FFI

FORDONSSTRATEGISK
FORSKNING OCH INNOVATION

# Traction Control II

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Delprogram: Fordonsutveckling

# Innehåll



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FFI är ett samarbete mellan staten och fordonsindustrin om att gemensamt finansiera forsknings-, innovations- och utvecklingsaktiviteter med fokus på områdena Klimat & Miljö samt Säkerhet. Satsningen innebär verksamhet för ca 1 miljard kr per år varav de offentliga medlen utgör hälften.

För närvarande finns fem delprogram Energi & miljö, Fordons- och trafiksäkerhet, Fordonsutveckling, Hållbar produktionsteknik och Transporteffektivitet. Läs mer på www.vinnova.se/ffi

# 1. Sammanfattning

Construction machines manufactured by Volvo CE operate in many different environments and driving conditions. In particular they need to be able to perform well with road conditions and loads that can change drastically, setting hard requirements on performances and robustness. The control challenges for off-road construction machines are hence quite different from standard cars or trucks which mostly drive on regular roads. However, increasing fuel prices and increasing environmental awareness have influenced all the main vehicle manufacturers so that the commitment towards less fuel consumption has become one of the main goals for development. The market of the most recent years has been characterized by increasing competition and in order for Volvo CE to stay ahead a constant effort in research and development needs to be performed.

Based on the above discussion the project adressed the following topics:

- Study efficiency and slip under transient conditions and work with slip estimators.
- Decide efficiency measures to use in design of traction controllers that are suitable for the different modes of the typical working cycle of a hauler and a wheel loader.
- Formulate a traction control structure that can account for different efficiency measures.
- Transform results tested/validated on a small-scale vehicle (ArtiTrax) to a full scale-vehicle and perform corresponding test on the full-scale vehicle

The project had three main deliverables:

1. To increase Volvo CE internal knowledge on automatic control and modeling in the field of traction control.
2. To develop new solutions for automatic traction control for construction machines in order to decrease wear of the driveline, fuel consumption and tire wear.
3. One PhD dissemination.

During the project all experimental work has been done on a small-scale vehicle. The project has so far resulted in a verified low complexity dynamic model for a small-scale articulated vehicle that is meaningful to use in online optimal controllers. For optimal slip and traction control the ground contact through tires are essential, field measurements on full-scale machines with high accuracy has increased quality of current tire models. An estimator for slip and effective tire radius has been developed and experimentally verified. A preliminary framework for designing optimal controllers based on different models and cost functions has been established. The PhD dissemination is planned in april 2016.

# 2. Bakgrund

Volvo CE aims at improving the actual driveline solutions in order to achieve better drivability for increased productivity from the four and six-wheel drive for its wheel loaders and haulers. During the last few years hybrid vehicles have been vigorously developed. For wheel loaders, in particular, the series hybrid concept seems to be suitable whereby a diesel engine generates electricity for a battery from where individual wheel (hub) motors are driven, enabling regenerative braking as well as partial recovery of the energy necessary to lift the load. Hence, traction control algorithms should be adapted for use with individual hub motors.

Another important aspect characterizing construction machines is the fact that wheel slip may cause severe damage to the wheels and ground. Particularly, tire lifespan is a serious problem since for instance in a modern hauler a tire can cost up to 400.000 SEK and often represents 20%-25% of a hauler overall operating cost. Better traction control algorithms can strongly contribute to reducing tire wear and hence operating costs. However, in order for an automatic traction control system to be useful for these kinds of vehicle, it is necessary that it detects potential excessive wheel slip before it occurs.

During 2009-2013 Volvo CE in collaboration with LTU conducted practical and theoretical analysis on off-road construction machines to gain more knowledge on how the torque distribution between wheels and axels affects different machine properties, in particular fuel efficiency (FE).
This study was part of the research project "Traction Control for Off-road Construction Vehicles", reference number 2009-00298, partially financed by FFI.

The first part of the project focused with articulated haulers and on how different differential combinations affected mobility and FE. Advanced measurement techniques (GPS/IMU) have been employed to measure side slip angles and to verify kinematic models.

The second part of the project focused instead on 4-wheels electrical drive articulated vehicles. During the project a small 4-wheel drive articulated vehicle has been employed for analysis and control. The vehicle, ArtiTrax II, is a 4-wheel drive wheel chair that was initially built during a previous student project at LTU. It is made of 2 interconnected Permobil Trax wheel chairs. All four wheels are provided with electrical motors for propulsion. In addition there is an extra electrical motor for controlling the steering angles. All the motors are individually controlled.
ArtiTrax II is an improved version with extra sensors, new power electronic units and micro controllers which has been assembled, as part of the project, by one of the PhD students.

Several tests have been performed with the ArtiTrax II in different driving conditions and with different load distributions to validate existing models and gain more knowledge. The preliminary results showed that torque distribution plays a large role in FE, as in other vehicle characteristics such as cornering and mobility. In addition, the literature research showed that the field of torque vectoring for articulated vehicles is quite poor. Few results have been found in this area and mainly in simulation environment and for steady state conditions.

The preliminary results from the tests with ArtiTrax II show that torque distribution and its control is a very important area that deeply affects several properties of the vehicle (see next section). It is however necessary to perform more tests and a deeper theoretical analysis to be able to develop optimal control strategies for different driving situations and cost functions.

## 3. Syfte

As found in previous work, the energy consumption as a function of torque distribution has a minima that moves towards higher torque split to the outer wheels as the articulation of the joint increases. Most of the work during this project has been to identify the reason(s) that cause this minimum to move depending on the driving conditions. While the driving condition does not affect as much during straight driving on a planar surface, it is still relevant for e.g. off-road conditions. During straight driving the optimal torque distribution is changed mainly due to rotational velocities of the tires and frictional forces arising both from the tyre-ground interaction but also from other powertrain losses. It is believed that controlling the torque optimally could improve the average energy efficiency by up to 3%. In order to use optimal control, a model would have to be developed that can represent the power usage of the vehicle for a wide variety of cases.

## 4. Genomförande

In the previous project, experiments were performed to identify the power usage by varying the weight over each wheel, changing tyre pressure and while driving at different velocities. This work continued into the continued project with the end result being that for torque distributions close to the optimal point, the change in energy efficiency was small. The measurement noise at close to optimal torque distribution required much time and effort spent on performing measurements. The noise was not only measurement noise, but more importantly the surfaces driven on were not perfect and small variations in the driven path could greatly affect the measurements. The decision was made to use a dynamic model and to do simulations where repeatability was not an issue, and whereas the model could be used for control in the future.

Two models were developed, the first model is a robust high complexity model, it works well for simulation but starts being too complex when it comes to optimization. The second model, implemented in Modelica, is an equation-based low complexity model. It is believed, that this model can be used in online control of the vehicle to minimize the energy consumption, both on smooth-surfaces and during off-road conditions.

Figure 1 - Torque measurement rig

Using the torque measurement experimental bench described in the previous project (Traction Control), a relatively good representation of the powertrain could be achieved. The mapped behavior could then be used to translate the mechanical power from the dynamic model to the electrical power pulled from the batteries with high accuracy.

# 5. Resultat

The dynamic model is designed to have as low complexity as possible while still providing accurate results in energy consumption. This means that dynamic behavior with a strong correlation to energy consumption was modelled with a higher complexity. The vertical dynamics is one of the more important parts of the model and was chosen to be used in a comparison between experimental and simulated data. In figure 2, the weight on each wheel is shown at standstill when the steering angle is changed on the vehicle while figure 3 shows the resulting effective tyre radius during cornering at 2 m/s with a steering angle of 45 degrees.

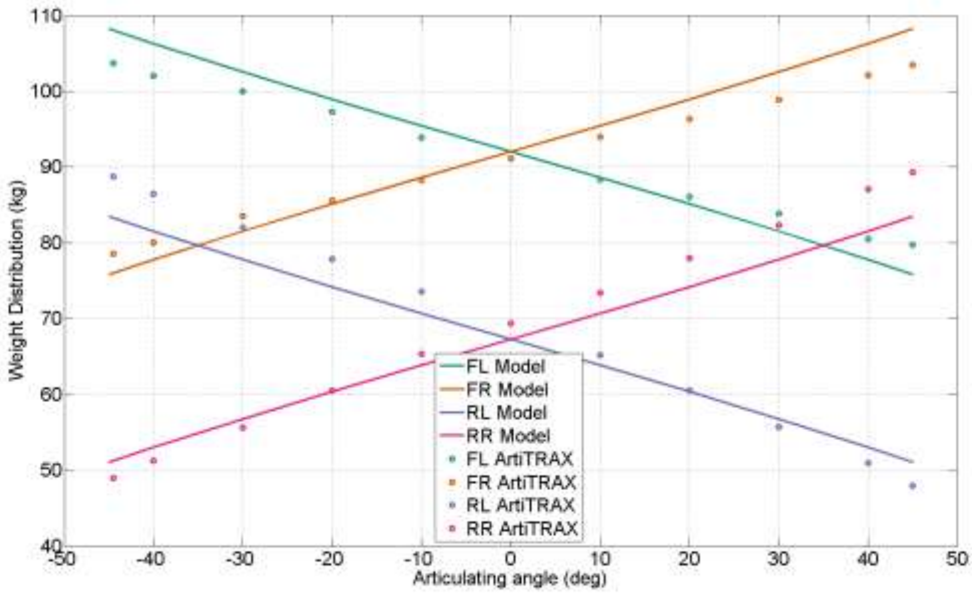


Figure 2 - Weight distribution as a function of steering angle when comparing the model (solid lines) to experimental data (circles) at standstill.

The model reflects the vertical dynamics of ArtiTRAX relatively well at standstill, certain differences exist however as can be seen in figure 2. At a steering angle of zero degrees, the model overestimates the weight on the front wheels while underestimating the weight on the rear wheels. This is most likely an effect of slightly misaligned center of gravities of the front and rear frame. Furthermore, the almost linear relation that exists seem to have slightly different slopes between the front and rear wheel in reality while the model fails to capture this. This could be from the fact that the front and rear wheels of ArtiTRAX differ slightly, but it is more likely that the relatively simple dynamics of the joint in the model is the cause of this. Some vehicles, such as ArtiTRAX, allow for a certain roll (rotation around the forward axis) between the frames. The model does not allow for this roll rotation, and might be the reason for the divergence as the steering angle increases.

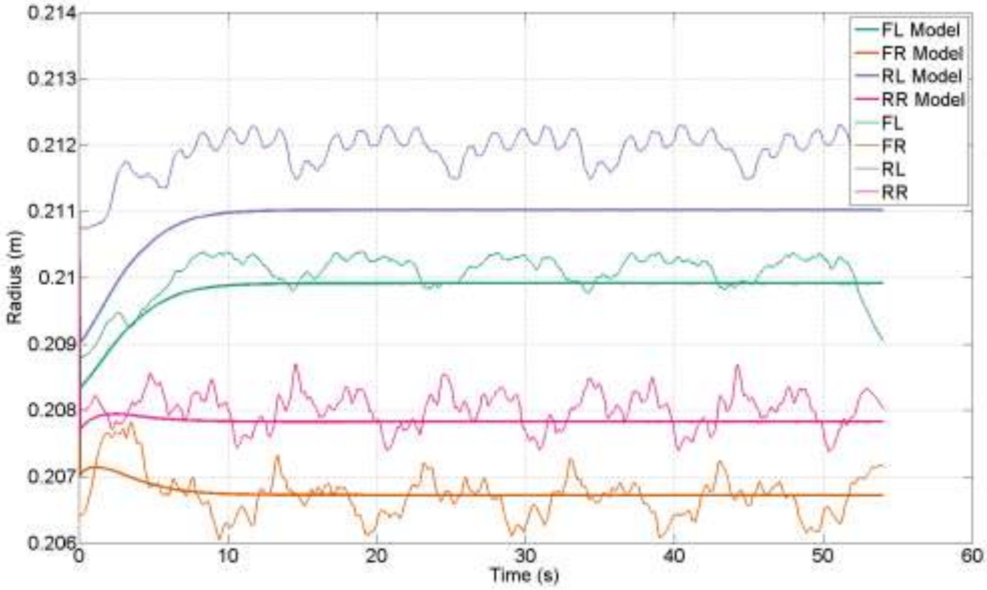


Figure 4 - Effective tyre radius comparison while cornering at 2 m/s and with a steering angle of 45 degrees.

When driving in a circle, the outer wheels become further compressed due to the lateral tyre forces acting to keep the vehicle in the circle. This results in an outward roll increasing the normal forces on the outer wheels while decreasing the forces on the inner wheels. Figure 4 shows a comparison between the model and  measurements of the effective tyre radius while ArtiTRAX is driving in a circle with a 45 degree steering angle at a velocity of 2 m/s. The model reflects the tyre radius relatively well in the linear deformation region of the tyre, but overestimates the tyre deformation during low normal forces. The non-linearity found on ArtiTRAX tires might be from the terrain tires having a stiff carcass, and was not added to the model as tires found in literature have a linear relationship.

However, a good estimation of the effective tyre radius is just the start when predicting power consumption. The effective tyre radius and the rotational velocity affects the frictional forces acting on the wheels. Effort was put into doing an extensive sensitivity analysis of how different parameters change the power consumption, and are further explained in the technical report.

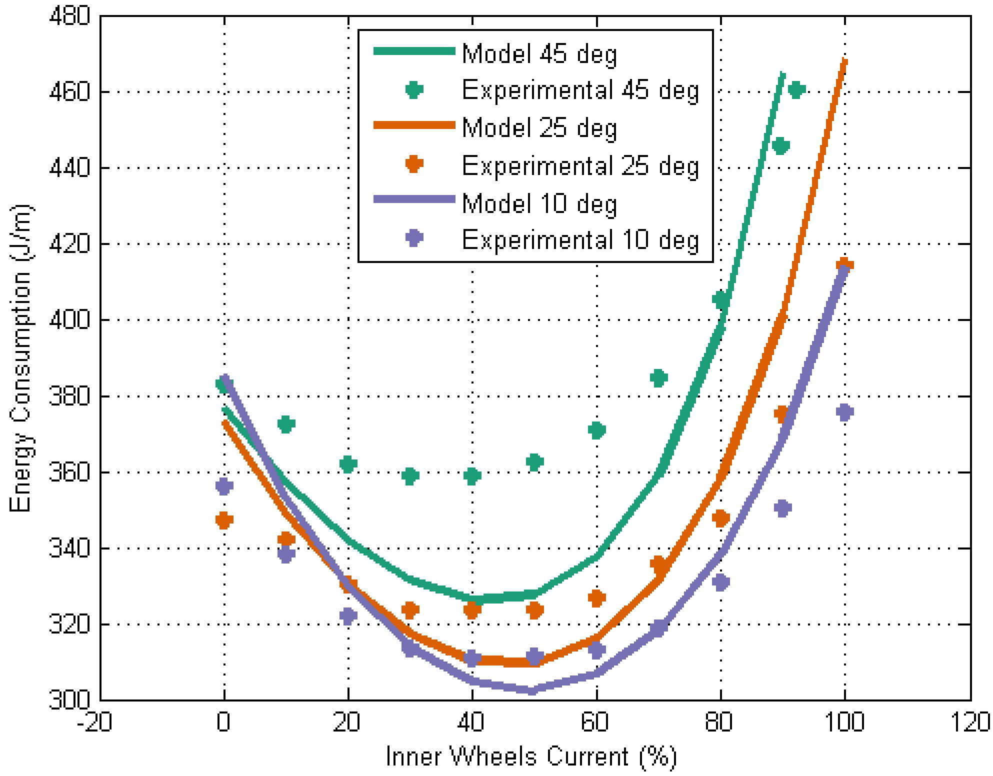


Figure 5 – Power consumption comparison between model and experimental measurements while cornering with different steering angles.

A comparison between model and experimental measurements for three different steering angles can be seen in figure 5. With the current parameters the model approximates the general behavior of ArtiTRAX relatively well, but two major differences exist. The power consumption increases too much with increasing torque difference between the tires while the frictional forces at an even torque split is too low. This is due to the tyre elasticity as a function of torque, and is being worked on for the second article in the series. In reality the elasticity of a tyre depends on the amount of compression it has already suffered meaning that at low normal forces, the torque applied to a wheel can change the tyre radius dramatically, while at high normal forces the tyre radius would be changed less.

### 5.1 Bidrag till FFI-mål

The project has contributed to a close collaboration between Volvo and LTU where people from academia, especially in the beginning of the project, has been working at Volvo on a regular basis as a part of Volvos internal development. Knowledge transfer between this and other project at Volvo has led to a change in the project focus to better meet the future needs at Volvo.

# 6. Spridning och publicering

### 6.1 Kunskaps- och resultatspridning

The results of this project can be utilized in other internal development projects at Volvo. There have also been a number of seminars within Volvo aiming at education the organization and spread the knowledge build and results in the project.

There is also a strong connection between this projects and new applications within the driveline control and electromobility area.

### 6.2 Publikationer

There are currently three journal papers in the works tying up the research in this project. The first paper presents the dynamic model developed and shows the vertical dynamics and sensitivity analysis of the model and is planned to be submitted shortly. The second paper goes into detail about the energy consumption of the model and shows how the model can be used to control a vehicle while minimizing the energy consumption. The third paper in the series is planned to show online optimization of the experimental platform and how it compares with the offline optimization.

Paper 1 (Journal) - Low Complexity Dynamic Model for Articulated Vehicles
This paper presents the dynamic model created for ArtiTRAX. The model is a low complexity model that was designed to handle running optimization of energy efficiency online. The paper goes into detail about the model and shows a sensitivity analysis of important parameters in the model and their effect on the behaviour. The results show that the model approximates the behaviour of ArtiTRAX relatively well in the vertical dynamics, which is the key to calculating the power consumption of the vehicle.

Paper 2 (Journal) - Optimal Control of Articulated Vehicles
This paper presents the power consumption part of the previously mentioned model and shows how optimal control can be used to find the torque distribution required to minimize the power consumption for a short y-cycle with ArtiTRAX. The paper shows how the parameters of the model change the required mechanical power and how this is translated via efficiency maps of DC-motors to the electrical power consumption of the vehicle.

Paper 3 (Journal) - Online Energy Efficient Control of Articulated Vehicles
This paper presents attempts at reaching the optimal point while doing calculations online. The results will be compared to the global optimum found in the 2nd paper and the necessary sensors required to perform this on a full-scale vehicle will be discussed.

# 7. Slutsatser och fortsatt forskning

Going towards online optimization of energy efficiency has been a long journey, where most of the time has been focused towards measuring and modeling the behavior of the experimental platform ArtiTRAX. However, the model still overestimates certain behavior while it underestimating other. The vertical dynamics of the model is working well while the mechanical power calculations are lacking. As it stands right now, the only missing part is the calculation of the elasticity of the tyre as this is dependent of the normal force.

The electrical power consumed gets affected by the current mechanical power losses and therefore underestimates the distribution required to reach the optima reported by experimental measurements. Lateral tyre forces are affected during e.g.; cornering, where the outer tires can reach a higher lateral friction due to normal forces, or when driving on inclined surfaces. The friction of air, or drag, can result in changed deformation of tires during driving and even at steady state velocities where it can cause torque around the mass centers. However, this effect is normally only visible at higher velocities and was not modelled for the experimental platform that has a maximum velocity of 3 m/s.

Simple control schemes have been tried with the help of the model but none of the simple control schemes, such as slip control, are optimal. Assuming that the motors are ideal (100% efficiency), results in that the frictional minima being the optimal point of energy efficiency considerations. However, electric motors are not ideal, and should be mapped to use in conjunction with the model for mechanical power to achieve results closer to reality.

The work will continue with optimization by use of the model in the near future. Likely, convex optimization will be the end goal for online performance. Other methods, such as extremum seeking control might also be viable, and should be investigated.

# 8. Deltagande parter och kontaktpersoner

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