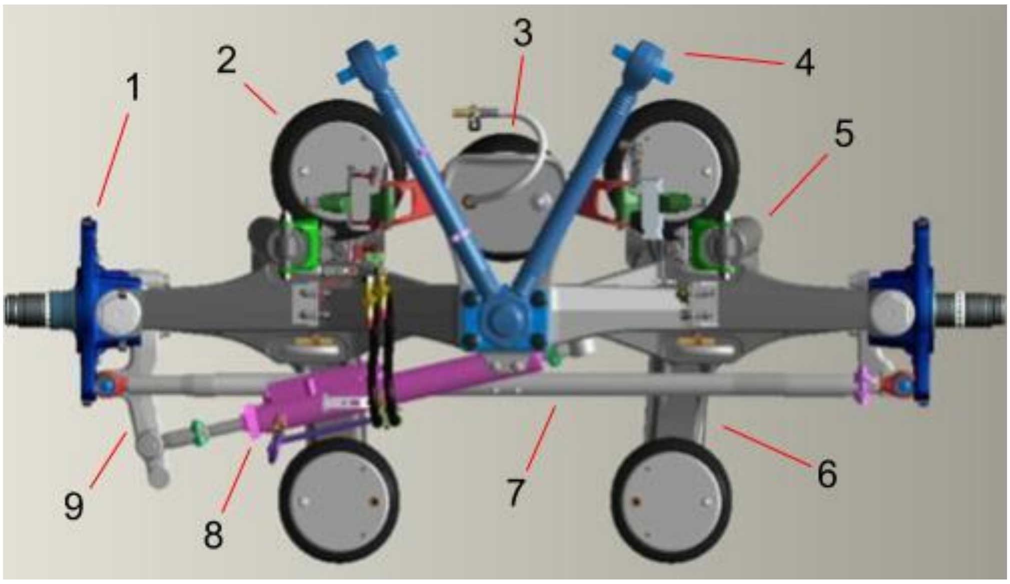

Figure 2.2-1. Overview of Volvo's current tag axle steering system.

Components in figure 2.2-1 above:

1. Left steering knuckle (on which the wheels are mounted)
2. Air spring (x4)
3. Axle lifting air system
4. V-stay
5. Shock absorber (x2)
6. Air spring member (supports the tag axle)
7. Tie rod
8. Steering cylinder
9. Left tie rod arm

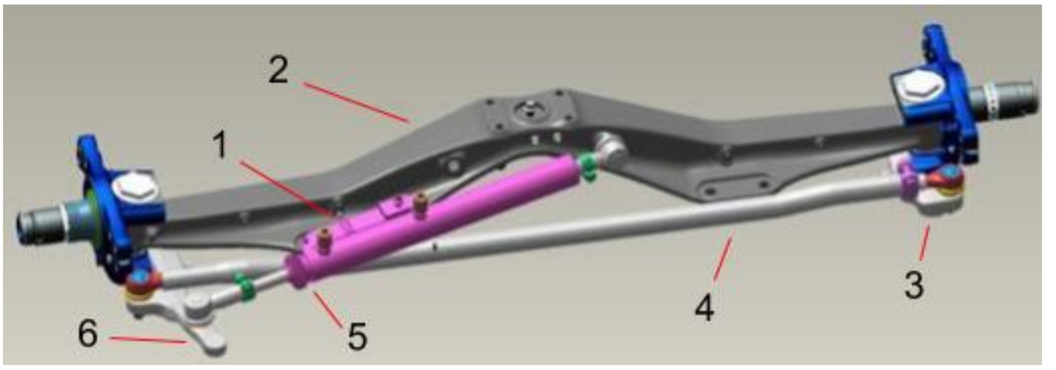

Figure 2.2-2. Overview of Volvo's current tag axle steering system.

Components in figure 2.2-2 above:
1. Linear sensor mounted on the steering cylinder
2. Tag axle
3. Right tie rod arm
4. Tie rod
5. Steering cylinder
6. Left tie rod arm

The Ackermann steering of a tridem tag truck is achieved when the trucks rotation center lies between the drive axles. This is because the drive axles which are non-steerable, have to be as close to the rotation center as possible for minimum tire slip (tire slip is explained further in section 2.4 in this report). This result in reduced tire wear and allows for the best possible maneuverability of the truck.

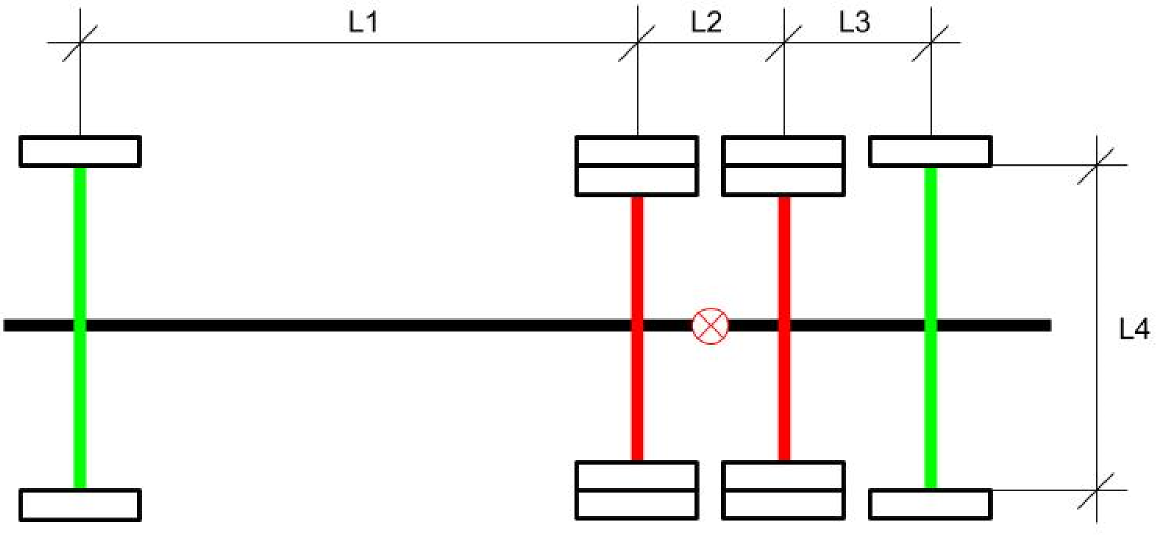

Figure 2.2-3. Principled overview of a tridem tag truck (L1 = wheelbase).

In figure 2.2-3 above, an overview of a tridem tag truck is presented. Axles from left to right; front axle (steered), first drive axle, second drive axle and tag axle (steered). The ring with a cross represents the wanted rotation center for Ackermann geometry for this truck type.

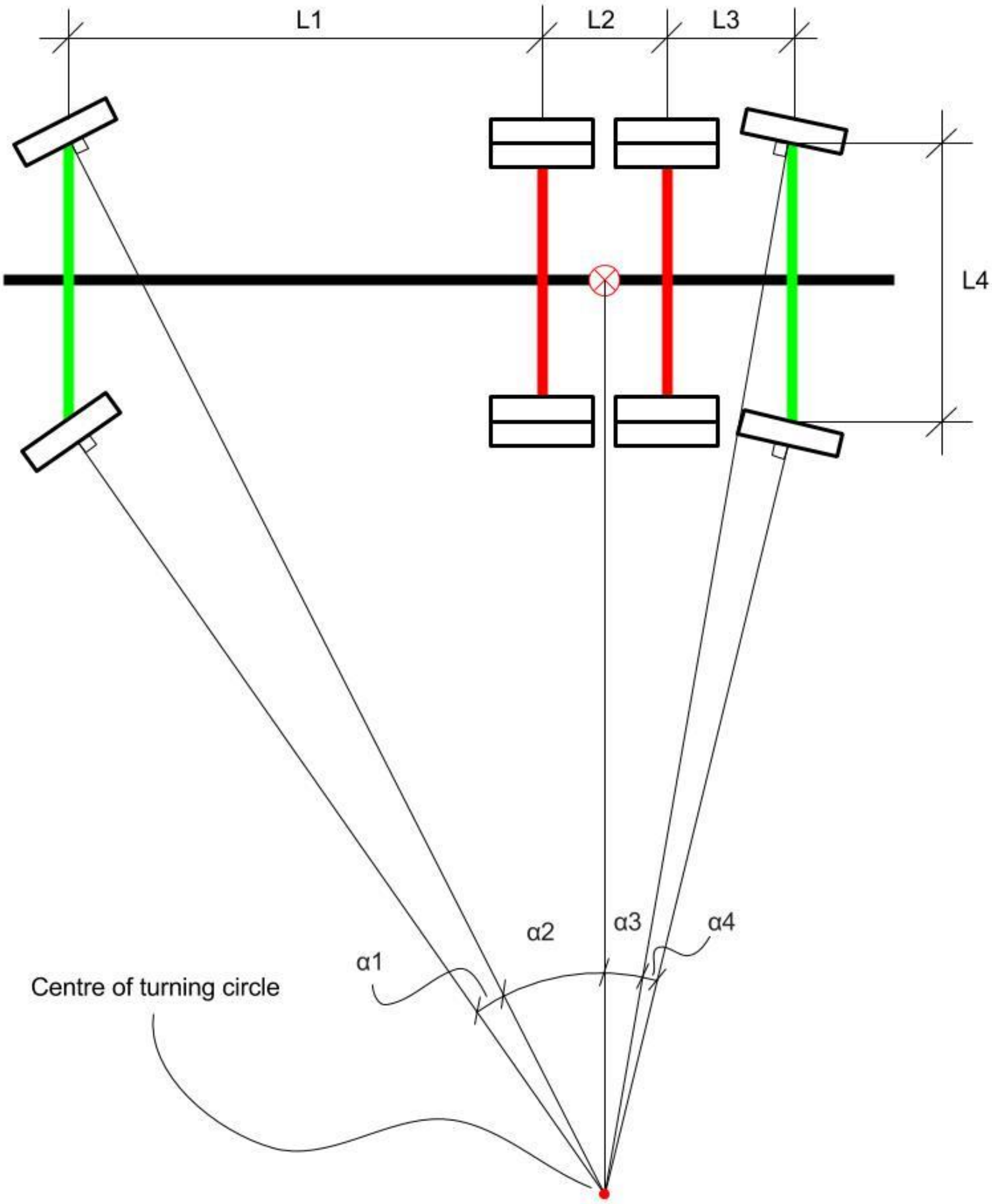

Figure 2.2-4. Ackermann steering geometry of a tridem tag truck.

As seen in figure 2.2-4 above, the inner wheels of a turn have to steer at a greater angle than the outer wheels. The inner front wheel needs to steer with the angle of α1 + α2 and the outer front wheel with the angle of α2. The inner tag axle wheel needs to steer with the angle of α3 + α4 and the outer tag axle wheel with the angle of α3. The geometry of the figure above shows that the angles α1, α2, α3 and α4 are equivalent to the steering angles of the wheels when measured from the chassis. The lines perpendicular to the wheels intersect at the center point of the turning circle. At greater steering angles, the intersection point will end up closer to the truck. For true Ackermann steering the intersection should always lie on the line drawn between the truck's rotation center and the center point of the turning circle in the figure above.

On Volvo's standard tag axle steering solution the tie rod sits behind the axle. This causes undesirable geometry and spacing for the tie rod arms which in turn makes it difficult to achieve Ackermann geometry. Furthermore, this also results in an almost complete parallelism between the wheels when turning. If the tie rod arms were to have more space, it would be possible to redesign them so that the wheels turn at different angles (depending on if the wheel is the outer or inner one of the turn). Therefore, a redesign of the tag axle steering components would be advantageous (see figure 2.2-5 and 2.2-6 below).

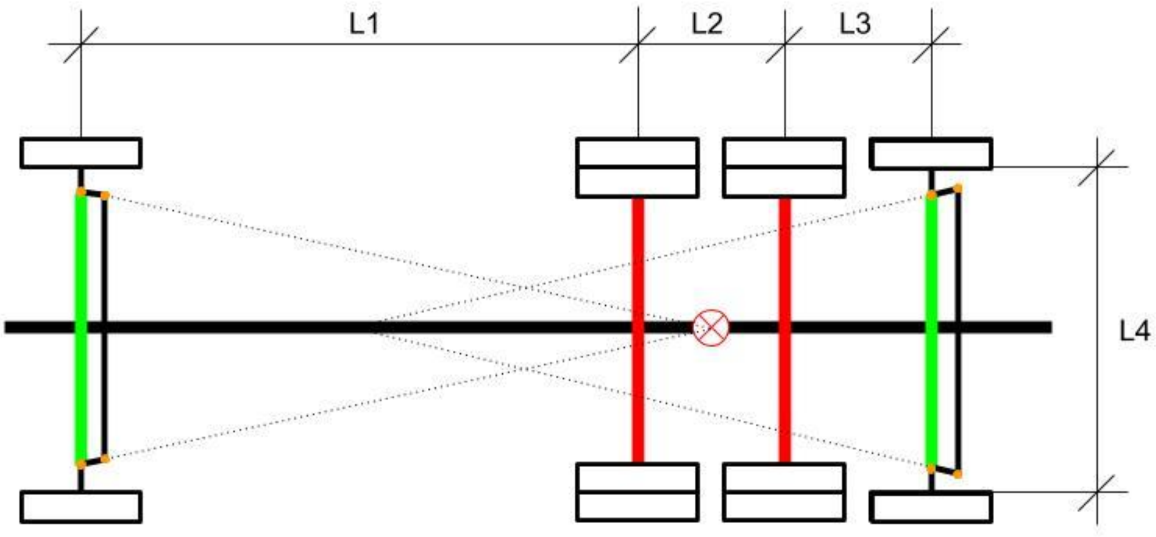

Figure 2.2-5. Principled overview of the standard Volvo tag axle setup (with tie rod arms and tie rods).

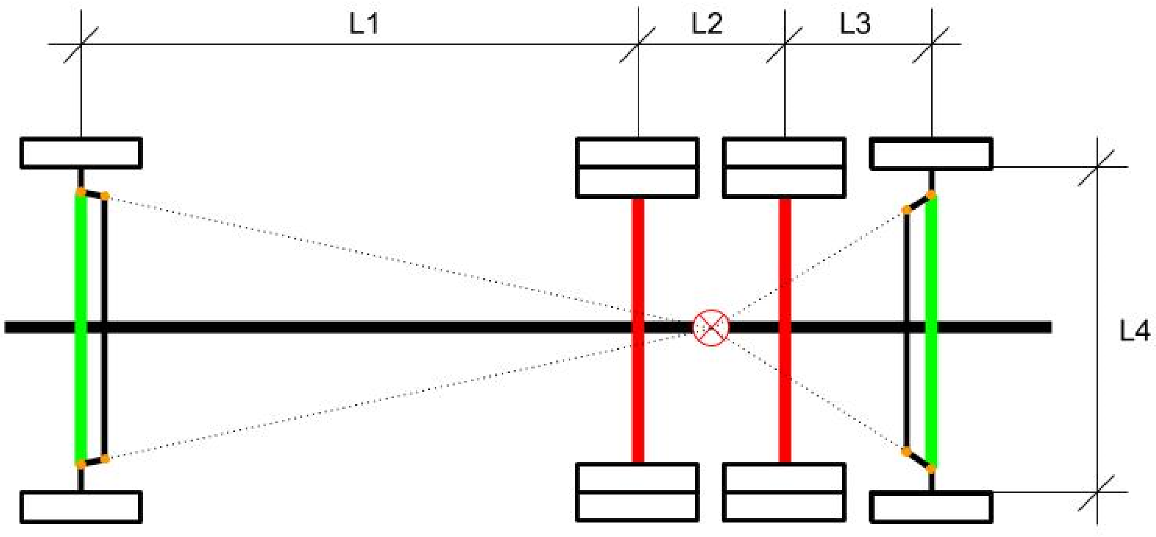

Figure 2.2-6. Principled overview of the preferred steering setup with the tag axle 180 degrees turned around.

2.2.1 General issues of Volvo's tag axle steering system

In this section, different issues of the Volvo tag axle steering system are discussed.

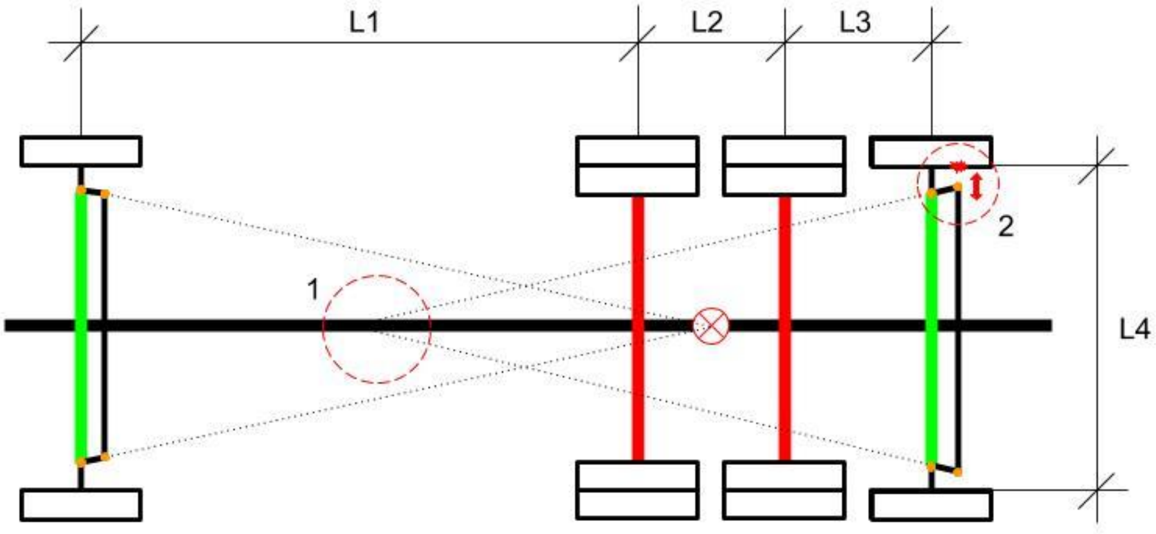

Figure 2.2-7. Principled overview of the steering geometry issues of Volvo's tag axle steering system.

Figure 2.2-7 above presents the two issues of the current Volvo tridem tag steering setup. Mark 1 (dotted circle) shows that the lines drawn from the tie rod arms (a line drawn from the ball joint of the tie rod thru the kingpin) does not converge at the truck's center of rotation. Furthermore, with the tie rod behind the tag axle, there is not enough room (shown by mark number 2, dotted circle) to redesign the tie rod arms and tie rod so that the lines (that converges at mark 1) converge at the trucks center of rotation. It would be advantageous to turn the tag axle 180 degrees relative to the chassis. If the tie rod was to face the other way around, there would be room for the necessary redesigns. Then the tie rod arms would be angled inwards, towards the center line of the truck. In figure 2.2-8 below, another issue is presented. At large steering angles, the tie rod is at risk of clashing with the tag axle.

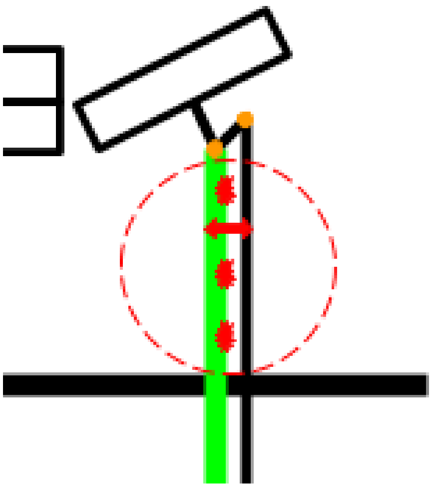

Figure 2.2-8. Another issue of the current steering setup of the tag axle.

The issues presented in the section above results in an insufficient steering of Volvo's tag axle steering system.

2.2.2 Design criteria, optimization for the wheelbase of 3700 [mm]

Further work will be done to optimize the steering for Volvos shortest wheelbase on tridem trucks, WB3700. This is due to the maximum steering angle of the front axle. On Volvo tridems, the distances between the rear axles are standardized. Therefore, the tag axle will always be located at the same distance from the trucks center of rotation, independent of the various wheelbases. Although this is not the case for the front axle, which will have different distances to the trucks center of rotation depending on the wheelbase. Thus, a shorter wheelbase equals a shorter turning radius, supposing that the front wheel angles remain constant.

On a truck with WB3700, the turning radius will be the shortest (compared to trucks with longer wheelbase). Hence the tag axle will need the greatest steering angles, to achieve Ackermann steering. This is why the steering of the tag axle will be optimized for WB3700. If this system was to be installed on a truck with a longer wheelbase (which would require smaller steering angles of the tag axle), the onboard computer software could be updated to steer at Ackermann angles for that specific wheelbase.

In order to optimize the steering for WB3700, a calculation for true Ackermann geometry has been done. This calculation is based on the maximum steering angle of the inner front wheel on Volvo's standard tridem tag trucks and on different standardized dimensions [3]. The calculation is presented in appendix 1, page 51. For a summary of the results, read section 4.1.1, page 24 of this report.

2.2.3 Offset of the truck's center of rotation when the second drive axle is lifted

Another subject to investigate is the benefits of lifting the second drive axle instead of the tag axle when the truck does not carry any cargo. This will affect the steering of the truck by offsetting the truck's wanted center of rotation forward. The center of rotation for minimum tire slip and best handling will then be located at the center point of the first drive axle, as seen in the figure below. This results in a need for even greater steering angles of the tag axle to achieve true Ackermann steering. In today's automotive industry, the major truck manufacturers do not produce any tridem tag trucks with lifting equipment for the second drive axle [3].

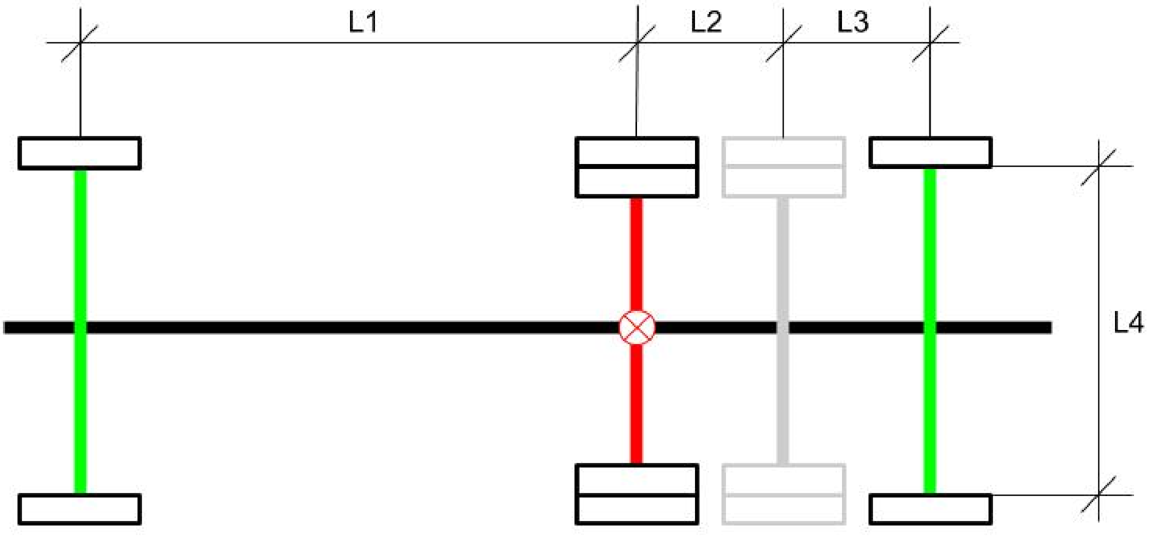

Figure 2.2-9. Principled overview of the center of rotation offset when the second drive axle is lifted (marked by the ring with a cross).

2.3 Volvo FH-1672

The Volvo FH-1672 (chassis number: A-756109) is a rigid field test truck within the VETT-project. It is a HCT truck that can carry up to 74 [tons] in gross combination weight. Pictures of the truck can be viewed in figure 2.3-1 below. The truck’s purpose is to test out new improvements intended to increase the truck's performance. The new systems and upgrades are developed with the goal of being implemented into Volvo’s CAST range. The FH-1672 has several differences compared to a standard Volvo tridem tag. Many of its components and systems have been redesigned in order to be tested in daily use. For example, it has front wheels with hydraulic drive which can be engaged when extra torque and traction is needed. It also has a redesigned tag axle steering system, the ETS1 system.

Figure 2.3-1. Compilation of photos of the Volvo FH-1672.

The ETS1 tag axle steering system of the Volvo FH-1672 consists of a variety of different non-standard components. Below is an overview the current design, figure 2.3-2.

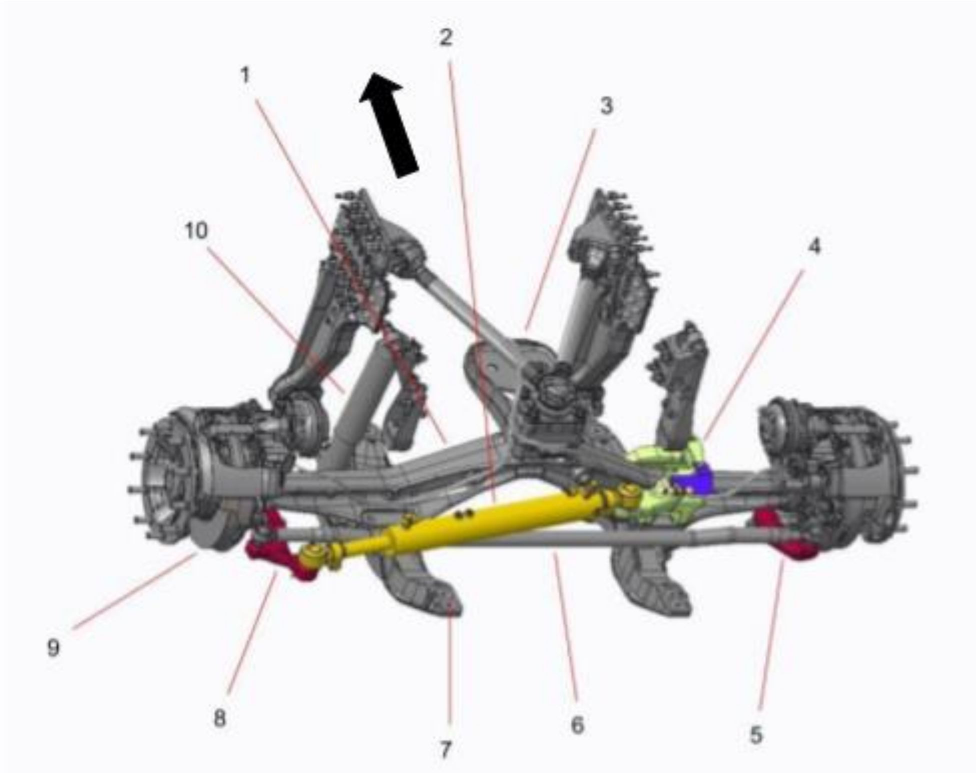

Figure 2.3-2. Overview of the ETS1 tag axle steering system (the arrow indicates the travel direction of the vehicle).

Components in figure 2.3-2 above:
1. Tag axle (standard component)
2. Steering cylinder (ETS1, non-standard, product from VSE)
3. Mount for the axle lifting air system (standard component)
4. Mount for the steering cylinders ball joint (ETS1, non-standard, product from VSE)
5. Right tie rod arm (ETS1, modified, prototype)
6. Tie rod (standard component)
7. Mount for the air suspension springs (x4) (standard component)
8. Left tie rod arm (ETS1, modified, prototype)
9. Brake (x2) (standard component)
10. Shock absorber (x2) (standard component)

Today the Volvo FH-1672's tag axle does not have true Ackermann steering geometry. The wheels of the tag axle are almost completely parallel to each other during turns. As explained in chapter 2.1, this is not an optimal geometry. The Volvo FH-1672 has been fitted with the ETS1 steering system and has during tests produced a rear steering angle of 18 degrees on the inner wheel (together with a 43 degree steering angle of the inner front wheel) at 14 [km/h] [3].

In the following table 2.3-1, measurements done in a previous VETT-report of the FH-1672 test vehicle (with the ETS1 solution installed) is presented:

*Table 2.3-1. Turning diameters of the FH-1672 [3]. (Notions in table: **PC24, (1) aftermarket solution, (2) ETS1 solution).*

Truck brand	Volvo	Volvo
Truck type	Timber Truck	Timber Truck
Truck ID	FH-1672**	FH-1672**
Tie rod	Modified (1)	Modified (2)
Wheelbase [mm]	4300	4300
Weight [tons]	32,00	31,90
Rear steering angle [°]	-	14,20
Turning diameter, inner front wheel [m], d1	16,52	14,30
Turning diameter, inner front drive wheel [m], d2	13,47	11,05
Turning diameter, inner rear drive wheel [m], d3	-	10,73
Road condition	Dry asphalt	Dry asphalt
Other	-	-

The angles presented in the table above are mean angles (for a principled figure of mean angle, see appendix 1, page 51 of this report). Also see section 2.5, on page 17 for an explanation of how the tests were done.

Turning at low speed result an increase in required power of the steering cylinders. The FH-1672 only reached 14,4 degrees on the inner tag axle wheel, but under ideal conditions it would be able to achieve 18 degrees (at a speed of 14 [km/h]) [3]. When compared to the maneuverability when the aftermarket solution was installed (first column), it is verified that the ETS1 system reduces the turning diameters.

2.4 Tire slip and caster angle

In this section theory of tire slip and caster angle is explained.

Tire slip

Fundamental theory of mechanics explain that the speed of a wheel relative to the road is equal to the rotation speed times the radius of the wheel. In other words there is a proportionality constant between the translational velocity and the angular velocity.

For vehicles this is a simplification. The weight of the vehicle deforms the tire so that it is not perfectly round. This causes longitudinal slip and it is due to the acceleration caused by the shorter radius acquired when the tire is deformed. High torque can also result in more tire slip. This is illustrated in figure 2.4-1 below.

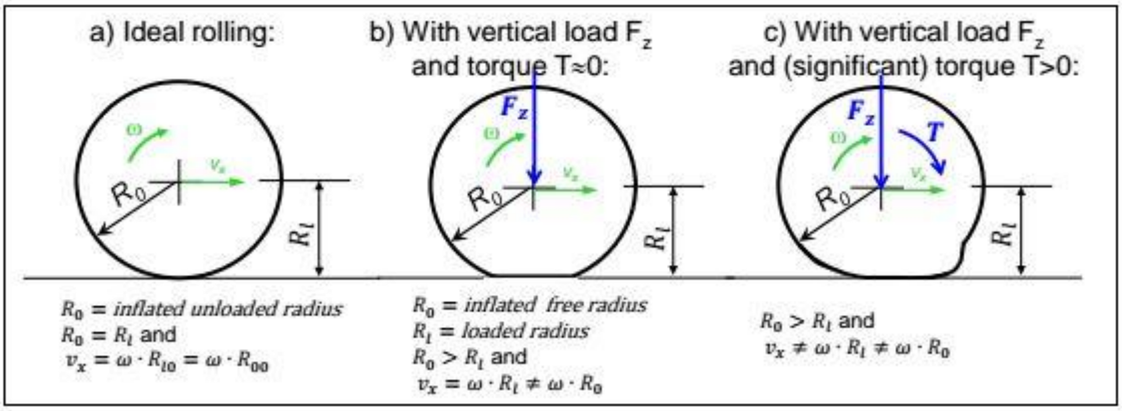

Figure 2.4-1. Radius and speed relations of a rolling tire (R_0 and R_l does not have the same numerical values across a), b) and c)). Figure acquired from reference [1].

When sideway forces on the tire are greater than the counteracting friction forces, lateral slip occurs. This means that the wheel will not travel the exact route as it is heading. This can occur when a car turns at high velocity. Lack of Ackermann steering geometry also entails lateral slip. As explained in chapter 2.2, this happens when the rotation center of the vehicle does not coincide with the point between the two drive axles (on a tridem truck). This forces the tires to slip, especially during tight turns. The difference between the travel route and the heading route is called slip angle and can be viewed in figure 2.4-2, as α.

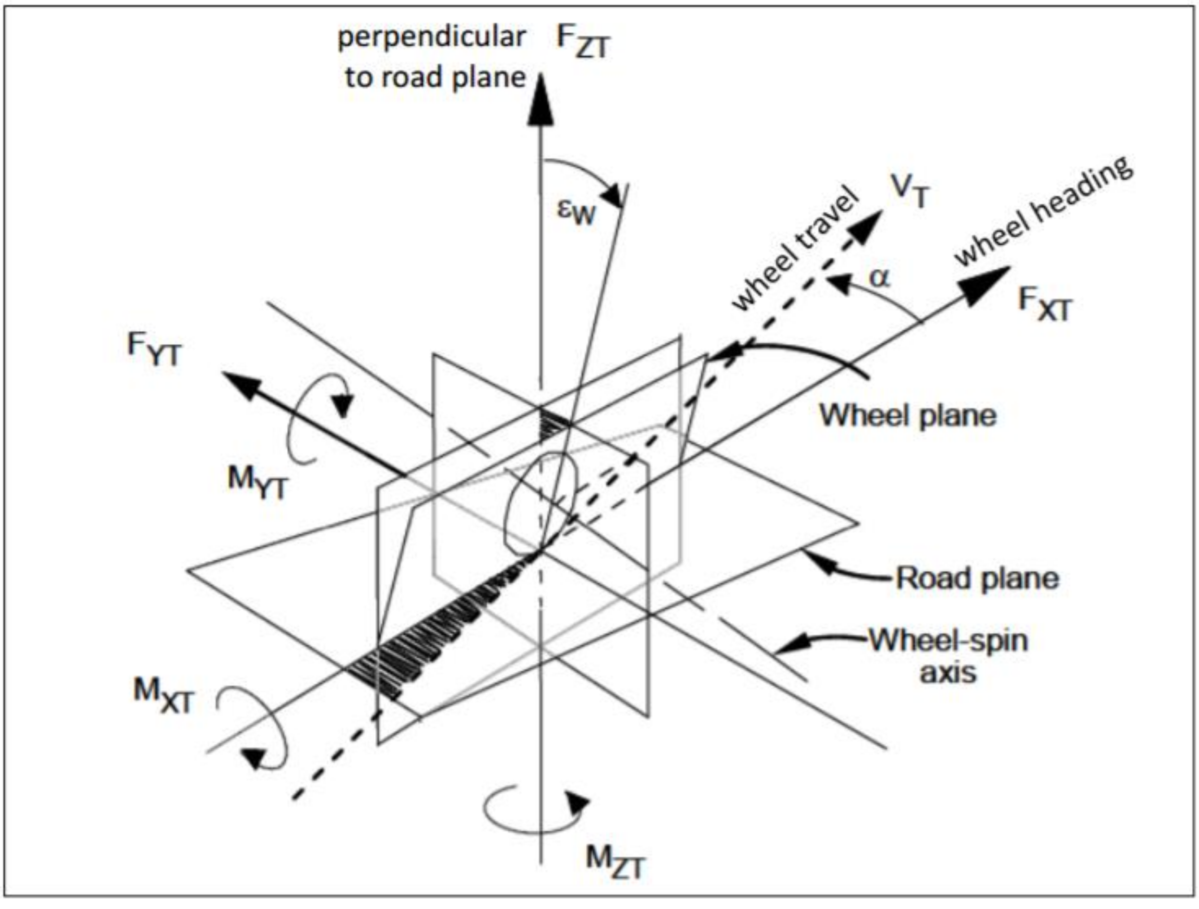

Figure 2.4-2. Shows the theoretical difference between the wheel heading and the wheel travel. α is called slip angle. Figure acquired from reference [1].

There is a correlation between tire slip (both longitudinal and lateral) and tire wear. More slip means more tire wear due to friction between the wheel's rubber and the road surface. Tire slip should therefore be avoided if possible. High slip will also contribute to higher fuel consumption due to increased friction forces [1].

Caster angle
The caster angle affects the steering and road stability of a vehicle. It is the angle between the steering axis and the vertical axis thru a steered wheel. On most modern vehicles this angle is positive (see figure 2.4-3 below, positive caster angle means that θ's direction is counterclockwise), and the wheel rotates around this tilted axis. The contact patch between the road surface and the tire lies behind the intersection point of the wheel axis and ground level. This result in a twisting moment that strives to reposition the wheel to its initial position parallel to the chassis when the wheel is turned [1]. This makes the vehicle more stable but heavier to steer. However, the power steering of today's vehicles provides more than enough power to overcome this moment.

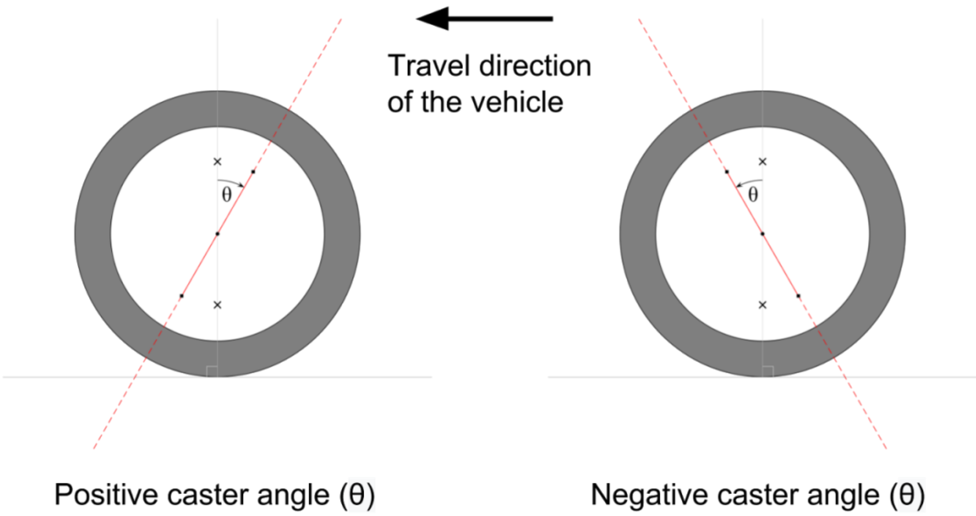

Figure 2.4-3. Positive and negative caster angle [6].

2.5 Competitor analysis and investigation of steering performance of different Volvo FH trucks

There are several other truck manufacturers producing tridem tag trucks with steerable tag axles. An analysis of the competitor trucks maneuverability can be used as a reference for the potential redesign of the Volvo tag axle steering system. This analysis only takes 8x4 tridem tag trucks with steerable tag axles into account. The following section presents performance data of some competitor trucks and a handful of different Volvo FH trucks.

Previous study
A study done in a thesis written in 2013 [2], investigates the maneuverability of trucks from different manufacturers. Therefore, this competitor analysis will be based on the results of that study. Table 2.5-1 below presents measured performance data of some competitor trucks and Volvo FH trucks. It also presents some of their specifications.

*Table 2.5-1. Maneuverability data from field tests [2]. (Notions in table: *PC04, **PC24, (1) aftermarket steering solution).*

Truck brand	Volvo	Volvo	Volvo	Scania	Volvo	Volvo	MAN
Truck type	Timber Truck	Timber Truck	Timber Truck	N/A	Hook	Gravel Truck	Hook
Truck ID	FH-(N/A)*	FH-(N/A)*	FH-517	-	FH-(N/A)**	FH-(N/A)**	-
Tie rod	Original	Original	Modified (1)	Original	Modified (1)	Modified (1)	Original
Wheelbase [mm]	4100	4100	4100	4200	3700	3700	3600
Weight [tons]	29,30 - 29,70	31,10	32,10 - 32,60	10,6 - 11,00	31,60	32,00 - 33,00	13,00
Rear steering angle [°]	12,54	11,00	13,50	12,55	14,40	12,55	17,00
Turning diameter, inner front wheel [m], d1	16,33	16,25	15,10	14,78	14,33	13,56	-
Turning diameter, inner front drive wheel [m], d2	13,53	13,17	12,01	11,33	11,25	10,61	-
Turning diameter, inner rear drive wheel [m], d3	13,40	12,91	11,78	11,17	10,97	10,43	-
Road condition	Dry asphalt with little gravel	Dry asphalt	Dry asphalt	Dry asphalt	Dry asphalt	Dry asphalt with little gravel	Dry asphalt
Other	-	-	-	-	-	Modified front steering	-

The angles presented in table 2.5-1 above are mean angles (for a principled figure of mean angle, see appendix 1, page 51 of this report). These values can also be compared to the FH-1672, see table 2.3-1, page 15 of this report.

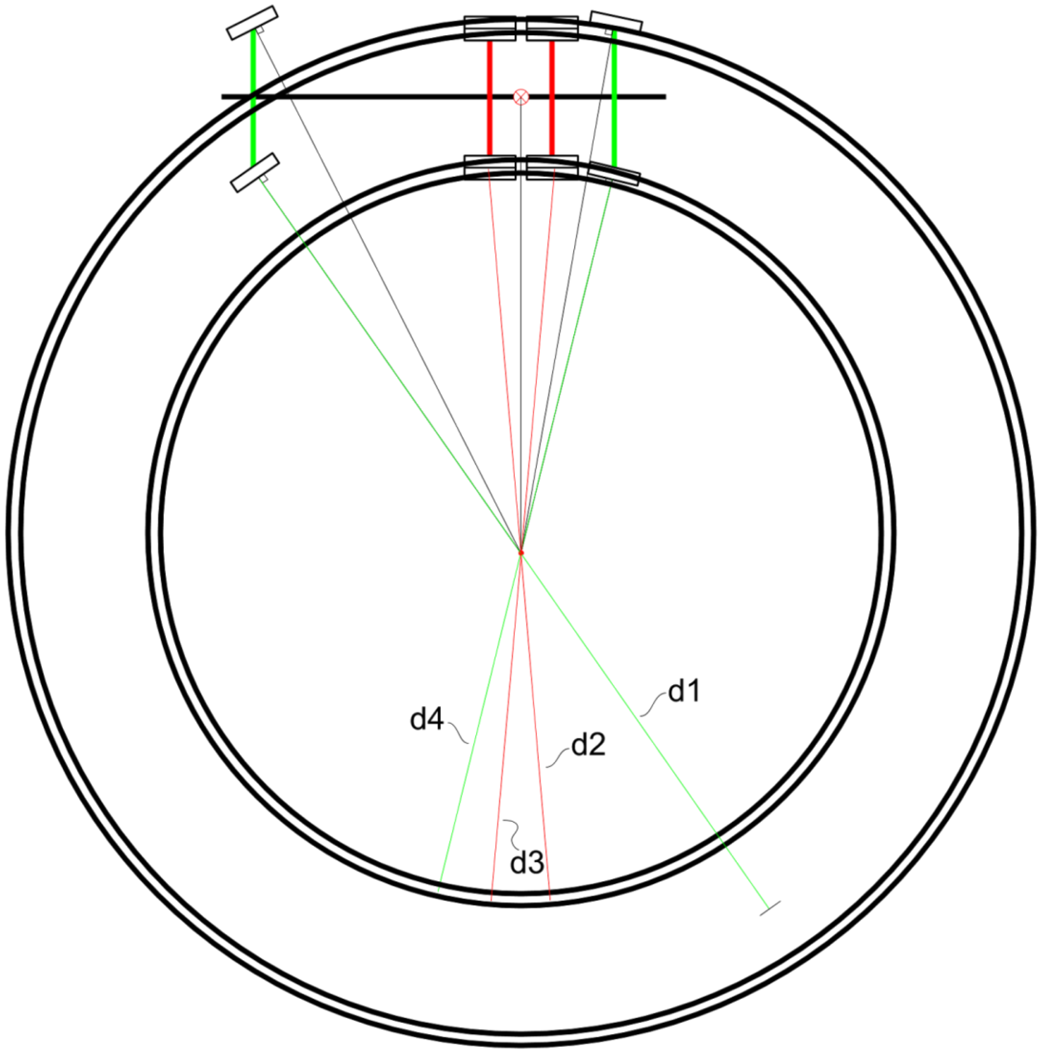

Figure 2.5-2. Principled 360 degree turn of a tridem tag truck.

Figure 2.5-2 presents a principled full circle turn with an 8x4 tridem tag truck. The rings that coincide with the drive axle wheels represent the tire wear marks produced on the tarmac during a sharp turn. The tire marks allow for measurement of the trucks drive wheel turning diameters. The values in figure 2.5-1 from a previous report were measured using this method. To determine the turning diameters of the steerable wheels, marks with street chalk was put on the ground at multiple points during the full circle turn.

As explained in chapter 2.2.1 the maneuverability depends on several factors. This includes turning angles of the front and rear wheels, wheelbase and other dimensions of the chassis. By examining table 2.5-1 above, some conclusions can be made. A shorter wheelbase equals a shorter turning diameter. However, better rear wheel steering angles can compensate for a longer wheelbase. This can clearly be seen when comparing the Volvo FH-1672 to the older Volvo FH with a shorter wheelbase. The FH-1672 has shorter turning diameter, despite its longer wheelbase. It also has a shorter turning diameter than the Scania truck. What can be concluded is that the custom tag axle steering system of the Volvo FH-1672 already outperforms some of its competitors. However, since the test was conducted some competitors have updated their products. Scania has launched a new truck generation in 2016 with improved performance [4].

As mentioned above, data is missing in the previous tests. For example, there are no values of the turning angles of the front wheels. It is therefore not possible to determine if competitor trucks achieve Ackermann or not. Despite this flaw the table still gives an insight into how well the competitor trucks are performing. The new system must be able to reduce the turning diameter/radius and allow the truck to achieve better maneuverability than its competitors.

3. METHODOLOGY
In this section, the methodology of this work is explained. The report is mainly divided into four parts, a pilot study, CAD study, concept generation and redesigning work.

3.1 Pilot study
This section explains how the pilot study was conducted.

3.1.1 Study of optimal steering geometry and Volvo's standard tag axle steering system
In order to determine how an optimal steering system of the tag axle should be designed the theory of Ackermann steering geometry has been studied thru literature from a Chalmers course in vehicle dynamics, and also thru meetings with engineers at both Volvo Trucks and ÅF Consult.

This part of the pilot study was divided into different parts including study of Ackermann steering geometry in general, study of Volvo tridem tag truck steering and Ackermann geometry of 8x4 tridem tag trucks. Furthermore, an analysis of the Volvo FH-1672 was carried out, as well as research of tire slip and caster angle. In this section calculations of Ackermann geometry for tridem tag trucks was conducted. The calculations included both the case where all axles are lowered and the case when the second drive axle is lifted.

3.1.2 Competitor analysis and investigation of steering performance of different Volvo FH trucks
The steering performance of competitor trucks has been evaluated through a study of data acquired from maneuverability tests done in previous theses and reports within Volvo Trucks and ÅF Consult. The data was compiled into a table that provides an overview of the truck's steering performance with respect to several factors.

3.1.3 Discussions and meetings
For insight into the problems of Volvo's tridem tag trucks, a number of discussions, meetings and visits took place. Both within Volvo Trucks and outside of the company.

A day in the field with the Volvo FH-1672, Ed, Sweden
A visit to the Volvo FH-1672 was made. For one day, the truck and driver were observed at work in the area of Ed, Sweden. The day consisted of timber delivery from logging site to paper mill. The driver was also questioned to acquire knowledge about how the truck was performing steering wise.

Meeting at Volvo Trucks, Lundby, Gothenburg, Sweden
A meeting with the chassis department of Volvo Trucks was set up. During this meeting, a discussion alongside four Volvo engineers was held. Steering geometry, steering components, chassis strength and how potential redesigns would affect the truck handling were some of the topics discussed.

3.2 CAD study
The Volvo FH-1672 has been analyzed using the CAD program Creo Parametrics. The analysis evaluated the Volvo FH-1672 setup, the original design of the tag axle and the rebuilt system with greater steering angles (ETS1 steering system). Measurements and rearrangements were carried out in the model to evaluate potential clashes when turning tag

axle and its constituent parts 180 degrees relative to the chassis. Other tests were also carried out in a similar way.

The majority of the CAD work and design of new components/systems in Creo Parametrics was done using a certain workflow. Figure 3.2-1 below presents that workflow (the measurements in the first step of the sequence were taken in CAD assemblies acquired from Volvo Trucks).

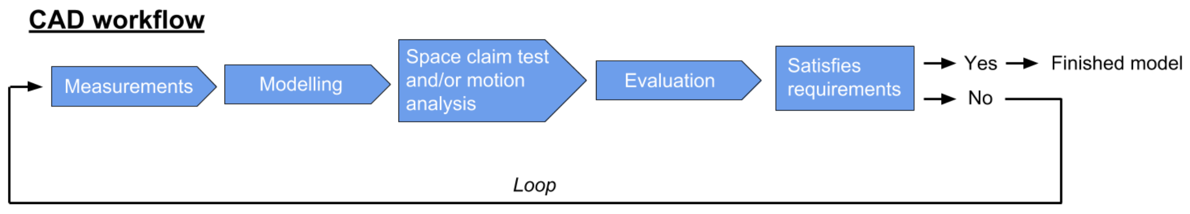

Figure 3.2-1. CAD workflow.

3.2.1 Creating a template assembly

The first step in the CAD study was to create a template CAD assembly that was to be used for different tests and redesigns further on. This template was based on the FH-1672 and was fitted with the ETS1 steering system. To get a better overview of the constituent parts and their functionality, less relevant parts were not assembled into the model. All of the cabling and hydraulic routing was excluded. The wheels, engine, gearbox, cabin and more were also excluded.

3.2.2 Installation of lifting equipment for the second drive axle

In this part of the work lifting equipment was assembled into the template assembly. A drive axle of the same type as in the 8x4 truck with lifting equipment was chosen from a 6x4 truck. After the system was installed, measurements were taken in Creo Parametrics to state whether the new equipment would fit in the model of the FH-1672.

3.2.3 Creating CAD concepts

During the CAD work, different concepts of a redesigned tag axle system were generated from the template. Some other ideas were also explored and turned into concepts. These concepts were derived partially from brainstorming and partially from discussions and work alongside the ÅF engineers. Approximations were made to acclaim a starting point for the continued work. To achieve a fully functional concept in Creo Parametrics, a lot of trial and error was used for the development.

The new components of the different concepts were created using measurements of the different standard tag axle parts. Components with a basic and primitive geometry were created to test their functionality. A motion analysis was also done in Creo Parametrics to locate eventual clashing of parts. Furthermore, the space claim of the new components was also analyzed. The new parts were refined using the previously mentioned subjects.

Because of the many aspects of a change in the design of such a crucial system, the concepts had to be evaluated and ranked. This provided a good insight into how the components affect the truck and its driving characteristics. The two concepts that proved to be the most advantageous were chosen for further work.

3.2.4 Evaluation of the concepts

The evaluation was done under a long period alongside the actual development of the concept using the thesis supervisor and other engineers as counselors. The meeting with the chassis department gave insights that help to understand which parameters and aspects that are important for a well working tag axle steering system.

Also, a mid-project presentation was held where engineers from both ÅF and Volvo were invited. Three concepts were presented. Afterwards a discussion took place. The discussion led to a deeper understanding of the parameters that influence the concepts pros and cons. The team of engineers helped to identify which concepts that should be developed further.

The evaluation also consisted of a Kesselring matrix. It was set up to get an understanding of how well the concepts achieve certain requirements and therefore to determine which are the most beneficial. A lot of the knowledge acquired from different meetings was used to determine which factors should be taken into consideration in this selection matrix. A reference solution was also added into the matrix for comparison with the new concepts. Volvos original tag axle steering system was chosen as this reference. The weighting was done based on logical assumptions. The matrix was used to confirm the opinions of which concepts that should be developed further.

3.3 Further development of the winning concepts

For the continued development of the concepts the results and insights gained from the previous meetings, CAD work and mid-project presentation was crucial. These made it possible to optimize the concepts and to adapt them to the Volvo CAST range. Also, the day-to-day conversations with the ÅF engineers laid the foundation for the continued work. The methodology of the development of concept 1 and 2 is presented below.

3.3.1 Development of the concept 1 and 2

For concept 1 new tie rod arms were needed to achieve Ackermann steering geometry. A new attachment for the steering cylinders was needed for concept 2. When designing the new components, the dimensions were determined by measurement in the template assembly in Creo Parametrics. Different components of the tag axle system were measured and then approximate dimensions for the new parts could be decided. In this stage of the work, it was also realized that the concepts needed to consist of as many standard parts as possible, to reduce cost and to make them easier to implement. Standard components that satisfied the specific requirements of the concepts were installed into the assemblies. Also, new components were modelled and assembled into the concepts. Afterwards, a new analysis of space claim and potential clashing was done. Measurements in the assemblies were taken to confirm if the concepts achieve the wanted steering geometry and steering angles.

FEM calculations of left tie rod arm

One of the new tie rod arms of concept 1 was analyzed with the finite element method using the FEM plugin in Creo Parametrics. During this analysis, different mesh sizes were tested to get reliable results. The results of the new component were then compared to results of an old component. The stresses were also compared with the material properties.

4. RESULTS
This section presents the different results that have been acclaimed during the work.

4.1 Pilot study
This section presents the results of the pilot study.

4.1.1 Study of optimal steering geometry and Volvo's standard tag axle steering system
Firstly, the study of steering geometry gave valuable insight into steering and vehicle dynamics in general. Secondly, the study resulted in requirements and target values for the forthcoming construction work of steering components.

Appendix 1, page 51 presents calculations for true Ackermann geometry of an 8x4 tridem tag truck with steerable tag axle, with a wheelbase of 3700 [mm]. The following list is a summary of the results of the calculation:

Front wheel angles
- *Steering angle of inner front wheel:* α(if)* = 44,00 [°]
- *Steering angle of outer front wheel:* α(of)* = 33,42 [°]
- *Mean angle of the front wheels:* α(mf)* = 42,90 [°]
- *Angular difference between the inner and outer wheel:* Δα = 10,58 [°]

Rear wheel angles (all axles lowered)
- *Steering angle of inner rear wheel:* β(ir)* = 28,32 [°]
- *Steering angle of outer rear wheel:* β(or)* = 20,22 [°]
- *Mean angle of the rear wheels:* β(mr)* = 23,58 [°]
- *Angular difference between the inner and outer wheel:* Δβ = 8,10 [°]

**if=inner front, of=outer front, mf=mean front, ir=inner rear, or=outer rear and mr=mean rear*

Rear wheel angles (second drive axle lifted)
- *Steering angle of inner rear wheel:* βi2* = 35,67 [°]
- *Steering angle of outer rear wheel:* βo2* = 26,12 [°]

**βi2=inner tag axle steering angle when second drive axle is lifted, βo2=outer tag axle steering angle when second drive axle is lifted*

4.1.2 Competitor analysis and investigation of steering performance of different Volvo FH trucks
This study resulted in an insight into how well the Volvo trucks perform when compared to competitors. It also resulted in reference values for the forthcoming redesign of the tag axle steering system. These values can be viewed in table 2.3-1 and 2.5-1, page 15 and page 18 of this report. When examining the competitor data, it is realized that the Volvo FH-1672 performs well and has a shorter turning diameter than the old Scania truck, despite having a longer wheelbase. The goal of the forthcoming redesigns is to (at minimum) outperform the trucks in this analysis in terms of maneuverability.

4.1.3 Discussions and meetings

In this section, the results of the discussions and meetings are presented.

A day in the field with the Volvo FH-1672, Ed, Sweden

During this day, insights into how the timber truck is used was acclaimed. The truck is mostly driven on gravel roads, which at certain places requires sharp turns or even U-turns. It is therefore realized that a high maneuverability is advantageous. In one day's work, the truck is driven unloaded for half of the total driving distance. This suggests that lifting of rear axles when they are not needed is sought after.

The result of the interview with the driver of the FH-1672 is that the truck performs better and has greater maneuverability than previous unmodified Volvo FHs that he has been using. The ETS1 tag axle steering system has reduced the turning radius and the driver indicated that it should be reduced even further to facilitate his work.

Photos of the truck when loading its cargo can be viewed in figure 2.3-1, page 13 of this report.

Meeting at Volvo Trucks, Lundby, Gothenburg, Sweden

The engineers at Volvo contributed with a lot of valuable knowledge for the continued work. New insights into how turning the tag axle will affect the handling characteristics of the truck were acclaimed. These insights are valuable for the forthcoming evaluation of the redesigns. The team also confirmed that there should be no problems purely in terms of chassis strength when turning the tag axle 180 degrees relative to the chassis.

4.2 CAD study

In this section, the results of the development of the concepts are presented. The results of the template assembly, installation of lifting equipment for the second drive axle and the evaluation of the different concepts are also presented in the following sections.

4.2.1 CAD template assembly

The result of the creation of the template assembly was a 3D model that later on was used to derive the different concepts. This model has all of its components mounted in their original position. The template assembly can be viewed in figure 4.2-1 below.

Figure 4.2-1. CAD template assembly (only rear axles mounted on the chassis frame, the arrow indicates the travel direction of the vehicle).

4.2.2 Installation of lifting equipment for the second drive axle

The standard lifting equipment in figure 4.2-2 below has a lift bracket and air spring members from RADDT-GR with RIH170. The equipment was able to be mounted into the template assembly without any major redesigns, although some changes in pipe and cable routing will be needed. In fact, the spacing around the second drive axle, chassis etcetera was identical to that of an original 6x4 assembly.

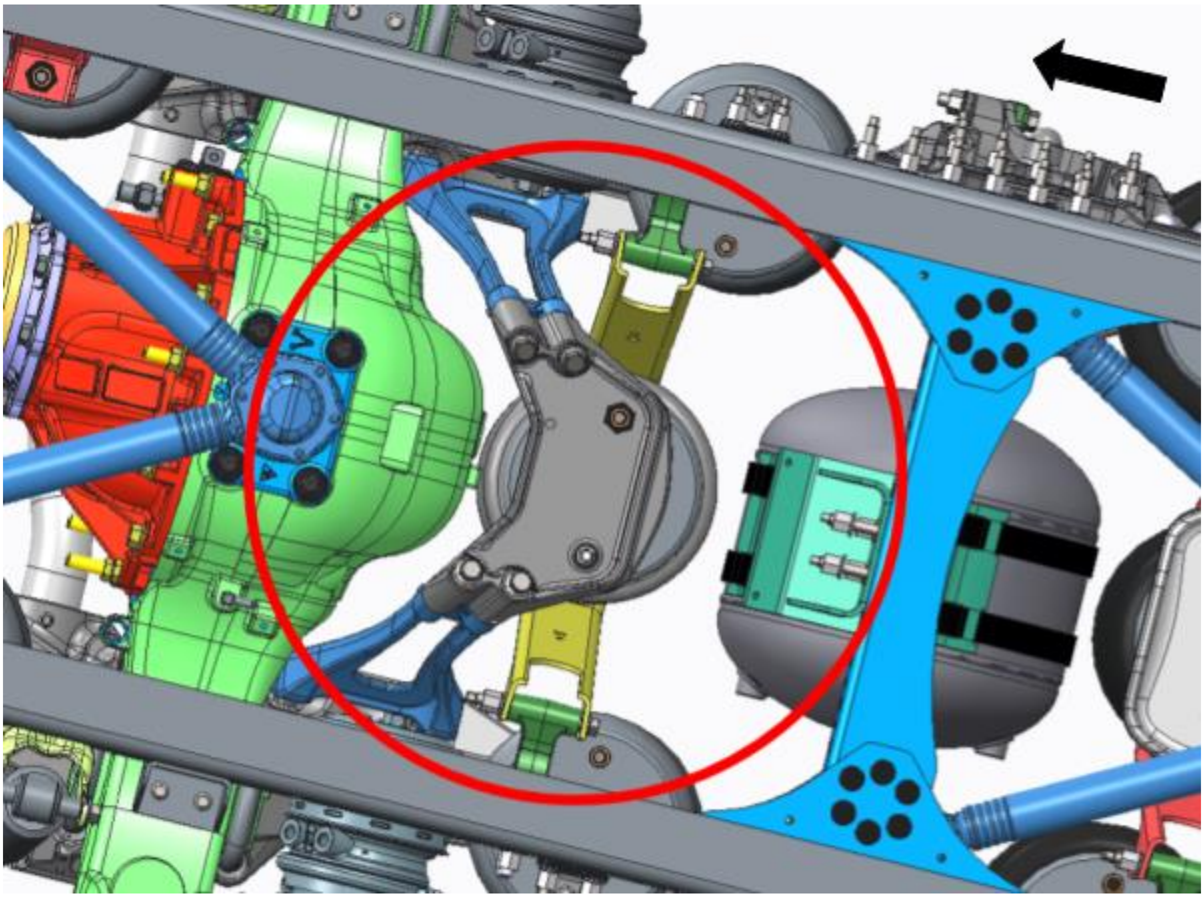

Figure 4.2-2. Close up image of the mounted lifting equipment for second drive axle (marked with a ring, the arrow indicates the travel direction of the vehicle).

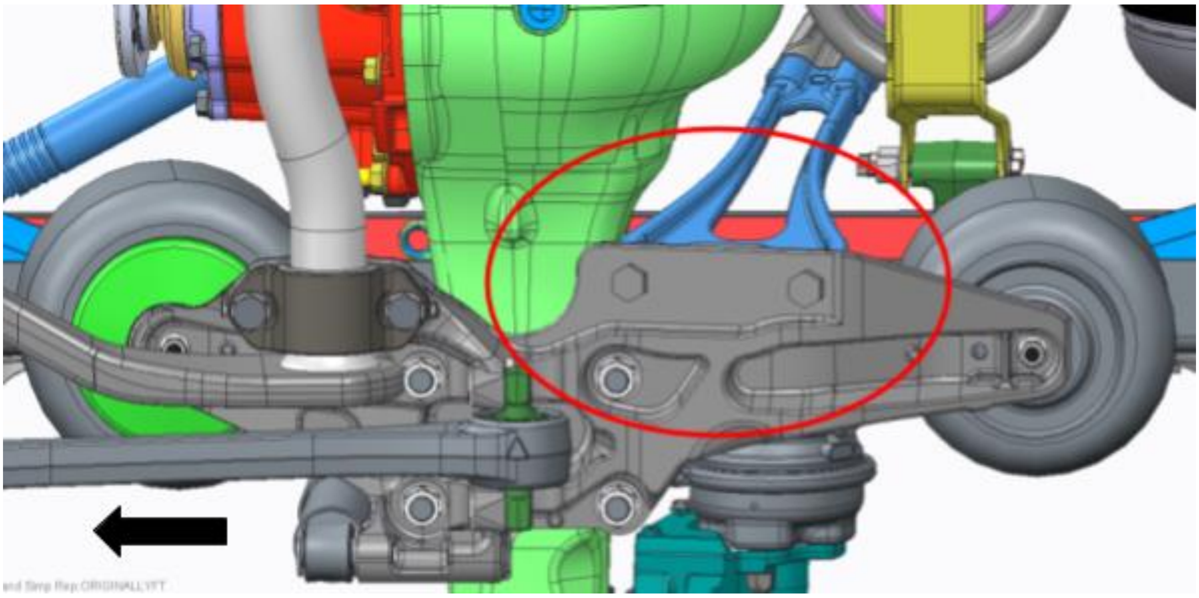

Figure 4.2-3. Shows one of two new air spring members with mounts (the right side mount is marked with the ring) for the lifting equipment (the arrow indicates the travel direction of the vehicle).

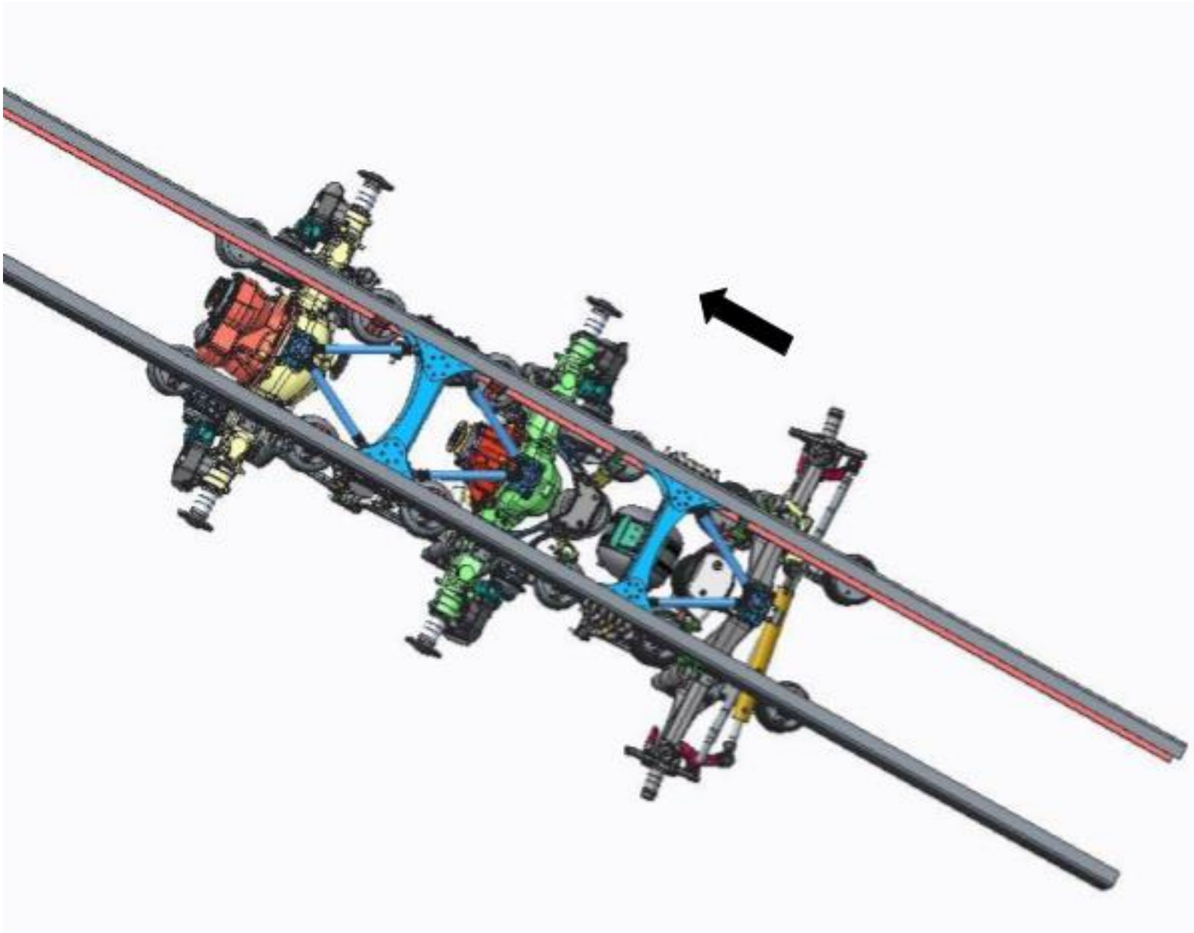

Figure 4.2-4. Chassis overview with mounted lifting equipment for second drive axle (the arrow indicates the travel direction of the vehicle).

4.2.3 Creating CAD concepts

In this section, the results from the generation of different CAD concepts are presented. Three different concepts were derived from the template assembly. In this part of the work it was realized that the wanted steering geometry could possibly be achieved without turning the whole tag axle assembly around. Concept 2 is an example of an idea of this type. The combination of brainstorming and help from the Volvo and ÅF engineers resulted in this new approach of the problem.

Concept 1

Concept 1 is based on the idea of taking the tag axle system with all of its constituent parts off the chassis and then turning them 180 degrees around (relative to the chassis). Therefore, the components that are mounted on the tag axle itself will stay in the same position relative to each other. The tag axle is still placed at the same distance from the second drive axle, 1380 [mm]. Turning the tag axle frees space for the steering components as explained in chapter 2.2. If the steering components then were to be redesigned, the steering geometry would become more advantageous. This is due to the rod arms pointing towards each other instead of pointing outwards (this was also explained in chapter 2.2).

A problem with this concept is that the caster angle becomes negative. This angle need to be positive as explained in the chapter 2.4. Because of this, the tag axle itself need to be redesigned.

Turning the tag axle will affect many components of the truck. Cross member, brackets, routing of air/hydraulic pipes/hoses and electric cables needs to be rearranged. Everything that has to be rearranged or redesigned results in an extra cost and therefore has to be avoided if possible.

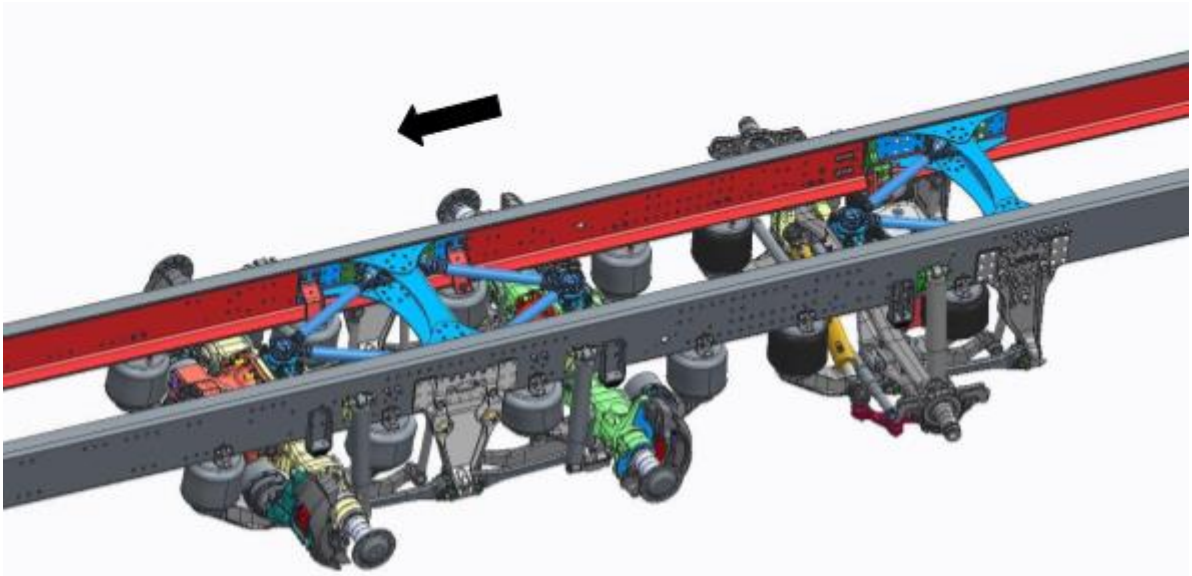

Figure 4.2-5. Overview of concept 1 (the arrow indicates the travel direction of the vehicle).

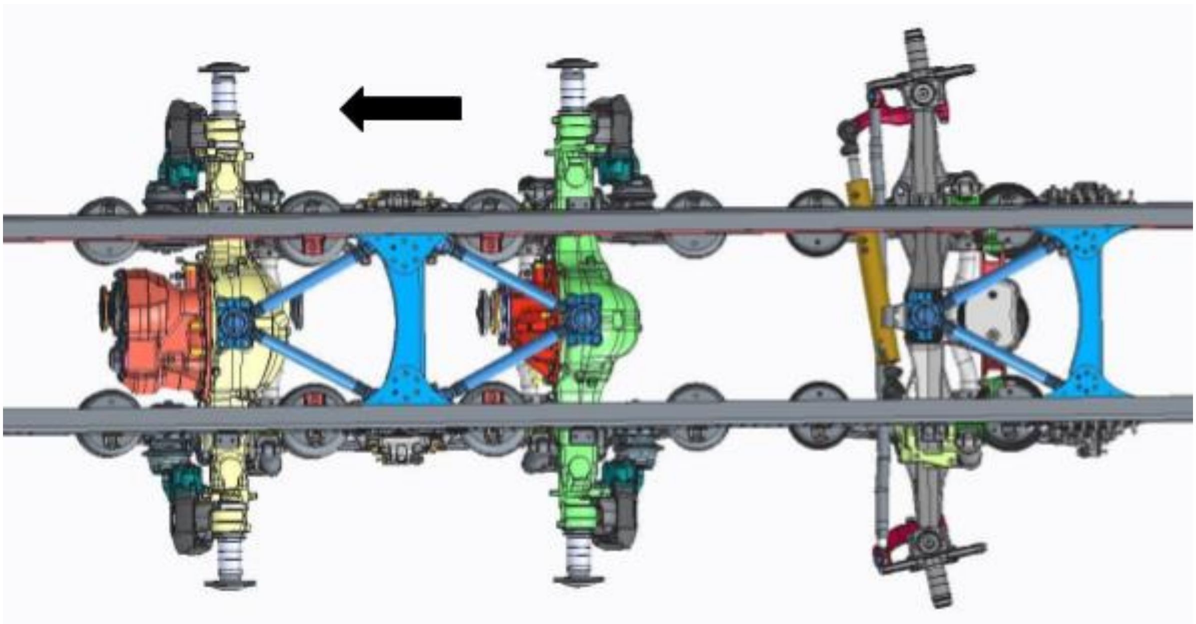

Figure 4.2-6. View from above, concept 1 (the arrow indicates the travel direction of the vehicle).

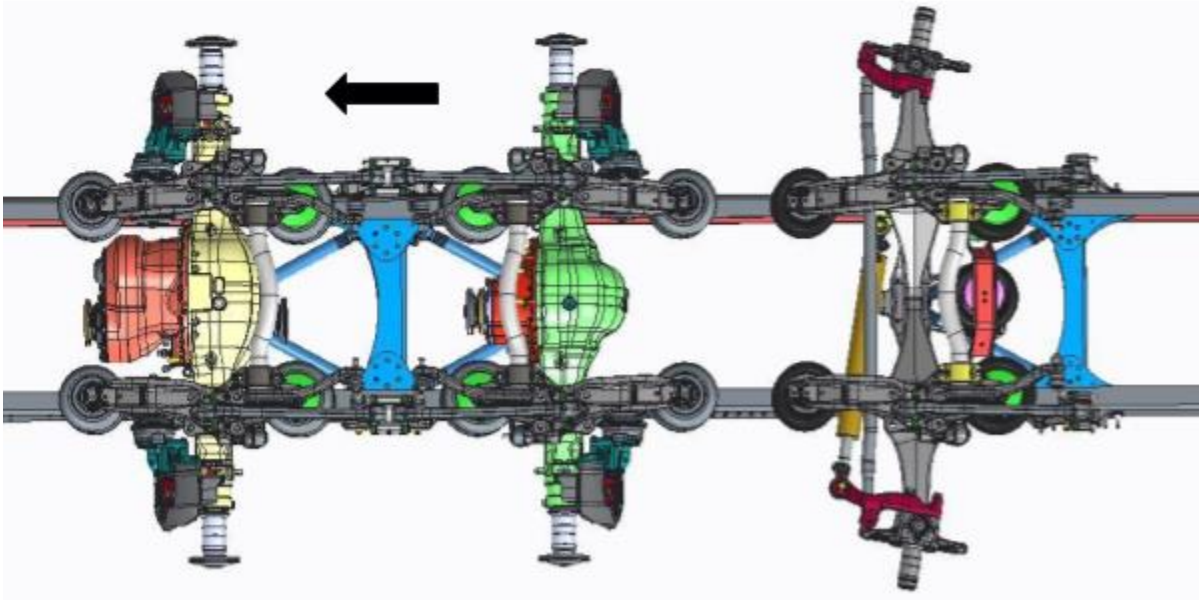

Figure 4.2-7. View from below, concept 1 (the arrow indicates the travel direction of the vehicle).

Concept 2

Concept 2 is based on the idea of keeping the tag axle system in its original orientation and placement but installing new steering components. The new system includes two separate steering cylinders, each steering one of the wheels separately. The system will include either linear sensors on the cylinders or angle sensors in the steering knuckle to measure the exact turning angle of the wheel in real time. By programming the ECU for the tag axle steering for different truck configurations, true Ackermann steering can be achieved for a wide range of setups. For example, if the second drive axle was to be lifted, there would be an offset of the trucks center of rotation. Then the ECU could adjust the steering angles for Ackermann of the tag axle wheels accordingly.

However, removing the tie rod completely results in a case where the level of safety of the system cannot be easily determined. A failure of the system can cause the wheels to steer in different directions, unlike the original solution with a tie rod. As mentioned in the pilot study, the tag axle only steers at low speeds. A possible safety measure could be some sort of mechanical lock that ensures that the wheels stay in a locked position parallel to the chassis at high speeds. However, this subject need further investigation.

Screenshots taken in Creo Parametrics of concept 2 are presented below in figures 4.2-8 to 4.2-11.

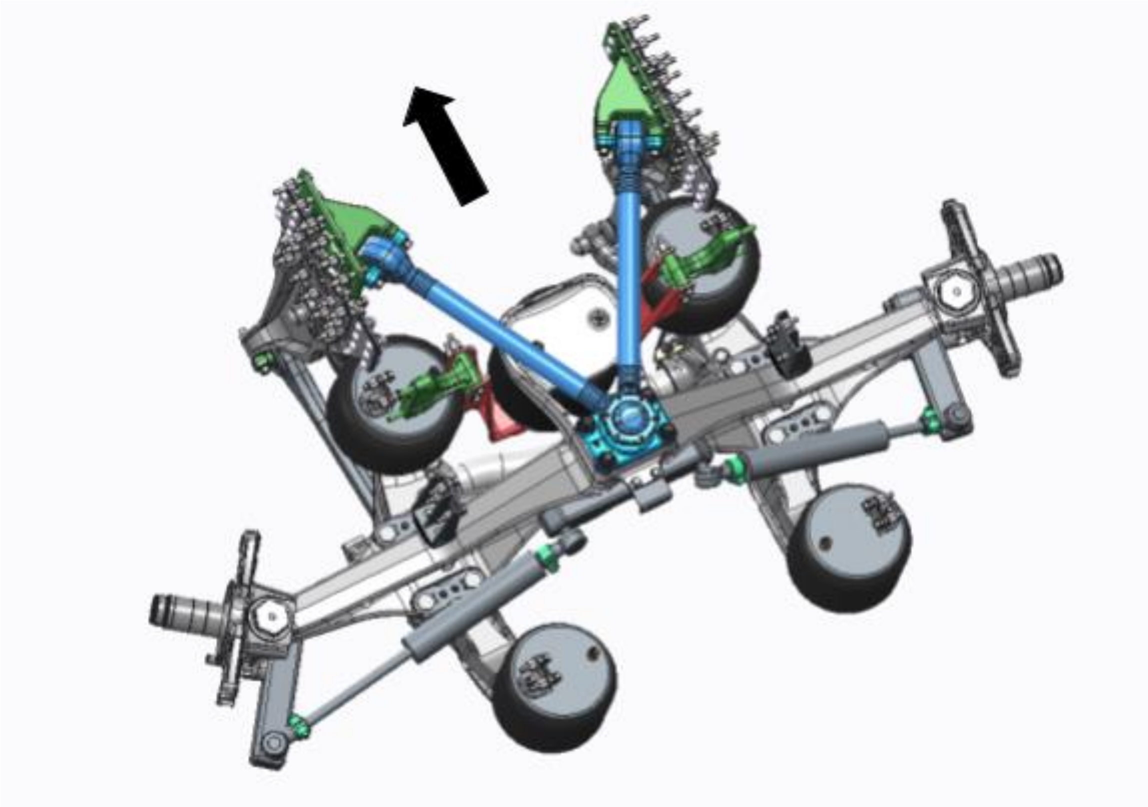

Figure 4.2-8. Overview of concept 2 (the arrow indicates the travel direction of the vehicle).

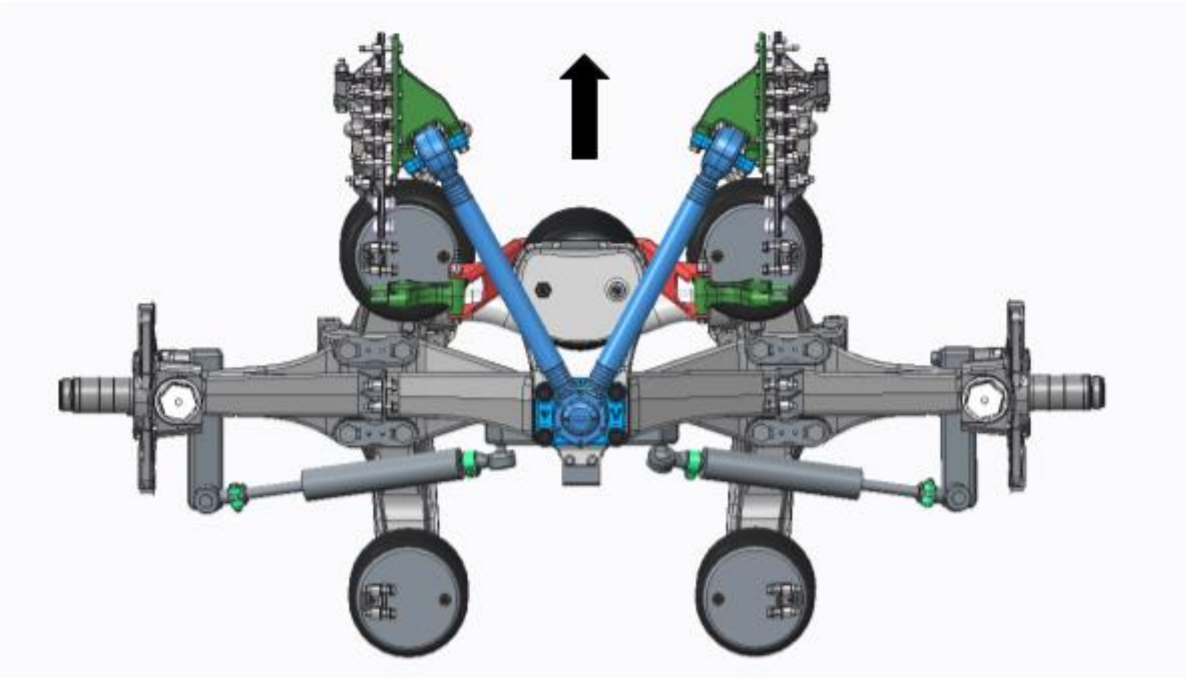

Figure 4.2-9. View from above, concept 2 (the arrow indicates the travel direction of the vehicle).

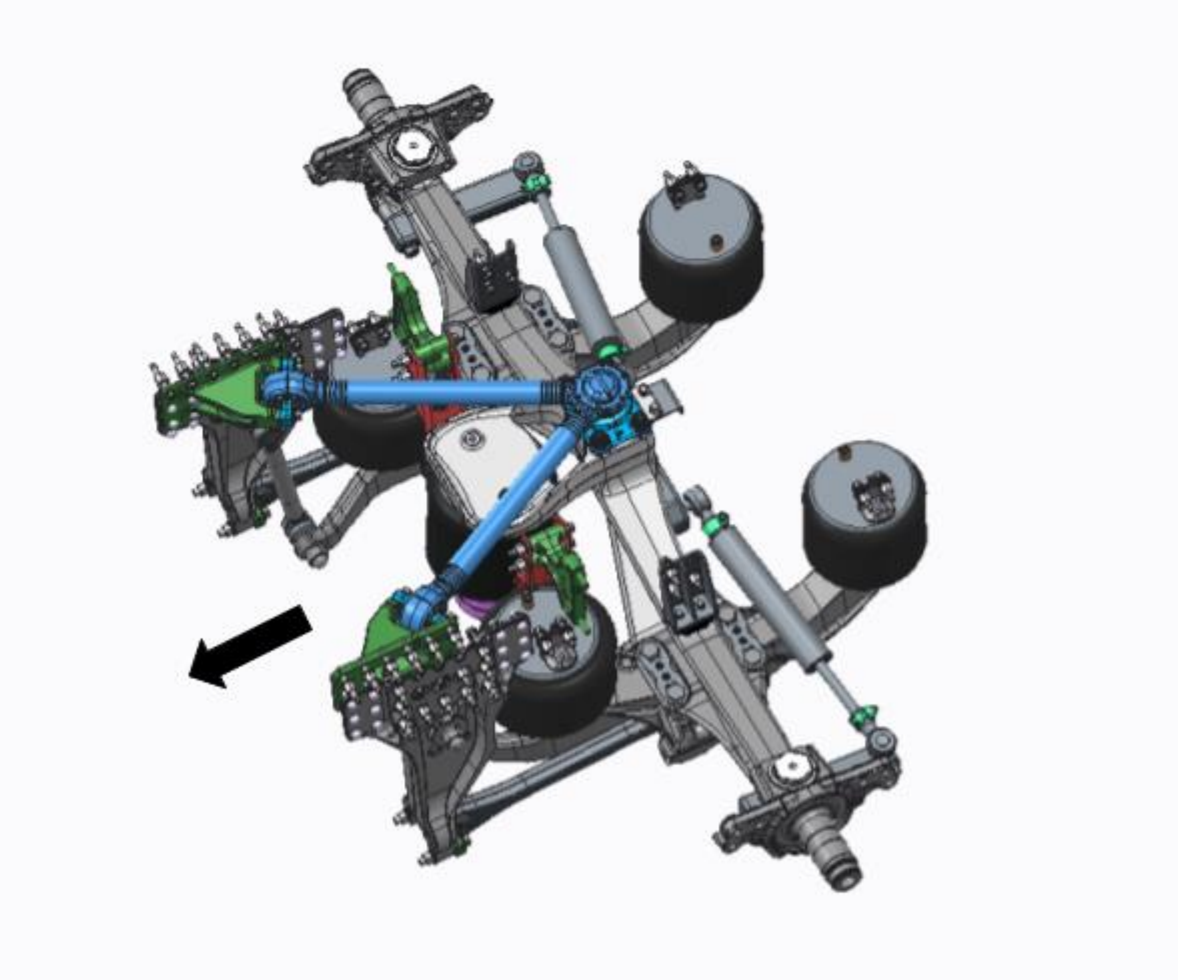

Figure 4.2-10. View from the left side, concept 2 (the arrow indicates the travel direction of the vehicle).

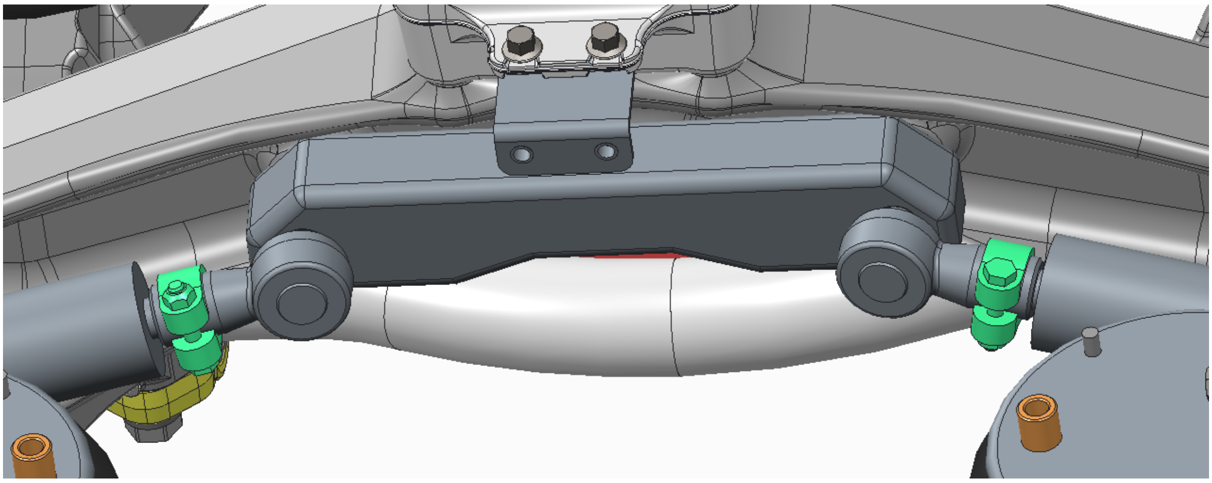

Figure 4.2-11. Steering cylinder adapter, concept 2.

Concept 3

Concept 3 is based on the idea of only turning the air spring members on which the tag axle is mounted. This will free space for the steering components ahead of the tag axle. Therefore, Ackermann steering geometry can be achieved. Unfortunately, this concept will require major redesigns. After studies and measurements in Creo Parametrics, it was clear that the two front air springs clashes with the reaction rod bracket. Also, the air spring members would need to be modified due to clashes with the reaction rod. These clashes are affecting crucial parts of the rear axle suspension and would essentially result in an extensive redesign of the whole suspension. However, two advantages with this concept are that the wanted steering geometry can be achieved and that the caster angle of the kingpin is still positive.

The figures 4.2-12 and 4.2-13 below shows the concept assembly and critical areas where some components clash. The clashes can be viewed in figure 4.2-13. The left circle in figure 4.2-13 highlights the clash between the reaction rod bracket and the air spring. The right circle in figure 4.2-13 highlights the clash between the air spring member and the reaction rod.

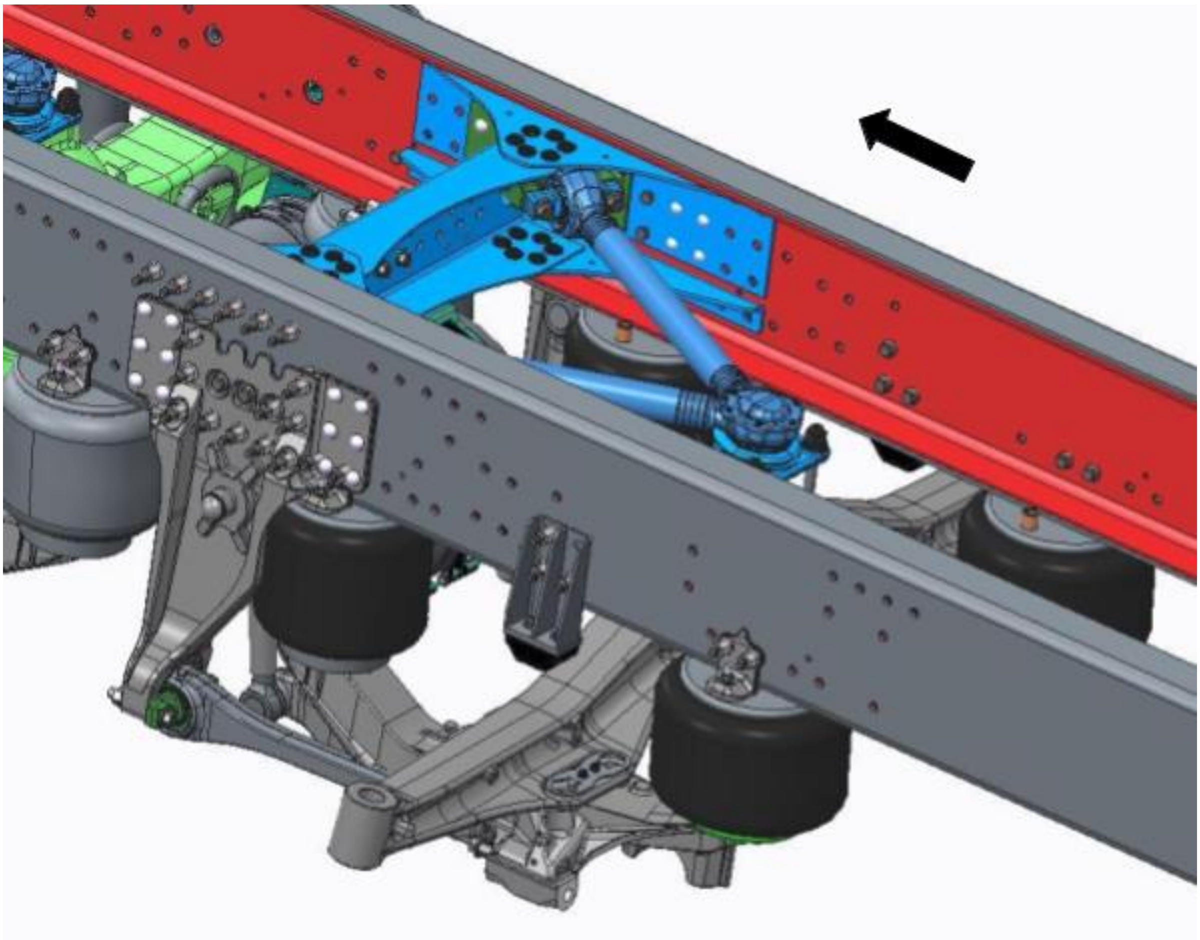

Figure 4.2-12. View from the left side, concept 3 (the arrow indicates the travel direction of the vehicle).

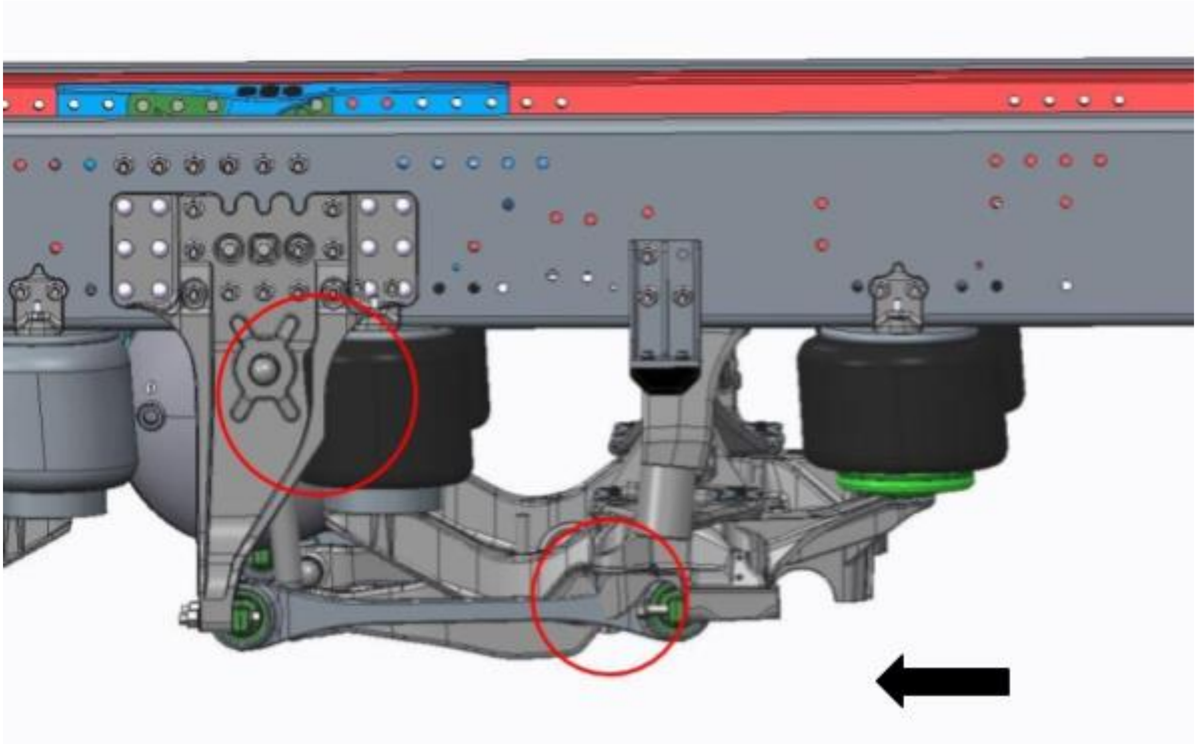

Figure 4.2-13. Clashes in the concept 3 assembly. The arrow indicates the travel direction of the vehicle.

4.2.4 Evaluation of the concepts

The evaluation of the three former concepts resulted in two winning concepts that were chosen for further work. These are concepts 1 and 2.

The team of engineers that were present during the mid-project presentation suggested that concept 1 and 2 should be developed parallelly. The overall opinion of concept 3 was that the substantial clashes in the assembly would result in extensive redesigns of the whole tag axle assembly. There was also uncertainty of how it would affect the truck handling.

The former was also confirmed using a Kesselring matrix as mentioned in the methodology. The matrix is presented below:

Matrix 4.2-1. Kesselring matrix.

Kesselring matrix					
Factors	**Concept 1**	**Concept 2**	**Concept 3**	**Reference**	**Comments**
Achives Ackermann geometry between the tag axle wheels	4	5	3	1	Concept 1 only achives Ackermann when all of the axles are lowered, not when the second drive axle is hoisted up. The same goes for the reference.
Achives sufficient steering angles for true Ackermann steering	5	5	3	2	-
Usage of CAST parts	3	3	1	4	High score means usage of mostly CAST parts
Overall safety of the system	4	2	4	4	-
Has minor influence on driving characteristics of the truck	1	4	3	3	-
Low cost (approximation)	2	2	1	3	-
Simplicity	3	1	1	3	-
					-
					-
Total score:	22	22	16	20	-
Final answer: Concept 1 and 2 both have the same score of 19.					

As seen in matrix 4.2-1 above, concept 1 and 2 achieved the highest overall scores.

4.3 Further development of the winning concepts

In this section, the results of the development of the two winning concepts are presented.

4.3.1 Development of concept 1

Turning the tag axle frees space for the new steering components as explained in chapter 2.2. But to achieve Ackermann steering geometry and to increase the maximum steering angle new tie rod arms are required. Calculations were made with respect to the Ackermann steering geometry to figure out the required dimensions of the new tie rod arms, when second drive axle is not lifted. However, the scenario which demands the largest steering angles was taken into account. As explained in the pilot study shorter wheelbase demands larger steering angles. New simplified tie rod arms were designed in Creo Parametrics to analyze space claim and movement. This analysis gave input to the definitive design for the new arms. For instance, it showed that the tie rod needs to be placed further away from the tag axle. When creating the new arms there were some other factors which influenced the design. Tie rod arms are forged, therefore a draft angle is required to make the manufacturing possible. Figure 4.3-1 and 4.3-2 below presents the new arms.

The movement analysis of this concept showed that there is a need for a steering cylinder with a greater stroke to achieve the desired maximum and minimum steering angles (+36 to -27 degrees, (+) means clockwise rotation for the left side, (-) means counterclockwise rotation for the left side and vice versa for the right side). In the assembly of concept 1, the steering cylinder was acquired from a Volvo standard tag axle system.

The new tie rod arms provide true Ackerman for the steering angles of +28,32 to -20,22 (the case when all axles are lowered). Although, the concept is designed so that it can achieve +36 to -27 degrees without clashing but with non-Ackermann geometry. This is because the steering geometry of concept 1 is fixed.

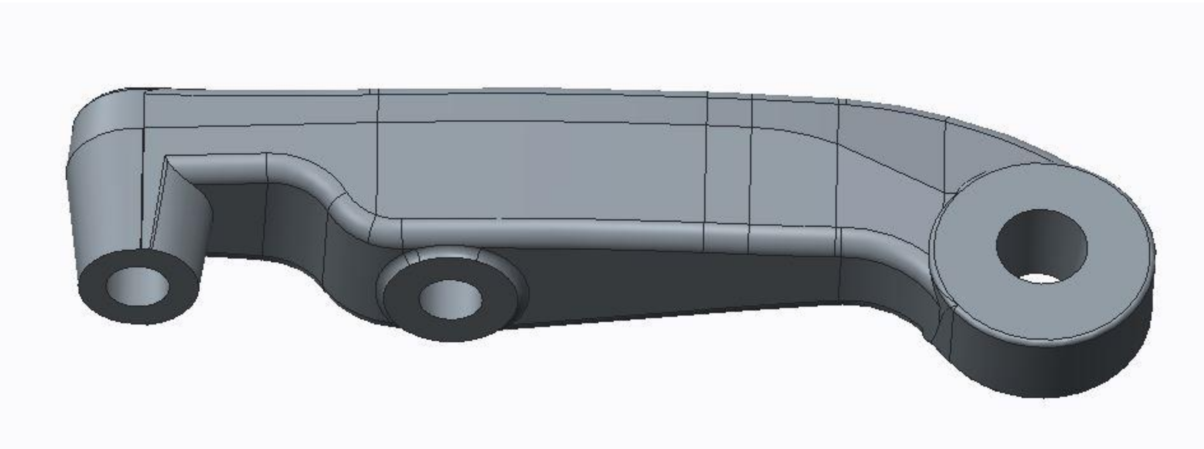

Figure 4.3-1. The redesigned left tie rod arm of concept 1.

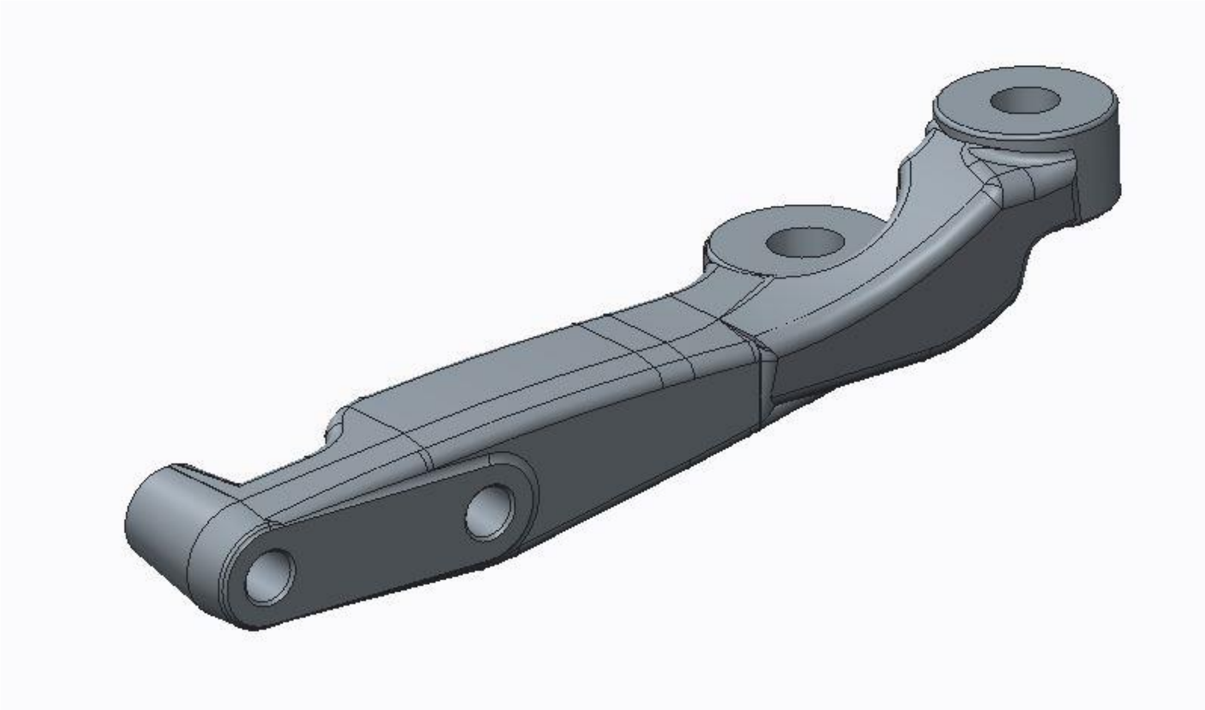

Figure 4.3-2. The redesigned right tie rod arm of concept 1.

Figures of the concept 1 CAD assembly are presented below in figures 4.3-3 to 4.3-5.

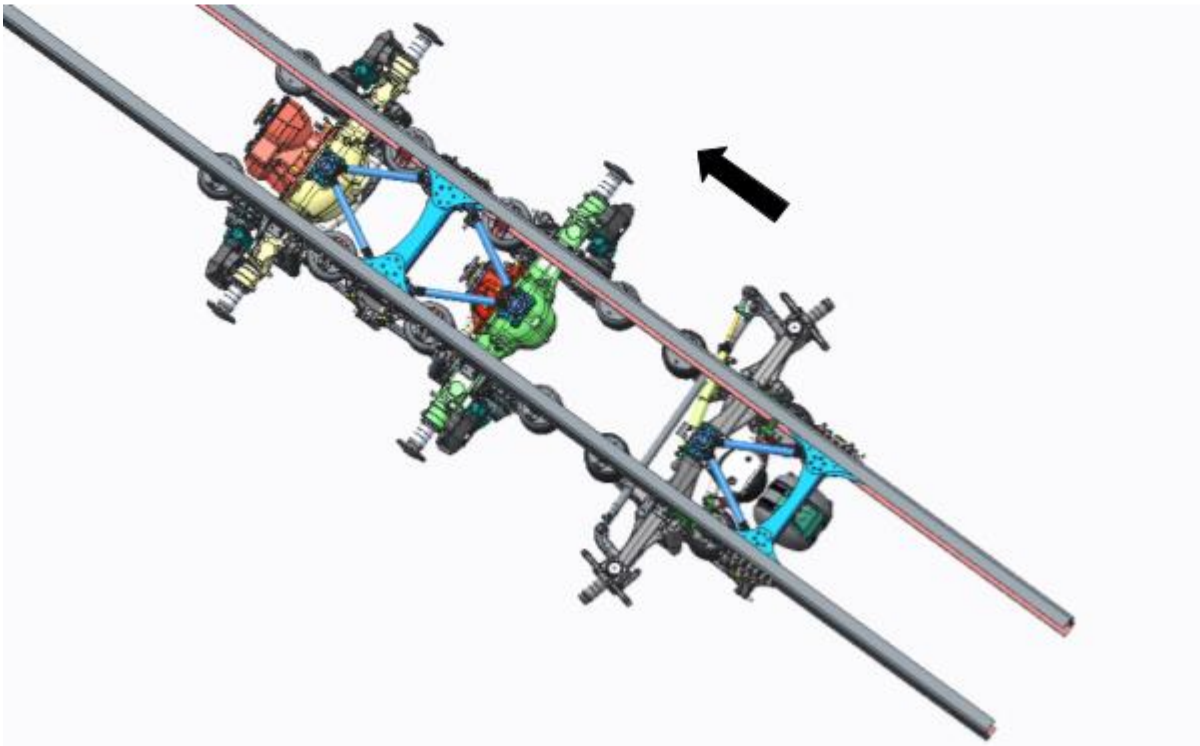

Figure 4.3-3. Overview of concept 1 (the arrow indicates the travel direction of the vehicle).

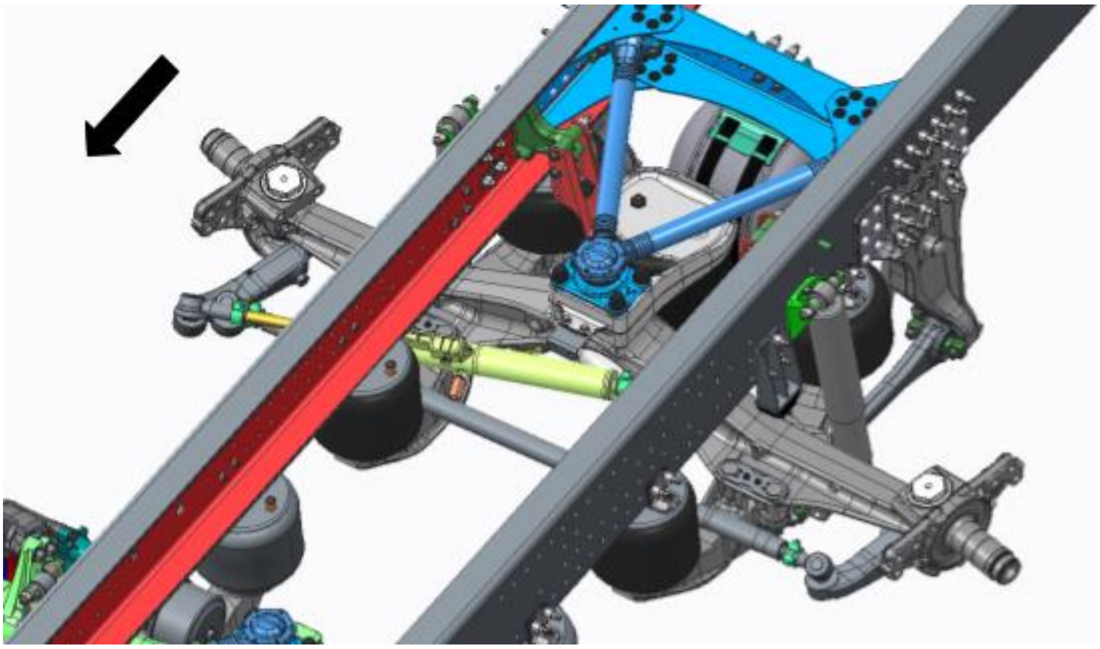

Figure 4.3-4. Close up of concept 1 from above (the arrow indicates the travel direction of the vehicle).

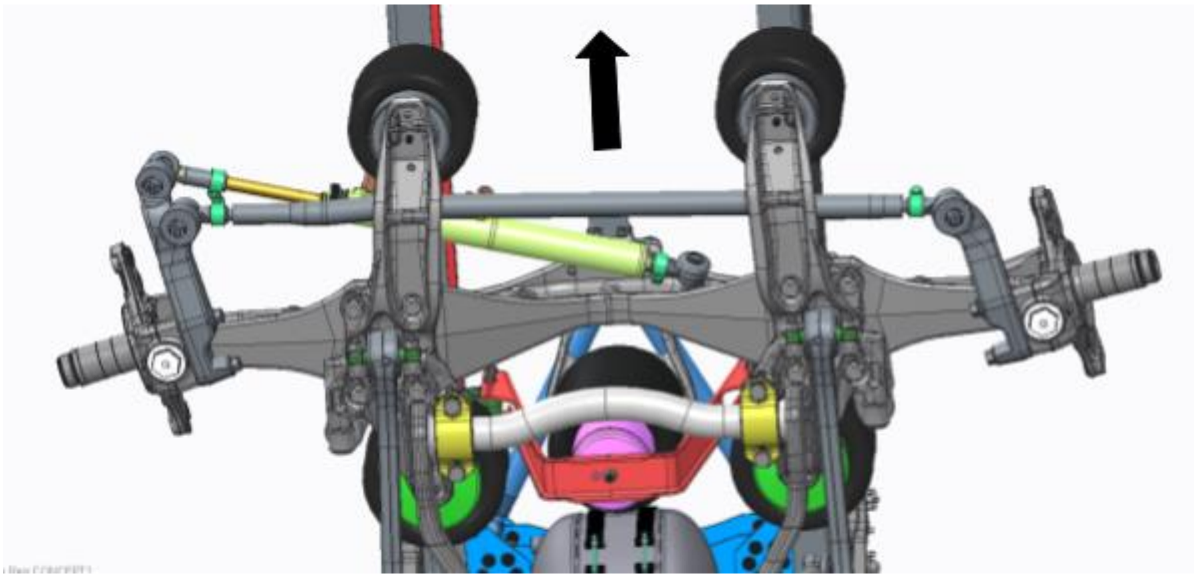

Figure 4.3-5. View of concept 1 from underneath (the arrow indicates the travel direction of the vehicle).

Components of concept 1 (brand new, modified and/or CAST components):
To reduce cost and complexity, the concept need to consist of as many standard (CAST) Volvo parts as possible. To achieve Ackermann geometry, concept 1 need a set of new tie rod arms. These would be the only new parts in need of manufacturing. Other components of this concept have been produced from modified CAST parts and are listed below.

List of concept 1:s constituent parts that has been added or changed:
1. Two new tie rod arms. These components will have to be forged.

2. Modified, shorter tie rod. It could be manufactured by modifying an existing CAST tie rod.

3. Modified tag axle, the kingpin needs a positive caster angle.

4. Rearrangements of the cable and pipe routing.

Figure 4.3-6 below presents some of the components listed above in the actual CAD assembly.

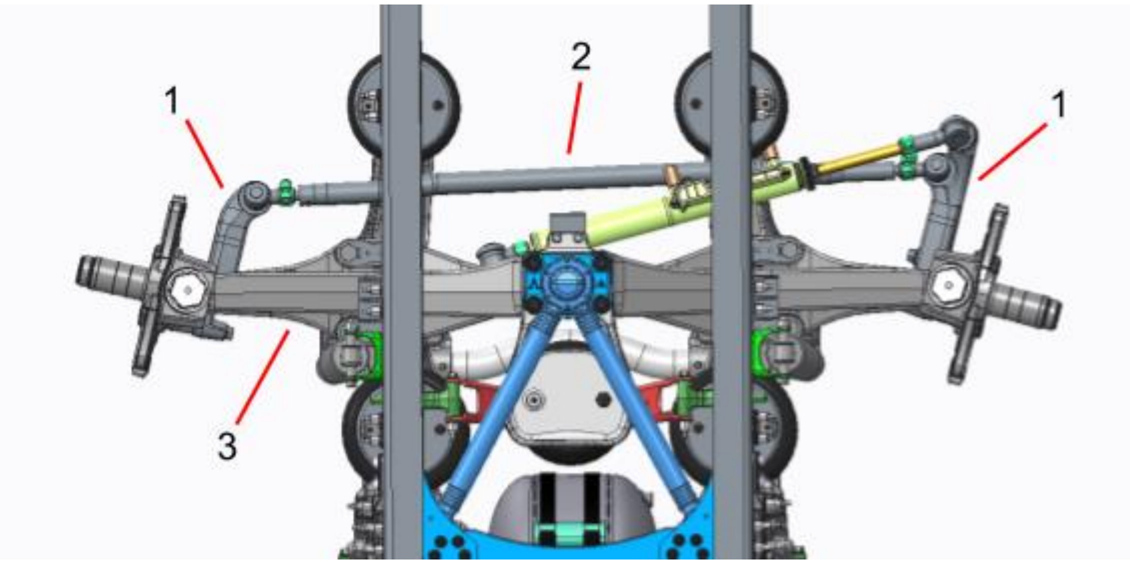

Figure 4.3-6. Numbering (see list above figure) of new/changed components of concept 2.

FEM calculations of new tie rod arm

It is of great importance that components like tie rod arms cope with the high loads that they might be exposed to, due safety. A broken tie rod arm can cause fatal accidents. Therefore, the stresses of the tie rod arms need to be analyzed. This analysis was performed on only one of two tie rod arms because of time limitation. The loads acting on a tie rod arm are static load (approximation): 10 [kN] and chock load: 40 [kN] [3]. In the FEM analysis, the load acting on the tie rod arm was set to 40 [kN].

Different directions of the loads were tested to simulate every possible case. Appendix 2, page 54, demonstrate the constraints and the different directions of the loads.

Figure 4.3-7 below presents the result of an analysis of the new arm, when it is exposed to a load according to figure A2 in appendix 2. According to the FEM results the highest stress occurs at an edge where the arm is attached to the steering knuckle by screw joints. Pay attention to the scale in the corner of the picture. The stresses at this edge are much higher than anywhere else.

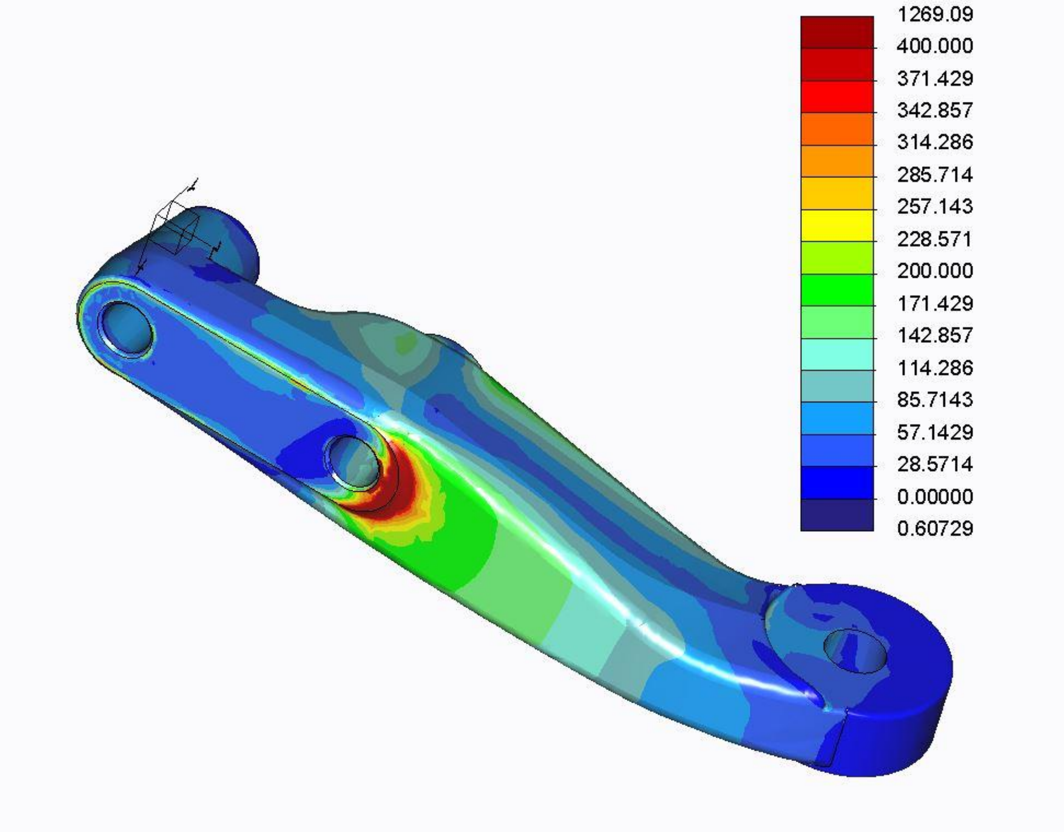

Figure 4.3-7. FEM result of the new tie rod arm with loads and constraints according to A2, appendix 2 (scale in [MPa]).

The figure below shows the opposite side of the new tie rod arm.

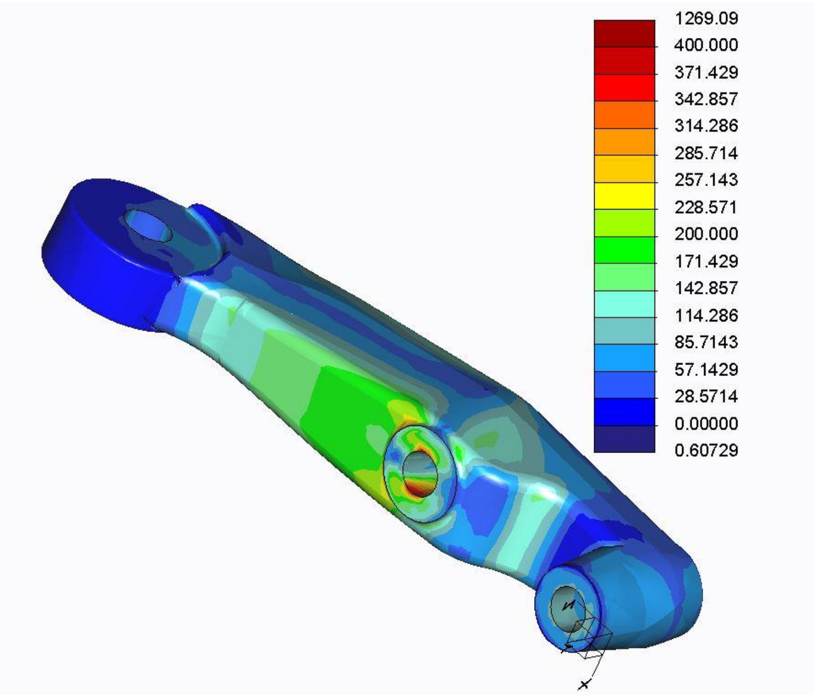

Figure 4.3-8. FEM result of the new tie rod arm with loads and constraints according to A2, appendix 2 (scale in [MPa]).

An easy and useful way to analyze results from FEM calculations is to compare results of new components with results of previous components. If the results are similar, the stresses in the new components will with great probability be acceptable.

The new tie rod arm results are compared to results of an old standard tie rod arm. The stresses of the standard and new arm it is realized that they are approximately the same. The stresses in the new arm are most likely acceptable. However, the tie rod arms are components which demand a high level of safety. Therefore, the FEM results would need to be verified using a test rig.

Figure 4.3-9 below demonstrates the FEM results of the new tie rod arm with loads and constraints according to figure A3, appendix 2. Stresses in the new arm are approximately the same as in the old standard arm. The highest stress is located at the edge where the arm is attached to the steering knuckle.

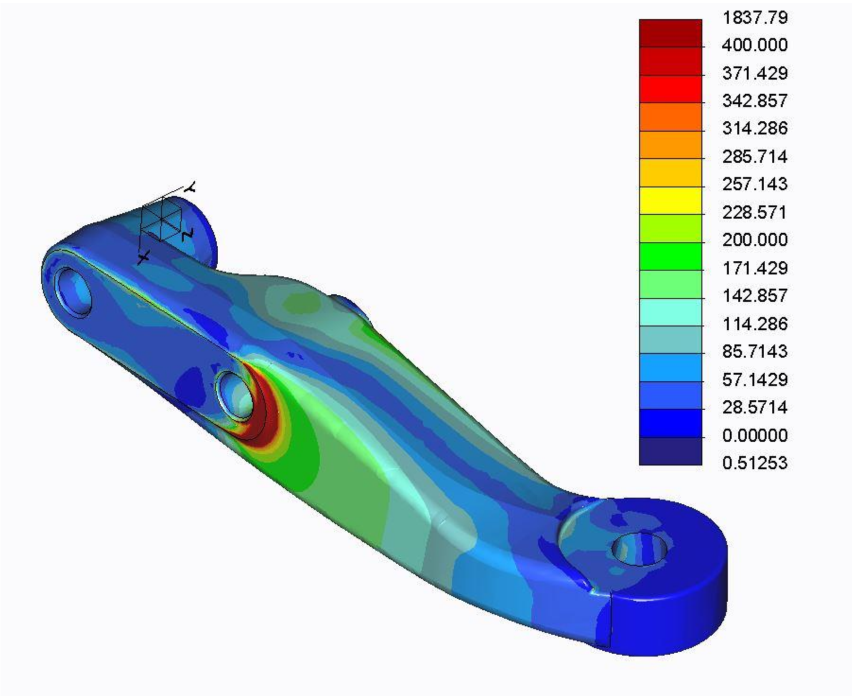

Figure 4.3-9. New tie rod arm with loads and constraints according to A3, appendix 2 (scale in [MPa]).

The tie rod arms are forged components which are made of a high strength steel alloy [3]. This steel has the properties presented below.

Material properties:
$R_{p0.2}$ = 690 [MPa]
R_m = 900-1050 [MPa]

According to the material properties, stresses are higher than the ultimate tensile strength in some small areas of the arm. This applies to both the new and old arms. However, this is not a problem. The old arm has been used and tested and it is proven that the design withstands the loads. Also, as previously mentioned, the loads used in these FEM calculations are chock loads, and they probably only occur extreme cases like during an accident e.g. The high stresses only occur in small areas of the tie rod arm and after time they decrease due to material deformation.

The two figures below show the displacement of the new tie rod arm. In this calculation, the arm has loads and constraints according to figure A2, appendix 2. The displacement of the new arm is somewhat lower than the current.

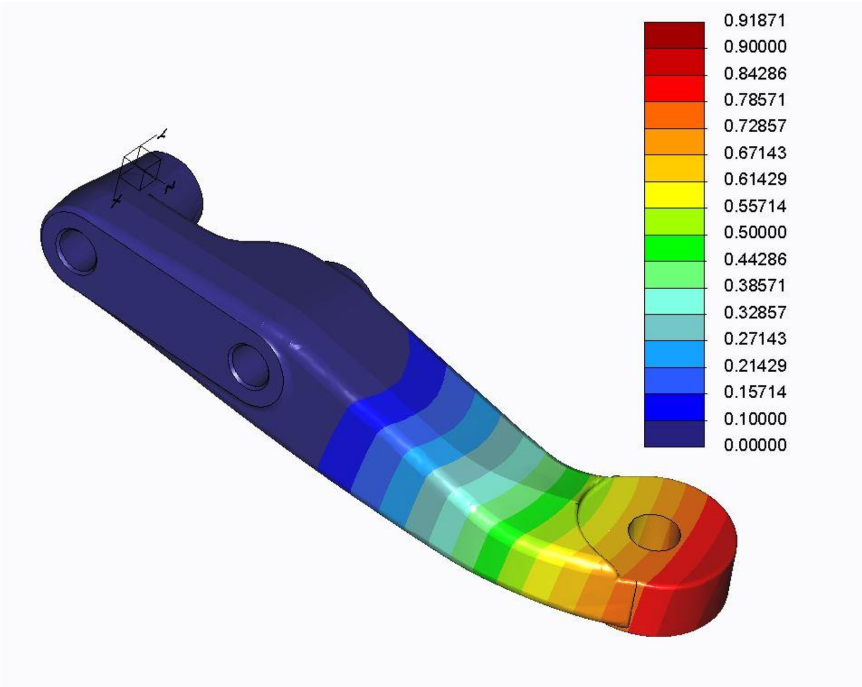

Figure 4.3-10. Displacement, new tie rod arm (scale in [mm]).

4.3.2 Development of concept 2

During the development of concept 2, the steering cylinder adapter was redesigned. It was extended backwards to free space between the tag axle and the steering cylinder. A motion analysis and angle measurement of the steering system showed that this extra space allowed the concept to achieve +36 to -27 degrees (steering angle) without any clashing of the different components. The new adapter is presented in figure 4.3-11 below.

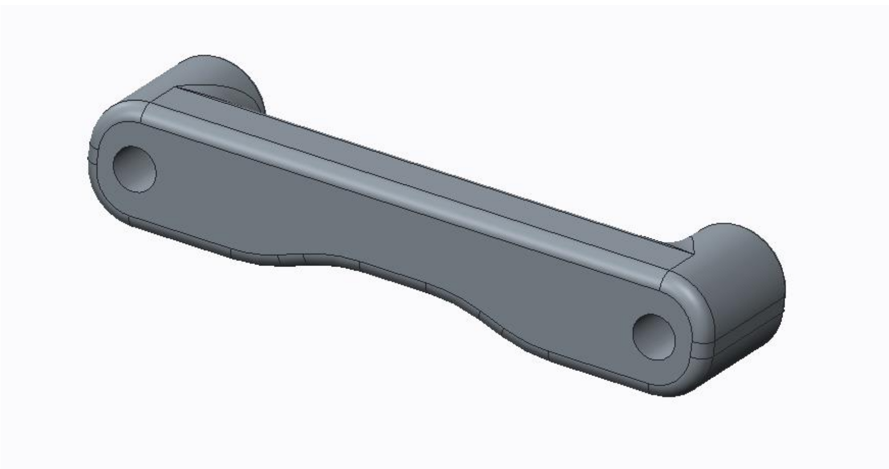

Figure 4.3-11. Redesigned steering cylinder adapter.

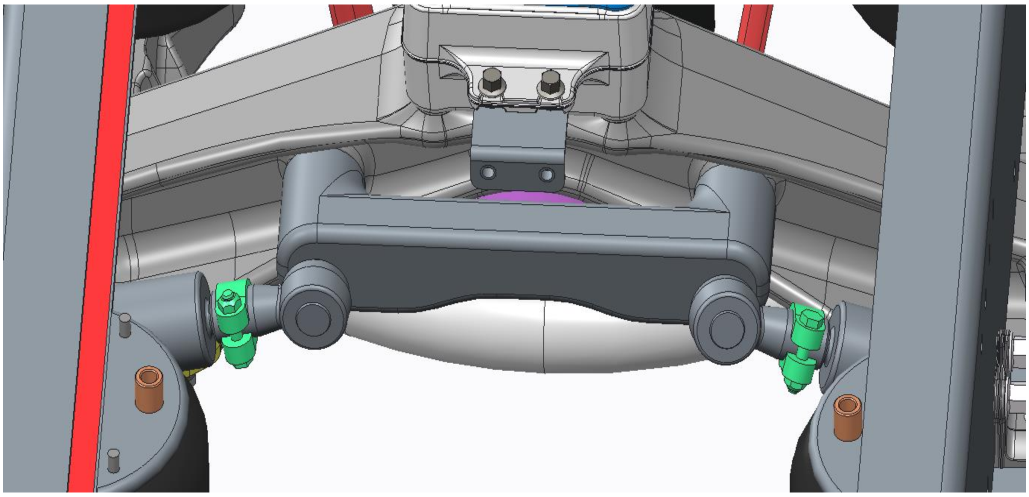
Figure 4.3-12. Redesigned steering cylinder adapter, mounted on the tag axle.

Concept 2 was also fitted with two new tie rod arms. These were taken from an existing Volvo tag axle system with fixed tie rod arms (these arms can be viewed in figure 4.3-22 below). Therefore, the concept only needs two new steering cylinders and the adapter. The ball joints were taken from Volvo's CAST range, with an exception for two ball joint pins that are assembled into the adapter holes. The new steering cylinders have a stroke of 255 [mm] to achieve the required steering angles. The outer diameter of the cylinder housing and the piston are equivalent to that of a standard Volvo tag axle steering cylinder. Because this concept has two cylinders, it needs added hydraulic routing.

The concept also has two angle sensors placed in the two steering knuckles. These sensors read the wheels steering angles in real time and sends the information to an ECU. To achieve true Ackermann steering for different truck setups the steering system of this concept needs to be reprogrammed so that it steers at the needed angles of the particular truck setup. Furthermore, this system needs added electrical cable routing when compared to the original steering system due to the added angle sensor.

Presented below in figures 4.3-13 to 4.3-16 are screenshots taken from the CAD assembly of concept 2.

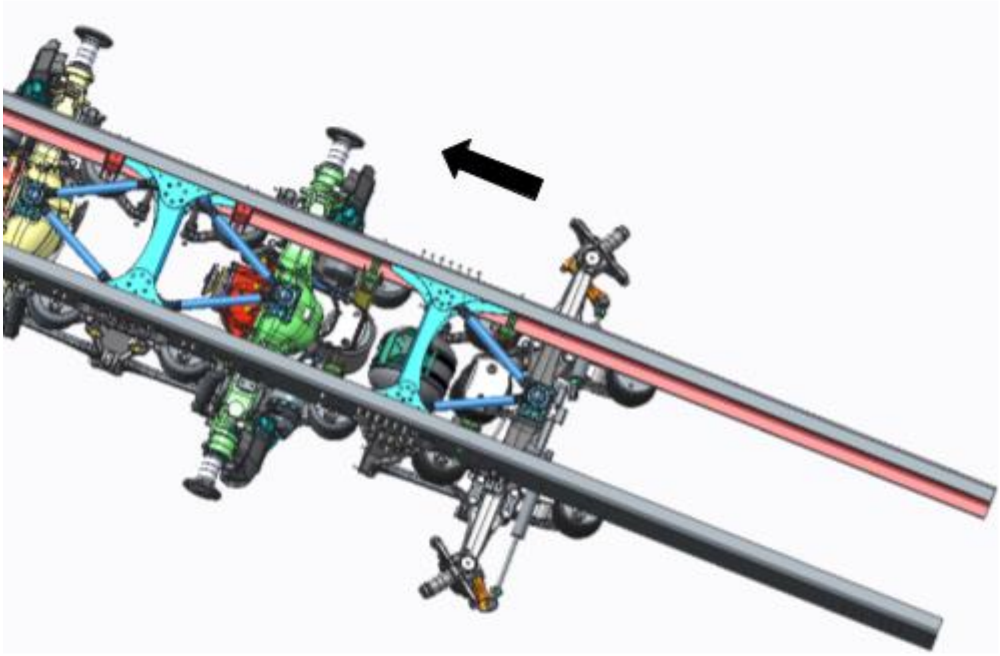

Figure 4.3-13. Overview of concept 2 (the arrow indicates the travel direction of the vehicle).

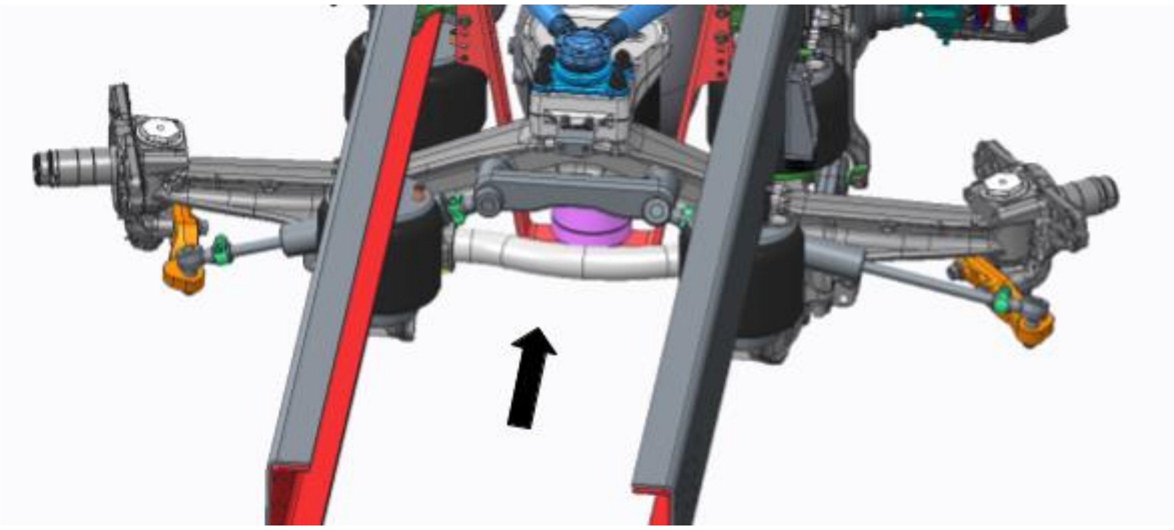

Figure 4.3-14. Close up of concept 2 (the arrow indicates the travel direction of the vehicle).

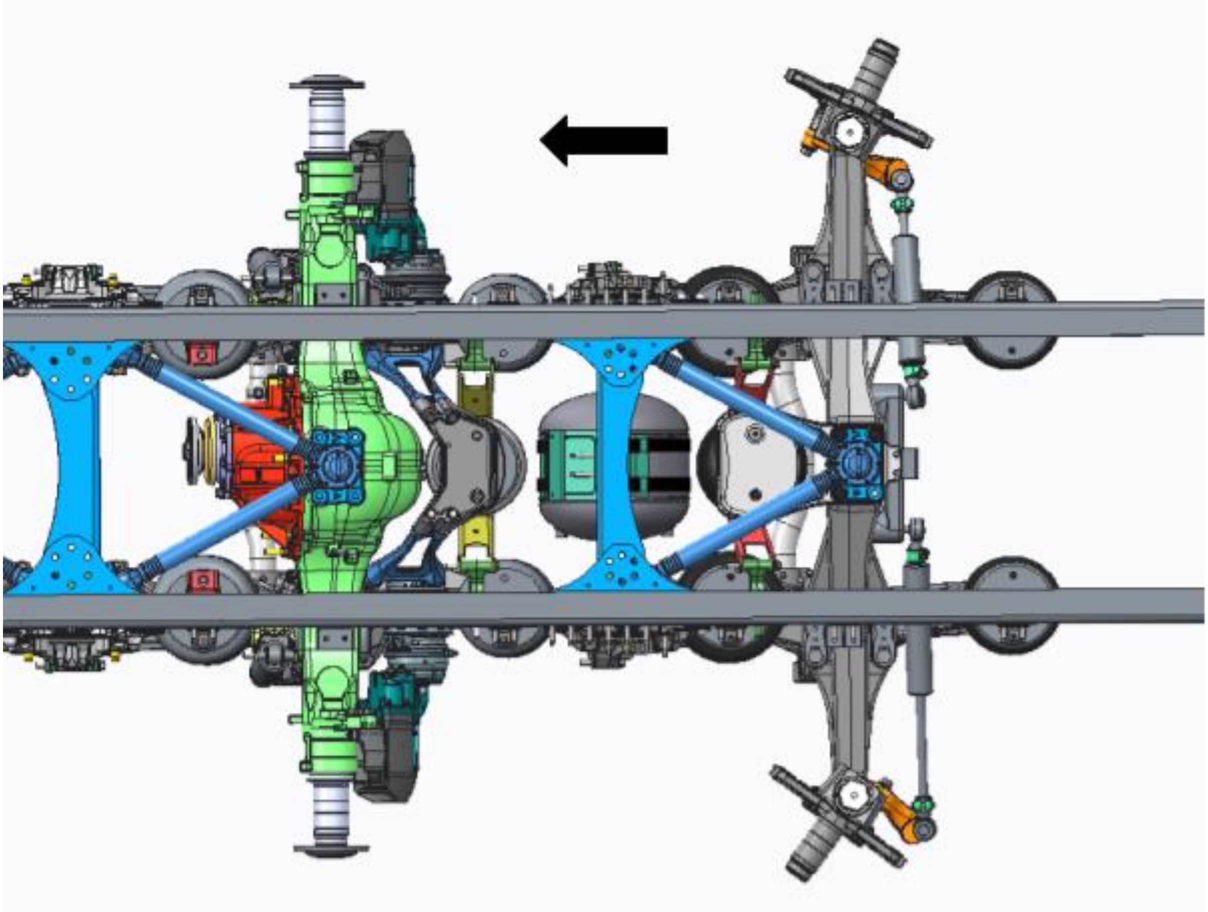

Figure 4.3-15. View from above, concept 2 (the arrow indicates the travel direction of the vehicle).

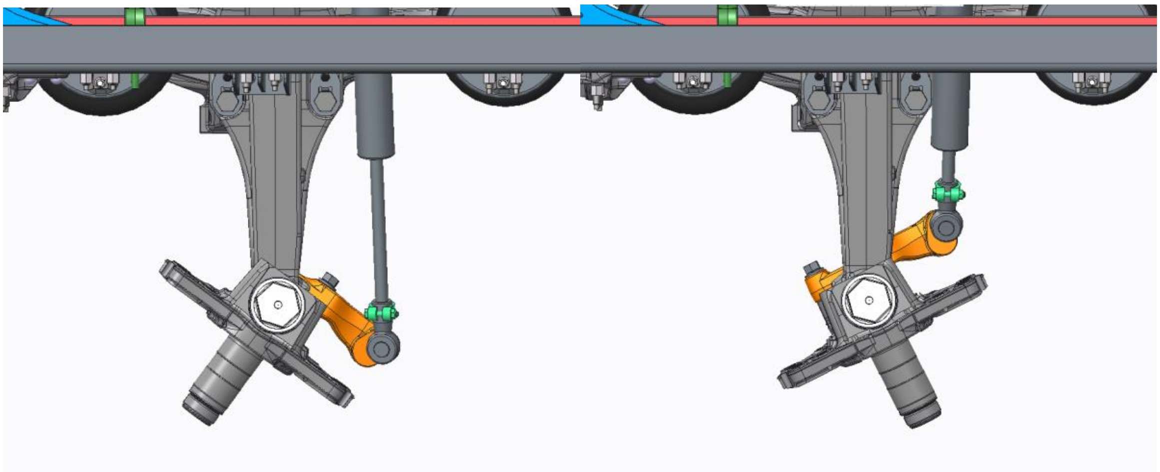

Figure 4.3-16. Steering angles of +36 degrees (left image) and -27 degrees (right image), concept 2 (screenshots taken on the left side of the truck).

Components of concept 2 (brand new, modified and/or CAST-components):
To reduce cost and complexity, the concept needs to consist of as many standard Volvo parts as possible. To achieve the wanted design, concept 2 needs two new steering cylinders. It also needs a steering cylinder adapter and two new ball joint pins. Other components of this concept have been produced from CAST.

List of concept 2:s constituent parts that has been added or changed:
1. Two new steering cylinders that steers separately. These cylinders may need to be purchased from an outsource company like VSE.

2. Left and right tie rod arm from an existing Volvo tag axle assembly (standard components). These can be viewed in figure 4.3-18 below.

3. Adapter for the two new steering cylinders, mounted in existing conical holes on the tag axle. This component will need to be forged.

4. Two new ball joint pins need to be manufactured. These will be mounted to the tag axle and the adapter as well as to the cylinders.

5. New cable and hydraulic routing. The two steering cylinders need added cable and hydraulic routing.

Figure 4.3-17 below presents some of the components listed above in the actual CAD assembly.

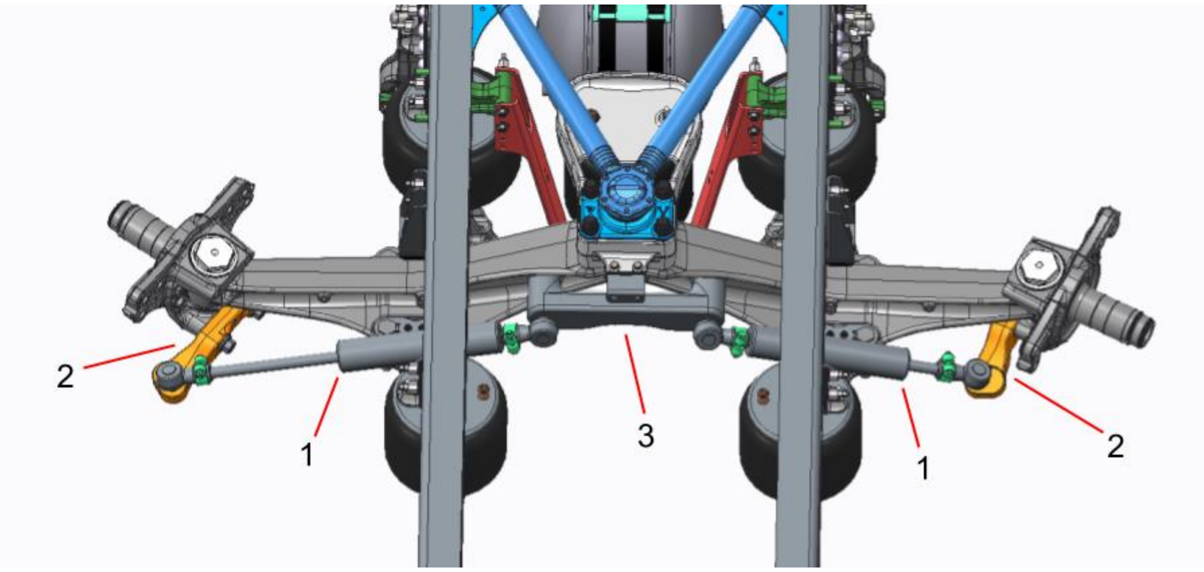

Figure 4.3-17. Numbering (see list above figure) of new/changed components of concept 2.

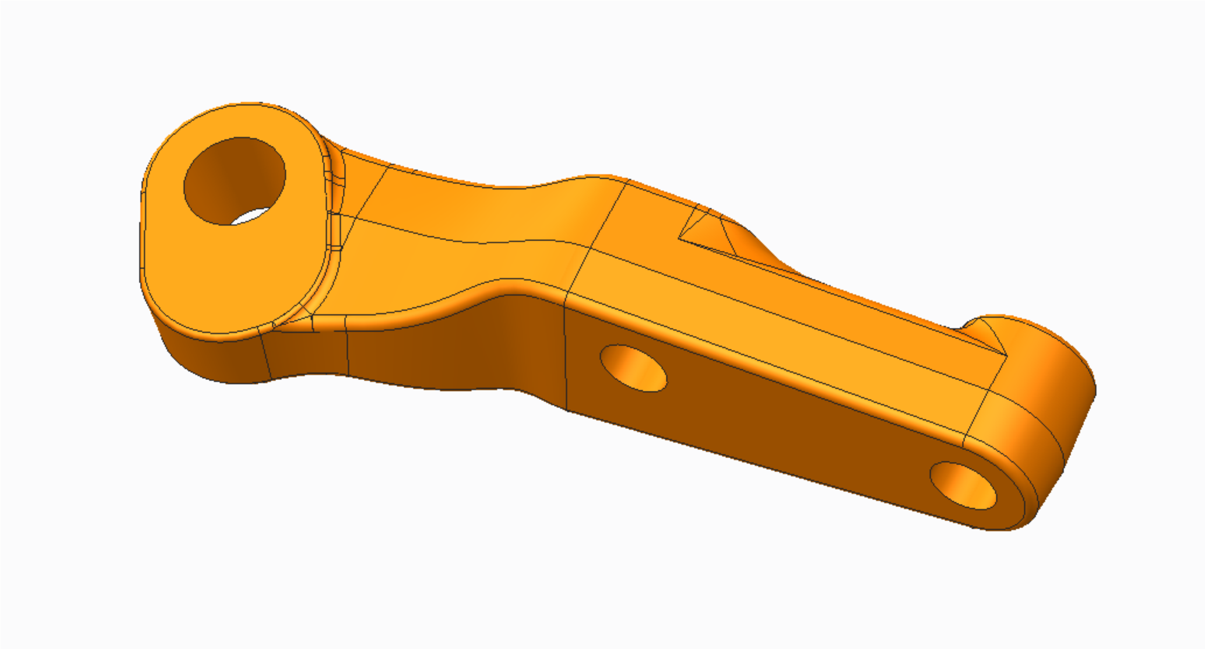

Figure 4.3-18. Standard Volvo tie rod arm, from a tag axle assembly with fixed steering knuckles.

5. CONCLUSION

The purpose of this thesis was in the beginning to investigate if turning the tag axle 180 degrees would enable a redesign of the steering components. This redesign would then result in an improved steering geometry. The purpose was also to investigate if turning the tag axle would provide room for installation lifting equipment for second drive axle.

The conclusion that the CAST lifting equipment was able to be fitted into the truck without any major redesigns influenced the project and its heading. There was no longer a need for the requirement of turning the tag axle around to provide room for the lifting equipment. Therefore, other solutions for the steering improvement were enabled.

Concept 1 achieves true Ackermann geometry for the steering angles of +28,32 to -20,22 degrees (the case with all axles lowered). However, concept 1 achieves +36 to -27 degrees without clashing but with non-Ackermann geometry (the case with the second drive axle lifted). This concept is compatible with the lifting system for the second drive axle. Concept 1 has a fixed steering geometry but it is still more advantageous than the original steering system if the second drive axle was to be lifted because of the increased maximum steering angles.

Concept 2 achieves the steering angles of +36 and -27 and can be programmed to steer at the correct Ackermann angles for any truck setup, due to the independently steered cylinders. This concept is compatible with the lifting system for the second drive axle.

Several questions were presented in chapter 1.4, clarification of the question. Most of them are answered in this thesis. To address all the subjects mentioned in chapter 1.4, more time is needed. It is possible to improve the steering geometry with a redesign of the steering components. However, what influence the concepts have on the turning diameter, tire wear and fuel consumption needs to be tested and evaluated via a field test.

Recommendations for continued work

Due to the short amount of time for this thesis and the complexity of the steering systems, it is recommended that further work should be done. To develop a fully optimized system with great performance, it is suggested that both concept 1 and 2 are improved and compared further. Various subjects that need improvements are listed below.

Concept 1

- Continued development of the new tie rod arms
- Investigate how the new pipe and cable routing should be laid out
- Space claim analysis of fully turned wheels inside of the wheel housing
- Variant compatibility, investigate which truck types and setups the new system is compatible with
- An investigation of the advantages of designing a system where the geometry is a compromise of the two different Ackermann geometry cases (the case of all axles lowered and the case when the second drive axle is lifted)
- Modification of the tag axle to give the kingpins a positive caster angle
- Cost estimation
- Weight estimation

Concept 2

- Acquire new steering cylinders from an outsource specialist company
- Continued development of the steering cylinder adapter, redesign for manufacturing
- Investigate how the new pipe and cable routing should be laid out
- Space claim analysis of fully turned wheels inside of the wheel housing
- Analyze the safety aspects of a steering system with independently steered cylinders
- Variant compatibility, investigate which truck types and setups the new system is compatible with
- Cost estimation
- Weight estimation

6. DISCUSSION

This thesis work turned out to be more complex and time consuming than first estimated. Due to lack of experience with Volvo database systems and Creo Parametrics, the first months of the work was mostly occupied with learning of new computer software. Acquiring of information for the pilot study also claimed a lot of time. Vehicle dynamics was a subject that had not been addressed in the engineering programme of Mechanical Engineering at Chalmers Lindholmen. Therefore, this subject needed extensive research in the beginning of the work. Because of the limitation of time for actual development of the concepts, the thesis work did not reach wanted level of progression.

This thesis focused on a particular system incorporated in an already developed and optimized truck design. Therefore, a variety of design criteria's and circumstances controlled the work. Every change in the design resulted in a need for evaluating its influence on the surrounding components and the trucks driving characteristics. If the thesis was to have a less design criteria's to satisfy, it would have been less complex to develop new concepts.

For a quality thesis with a high academic level there is a need for using different methods for addressing the problem in question. The student's routine of writing academic reports has great effect on the documentation of the work and the quality of the content. At the Mechanical Engineering programme of Chalmers Lindholmen, the courses usually do not incorporate academic writing. Therefore, this thesis could be lacking in academic quality and in the number of scientific methods used. Also, the documentation might have been lacking in continuity during the work.

It was realized during this thesis work was that the insights and knowledge acquired in meetings with Volvo and ÅF engineers has played a crucial part in the achievements of this work. It had a major influence on the direction of the work and has elevated the quality of its content.

7. REFERENCES

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6. Wikimedia, 2006, theoretical image of caster angle, https://commons.wikimedia.org/wiki/File:Caster_angle.svg (found using google.com with advanced image search, filtered by user rights, this picture is free to use, share and modify)

APPENDICES
In this section several different appendices are presented.

APPENDIX 1 - Calculation of Ackermann angles
Calculation of desirable Ackermann steering angles for 8x4 tridem tag trucks (WB3700). This calculation is based on the maximum steering angle of the inner front wheel (44 degrees) on Volvo's standard tridem trucks and different standard dimensions.

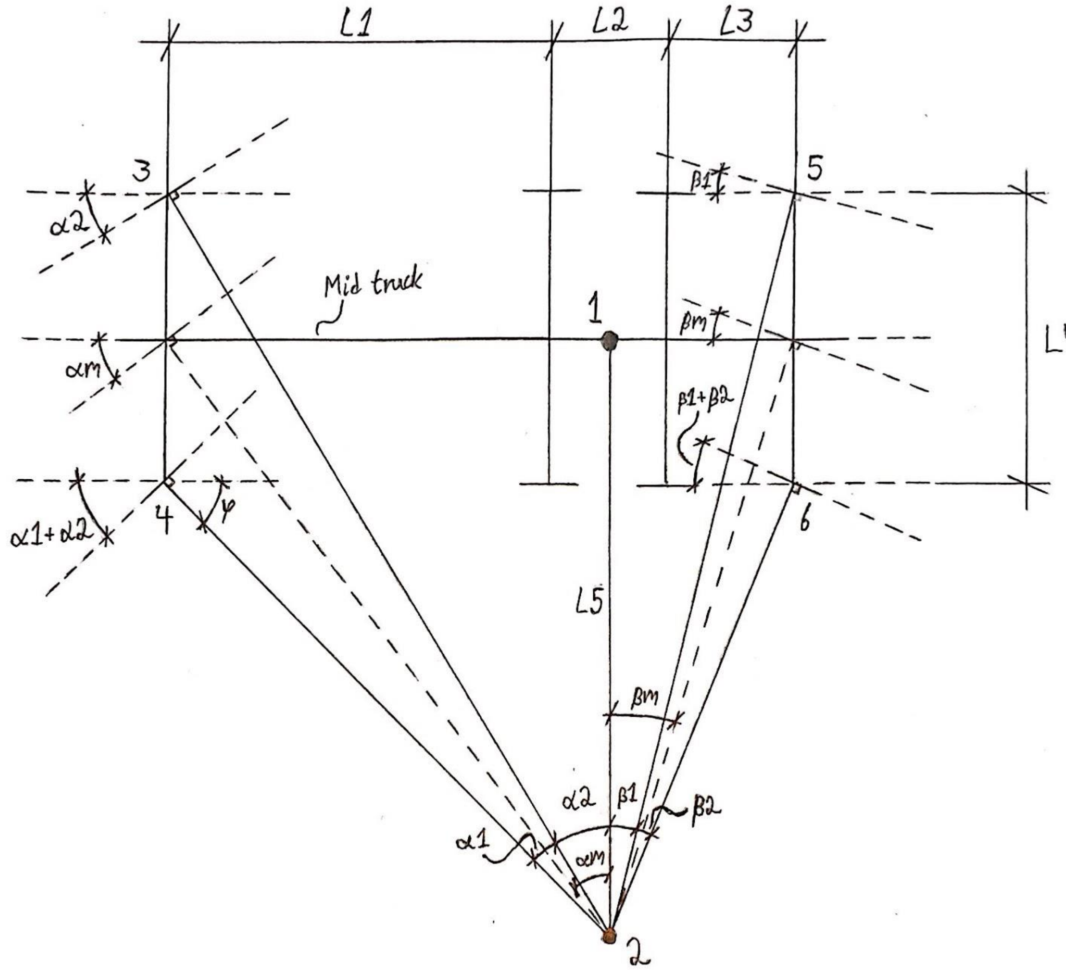

*Figure A1. Figure of Ackermann geometry of a tridem tag truck (with mean angles drawn mid truck). *There may be slight proportional errors in the figure.*

Numbered marks in the figure above:
1. Truck's center of rotation
2. Centre point of the turning circle (measured from mid truck)
3. Outer front wheel
4. Inner front wheel
5. Outer rear wheel
6. Inner rear wheel

On a standard Volvo front axle the inner wheel steers up to 44 degrees. Furthermore, the distances between the rear axles are standardized. The calculations below are done using the following input values [3]:

Lengths:
L1 = 3700 [mm] *(wheelbase)*
L2 = 1370 [mm] *(distance between the first and second drive axles)*
L3 = 1380 [mm] *(distance between the second drive axle and tag axle)*
L4 = 1776 [mm] *(distance between the tag axle kingpins)*
L5 = ? [mm] *(turning radius measured from mid truck)*

Angles:
$\alpha1+\alpha2$ = 44,00 [°] *(steering angle of the inner front wheel)*
$\alpha2$ = ? [°] *(steering angle of the outer front wheel)*
$\Delta\alpha$ = ? [°] *(difference between front inner and outer angles)*
φ = ? [°] *(translation angle)*
$\beta1+\beta2$ = ? [°] *(steering angle of the inner rear wheel)*
$\beta1$ = ? [°] *(steering angle of the outer rear wheel)*
$\Delta\beta$ = ? [°] *(difference between rear inner and outer angles)*
αm = ? [°] *(front mean angle)*
βm = ? [°] *(rear mean angle)*

(the question marks above mean sought-after value that has not been calculated yet)

<u>Step 1, calculation of L5</u>

$$180° = \varphi + \alpha1 + \alpha2 + 90° \Rightarrow \varphi = 180° - 44° - 90° = 46° \Rightarrow$$

$$\Rightarrow L5 - \frac{L4}{2} = tan(\varphi) * L1 \Rightarrow L5 = tan(46°) * 3700 + \frac{1776}{2}) \approx 4719,46\ [mm]$$

<u>Step 2, calculation of α2 and Δα</u>

$$tan(\alpha2) = \frac{L1}{L5+\frac{L4}{2}} \Rightarrow \alpha2 = arctan(\frac{L1}{L5+\frac{L4}{2}}) = arctan(\frac{3700}{4719,46+\frac{1776}{2}}) \approx 33,42°$$

$$\Delta\alpha = (\alpha1 + \alpha2) - \alpha2 = 44° - 33,42° = 10,58°$$

<u>Step 3, calculation of β1</u>

$$tan(\beta1) = \frac{\frac{L2}{2}+L3}{L5+\frac{L4}{2}} \Rightarrow \beta1 = arctan(\frac{\frac{L2}{2}+L3}{L5+\frac{L4}{2}}) = arctan(\frac{\frac{1370}{2}+1380}{4719,46+\frac{1776}{2}}) \approx 20,22°$$

<u>Step 4, calculation of β2 and Δβ</u>

$$tan(\beta1 + \beta2) = \frac{\frac{L2}{2}+L3}{L5-\frac{L4}{2}} \Rightarrow \beta1 + \beta2 = arctan(\frac{\frac{L2}{2}+L3}{L5-\frac{L4}{2}}) = arctan(\frac{\frac{1370}{2}+1380}{4719,46-\frac{1776}{2}}) \approx 28,32°$$

$$\Delta\beta = (\beta1 + \beta2) - \beta1 = 28,32° - 20,22° = 8,10°$$

Step 5, calculation of αm

$$tan(\alpha m) = \frac{L1+\frac{L2}{2}}{L5} \Rightarrow \alpha m = arctan(\frac{L1+\frac{L2}{2}}{L5}) = arctan(\frac{3700+\frac{1370}{2}}{4719{,}46}) \approx 42{,}90°$$

Step 6, calculation of βm

$$tan(\beta m) = \frac{L2+\frac{L3}{2}}{L5} \Rightarrow \beta m = arctan(\frac{L2+\frac{L3}{2}}{L5}) = arctan(\frac{1370+\frac{1380}{2}}{4719{,}46}) \approx 23{,}58°$$

Summary of calculated values

The following data are the different values for true Ackermann steering of a 8x4 tridem tag truck with a wheelbase of 3700 [mm].

Lengths:

L1 = 3700 [mm] *(wheelbase)*
L2 = 1370 [mm] *(distance between the first and second drive axles)*
L3 = 1380 [mm] *(distance between the second drive axle and tag axle)*
L4 = 1776 [mm] *(distance between the tag axle kingpins)*
L5 = 4719,46 [mm] *(turning radius measured from mid truck)*

Angles of front wheels:

α1+α2 = 44,00 [°] *(steering angle of the inner front wheel, named* α(if) in the report*)*
α2 = 33,42 [°] *(steering angle of the outer front wheel , named* α(of) in the report*)*
Δα = 10,58 [°] *(difference between the front wheels inner and outer angles)*
αm = 42,90 [°] *(front mean angle, named* α(mf) in the report*)*

Angles of rear wheels (all axles lowered):

β1+β2 = 28,32 [°] *(steering angle of the inner rear wheel, named* α(ir) in the report*)*
β1 = 20,22 [°] *(steering angle of the outer rear wheel, named* α(or) in the report*)*
Δβ = 8,10 [°] *(difference between the rear wheels inner and outer angles)*
βm = 23,58 [°] *(rear mean angle, named* α(mr) in the report*)*

Additional calculation of tag axle steering angles for true Ackermann when the second drive axle is lifted

Inner wheel βi2 (βi2 = inner tag axle steering angle when second drive axle is lifted):

$$tan(\beta i2) = \frac{L2+L3}{L5-\frac{L4}{2}} \Rightarrow \beta i2 = arctan(\frac{L2+L3}{L5-\frac{L4}{2}}) = arctan(\frac{1370+1380}{4719{,}46-\frac{1776}{2}}) \approx 35{,}67°$$

Outer wheel βo2 (βo2 = outer tag axle steering angle when second drive axle is lifted):

$$tan(\beta o2) = \frac{L2+L3}{L5+\frac{L4}{2}} \Rightarrow \beta i2 = arctan(\frac{L2+L3}{L5+\frac{L4}{2}}) = arctan(\frac{1370+1380}{4719{,}46+\frac{1776}{2}}) \approx 26{,}12°$$

APPENDIX 2 – FEM loads

The two figures A2 and A3 below demonstrate the different loads used in the FEM calculations. The first one represents the load for steering right and the second one for steering left. The arrows to the right in the figures simulate the pressure of the screws joints.

Load 1, right turn

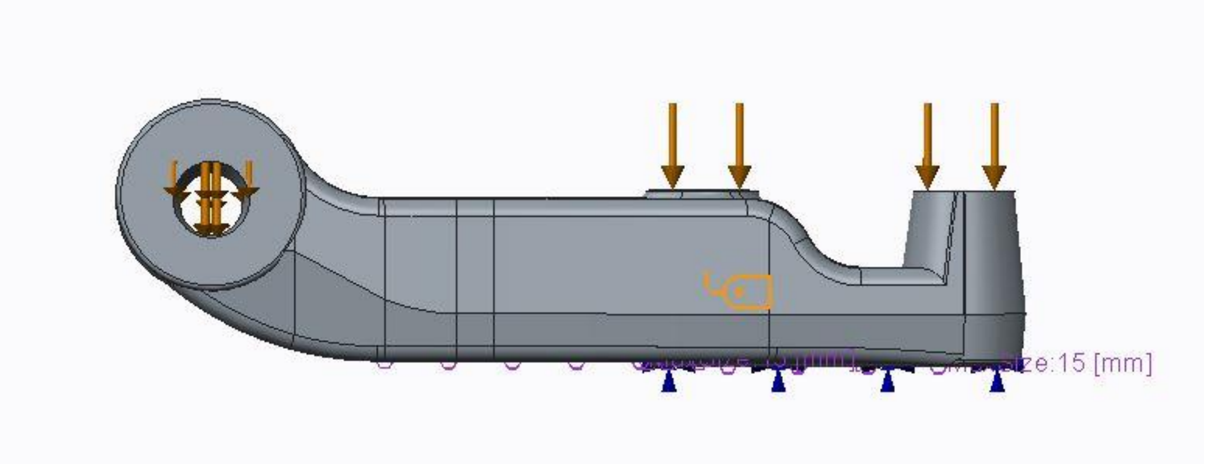

Figure A2. The arrows to the left demonstrate the load when turning right.

Load 2, left turn

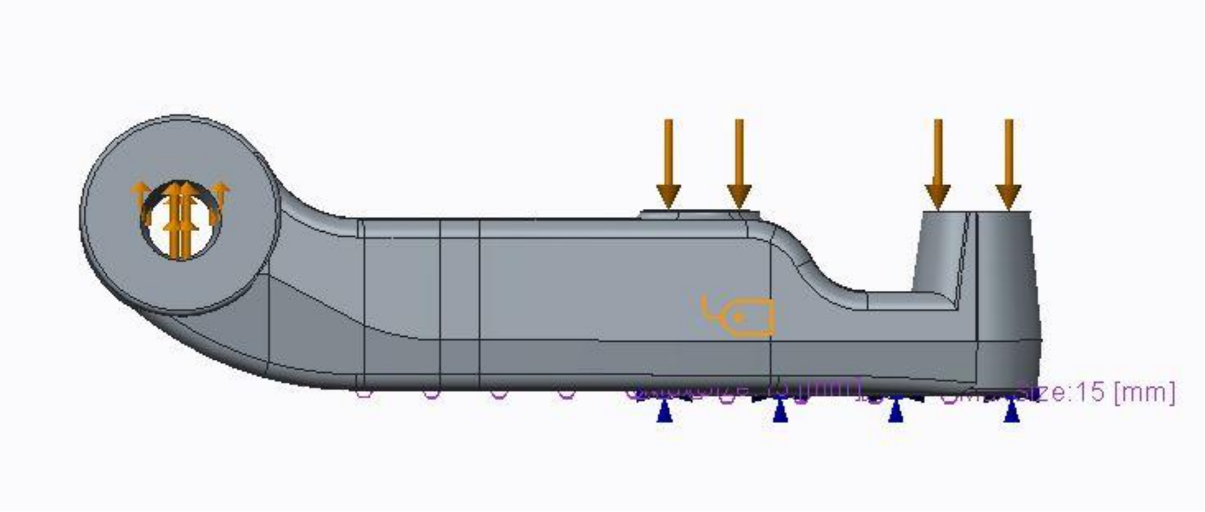

Figure A3. The arrows to the left demonstrate the load when turning left.