CHALMERS

Improving and Evaluating Hydraulic Front Wheel Drive for Trucks

Master's Thesis in the Automotive Engineering programme

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Department of Applied Mechanics
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
ST - crane truck (see 1.1) with hydraulic drive in winter conditions.

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ABSTRACT

In this thesis on hydraulic FWD for trucks the aim have been to produce new function and control strategies with the aim to aid the truck in the real world situations with improvements in start ability and vehicle handling.

In a simulation model from Volvo trucks a series of control strategies for the hydraulic FWD was tested during cornering. The result of this was a new control strategy was design. The idée is to increase the torque percentage directed to the front during cornering at low speeds. A real world test of this theory indicates that this would work as intended. A more extensive test and simulation of more types of truck is recommended for evaluation of the simulation results.

The outer improvement is to create a simple differential lock by using the conventional friction brake to reduce the speed of the wheel that are struggling more for grip. This kind of system is already used at the rear driven wheel and should be rather easy to implement at front as well.

Contents

Preface

This thesis is a result of many people's effort, this have been a very big support for me during this project. First I like to thank my supervisor Alfred Johansson at Epsilon which gave me the opportunity to do this thesis and has always been close for guidance. I also want to give a big thanks to Lena Larsson at Volvo GTT and the consultant Filip Alm, which have communicated their knowledge of Trucks and hydraulics throughout this project.

I am also very thankful to the group responsible for VTM at Volvo GTT especially Kristoffer Tagesson, Peter Sundström and Leo Laine, how provided me with VTM and also answered my questions about it.

Finally, thanks to my Chalmers supervisor Bengt Jacobson how have shared his knowledge about vehicle dynamics throughout this project and supported me during the writing of this report.

1 Introduction

1.1 ETT – Modular system for timber haulage

This Master of Science thesis is a subproject within the ETT project. The ETT project investigates the potential and consequences of higher gross weight and longer timber hauler. The project is divided in two parts, ST (bigger stacks) and ETT (one more stack). Conventional timber haulers have maximum length of 24 meters and a maximum gross weight of 60 tons, by exciding these the fuel consumption and other operational cost freight weight is lowered.

The ST part is about increasing the gross weight on conventional timber hauler types by increasing the height of the timber stacks. To avoid exceeding the maximum axle pressure the amount of axles has become increased compared to regular timber haulers. There are two test vehicles that are being evaluated, ST - crane and ST – haul. They are both 24 meters long and have a gross weight of 74 tons when fully loaded. The ST – crane truck is equipped with a hydraulic front wheel drive to improve traction on slippery roads.

The ETT part is about increasing the amount of stacks with one (from three to four). This means that the maximum legal length is exceeded. The combination is 30 meters long and has a gross weight of 90 tons. More information on the ETT project can be found at ref [4].

1.2 Background

Front wheel drive as an addition to conventional rear wheel drive on truck is much desired on trucks that travel on roads with bad traction. The optimum is to distribute the power from the internal combustion engine (ICE) according to the weight distribution of the axles. Unloaded trucks have a large percentage of the weight on their front wheels due to the engine, in these situation front wheel drive is an even bigger advantage compared to only rear wheel drive.

Mechanical front wheel drive is the traditional way of achieving FWD. The front wheels are connected with the ICE with a drive shaft. Due to the limited space available in some trucks this can be geometrically impossible without completely redesigning the truck.

1.2.1 Hydraulic transmissions

A hydraulic transmission work on the same basic principle as an ordinary transmission. The power [W=N*m/s] is approximately constant which means if the rotational speed [rad/s] is reduced the torque [N*m] is increased proportional.

The big exception between a hydraulic transmission and a mechanical is that the maximum pressure limitation can make the system in some circumstances dump the excess flow to avoid overstepping the maximum pressure. The result of this is that the hydraulic pump is requiring more power than the hydraulic motors is receiving.

There are two different types of hydraulic transmissions open loop and close loop

Open loop is often used in hydraulic equipment such as hydraulic cranes and power tools etcetera. The pump inlet and the motor outlet are connected directly to the hydraulic tank which means that the oil is constantly replaced. This means that overheating of the oil is a relatively small problem. It also means that the pressure not used by the motor is being dumped in the hydraulic tank with a reduction in efficiency as a result.

In a close loop system the pump inlet is directly connected to the outlet on the motor. The advantage of this system is that is can be used both ways without a valve and can work in higher pressures. The disadvantage is that the hydraulic pump cannot be used for other hydraulic function and problem with oil heating can also be issue due to the limited exchange of oil.

1.3 Objectives

The aim of this thesis work is to examine and evaluate the control strategy of the hydraulic FWD described in chapter 2.3. The system should improve the trucks ability to avoid being stalled in slopes and muddy roads. The system should also improve the handling and help the driver to avoid going off the road. Improvements are defined in comparison with an identical truck without FWD and one with a more traditional mechanic FWD.

- The first part of the thesis work is to examine the relationship between the hydraulic components top speed and torque. This is very important to achieve a high enough speed without compromising the maximum needed torque. See 5.1

- The second part is to investigate whether the hydraulic FWD control strategy during a corner is optimal. If not, a proposal of how to control it should be made. See 5.2

- The 3rd part is to investigate a way to improve the maximum traction force when one of the front wheels is over a slippery surface (split-mu). See 5.3 & 5.4

1.4 Limitations

The work has been limited to only be on the ST – crane truck that has the first generation Volvo hydraulic FWD. This enables a real world comparison since log data is available from this vehicle.

The ST – crane truck is a 4 axle were 2 are driven directly by the ICE and the front is hydraulically driven, the last axle is undriven and is called “tag axle”. The truck is pulling a dolly which is connected to a semitrailer.

1.5 Literature review

1.5.1 Vehicle dynamic books

Much of the theoretical background on the tyre model used in the model can be found in Tire and Vehicle Dynamics Second Edition ref [1]. In the strictly vehicle dynamic theory much of the knowledge is taken from a lecture notes compendium for a Chalmers course in vehicle dynamic ref[2].

1.5.2 Master thesis

There have been a number of theses on the subject of hydraulic FWD on Volvo trucks all with slightly different focus. The most recent one is Patrik Jonséns thesis work ref [3], which had focus on slip curves and hydraulic motor and pump sizes. This report has been very helpful in understanding how the hydraulic system is built up and has given experimental measurement of the slip curve on gravel with the ST – crane truck. Patrik Jonsén has also been available to answer questions about the experiment and hydraulic system

2 Theory

2.1 Mechanical FWD

Mechanical FWD is the conventional way of achieving FWD, the front wheel is connected to the ICE with a drive shaft in the same way as the rear driven wheels. See figure 1. In Volvo trucks with mechanical FWD there is no differential between front and rear this means that the rotational speed of the rear and front wheels have a fixed ratio. The fixed ratio is one, in order to have the same slip front and rear, meaning approximately traction force proportional to normal load, when driving straight ahead.

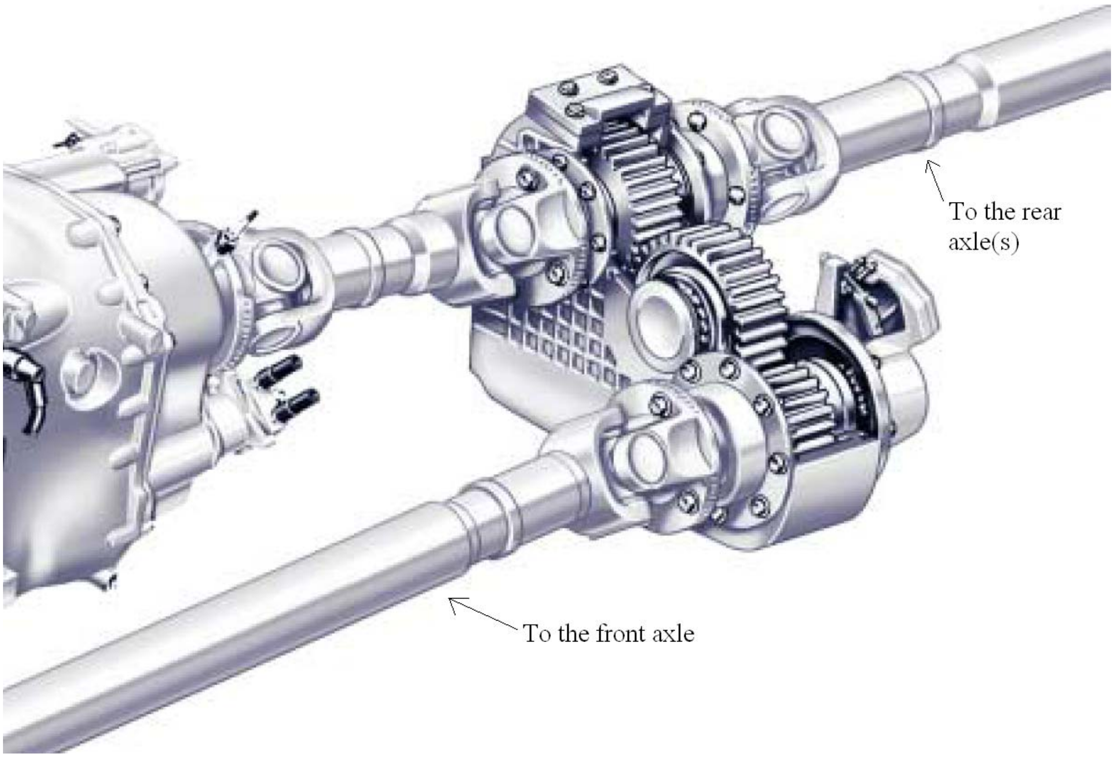

Figure 1: The power from the engine is transferred to the front wheels though a distribution gearbox.

This fixed ratio of one can be an issue when turning due to the fact that the front wheel travelling a longer distance, which means that the front wheel want to have higher speed then the rear (up to 35.6% with maximum steering angle). This means that the front wheels will give a braking force on the vehicle when tuning. This makes the vehicle under steer heavily.

As a result the drivers with mechanical FWD only turn on the system when driving straight and making the system useless during corners.

2.2 Differentials

A differential is a transmission with one input shaft and two output shafts. A differential allow the rotational on the output shaft axle to be different , but the torque transfer left and right is the same.

The reason the differentials exist is that during a corner the rotational speed of a left and right wheel is different due to longer travel distance for the outer wheel, if the speed would be locked the vehicle would under steer heavily. The downside of differentials is that if there are different frictions left and right the most slippery side will be dominant and decide the maximum torque possible to be transferred to the other.

2.3 Hydraulic FWD

The system is a closed loop system with a single fully variable pump supplying two parallel connected motors, see figure 2. The pump, which is connected directly on the engine through a power out take, is controlling the speed of the front wheels by changing its displacement. The two motors are mounted in the left and right front wheel and fed with same pressure difference. This makes the FWD work as it was a differential, the torque left and right are the same but the rotating speed can be different.

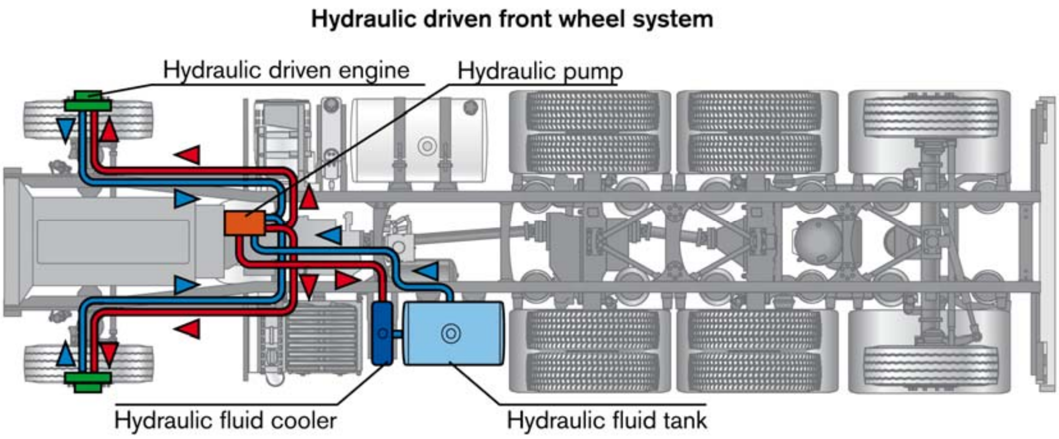

Figure 2, Rigid 8x4 with hydraulic FWD, one hydraulic pump parallel connected to two hydraulic motors in wheel hubs.

The big advantage with hydraulic FWD is that high torque can be transported in thin hydraulic houses and the high power density in the motors. The efficiency is about the same as for a mechanical FWD.

The disadvantage of the system is that the maximum torque available at the wheel is determined by a combination of the pump and motor size. The speed that the system can be operated is limited by the size of the pump and motors size and is about 22 km/h with the current system.

2.4 Advantages with front wheel drive

Start ability is one of the main performance criteria when designing a truck, it is a measurement on how steep of a slop a truck can start in. The startability of a truck on slippery roads is heavily dependent on how big percentage of the total weight that are driven, FWD increases this percentage especially when unloaded. This can easily be seen in the friction formula seen in equation 1.

$$Fx = N * \mu \qquad \text{Equation 1}$$

Fx is the driving force in the travel direction of the truck, N is the force generated by the combined weight on the driven wheels, μ is the friction factor depended of the surface and condition of the road.

Improving turn-in abilities in sharp turn can also be improved with FWD, The systems applies force to the front wheels during corners and in this way drags the front of the vehicle in to the corner.

2.5 Longitudinal slip curves

To achieve traction force there is need to have relative speed between the rubber and the ground. This is also known as slip see equation 2.

$$\lambda_{slip} = \frac{R * \omega - V_x}{(V_x + R * \omega)/2} \qquad \text{Equation 2}$$

Where the R is the radius of the tyre, ω is the rotational speed of the tyre and V_x is the speed at the center of the tyre.

The contact surface can be divided in to two zones the stick and slip. Stick zone means that the rubber is deforming to create the speed difference, slip means that the rubber is drawn over the surface. The slip characteristic is a very important factor when a maximum traction force is desirable. On dry asphalt road for example the traction force decreases if the speed differential differs too much as seen in Figure 3.

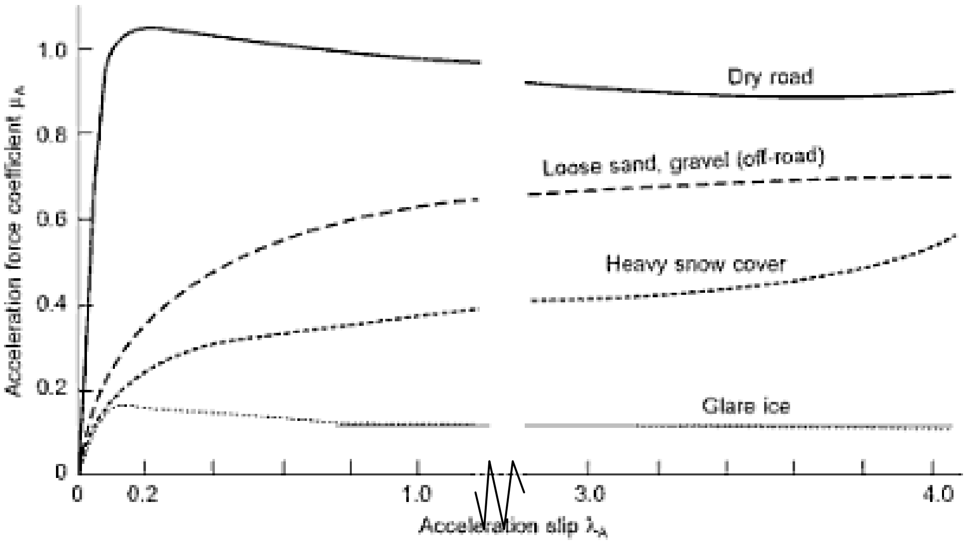

Figure 3, Longitudinal slip curves for different surfaces

2.6 Lateral slip curves

The lateral force of the front tyres is generated by the difference in wheel direction and wheel travel direction that occurs when a wheel is being turned. The angle between these two directions is called slip angle and is α in figure 4 not to be confused with steer angle.

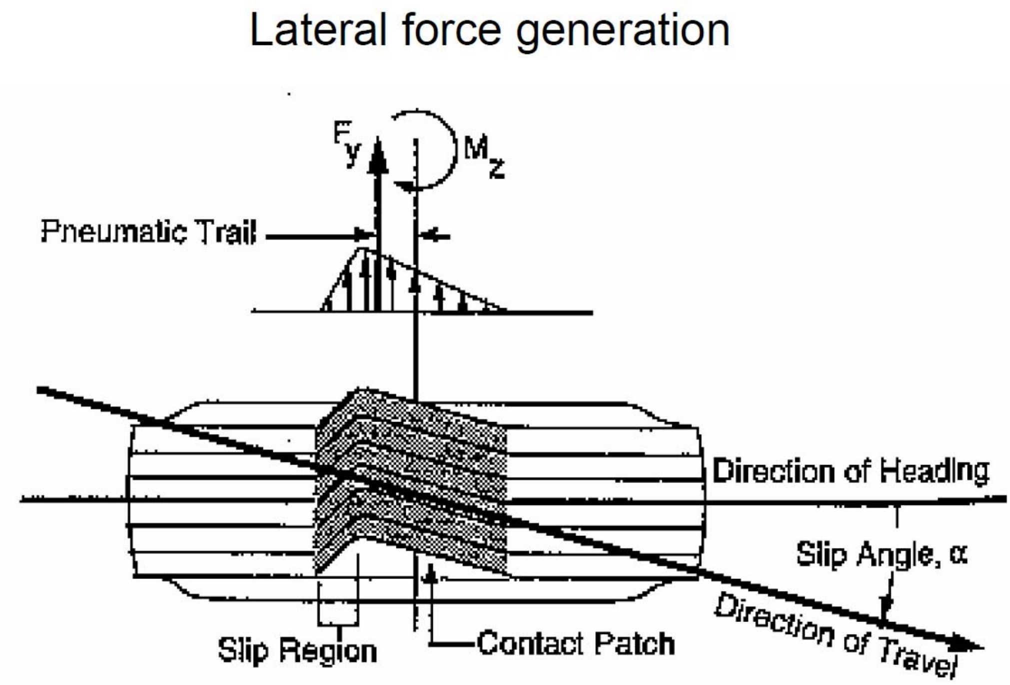

Figure 4, Tyre seen from underneath the contact patch is deformed and drawn over the surface creating a lateral force.

As seen the force generated by the contact patch is divided in to two parts one stick and one slip region. In the stick region the force is formed by the deformation of the rubber and in the slip part the tyre is simply dragged on the surface. The slip angle-lateral force curve is similar to the longitudinal slip - longitudinal force curve in shape for the same tyre and surface see figure 5. This means that if the longitudinal curve is measured the lateral curve can approximated with relatively good accuracy.

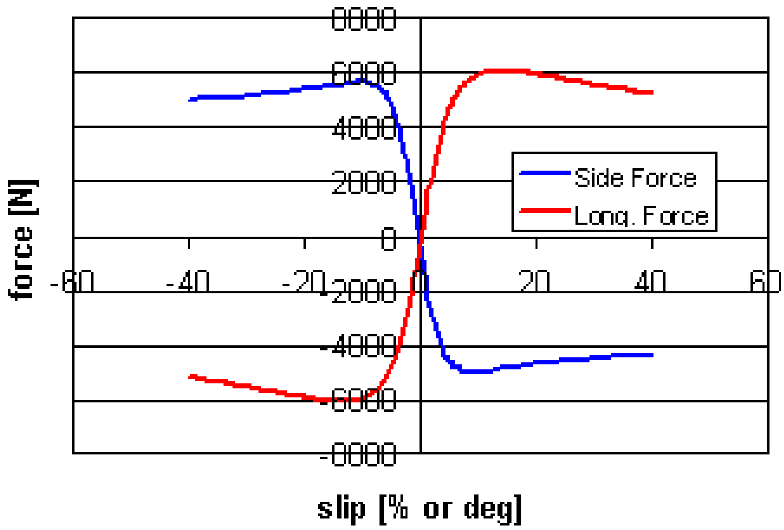

Figure 5, This image shows that the lateral and longitudinal slip curves are almost identical

2.7 Friction circle

If a tyre is cornering and braking or accelerating at the same time the slip curves for longitudinal and lateral forces are limited of the friction circle. This means that the hypotenuse of the lateral and longitudinal force can go outside of this circle see figure 6.

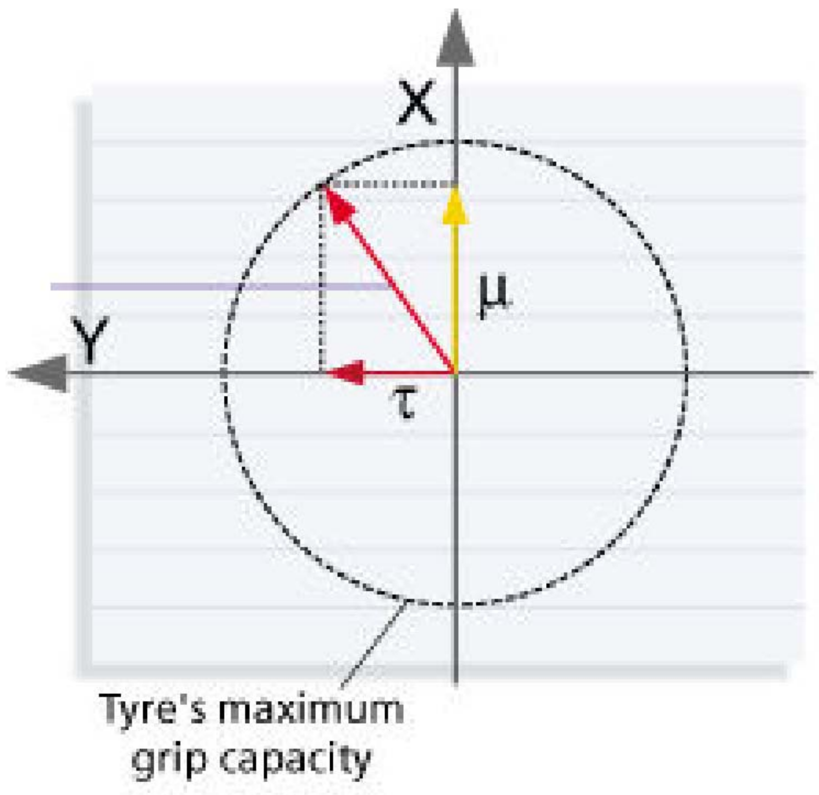

*Figure 6, Friction circle the yellow line is longitudinal and the red is the lateral one the X and Y in this image are local for the tyre, Fx=μ*N and Fy=τ*N. Figure drawn for when the contact grip is on the limit.*

2.8 Front wheel speed during cornering

The difference in average speed at the front and rear wheels at low speed can be described as in equation 3 called cornering compensation formula. This is due to that at low speed the rotational centre for the whole vehicle is located on the same longitudinal coordinate as the rear wheel, this and the relation between velocity and rotation speed $V = R * \omega$ because ω is the same for the whole vehicle the speed difference is the same as the R ratio see figure 7.

$$V_f = \frac{V_b}{\cos(\alpha_2)} \Rightarrow \{V = R * \omega\} \Rightarrow \omega_f = \frac{\omega_b}{\cos(\alpha_2)} \qquad \text{Equation 3}$$

Where V_f is the speed at the front axle, V_b is the speed at the rear axle, ω_f is the rotational speed at the front axle, ω_b is the rotational speed at the rear axle and α_2 is the steering angle.

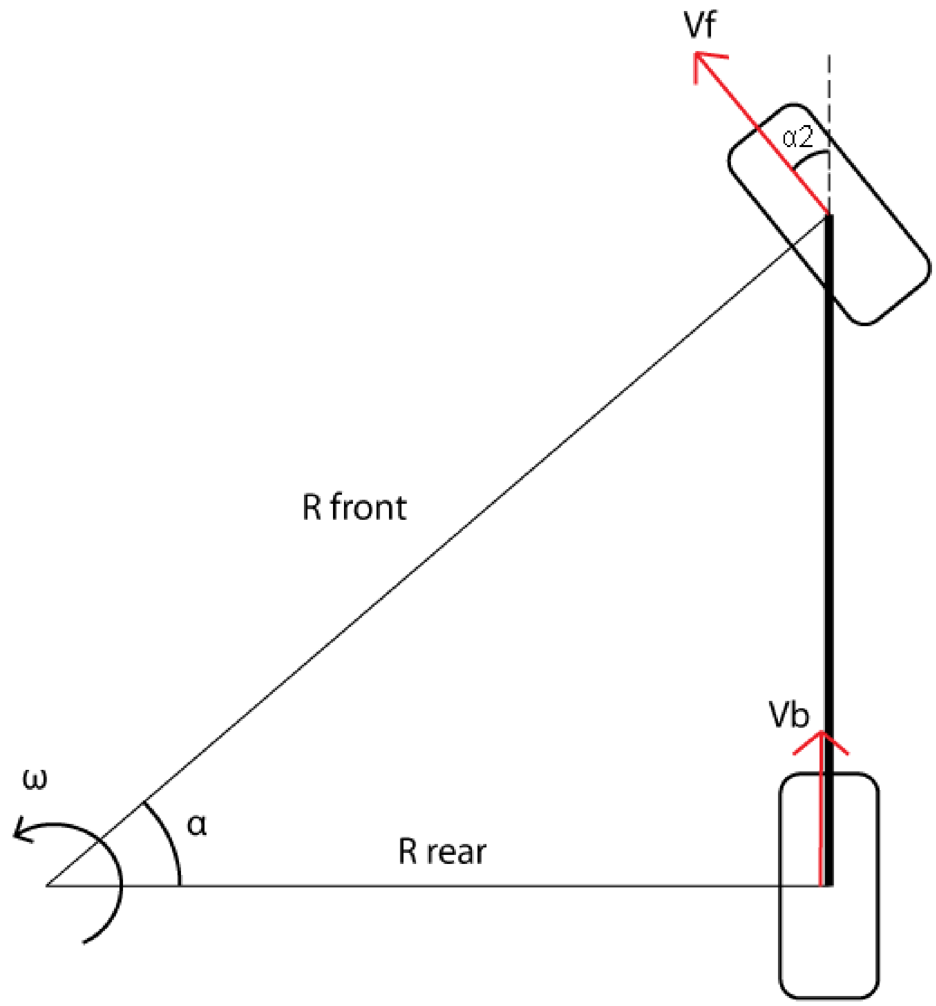

Figure 7, Bicycle cornering at low speed, f=front, b=rear.

2.8.1 Front wheel speed compensation

The basic of controlling the hydraulic FWD is that the slip on the front tyres should be the same as the slip on the rear tyres, but this doesn't work in a corner. Due to the extra speed on the front wheels in a corner the slip tends to become negative at the front and positive at the rear. There are some different ways of compensating for this.

1. First generation hydraulic FWD solution: A minimum hydraulic pressure to the motors front ensures that the minimum torque at the front wheels is at the least about 1000 Nm. This kicks in when the front wheels are spinning faster than the rear wheels. There is no need of steering angle or yaw rate information.

2. Second generation hydraulic FWD solution: By using the equation for the front and rear speed relationship during a corner see equation 4. The front wheels can have the same slip front and rear also during a corner. Here the steering angle is needed as a input to the control function.

3. Third generation is what is developed in this thesis work. In broad term it uses the equation in the second generation and adding a aggressiveness factor during cornering.

2.8.2 Improving cornering with hydraulic FWD

At low speed the main vehicle dynamic problem is under-steering. Under steering is when the truck is not turning as much as the drivers steering angle should give in ideal conditions. This is especially a problem at slippery roads.

The hydraulic FWD have the ability to let the rear and front wheels spin at different speeds. This can be used when turning in the following way see equation 4.

$$V_f = \frac{V_b * k}{cos(\alpha)} \qquad \text{Equation 4}$$

Where k is the aggressiveness factor controlling the over speed of the front tyres.

3 Methodology

3.1 Knowledge building

A lot of knowledge about the hydraulic FWD is gained through talking and interviewing the persons responsible of the hydraulic FWD project on AB Volvo and its partners see ref [5].

3.1.1 Field trip

The first prototype of a Volvo with hydraulic FWD is the winter of 2010/2011 being field tested in Dalsland, Sweden. A one day field trip was conducted were the truck drove on dirt roads and the driver could explain his ideas on the FWD. The road was very narrow and hilly and it became clear that the main purpose is to avoid to get stuck in upslope (improve start ability) and keep the truck on the road (prevent under steer). The driver really liked the system but said that it is important to make the system as simple and robust as possible to avoid breakdowns.

3.2 Brainstorming improvement of the hydraulic FWD system

So the main function of the system is to avoid getting stuck at upslope and keep the truck on the road. In close discussions with the persons involved in the project a number of improvements ideas was produced and ranked as follows, where first is most important.

1. Improving turn-in (reduce under-steering) during narrow curves through increasing torque to the front axle during cornering see 3.4(simulation) and 3.5 (test).

2. Improvement of starting ability when slippery surface under one of the front wheels by braking with a conventional friction brake on the slippery side. Same principle as a differential lock, except that some of the power produced by engine will be lost in friction brakes see 3.6.

3.3 Calculation of start ability

One of the main performance criteria of a truck is the start ability, start ability can be defined in many ways. The definition used here is the maximum gradient the truck can hold a constant speed in. The start ability is calculated on a range of different friction values μ to cover all different road conditions. The truck is always in first gear and the FWD is looked to the rotational speed of the front wheels. The slops are smooth and the calculations are ideal which means that real world result will have smaller angles on the slops. But the calculations give a good comparison between no FWD, hydraulic FWD and mechanic FWD.

The ST – crane truck is used to calculate the results. This means that due to the crane mounted on the back of the truck the front axle load is relative low compared with the total weight of the truck. This will give a smaller the improvement with the FWD compared to a more regular truck without a crane on the back. Due to the low speed the aerodynamic drag is neglected.

The start ability is limited by both the ICE ability to produce torque and the friction constant. The equation for calculation the angle limited by the maximum torque can be seen in equation 5.

$$\alpha = \arcsin\left(\frac{F}{Mtot * g}\right) \qquad \text{Equation 5}$$

Where F is the combined driving force, Mtot is the total weight for the truck and the trailer and g (=9.81) is the gravity constant.

The easiest way to calculate the curve limited by the friction constant is to calculate the friction required to produce the maximum force see equation 6 and make a straight line from this friction value and the maximum slop angle to 0 friction and 0 slope angle.

$$\mu = \frac{Fd}{Md * g * \cos(\beta)} \qquad \text{Equation 6}$$

Were Fd is the force produced, Md is the total weight on the driven axles and β is the angle of the slope.

The FWD curves are calculated on the same way but the hydraulic FWD has a maximum torque which limiting the start ability. The hydraulic FWD curve is calculated by calculating the friction constant recurred to handle the maximum force from the hydraulic motors. Then this friction value can then determine the amount of force from the ICE that can be produced. This two combined gives the angle where the hydraulic motors retches its maximum. After this angle the hydraulic gives constant improvement.

3.4 Simulation of cornering

VTM (Virtual Truck Modelling library) from Vehicle Dynamics group at VGTT (Volvo Group Truck Technology) is a simulation tool suitable to evaluate turn-in improvements in cornering. The models are further described in Section 4.1.

VTM contains a rather extensive help register and a number of template trucks of different variants. The truck that was simulated is based on a template truck with some modification on the weight and number of axles. The truck specification can be found in appendix C.

Next the FWD was made with 4 different settings:

- Mechanical FWD (Drive train from ICE to front axle)
- First generation hydraulic FWD (1000Nm to front tyres during cornering)
- Second generation hydraulic FWD (turning compensation formula with k=1)
- Third generation hydraulic FWD (turning compensation formula with k>1)

The second and third generation uses the curve compensation and aggressiveness factor k referred at 2.8.1 and 2.8.2.

A way of describing the turning behaviour was also needed. The way this is solved is that the truck drive straight ahead until it reach a steady predefined speed specified in the test, then the truck turns the steering wheel linearly under 2 seconds to a predefined angle and then hold this angle though out the corner. The imaginable radii of the curve are then taken via a sensor located in the front of the truck. The sensor register the y coordinate when the x coordinate reaches its maximum see figure 8. So the truck does a quarter rotations when the radius is being registered. This gives a rather good comparison between different control strategies. Because of the low speed and the big percentage of the weight located at the rear axles the focus is to avoid is under steering. The idée is that this kind of curve should be closer to real world driving then a steady state curve test.

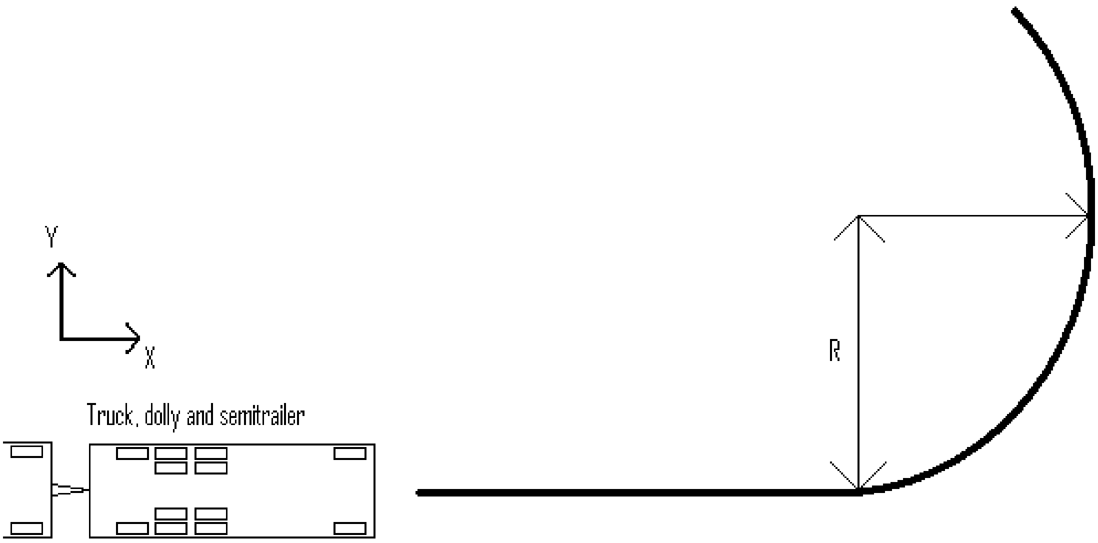

Figure 8, Simulation of the radius setup

The turn simulation can be parameterized through the parameters including interval for each selected to be studied:

- Longitudinal speed: 8 and 20km/h
- Steer angle on left front wheel: 0 to 45 degree
- Road friction: ice/gravel/asphalt

The vehicle configurations studied are:

- No FWD
- FWD mechanical FWD
- Hydraulic FWD, gen1
- Hydraulic FWD, gen2(with different k values)

3.5 Real world test with ST-crane

After the implementation of second generation hydraulic FWD hade being implemented in the system a field test was conducted in a gravel pit. The hydraulic FWD was set up so it could switch between non curve compensation and curve compensation both strategy included a minimum torque limit during cornering. The truck drove in narrow circles at low speeds with no FWD and the two different control strategy of hydraulic FWD.

The purpose of the test was to see if the curve compensation gave a change that could be felt when driving in the real world.

3.6 Friction braking of one front wheel

The calculation done on this is rather limited and is only taking account one particular situation. The calculation setup is a truck that is driving in an upslope on a snow road. One of the front tyres is then experience ice surface, the situation is common on winter roads. The difference in start ability can then be calculated for no FWD, FWD with braking of the wheel struggling for grip and FWD with no braking. This is to get a feeling for how much this system can improve traction.

4 Simulation model

This chapter describes the simulation model used for testing the improvement turn-in ability

4.1 VTM

The simulation was conducted in VTM (Virtual Truck Modelling library) which is a vehicle dynamic model made in Simulink by Volvo trucks. VTM contains all the main vehicle dynamic important part of a truck such as frames, axles and tyres. These Simulink blocks can then be modified and put together in a way that almost all different kinds truck and trailer combination can be simulated.

Many of the frame and axle blocks are made with Simmechanics part of Simulink, the centre of mass and its weight and other important property is modified in a separate Matlab file for convenience.

The tyre model is a very important part of a vehicle dynamic model. The tyre model used in VTM is called pac2002 and can be found in the book Tyre and Vehicle dynamic by Hans B. Pacejka, the model contains a version of a pack of equation commonly known as the magic tyre formula. These formulas is semi empirically which means that they are not scientifically derived but are a result of real world testing. They are rather close to the real world and relatively fast to simulate with.

The strictly longitudinal part can be seen in equation 7.

$$F_{X0} = D_X \sin\left[C_X \arctan\left\{B_X \kappa_X - E_X \left(B_X \kappa_X - \arctan\left(B_X \kappa_X\right)\right)\right\}\right] + S_{VX} \quad \text{Equation 7}$$

Where F_X is the longitudinal force and κ_X is the longitudinal slip ratio. The other variable B_X, C_X, D_X and S_{VX} are tuned to make the curve similar to a rear slip curve.

The equation see equation 8 used for lateral forces is similar to the longitudinal but the lateral slip is replaced by the slip angle.

$$F_{Y0} = D \sin\left[C_Y \arctan\left\{B_Y \alpha_Y - E_Y \left(B_Y \alpha_Y - \arctan\left(B_Y \alpha_Y\right)\right)\right\}\right] + S_{VY} \quad \text{Equation 8}$$

Where F_{Y0} is the lateral force and α_Y is the slip angel. The other variable B_Y, C_Y, D_Y and S_{VY} are tuned to make the curve similar to a real slip curve.

In the case of combined slip the combined lateral and longitudinal force is limited to the friction circle see image 1. This circle is calculated by multiply the lateral and longitudinal force with a variable that takes in to count the lateral and angular slip see equation 1.

If the vehicle is both turning and braking/accelerating a weighted function see equation 9 is used to calculate the lateral and longitudinal force, this is to simulate the friction circle.

$$F_X = F_{X0} * G_{X\alpha}(\alpha, \kappa, F_Z) \qquad \text{Equation 9}$$

Where F_X is the longitudinal force and $G_{X\alpha}$ is the variable that limits the force according to the friction circle. A similar function exists for the lateral force as well.

All the constants are modified and can be fitted to different kind of slip curves according to the surface that should be simulated. In VTM there are 28 lambdas coefficients that can be modified, these coefficients effects the slip curves drastically. At default these coefficient is all equal to 1 and this gives the tyre characteristics of a standard 315/80R22.5 truck tyre on asphalt. By modifying the value of these coefficients the slip curves can be modified to resemble different surfaces such as gravel, snow and ice.

4.2 ST-crane

The ST-crane truck is a 8x4 with three axle to the rear two mechanical driven and the rearmost is a steerable tag axle, the front axle is fitted with two hydraulic motors. The truck is connected to a dolly which in turn is connected to a semitrailer. It has a combined weight of 74 ton and a length of 24m.

The model in Simulink is based on a template vehicle with similar properties. The things that were modified are.

-The centre of gravity position and weight.

- Moment of inertia.

-Number of axle and theirs position.

-The length of the trailer and truck.

4.3 Mechanic FWD

The mechanical FWD was simulated to imitate a Volvo FM FWD which means a locked differential between rear and front wheels but an open differential between left and right wheel. Due to problem with locking the front axle speeds to the rear the front axle restive a high correctional torque when it differs slightly to the back axle. 50.000.000Nm/(rad/s) This makes the front and rear axle virtually spinning at the same speed.

4.4 Hydraulic FWD

The hydraulic FWD drive is modelled to resemble the first generation hydraulic FWD. The Matlab block is controlling the torque in a similar way as the mechanical FWD was simulated but with much lower toque values (in the same range as in the measured log files from the field tests). The maximum torque to the front wheels is limited to 16000 Nm due to the maximum torque in the hydraulic motors.

5 Results

5.1 Starting ability with FWD results

The start ability is calculated by way described in method and the results can be seen in figure 9 and 10 for fully loaded and unloaded with truck and trailer, respective.

In the fully loaded truck the red line representing the mechanical FWD have a bigger improvement in the higher friction values then the hydraulic FWD the green one. They follow each other until the hydraulic FWD reach its maximum torque, (8000 Nm in this case determined by the displacement of the hydraulic motors), then it cannot use the friction constant to its fullest. After that it gives a constant improvement compared to no FWD.

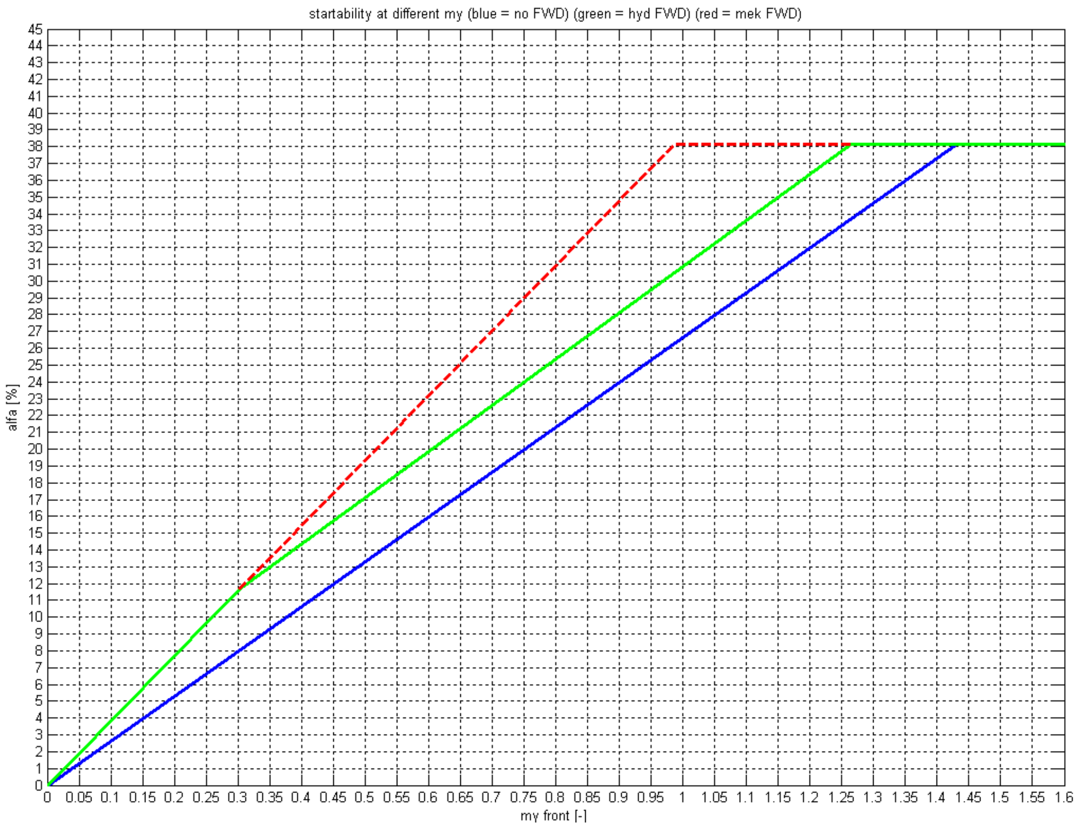

Figure 9: Fully loaded start ability [%] with different friction constants μ [-](x-axis: μ, y-axis: radius [m])

In the start ability when the truck and trailer is not loaded the hydraulic FWD and mechanical FWD is exactly the same because of the hydraulic motors don't reach it maximum torque.

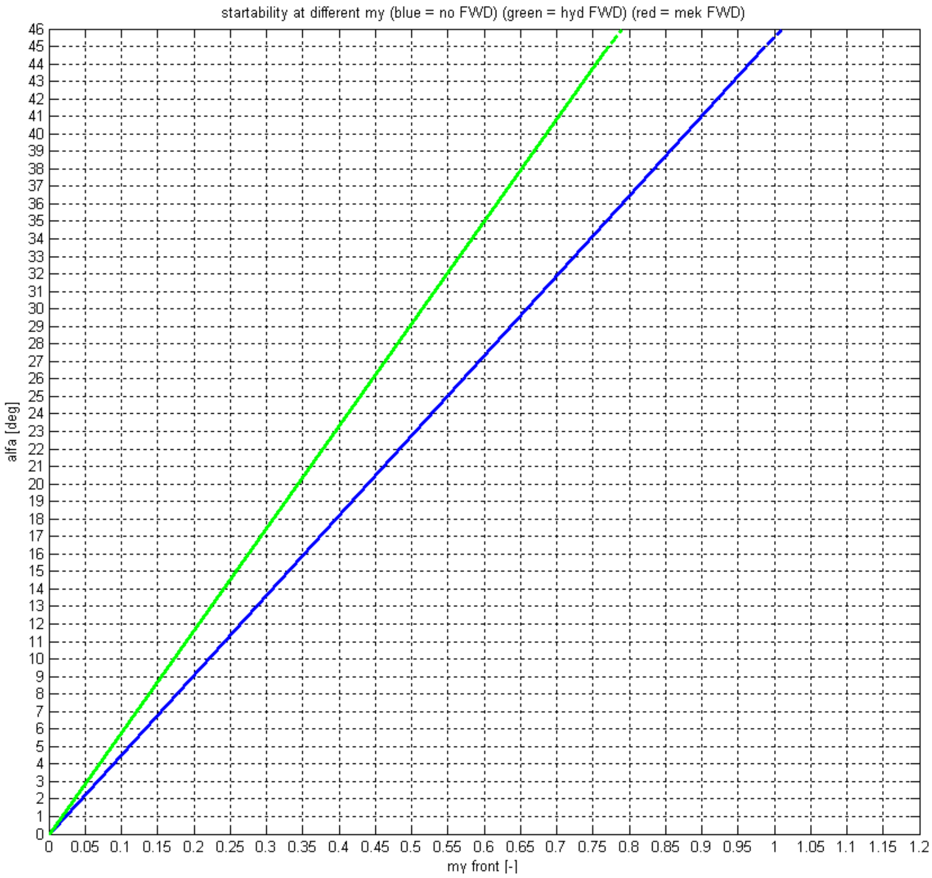

Figure 10: Unloaded start ability [%] with different friction constant my [-](x-axis: μ, y-axis: radius [m])

5.2 FWD during cornering results

As discussed in the theory part the main issue when cornering at low speed is under steering. This means that the radius produced by a specific steering input should be as low as possible. The hydraulic FWD can under certain conditions help with this by using steering angle compensation and aggressiveness factor k.

In figure 11 plot the truck make a left turn it have a speed of 8km/h and a left front wheel steering angle of 20 degrees the plot shows the radius compared with steering compensation and different values of k from 1 to 2.1. The dashed lines are the first generation hydraulic FWD. No FWD have a very similar radius as steering compensation and k=1 in this test.

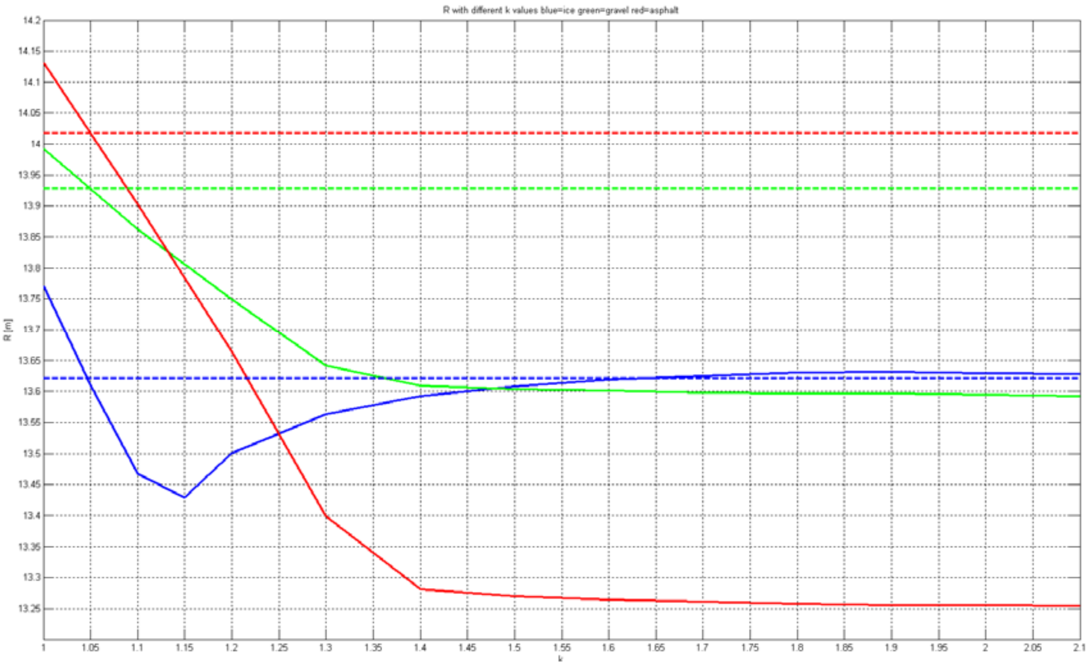

Figure 11, Different radius at different k values blue=ice, green=gravel and red=asphalt (x-axis: aggressiveness factor k [-], y-axis: radius [m])

As seen in this curves the radius can be improved for all the surfaces for the asphalt and gravel curve the more torque transferred to the front the smaller the radius will be. But for the ice surface there is a best k value after this the radius will go up. This behaviour is duo to that the friction circle is overstepped and when this happens more torque will reduce the lateral force produced from the turning of the wheel.

In the second plot the speed in the lower curves is 8km/h and in the upper 20km/h the left front wheel steering angle is changed from 5 to 45 degree which is the full range of the steering wheel, all the lines are gravel see figure 12.

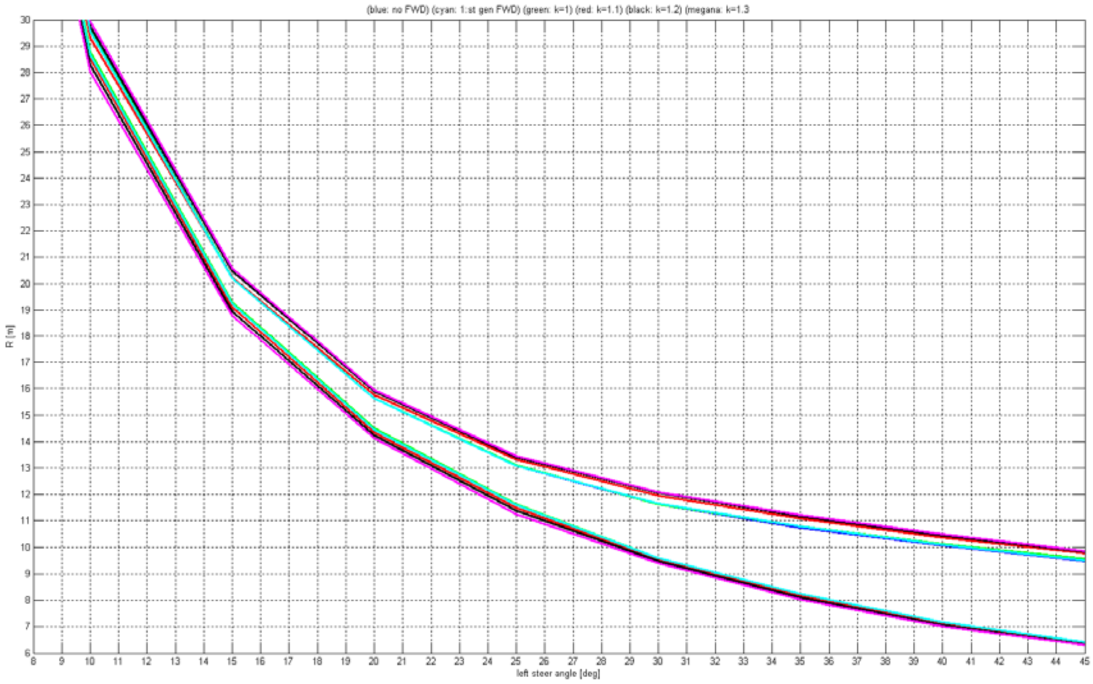

Figure 12, different radius at different steer angle, the higher curves it at 20km/h and the lower at 8km/h. blue=no FWD, cyan=1st gen FWD, green: k=1, red: k=1.1, black: k=1.2 and megana: k=1.3(x-axis: left steer angle [deg], y-axis: radius [m])

The change is hard to see in this image but to get a better view image 9 is a zoomed in version of figure 13, it shows both the 8 and 20km/h lines at 15 to 20 degrees steer angle

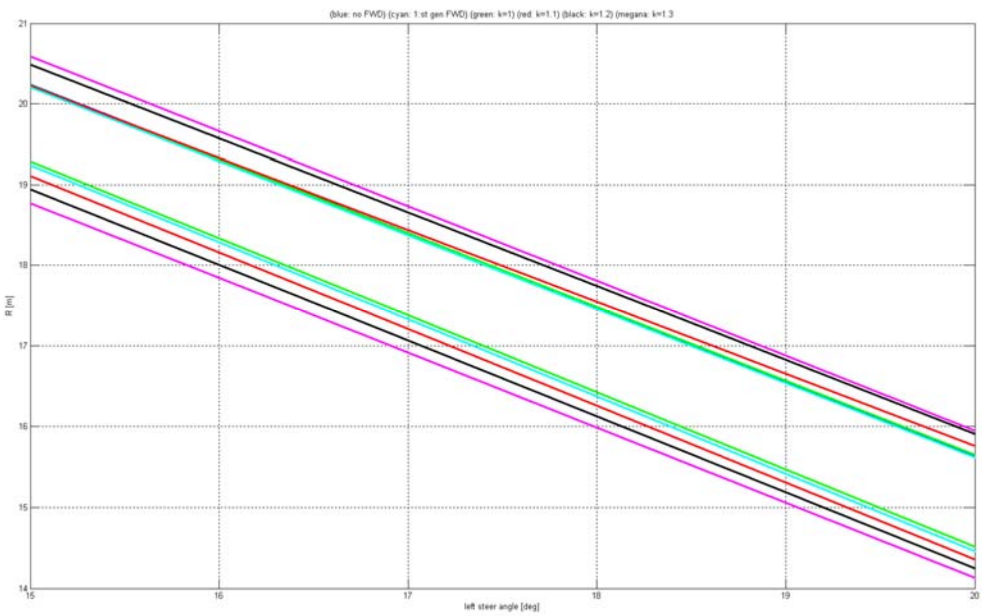

Figure 13, different radius at different steer angle, the higher curves it at 20km/h and the lower at 8km/h. blue=no FWD, cyan=1st gen FWD, green: k=1, red: k=1.1, black: k=1.2 and megana: k=1.3(x-axis: left steer angle [deg], y-axis: radius [m])

The plot in figure 13 shows that at 8km/h there is room for lowering the radius by applying more torque to the front. But at 20km/h the friction circle is disturbed too much and the radii is increased.

The next plot in figure 14 is showing the same plot as in image 9 but on ice.

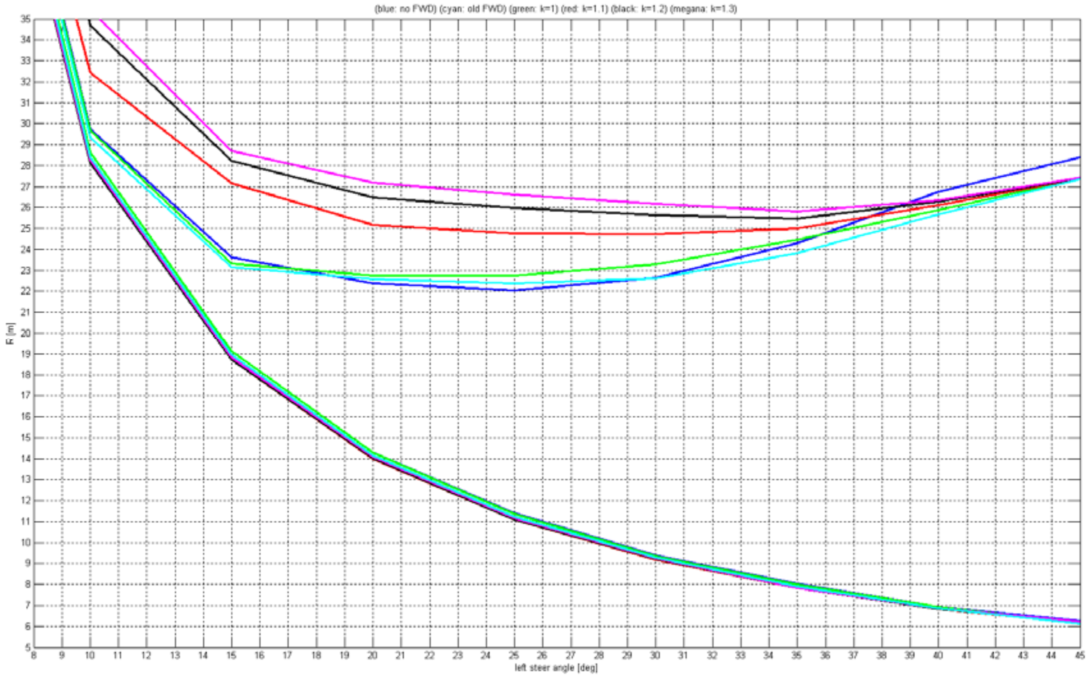

Figure 14, different radius at different steer angle, the higher curves it at 20km/h and the lower at 8km/h. blue=no FWD, cyan=1st gen FWD, green: k=1, red: k=1.1, black: k=1.2 and megana: k=1.3(x-axis: left steer angle [deg], y-axis: radius [m])

In figure 14 there are such big changes in the 20km/h lines that there is no need for a zoomed in image of these lines. Even at a slightly more aggressive steering of the system as k = 1.1 the truck needs a several meters more wide corner. This means that the friction circle is already used to the max by the lateral forces produced by the turning of the wheel. Another thing that suggests this that the minimum value of the radius is not reach at the highest steer angle.

The 8km/h values still need a zoomed in plot to see the changes this can be seen at figure 15 which is zoomed in at the same angle as figure 13 but on ice.

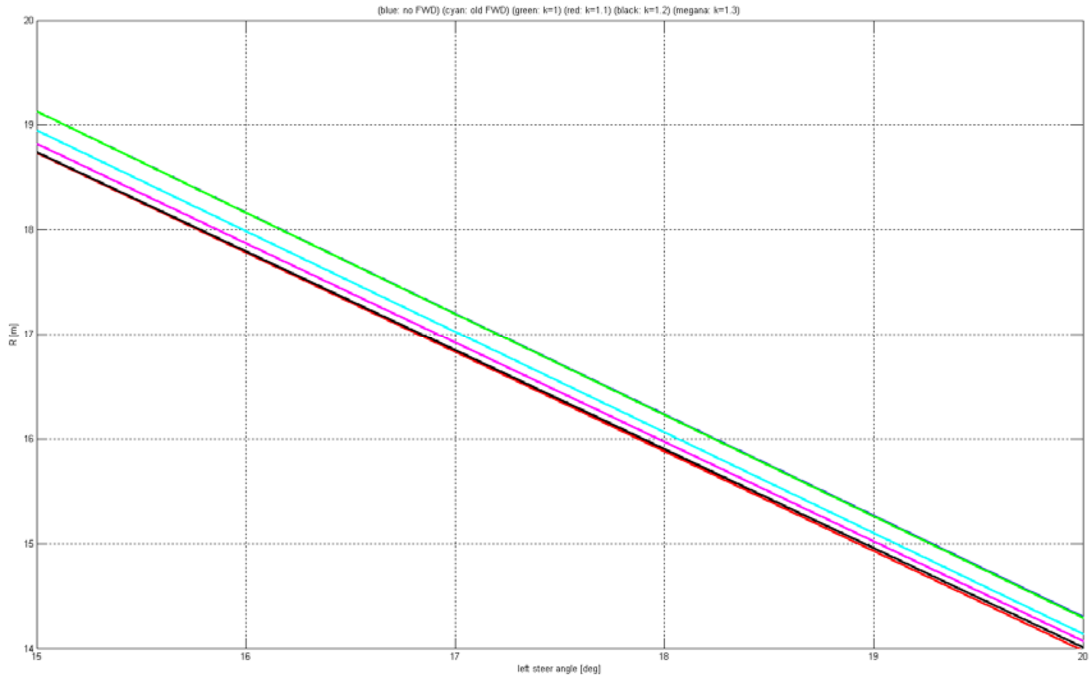

Figure 15 different radius at different steer angle all in 8km/h blue=no FWD, cyan=1st gen FWD, green: k=1, red: k=1.1, black: k=1.2 and megana: k=1.3(x-axis: left steer angle [deg], y-axis: radius [m])

The zoomed in plot in image 12 shows that on ice and 8km/h there is a improvement of directing more torque to the front with a minimum radius at k=1.1. This result is very interesting and suggest that speed is maybe the most important factor, this not really surprising because the side forces is much larger due to the large side acceleration generated by faster speed.

5.3 Real world testing of ST – crane truck results

The test was conducted at a gravel pit with probably roughly the same slip curve as the slip curve used as in the gravel simulations. The speed was about 8-10km/h and the steering angle was almost maximum.

There were no measurements conducted but the two drivers that tested the two different control strategies of the system and the FWD turned off said that they could feel a significant improvement, especially compared with no FWD but also some improvement with the corner compensation relative the old FWD system. The corner compensation was set with a k value of 1. This are similar to the result given by the simulations.

The improvement could be seen at videos that the test.

5.4 Improving traction by braking of a front wheel results

The start ability for the calculation of snow (μ=0.35) under all wheels without one front which have ice (μ=0.15) is as follows:

-No FWD: 8.2%

-With FWD no braking: 10.2%

-With FWD braking of front wheel struggling for grip: 11.1%

6 Conclusions

This chapter summarize the result chapter and give suggestion on how the hydraulic FWD can be improved. The first start ability calculation gives a feeling of the advantages compared with no FWD, it also gives a tool to decide hydraulic motor size.

In the biggest result part dealing corner radii reduction have it become clear that even on ice and 20km/h the first generation control strategy (minimum torque limit) gives a fairly good result. It is also less sensitive if the driver should try to accelerate through a corner on ice. But the first generation control strategy could also be improved on low speeds on ice and especially on gravel. This gives the conclusion that the k value should be speed dependent and maybe switch to a torque limit control at highest speeds.

Braking of one front wheel when it is struggling for grip are showing some potential and are probably even more useful in the real world where the truck can sometimes have different weight on the left and right wheel due to side sloping roads. This system is already available to the driven wheel at the back so it should be relatively simple to implement this also to the front.

7 Recommendations for further work

- The corner radii reduction control strategy should be tested in the real world to get a confirmation that the simulation is correct. The driver feeling and response is also an important part to consider.

- Make similar simulation on different trucks.

- Investigate how ESC and Traction Control cooperates with the new control strategy.

- Investigate whether the desired torque to the front axle could be decided in another way than with the speed.

8 References

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5. Personal communication with Filip Alm, Consultant at AB Volvo.

9 Appendix

<This appendix is confidential. Not printed in this version>