Modelling and Dynamic Simulation of Tracked Forwarder in Adams ATV Module

PRAVEEN RAMACHANDRAN

KTH Industrial Engineering and Management

Master of Science Thesis
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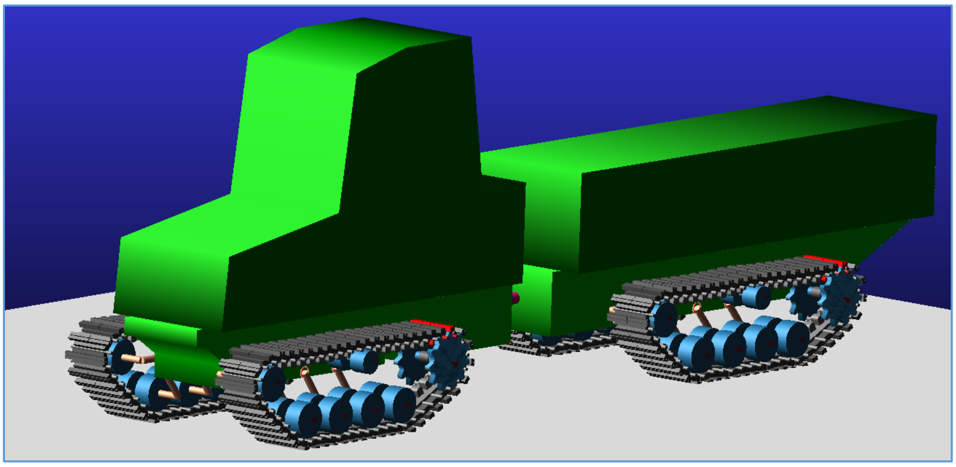

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	Examensarbete MMK 2015:51 MKN 138 **Modellering och dynamisk simulering av bandskotare i Adams ATV** Praveen Ramachandran	
KTH Industriell teknik och management		
Godkänt 2015-06-08	Examinator Ulf Sellgren	Handledare Ulf Sellgren (KTH) Bjorn Lofgren (Skogforsk)
	Uppdragsgivare Skogforsk	Kontaktperson Ulf Sellgren

Sammanfattning

Svensk skogsindustri jobbar efter kortvirkesmetoden för avträdavverkning. Den finns en en strävan efter att göra denna metod mera effektiv och samtidigt mera ekologiskt hållbar, so exempelvis en minskad markpåverkan reduktion av de helkroppsvibrationer som operatören utsätts för. Motivet till detta examensarbete är att utforska möjligheten att ersätta dagens hjulbaserade skogsmaskiner med banddrivna. Det överordnade syftet för examensarbetet är att utveckla en modelleringsmetodik för dynamiska systemsimuleringar. Metoden för detta är att modellera och simulera en banddriven skotare med Adams ATV-modul och att beskriva ett rekommenderat tillvägagångssätt och möjliga resultat..

Som en del avarbetet har en traditionell skotare valts och en konceptuell bandenhet har skapats och anpassats för att passa till skogsmaskinen. Konceptet modellerades och simulerades med Adams ATV för olika markunderlag. Ytterligare arbete lades på att identifiera de parametrar som är viktiga för grepp, fordonskontroll och framkomlighet. Baserat på några av resultaten valdes några för en fördjupad studie. Resultatet från examensarbetet kan ge riktlinjer för val av lämplig metodik för denna typ av prestandastudier. En konkret leverabel från projektet är också en dynamisk flerkroppsmodell, som kan utgöra en bas för fortsatta konstruktions- och prestandastudier.

Sökord: **Bandskotare, Flerkroppssimulering, MSC Adams ATV, Mallbaserad modellering**

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	Commissioner Skogforsk	Contact person Ulf Sellgren

Abstract

Swedish forest industry is relying on the cut-to-length method for logging and there has always been a constant quest to make it more efficient and sustainable. Reduction of forest soil damage and operator vibration dosages are crucial steps that could facilitate meeting the above stated targets. In this context Skogforsk- The Swedish Forest Research Institute has decided to explore the potential usage of caterpillar tracks on conventional wheeled forwarders. An efficient way to perform this study is to use multi body simulations to evaluate the performance of the tracked forwarder concept over different terrains. This thesis work aims to model and simulate a tracked forwarder in Adams ATV module.

As part of the thesis a conventional wheeled forwarder was selected and a track unit was conceptualised to fit it. The concept was modelled and simulate with Adams ATV for various ground conditions. An effort was also made to identify the performance parameters required to improve traction, handling, and ride performance. Based on this some results were selected and studied and inferences were made. The results from the thesis work could provide a guideline on the methodology to be followed and a a deliverable is also a multi-body dynamics model for future design research.

Keywords: ***Tracked Forwarder, Multi-body simulation, MSC. Adams ATV, Template Based Modelling***

FOREWORD

It's with great pleasure I wish to thank everyone who worked with me during the last five months of thesis work. It was their constant personal and professional support that helped me to make this endeavour fruitful. First and foremost I wish to express sincere gratitude towards my supervisors Dr. Ulf Sellgren from KTH and Mr. Bjorn Lofgren from Skogforsk who entrusted me the task. They were always patient to listen to my ideas, and guided me with their experience.

I was also fortunate to receive the guidance of Mr Henrik Skovbjerg from MSC. Software, Sweden. He spent his valuable time to clear my doubts on Adams ATV software. I wish to thank him for his help. Also I remember with gratitude the support I received from Professor Kjell Andersson from KTH in procuring the Adams ATV software. I also thank PHD student Mr. Abbos Ismoilov for his motivating words and technical support.

I wish to thank my classmates at forest master thesis school. It has always been a warm and friendly environment in our work place and we could always supported each other.

On this occasion I remember with gratitude the guidance and motivation I received from the mentors of my previous research work; Dr. Ganesha Udupa, Mr. Pramod Sreedharan and Dr. Ganesh Sundaram. It was during this work I got introduced to multi-body dynamics and the interest in Adams software spurred.

This would not be complete without thanking my parents whose hard work and constant support enabled me to pursue higher education in Sweden. I also wish to thank my girlfriend and her family and my brother for their constant encouragement that kept me positive.

I wish to keep myself open to suggestions, constructive criticisms and new ideas. I will be happy to discuss regarding this project or ATV in general and can contacted via my personal email id prkk2727@yahoo.co.in

Praveen Ramachandran

Stockholm, June 2015

Abbreviations

ATV	All-Terrain Vehicle
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CTL	Cut to length
GUI	Graphical User Interface
MBD	Multi-body Dynamics
MBS	Multi-body Simulation
RMS	Root Mean Square Value
PLM	Product Lifecycle Management

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1 INTRODUCTION

This chapter describes in brief, the background and purpose of the project as well as the limitations set by the researcher and the research methodology followed.

1.1 Background

Forest industry historically has been the cornerstone of the Swedish economy. Nearly 70 percent of Sweden's geographical area is covered with forest, out of which 25% are protected forest. With this valuable natural resource, in 2013 alone forest industry employed 60,000 people and contributed 120 billion SEK to economy through export. (Swedish forest Industries, 2013) In Sweden like most the European countries follow cut to length (CTL) logging. It is highly mechanised and involves mainly two machines; Harvester and Forwarder as shown in Figure 1.

Figure 1: Harvester and Forwarder (Lahtinen, 2011)

There has been continuous research on forest machines to make it more sustainable and environmental friendly without compromising the productivity. The issues like reducing soil damage, vibration on operator are of high significance. As can be seen in Figure 2 the irreversible damage to sensitive forest soil due to forestry machine operation must be prevented.

Figure 2: Wet and Sensitive Forest Floor Damaged by Forest Machine Motion (Lahtinen, 2011)

The idea to use tracks instead of conventional bogie and wheels finds it relevance in this context. It has been theoretically found by research (J. Y. Wong & Huang, 2006) that tracks have much better tractive performance compared to wheels due to full development of shear stress under the track contact patch. Also tracks have lesser ground pressure(J Y Wong, Garber, & Preston-Thomas, 2006) due to larger contact area making it possible to travel over soil with lesser compressive strength. In these contexts the decision has been made to explore the potential of a tracked forwarder for the Nordic forests to reduce the soil damage and improve mobility.

1.2 Problem Statement and Scope

The prime objective of the thesis work is to develop a reliable simulation model of the tracked forwarder in MSC. Adams ATV module. The multi body simulation developed, should equip the researcher with a significant tool to virtually build and test new track concepts. The potential of Adams ATV software to build reliable simulation models and the time required to build and simulate is studied as part of thesis work. The scope of the research work can be described as follows.

1. How to model a concept track unit that fits the reference forwarder?
2. How to model and simulate it in Adams ATV module?
3. How to model the traction of the track?
4. How to model track terrain interaction and motion over hard and rough terrain?
5. How to obtain meaningful data from the simulation?
6. Can Adams ATV provide reliable simulation?
7. Can it assist in the model based design of the forwarder?
8. Can it be used to improve and optimize the design?

1.3 Delimitations

The following delimitations has been set for the research.

- Only one concept will be evaluated as part of research since the aim of the research is to build reliable simulation model and not to build the optimum track concept.
- The research methodology will be limited to multi body simulation in Adams ATV and no mathematical modelling or experimental verification is done. Since the actual machine does not exist, even though an experimental verification can significantly improve the reliability of simulation it is not done.
- The simulation will be done on hard surfaces. The soft soil simulation is neglected at this stage as it takes a lot more simulation time. If time permits in the end, a capability evaluation of the software to do soft soil simulation will be performed.
- Some of the simulation parameters (e.g. the contact stiffness) will be assumed. All assumptions will be clearly specified in the thesis.

1.4 Research Methodology

Multi body simulation in Adams ATV module was chosen as the research methodology for the thesis as proposed by the company. It can be used to perform studies in system level as indicated by previous researches.

The methodology chosen for the thesis is represented as the Figure 3. The first phase involves a literature review where existing research work will be studied. Then a reference forwarder will be selected and a track unit concept will be developed. As the next step, ATV software will be studied and the modelling and simulation is done. As most Adams simulation models, testing will be done and model will be improved till a reliable simulation is obtained.

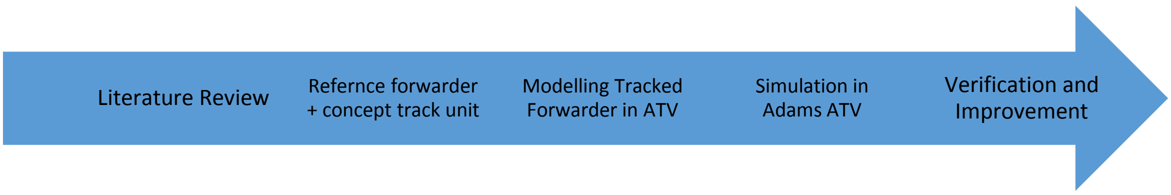

Figure 3: Research Methodology

This chapter summarises the assimilated knowledge and presents the theoretical frame work of the performed research.

2.1 Cut-to-length logging and Forest Machines

Cut to length logging (CTL) is the primary logging method adopted in the European nations. In this method, the harvesting is done with help of two machines; Harvester and Forwarder. The harvester fells, de-limbs and buck the trees, while the Forwarder is used to transport the logs from the felling area to the nearest access roads (Gerasimov, Sokolov, & Syunev, 2013). CTL is relatively more environmental friendly compared to other logging methods like, full-tree logging or tree-length logging. It produces cleaner woods due to no skidding on the ground, induces less damage to soil and the retained trees making it suitable for forest plantations.

A forwarder is used to transport logs from the felling area to the nearest access road. These machines run through near no road condition and subjected to extreme off-roading. This results in high vibrations and stress on the machine and operator. Since it need to traverse wet and clayey soil, the tractive performance is important. Typical forwarders are suspended by bogie and have wheels to reduce impact. Research is made to replace the bogie with passive or active pendulum suspensions so that vibrations can be further reduced (Baez, 2014). The concept forwarder XT28 as shown in Figure 4 is based on this.

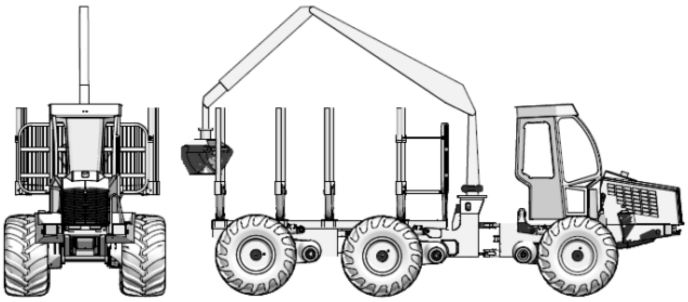

Figure 4: XT 28 Forwarder(Baez, 2014)

The tractive performance of the wheeled forwarders can be improved by adding wheel tracks as shown in Figure 5. The wheel tracks improve the contact area there by reducing the ground pressure of the wheels. It also improves the traction especially in snow and muddy terrains (Palaniappan, 2013).

Figure 5: Forwarder with Wheel Tracks

2.2 Evaluating Performance of the Forwarder

Forwarders are fundamentally off road non guided ground vehicles and can be evaluated by the characteristics for off road vehicles. A non-guided ground vehicle is one which is not supported by the guide and can move by choice in various directions (J.Y. Wong, 2010b). The characteristics of the forwarder can be classified into performance, handling and ride. Performance characteristics include motion resistance of vehicle running gear, drawbar performance, ability to overcome obstacles, ability to accelerate and decelerate etc. (Carroll, Stone, & Smith, 2006).

The lateral dynamics characteristics like response of the vehicle to driver's command, ability to stabilize the motion against external disturbances are studied under the handling (Carroll, 2006). The forwarders are steered by articulated steering(Azad, 2006). Articulated steering help to reduce the turning radius and help the forwarder to take tight turns in the forest filled with trees.

The ride quality of the forwarder can be defined as the ability of the vehicle not to transfer the external excitations due to surface irregularities to passengers and goods. Numerous studies have been performed to improve vibration characteristics of off road vehicles in general (S. Ryu, Park, & Suh, 2011) and forwarders in specific (Baez, 2014)

2.3 Traction Unit - Wheels vs. Track

The running gear used in forwarder either its wheels or track has primarily four main functions. It need to support the vehicle mass, it should dampen out the external vibration from surface irregularities, it should provide sufficient traction to move or to stop and the vehicle should be able to move with sufficient directional stability (J. Y. Wong & Huang, 2006). Several studies has been done to compare the performance of wheeled versus tracked vehicle for different application like agricultural machines, forestry and so on (Mico, 2013). In the case of tractive performance on unprepared terrain computer simulation models are used to provide reliable comparisons. The NTVPM computer simulation model(J.Y. Wong, 2010a) can be used for flexible track and RTVPM model for rigid tracks as in case of the agricultural machineries. (J. Y. Wong, 1999).

It's concluded from studies that the contact length of a tire is usually much shorter than that of a track. In many cases full development of shear stress on tire contact patches won't happen. Hence the tracked vehicles have comparatively better traction. The development of shear stress is influenced by shear deformation parameter of terrain. The soil can be broadly classified into frictional soil and cohesive soil. The traction is primarily dependent on normal load in frictional soil like sand, whereas the cohesive soil like clay it is dependent on total contact area. Hence it can be concluded that, the tracked vehicle will be better is clayey soil like one that found in Nordic forests. Also due to more contact area, the tracked vehicle exerts much lesser ground pressure. (J Y Wong, 2006)

In order to comprehensively compare wheeled versus track vehicle, system level analysis is required. The merits and demerits of tracked vehicle for a particular environment should not only limited to ride, handling and traction performances but also to assessment of full life cycle cost, reliability, maintainability etc. In this thesis work multi body simulation is chosen as research methodology and its can be used mainly to study traction, handling and ride performance and other factors are excluded from the scope of thesis work.

2.4 Modelling Approaches of Tracked vehicles

Mathematical modelling and simulation allows the researcher to understand and predict the dynamics of tracked vehicle under various operation conditions. It is essential to improve and optimise components and parameters of track unit. There are mainly two method; super element and multi body model that can be used to model tracked vehicles.

Super element method treats the track chain as single flexible body and the other components like road wheel, idler, sprocket as discrete rigid bodies with kinematic constrains. By treating track as a single force super element applied to each wheel instead of individual rigid bodies with frictional contact, the size of the problem can be reduced saving computational time (McCullough & Haug, 1986). The derived super element that can represent the spatial dynamics can be used to find out equation of motion of suspension system. Thus super element model create high fidelity simulation of the interaction between the track chain and other running gear components at shorter computational time. But the application of this method is limited to straight line motion because the model is based on the assumption that there are only longitudinal forces in the super element. Improved versions of super element model where the track chains are modelled by continuous uniform elastic rod. In order to discretise the nonlinear problem finite element methods are used and forces on the track chain is modelled with linear stiffness and damping. Though this model is also not suitable for non-straight line manoeuvres, it can be used to capture high frequency content of track, wheel and terrain interaction.

A Multi body model on the other hand treats the track units as individual track shoes connected by force elements. The research paper (Rubinstein & Hitron, 2004) consider each track shoe as rigid body connected to its neighbour by revolute joint. The road wheel- track contact is modelled with three dimensional contact force element and the track terrain interaction by pressure-sinkage force relationship based on Bekker (Laughery, Gerhart, & Goetz, 1990) and Janosi approach (Laughery et al., 1990). The simulation program LMS-DADS was used to model the tracked vehicle suspension as shown in Figure 6. The research showed promising results in predicting normal stress under the track. The predicted results matched the experimental stress values. The riding over obstacle simulation is done in DADs software but a good match was obtained only at lower frequency. At higher frequencies the application of this method is limited as there is significant difference in the predicted and test results.

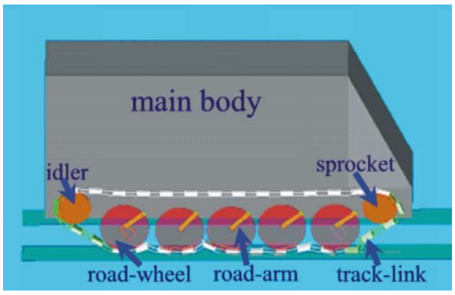

Figure 6: Track Link Model (Rubinstein & Hitron, 2004)

The research paper (H. S. Ryu, Bae, Choi, & Shabana, 2000) propose alternate method to model track units using multi-body simulation. Here in this method the revolute joint is replaced by compliant force elements which can be described by stiffness and damping values. These compliant track model was used to predict the dynamics of high speed, high mobility tracked vehicle. The methodology was further used to develop active track tensioners (Han Sik Ryu, Huh, Bae, & Choi, 2003).

2.5 Multi body simulations and Adams ATV module

Multi body simulations is an effective way to study dynamics of tracked vehicle is systems level. MSC. Adams is one of the most widely used MBS software. It has several advantages including a user friendly graphical user interface (GUI), automatic assembly of Equations of motion and a robust and efficient integration algorithm for differential equations. The Adams software uses generalised Cartesian coordinate and hence the assembled equations are a set of differential algebraic equation of index three (Madsen).

It make use of template based modelling as shown in Figure 7. Template based modelling allows user to quickly make changes saving time.

Figure 7: Adams Modelling Methodology

Adams ATV Module

Adams ATV is a plugin inside Adams Car environment specifically developed for tracked vehicle simulations. Like Adams Car it's also template based modelling and involves templates subsystems and assemblies. It has provision to build and assemble track unit components like hull, suspension, tensioner, support wheel, drive sprocket etc. The track itself is developed by connecting track shoes with a compliant force element in between. A built in routine is used to automatically wrap the track around the support wheels. Different road profiles can be imported using the road files. Both hard as well as soft soil can be used and the contacts are created accordingly.

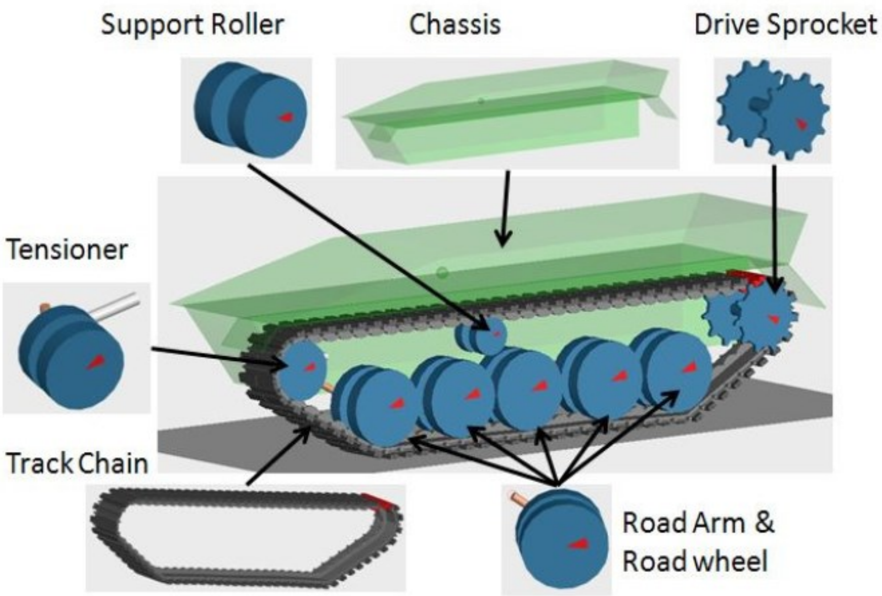

Figure 8: Subsystems of ATV Track Unit (Yin & Shao, 2005)

The chapter describes the crux of the thesis work; how the tracked forwarder is built and simulated in Adams ATV. The modelling process is described in detail to ensure the reproducibility of results in the future.

3.1 Introduction

The modelling process starts with developing a concept forwarder based on a reference model. A concept track unit is developed and is modelled in Adams ATV module as templates and finally assembled together. The process is described in detail in the following chapter. This chapter is written with the assumption that the reader is familiar with Adams ATV module and the basic ATV terminologies used.

3.2 Reference Forwarder

The first step of the modelling process is to identify an existing forwarder, which can be modified to mount the new concept track unit. The mass properties and dimensions of the base model are identified and will be used for simulation in Adams ATV module. Komatsu Valmet 860.3 as shown in Figure 9 is identified as the base model. Valmet 860 is a mid-size model which represnt major market segment. The dimensions of the forwarder are as given in the figure below and it is the reference for the ATV model.

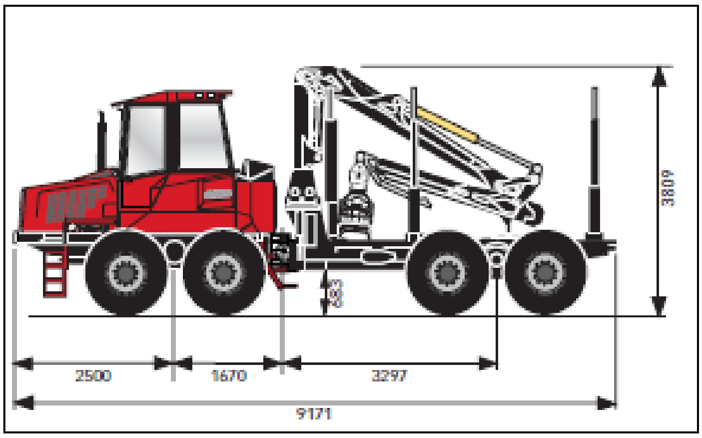

Figure 9 Valmet 860.3 Dimensions

The mass Properties are also identified as given in the Table 1. The centre of gravity of the front and rear part of the forwarder is identified with reference to the articulated steering centre as the origin.

Properties	Front Part	Rear Part
Mass –Unloaded (Kg)	8193	9111
- Loaded	8193	20111
C.G* – Unloaded (mm)	(-2128.5, 298.5)	(2888.7, 474.8)
- Loaded	(-2128.5, 298.5)	(3482.3, 1209.2)
* Reference: Centre of Articulated Joint		

Table 1: Mass Properties of the Forwarder

3.3 Track Unit Concept

The track unit concept designed in such a way that it can be fitted directly to the Valmet 860 forwarder. As the first step the wheels and bogies will be disassembled. The drive shaft will be attached to the sprocket of the track unit. Based on the available space, a track unit with the dimensions as shown in Figure 10 is designed.

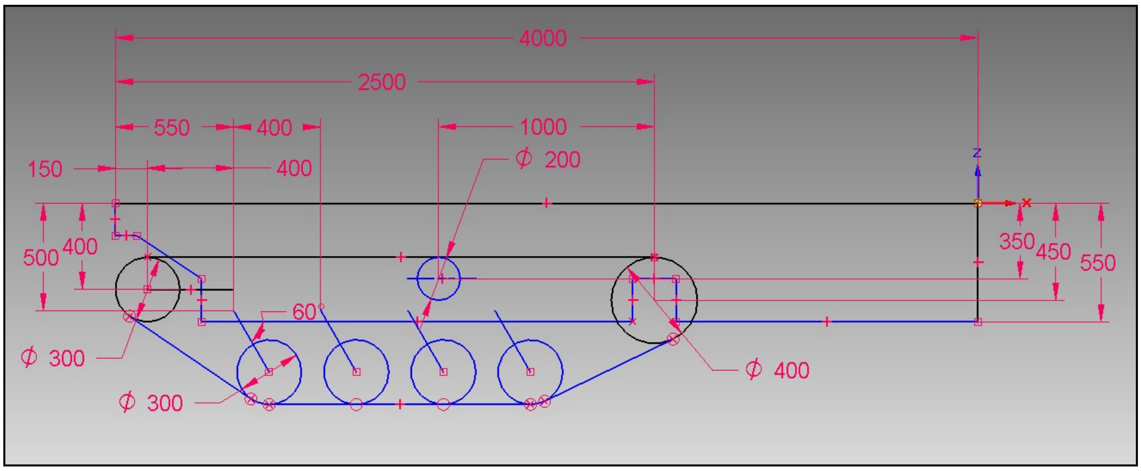

Figure 10: Concept Track Unit- Dimensions

The road clearance is changed from 683 to 383 millimetres in the simulation model because the longer road wheel arms, higher the torques on the suspension springs. In the actual model it can be solved by assembling the road wheels on a frame. The frame can be attached similar to bogie and the road wheel can be lowered without increasing the road wheel arm length.

The width of the track unit is assumed to be 400 millimetres. Every component in the track unit is designed to fit into this dimension.

3.3 Modelling in Adams ATV Module

Adams ATV module is an extra plugin that can be loaded into the Adams Car or Adams View software. It can be loaded from the plugin manager as shown in the Figure 11. The user can work mainly in two interfaces; standard interface for the subsystem and assembly and the template builder interface for templates. It is important to set the appropriate working directory and modelling database as soon as the plugin is loaded.

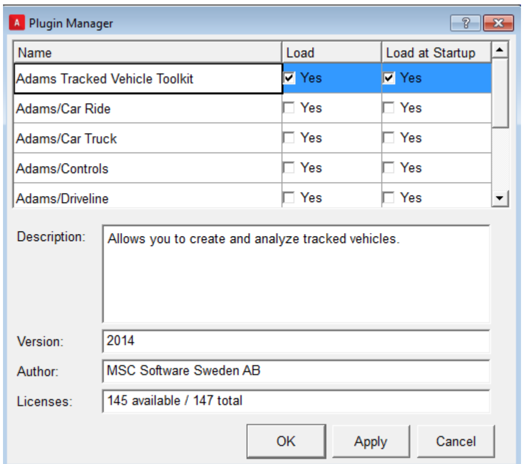

Figure 11: ATV Plugin Loading Dialogue Box

3.4 Building Templates

Templates are parametric models which defines the geometry and topology. It is built within in the 'template builder' environment inside ATV module. A template consists of design parameters like hard points, construction frames, ATV parts, general parts, parameter variables and property files. It also includes of input and output communicators, which are crucial to enable information exchange with other templates when assembled together. A template can be modified by the changing the value of design parameters, which will be reflected in the final assembly. The templates of the following components have been built inside the ATV Template Builder.

3.4.1 Front and Rear Forwarder Body

The front and Rear body of the forwarder is built as a hull file as shown in Figure 12 inside ATV module. The hull is a special part in ATV in which the geometry in inputted as coordinate points. Based on the dimensions of the base model Valmet 860, a hull property file is created (See Appendix). The mass, moment of inertia and C.G is also entered while creating the hull.

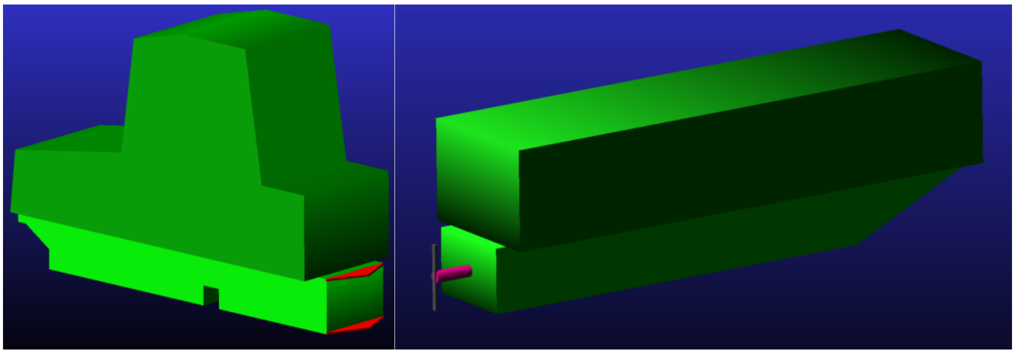

Figure 12: Front and Rear Chassis templates

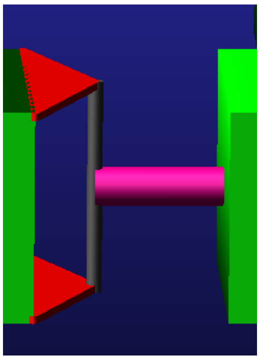

Figure 13 Steering for the forwarder

In order to set the reference for the template, hard points and construction frames are defined. Then the ATV special part hull is used to create the geometry of the chassis. Then the general part with 'arm' geometry is used to create the articulated steering. As the next step, mount part is created on the front body. It is used during assembly to ensure front and rear chassis are assemble together. A revolute joint is created between the front body and mount part which act as the yaw joint in the steering.

The input communicator, [hull01_to_hull02] with minor role 'inherited' is automatically created with the mount part. The output communicators with 'mount entity' which enable information exchange with road wheels, support wheel, power train has to be created. Also an output communicator [attach_to_hull] is created so that hull can communicate with the tracked vehicle test rig. The file is saved with 'hull' as the 'major role'.

3.4.2 Road Wheel

The road wheels are parts of track unit which supports the track section. It consists of an arm part, road wheel which is in contact with track segment, a torsional spring damper system that acts as shock-absorber. A front and rear road wheel template as in Figure 14 is created because of the presence two track sections in the model. The 'major role' for this template is track holder.

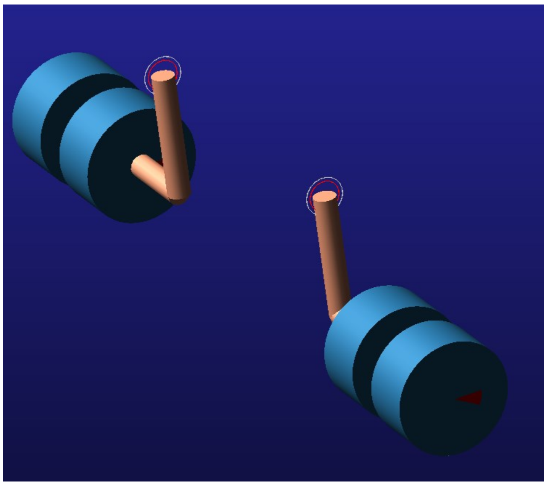

Figure 14: Road Wheel Template

As the first step, the hard points are created and general part with link geometry and type 'left' is used to create the arms and axle. A construction frame with z axis parallel to the axis is created to constrain the orientation of the track wheel. Then the special ATV part 'Track wheel' is used to create the wheel part as shown in Figure 15.

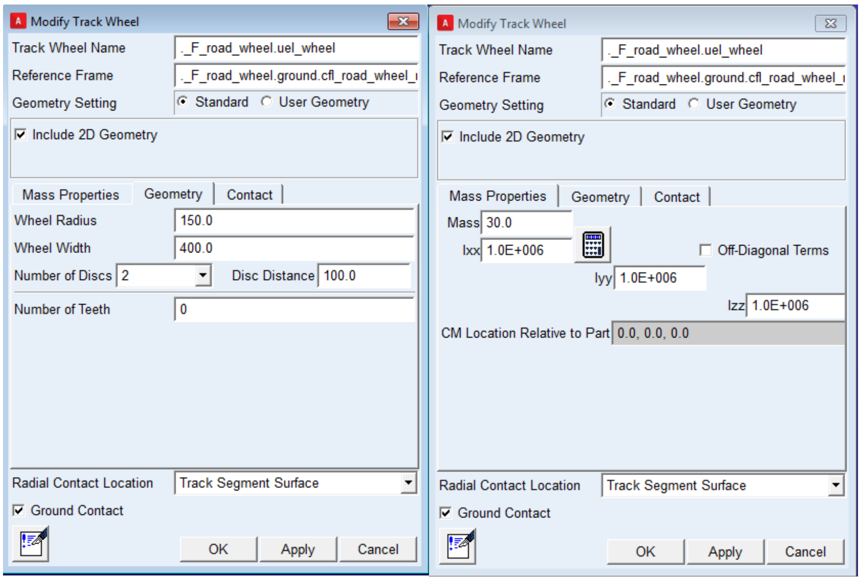

Figure 15: Modify Track Wheel dialogue box

The mass properties and geometry of track wheel is defined as per specification. It is important to note that the track wheel created is with two disks and without teeth. The track guide passes between these two disks. No changes have been made to the contact properties and the default values are used. The Radial contact location is set to 'Track segment surface' because the contact between wheel and the track segment is through the track segment surface. It is also important to set the 'Ground contact' since it ensures that the track section will not hang between the track wheel and the ground. Since the wrapping is done automatically, setting correct ground contacts ensures proper wrapping of track segment.

A mount part is created at the pivot point and construction frames are created at the road wheel centre and pivot point. The construction frames act as the orientation references for the revolute joints. The revolute joint as shown in Figure 16 is created to between the arm and the mount part which will constrain the motion of the road wheel with respect to hull in the assembly. Another revolute joint is created with the track wheel and the axle.

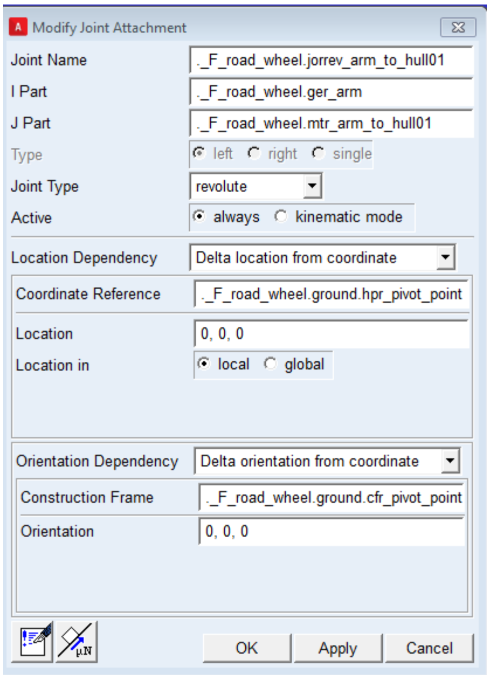

Figure 16: Joint modification dialogue box

In order to create the suspension part, the ATV forces rotational spring, rotational damper and rotational bumpstop as in Figure 17 is used. The property files used for the rotational spring, damper and bumpstop is attached in the appendix. Linear spring and damper is used for the suspension. The bumpstop of Bump-Reboundstop type is used with maximum angle of 50 degrees each.

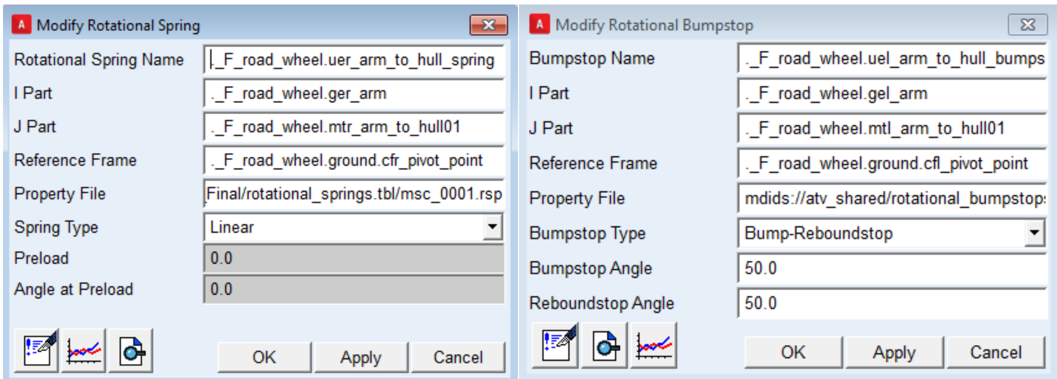

Figure 17: Spring and Bumpstop dialogue box

The input communicator of mount entity is created when the mount part is created. It should be ensured that the communicator in the front road wheel template, have hull01 and in the rear road wheel template have hull02 as the minor role. This helps the ATV to identify road wheels and to connect it to appropriate hull part.

As mentioned a front road wheel and rear road wheel template is created. From each one of these templates four subsystems corresponding to each road wheels are made. Further details about subsystem will be provided in the next section.

3.4.3 Idler

An Idler is the part of the track unit which is used to control the track tension force. It consists of a track wheel, axle, arm and a tensioner as shown in Figure 18. Tensioner consists of spring and has a provision to elongate to ensure necessary tension on the track. The ‘major role’ of this template is set as ‘track holder’.

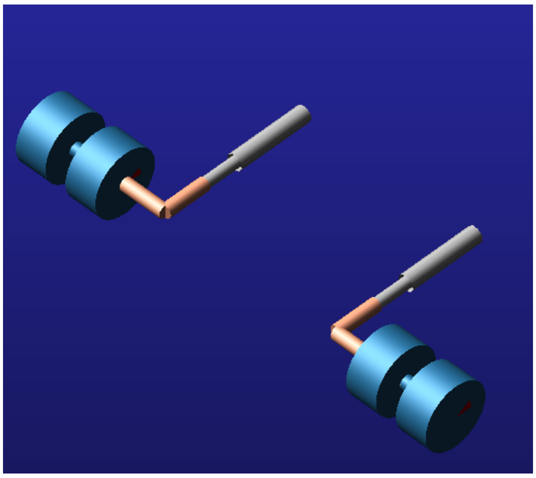

Figure 18: Idler Template

The road wheels and axles as in Figure 19 are created similar to the road wheel template. But the ground contact is disabled and the radial contact location is through track segment surface. The reference frame for the track wheel is the rotated construction frame (z- axis parallel to axle). A revolute joint constrains the track wheel with the axle.

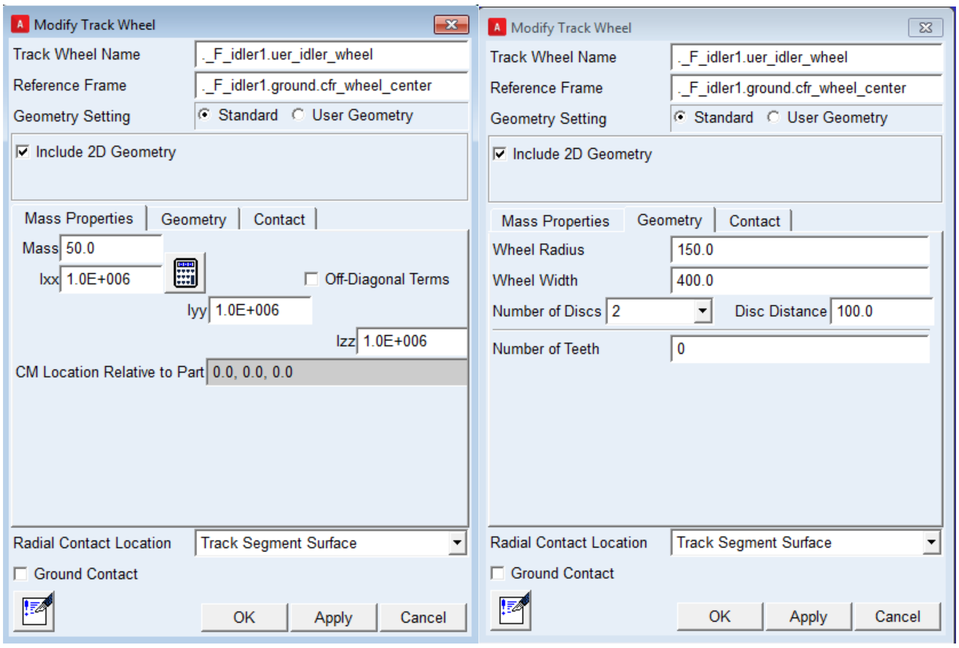

Figure 19: Idler Track Wheel Mass and Dimensions

The idler is attached to hull with the help of a fixed joint and to the arm with a translational joint. It consists of the ATV special force element Tensioner, which can elongate and control the track tension. A tensioner force displacement relation can be visualised in the Figure 20.

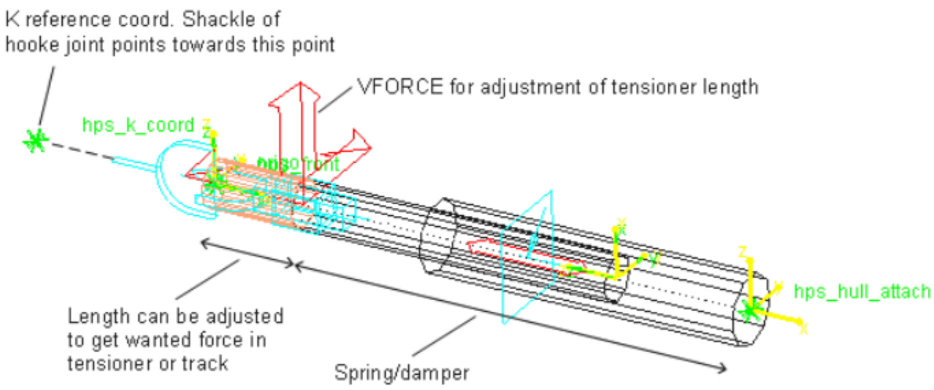

Figure 20: Tensioner Forces

A tensioner can be linear, nonlinear or rigid. In this case linear tensioner is chosen and it can be represented by following equation.

$$force = -k(x - x_0) - cV + F_{stop} + F_{prelaod} \qquad (1)$$

Where K = spring stiffness, c = viscous damping coefficient, x = spring length, X_0 = initial spring length, v = spring velocity, F_{stop} = min/max length stop force, $F_{preload}$ = spring preload force, F_{spring} = force-displacement spline defining spring characteristics.

The value of these coefficients is obtained from the tensioner property file (Refer Appendix). The value of F_{stop} is found out using the Adams solver BISTOP function. The tensioner can be modified using the modify tensioner option in ATV as shown in Figure 21.

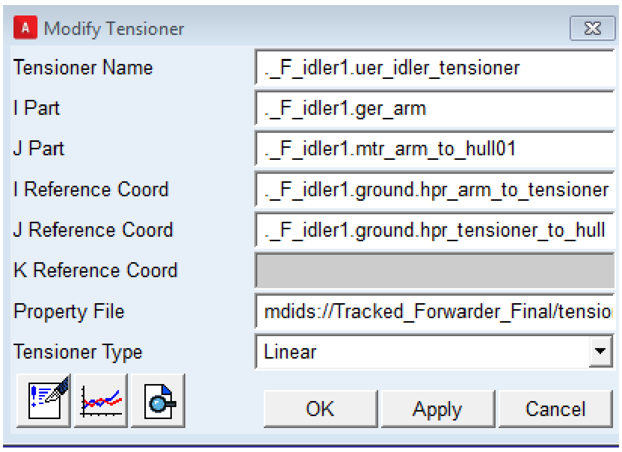

Figure 21: Tensioner Modification Dialogue Box

ATV provides user option to setup the tensioner in four different ways; Tensioner design length, Tensioner Force, Track element force, String Track Tensioner. It can be set when the template is converted to subsystem and then into assembly. The tensioner length is adjusted according to the desired force during the static analysis during simulation. Once the simulation is completed it is good to measure the tensioner force and to see the operation is successful.

The idler template consists of one input communicator that's used to communicate with hull. As mentioned two templates front and rear idler are made separately with appropriate communicator for front and rear track segment.

3.4.4 Support wheel

Support wheels as in Figure 22 are used on the upper part of the track unit as support for the track section. It ensures that track does not slack without support. It is built with help of track wheel part in ATV. The location and dimension of the part is as given in Figure 23.

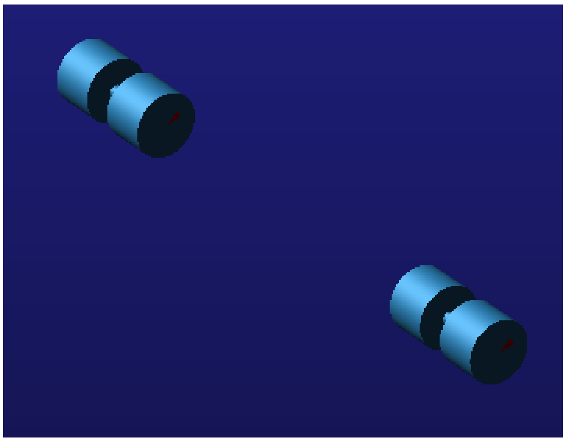

Figure 22: Support Wheel Template

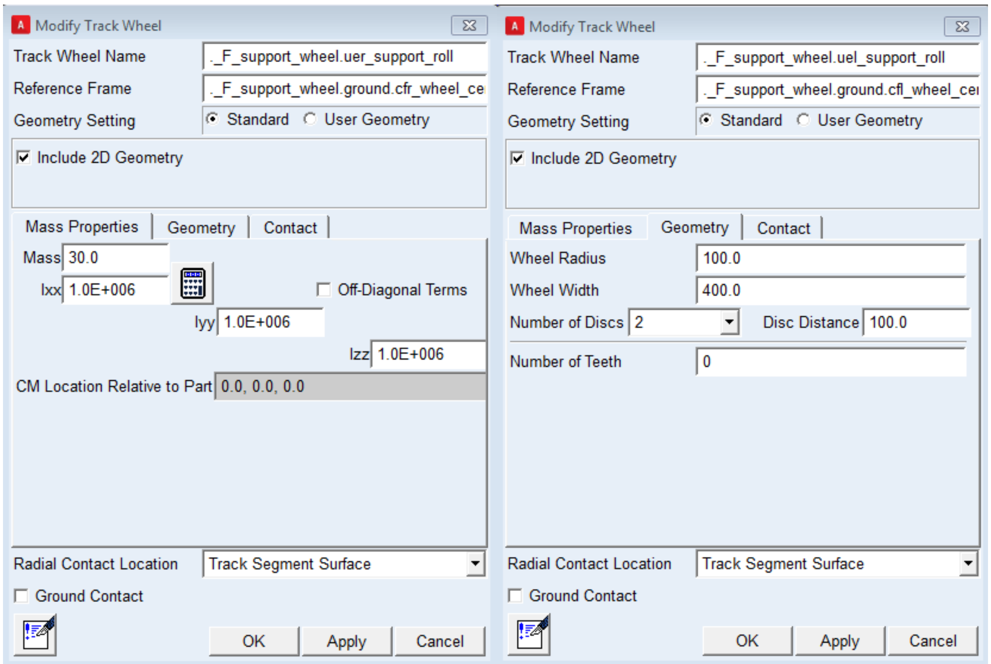

Figure 23: Track Wheel Geometry Modification Dialogue Box

It consist of a mount part [wheel_to_hull01/02] that will enable it to attach to hub while assembly. A revolute joint is created between the track wheel and the mount part, which ensures the free rotation of the support wheel in the track assembly. The ground contact is disabled and the track segment can slack between the wheels. The radial contact location will be the track segment surface. The inclusion of 2D geometry is optional and come into use only when 3D Dynamic Track – Analytical is in use. An input communicator [wheel_to_hull] with mount entity is automatically created with mount part. The minor role of this communicator should be set to Hull 01 for the front support wheel template and Hull 02 for the rear support wheel template.

3.4.5 Sprocket

The sprocket as in Figure 24 is similar to the sprocket in a chain drive. It is attached to the powertrain template and drives the track sections. The major role of the sprocket template is 'track holder'.

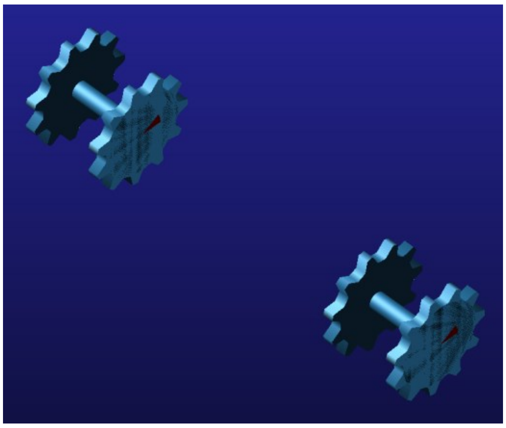

Figure 24: Sprocket Template

The sprocket is build using the 'track wheel' option in ATV as shown in Figure 25. Unlike the track wheels of the idler and the road wheel, sprocket has tooth. The various geometric properties like wheel radius, width, number of teeth, tooth width, length, height and flank angle need to be specified. The reference frame for this template is the construction frame at the wheel centre. It is also important to note that the radial contact location in the sprocket template is the track segment pin. The ground contact option is disabled.

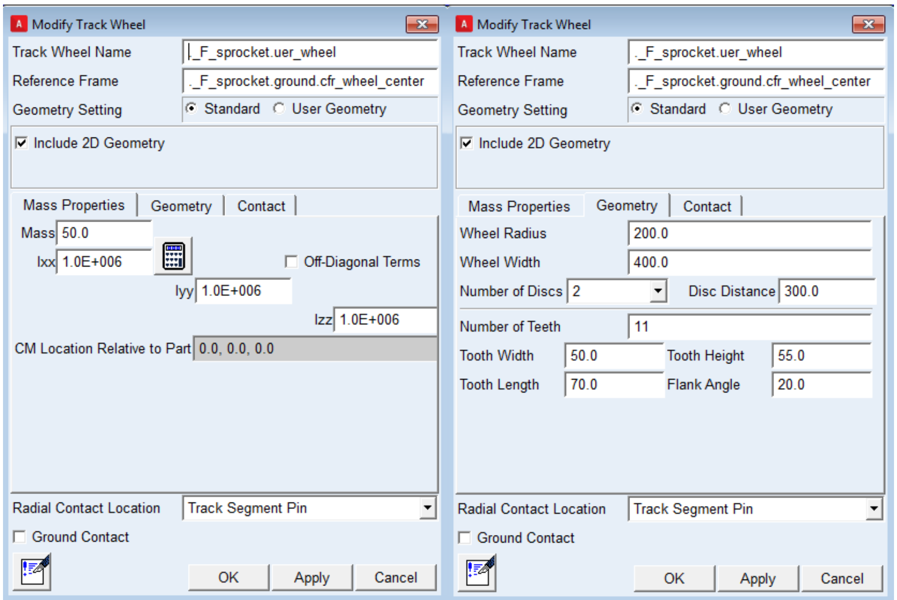

Figure 25: Track Wheel Modify Dialogue Box for Sprocket

It is connected to the powertrain template with the help of mount part and revolute joint. The communicators used in the sprocket template are; the input communicator of entity mount used to communicate with powertrain template. And the output communicators with entity 'orientation' and 'location' used to pass the location and orientation information to the powertrain. These communicators are significant because unlike other templates, the powertrain template location and orientation interlinked to the sprocket orientation and location. As other templates two sprocket templates are created one each for the front and rear track system.

3.4.5 Powertrain

The powertrain template is responsible motion and steering of the tracked forwarder. It is the real life equivalent of the drive shaft of the forwarder which transfers the power from the engine to the wheels. The 'major role' of the template is powertrain. There are two types of powertrain created as part of thesis. One is a simple powertrain as in Figure 26 on which the user can set the velocity. The second powertrain has actuators and can be used to control the motion of forwarder on a specified path.

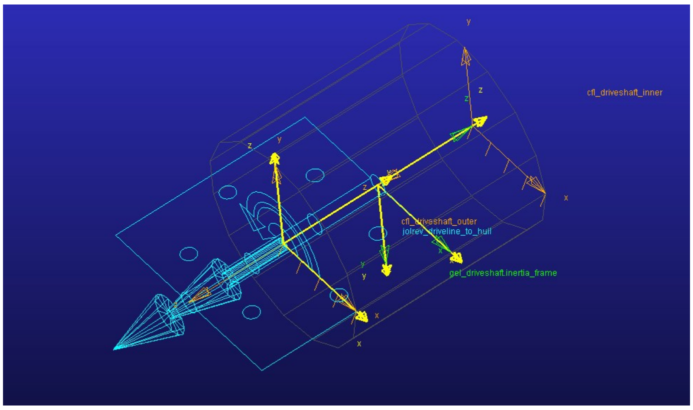

Figure 26: Powertrain Template

The creation of powertrain is different from other templates and is shown in Figure 27. First of all two construction frames [inner and outer] are created. The outer construction frames location and orientation is related to the orientation and location of sprocket using the communicators. The inner construction frame is defined with reference to the outer construction frame at specified distance and orientation. Then a general part is created connecting these two construction frames. This is done to ensure that the powertrain is automatically positioned to the centre of the sprocket subsystem.

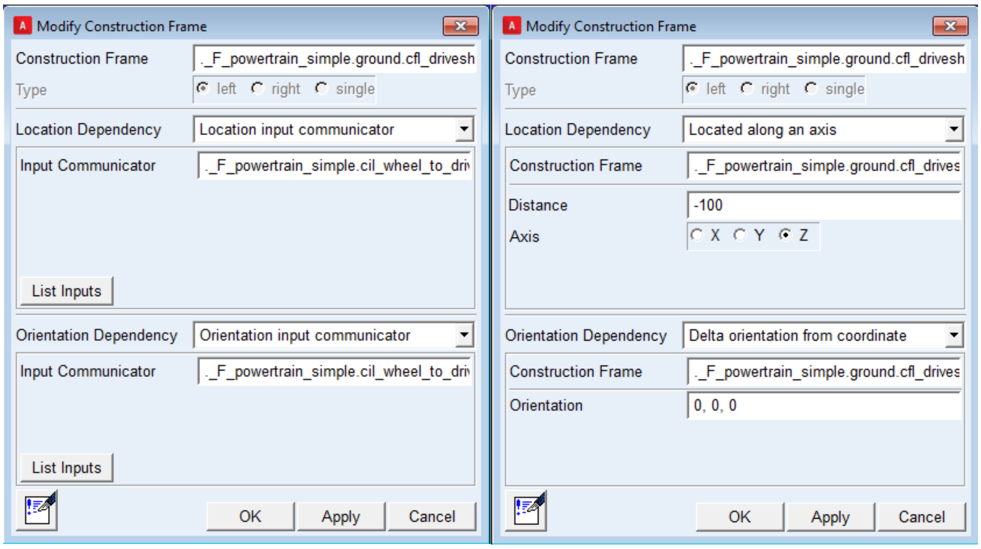

Figure 27: Construction Frame Outer and Inner Dialogue Box

A mount part and revolute joint is created to attach the powertrain the hull subsystem. The input communicators of entity orientation and location are created to input the orientation and location data of the sprocket. The output communicator wheel to shaft is also created to communicate with the powertrain template.

3.4.6 Track Segment

A track segment is an individual element of the tracks. During the wrapping stage the Adams assembles number of track segment (based on the track length) with compliant force element in between to create the tracks. The tack segment as in Figure 28 is created as a template with major role as 'track section'.

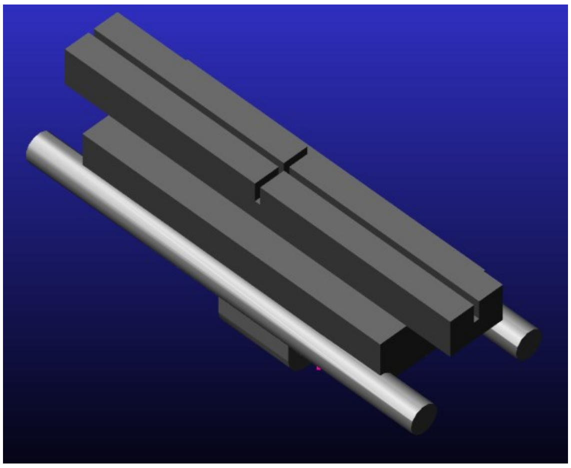

Figure 28: Track Segment Template

Track segment can be single pin, double pin or rubber track. In case of the forwarder single pin is chosen and is defined by the following geometry parameter. The most important parameter is the track pitch which is approximately equal to the (perimeter of sprocket/ number of teeth) + (2/3 of pin radius). This is crucial to ensure the track segment is wrapped without the pin interfering with the sprocket. The other geometry parameters are as in Table 2.

Parameters	Value (millimetres)
Track Pitch	120
Pin Radius	15
Plate Inner thickeness	26
Plate outer thickeness	50
Plate inner length	120
Plate outer length	120
Plate inner width	300
No: of guide	1
Guide width	80
Guide height	100
Guide length	70
Grouser position	0
Grouser ratio	0.5
Grouser Height	40
No: of tooth discs	2
Tooth width	50
Tooth height	55

Table 2: Track Segment Dimensions

No communicators are used in the template. Two track segments template one each for front and rear track unit are created and are converted to subsystems with minor role TS01 and TS02 respectively.

3.5 Building Subsystem

After building the templates the ATV interface is change into ‘standard’ and necessary subsystems are made. A subsystem contains the description of the component and is based on the template. It allows standard user to change the parametric data of the template as well as definition of some of the components. In order to build a new subsystem the user has to specify name, the minor role and select the template on which the subsystem is created as shown in Figure 29. Minor role is another crucial parameter need to be defined. The minor roles used to build the tracked forwarder are described in the Table 3.

As the next step the position of the subsystem in an assembly is defined using ‘translate from default position’. For e.g. the four subsystems (road wheel 1 -4) is created from one road wheel template. Each road wheels position in the assembly is defined when corresponding subsystem is made.

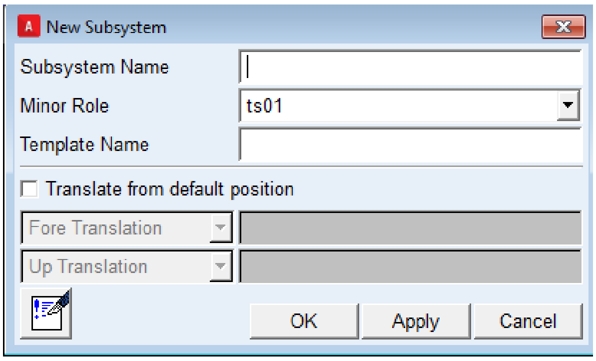

Figure 29: New Subsystem Dialogue Box

Sub System	Template	Major Role	Minor Role	Wrapping Order
F_Chassis	F_Chassis	Hull	Hull 01	
F_idler	F_idler	Track holder	Ts01_01	6
F_rw1	F_road_wheel	Track holder	Ts01_02	5
F_rw2	F_road_wheel	Track holder	Ts01_03	4
F_rw3	F_road_wheel	Track holder	Ts01_04	3
F_rw4	F_road_wheel	Track holder	Ts01_05	2
F_sprocket	F_road_wheel	Track holder	Ts01_06	1
F_powertrain	F_powertrain	Powertrain	Ts01_06	
F_suport_wheel	F_support_wheel	Track holder	Ts01_07	7
F_track_segment	F_track_segment	Track section	Ts01	
R_Chassis	R_Chassis	Hull	Hull 02	
R_idler	R_idler	Track holder	Ts02_01	6
R_rw1	R_road_wheel	Track holder	Ts02_02	5
R_rw2	R_road_wheel	Track holder	Ts02_03	4
R_rw3	R_road_wheel	Track holder	Ts02_04	3
R_rw4	R_road_wheel	Track holder	Ts02_05	2
R_sprocket	R_road_wheel	Track holder	Ts02_06	1
R_powertrain	R_powertrain	Powertrain	Ts02_06	
R_suport_wheel	R_support_wheel	Track holder	Ts02_07	7
R_track_segment	R_track_segment	Track section	Ts02	

Table 3: Subsystem Used and Properties

3.6 Building final Assembly

The subsystems are assembled together to make the final assembly of the tracked forwarder. It can be done from the generic assembly option as shown in Figure 30. The assembly name has to be provided and 'assembly class' is set to tracked vehicle. This will enable the tracked vehicle test rig. The most crucial challenge in the assembly stage is the getting the 'communicators' working. Communicators are responsible for the information exchange between the subsystems. It is made sure that every input communicator had a matching output communicator.

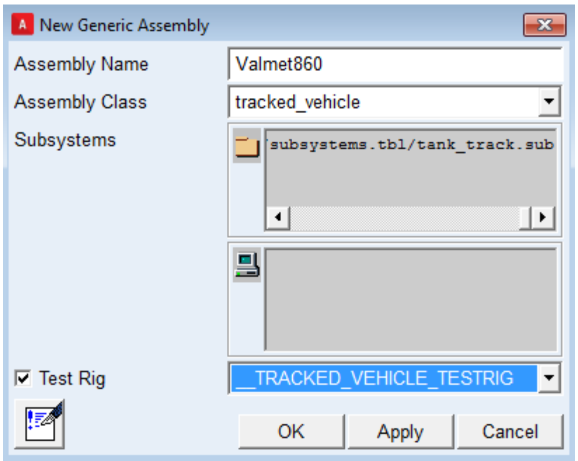

Figure 30: Tracked vehicle Assembly Dialogue Box

The final assembly of the modified Valmet 860 is as shown in Figure 31 and Figure 32. The track units are fully assembled. The track segment subsystem is located at the centre of the sprocket subsystem. This will ensure proper wrapping of the track segment.

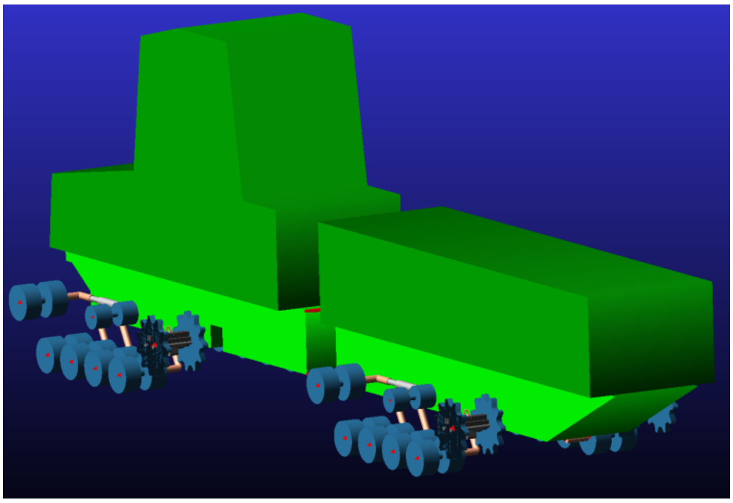

Figure 31: Final Assembly of modified Valmet 860 tracked forwarder

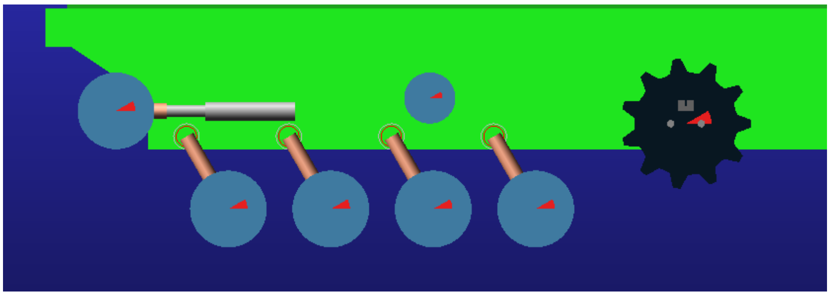

Figure 32: Track Unit Assembly Side View

3.7 Wrapping Track

Dynamic track wrapping is the procedure where the track system will be wrapped around the defined track system. The individual track segment template build will be assembled in series with compliant force element in between. The wrapping method used in this thesis work is 'Dynamic Track Wrapping' as in Figure 33. The wrapping can be done as 'full vehicle' where all the four track units are wrapped or 'half vehicle' in which only side will be wrapped. Half vehicle wrapping is used to save simulation time and can be used only when straight line simulations are done. The number of track segments and found out using trial and error. The final tracked forwarder model after wrapping is shown in Figure 34

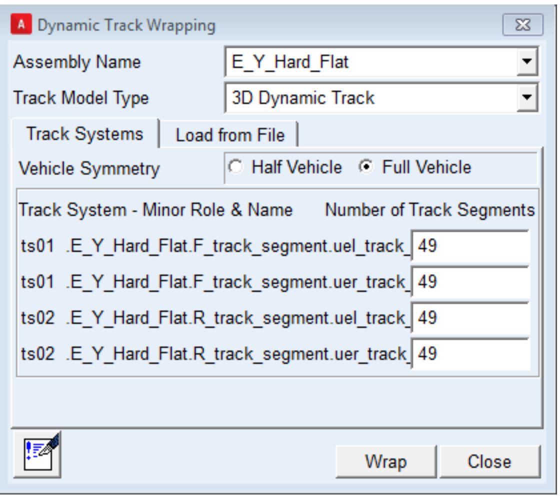

Figure 33: Wrapping Dialogue Box

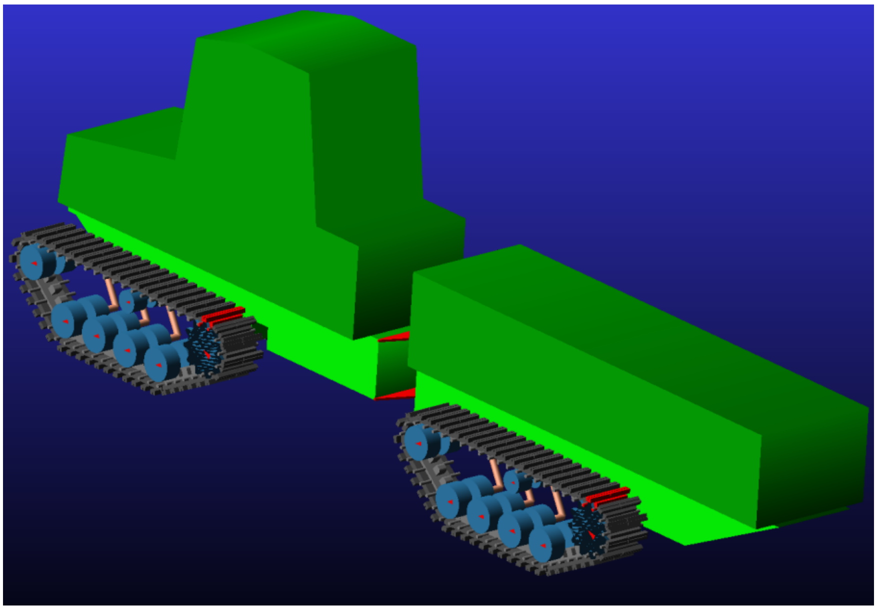

Figure 34: Forwarder Wrapped

Another method to do wrapping is the string track. String track models create tracks which are simpler and take lesser time to solve. It can be used for high speed manoeuvres on relatively smooth road and where the track dynamics and frequencies are of no interest. The sting track can be seen as longitudinal springs and dampers connecting the tangential points between the track wheels connected by the track. It is not much used in the thesis work but can be used if a design of experiment where numerous simulations are needed.

3.8 Setting up Road file

The road surface and properties can be added to the simulation model using the hard road setup option. The scope of the thesis is limited to the detailed study of hard road. It can be edited as shown in the Figure 35. The road and soil property file can be added and the appropriate orientation and location is set. It should be noted that the road need to set up at sufficient distance from the tracks. Otherwise while performing the simulation contact will not be enabled and an error 'contact is missing' will pop up. The Figure 36 shows a forwarder on a hard flat ground.

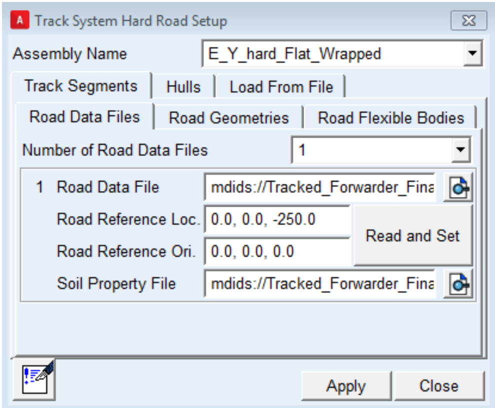

Figure 35: Hard Road Setup Dialogue Box

The two road files used in the simulation are hard flat and hard with obstacles (SKOGFORSK test track). Skogforsk test track as in Figure 37 is built in Adams as road file as in Figure 38.

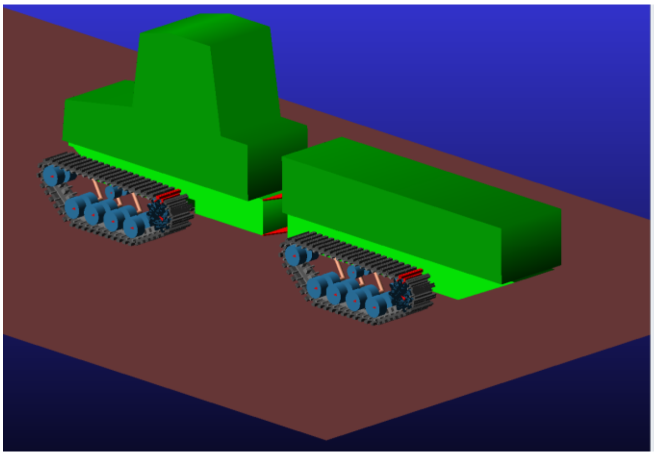

Figure 36: Forwarder on Hard Flat Ground

Figure 37: SKOGFORSK Test Track

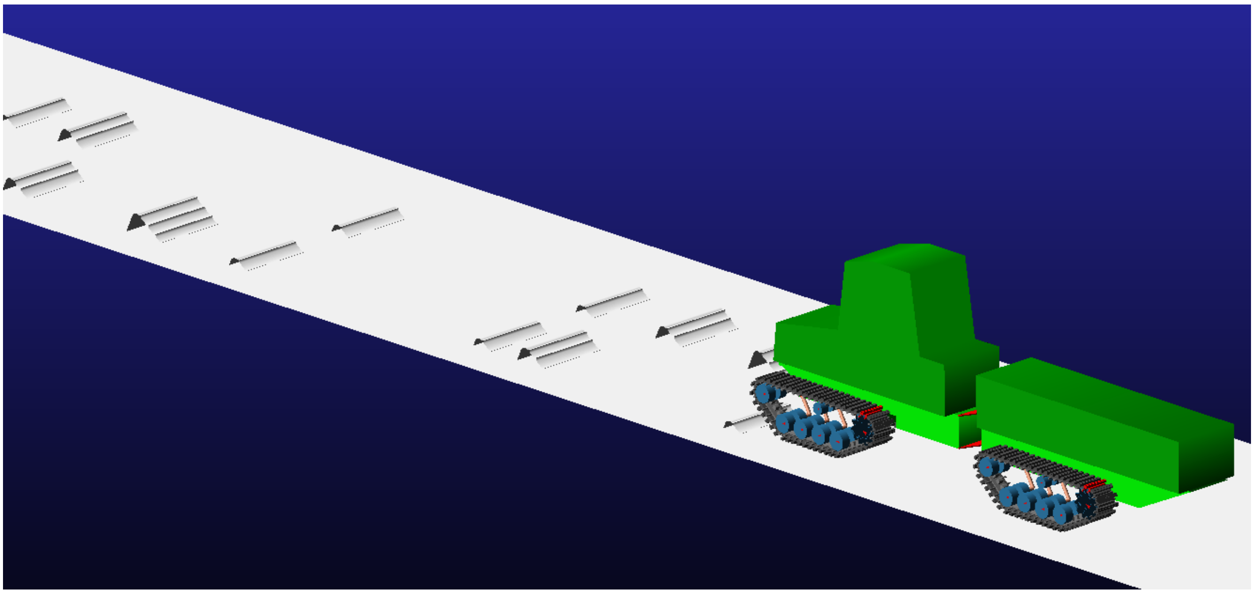

Figure 38: Forwarder on SKOGFORSK Test Track in Adams

3.9 Simulation

After modelling is done, the wrapped tracked forwarder with suitable road file can be simulated. The following parameters should be modified beforehand performing any simulations. The track segment request is a feature that allows creating displacement, velocity, connection force, connection displacement and contacting force measurements of the track segment. It can be modified as shown in the Figure 39.

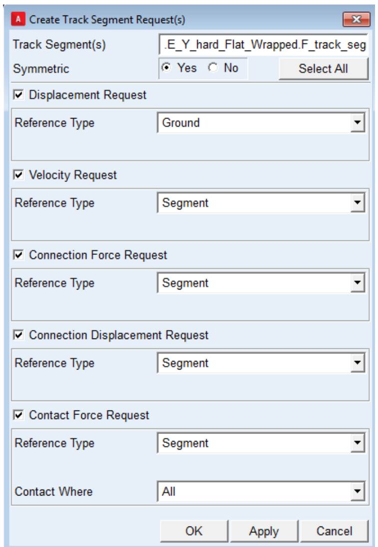

Figure 39: Track Segment Request Dialogue Box

The time of the simulation can be reduced by increasing the thread count in the solver settings ‘executable dialogue box’. By changing this setting we can enable parallel processing and simulation time is considerably reduced. A value of 4 is used for the simulations in the thesis. Also the dynamic solver parameters should be set as in the Figure 40.

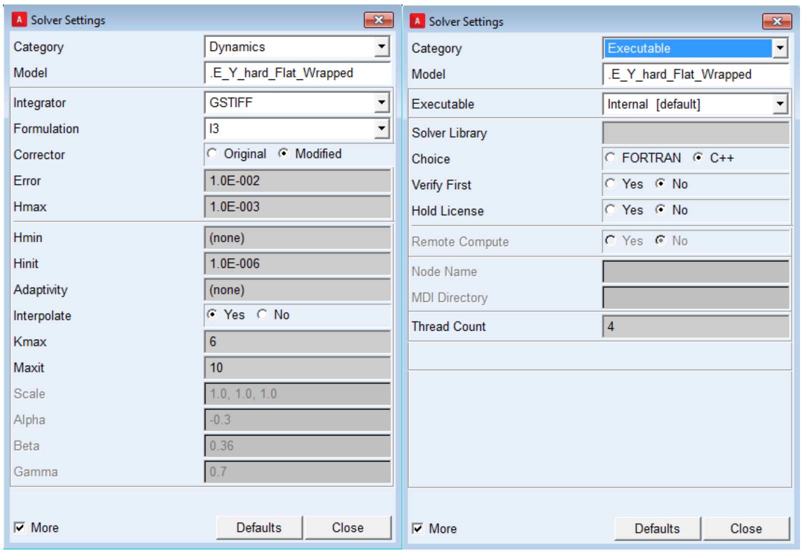

Figure 40: Solver Setting Dialogue Box

The tracked vehicle simulation is done for the required time with sufficient number of steps. It should be noted that, the tensioner can be setup during this step. Here its setup to design length. The equilibrium parameters is also set through a process called 'manual funnelling' and it ensures reliable static equilibrium is achieved faster. The tracked vehicle analysis is done as in Figure 41

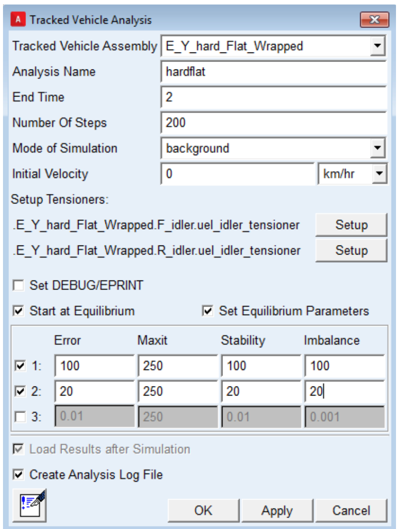

Figure 41: Tracked Vehicle Analysis Dialogue Box

The following simulations are done as part of the thesis work and results are presented in the next chapter.

- Hard flat ground static equilibrium
- Hard flat ground forwarder moving in straight line at angular velocity 100deg/s
- Hard ground with obstacle (SKOGFORSK test track) at angular velocity 100deg/s

In summary the modified Valmet 860 forwarder with track unit is modelled inside ATV and the results are generated in the postprocessor and it is studied.

The results obtained after simulation are compiled, analysed and compared to the frame of reference and presented here.

4.1 Introduction

The forwarder is simulated under different operating and terrain conditions and the results obtained here are presented here. A brief discussion about the each results and how can it be used in the overall tracked vehicle development process is also presented. The global coordinate system is oriented in such a way that, the vehicle moves in negative x direction which is the longitudinal direction. The z-axis is pointed upward which represent the vertical direction. The Y-axis, when facing in the direction to the front of the forwarder will be pointing to right, which represent the lateral direction. The angular rotation roll, pitch and yaw are rotation with respect to X-axis, Y-axis and Z-axis respectively. Please refer Figure 42 as reference.

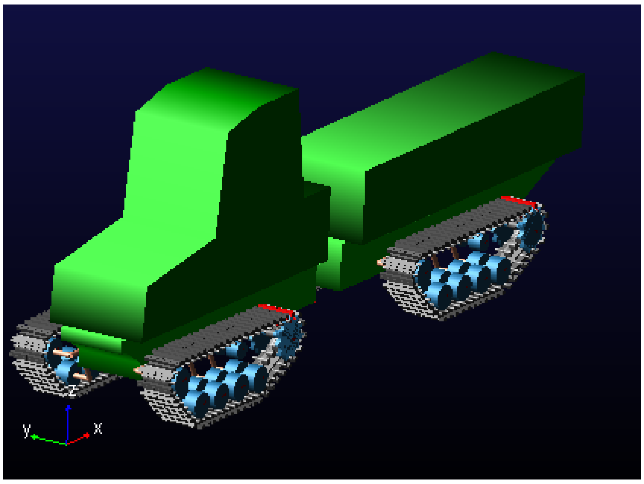

Figure 42: The Forwarder and Coordinate System

4.2 Hard Flat Ground Simulation – Static Equilibrium

The motion of forwarder over a hard flat road is simulated. The simulating setting described in the section 3.10 is used. A static equilibrium operation with vehicle velocity 0 is done first to find out proper stiffness for the torsional spring as shown in Figure 43. Some of the results studied from the simulation are plotted below.

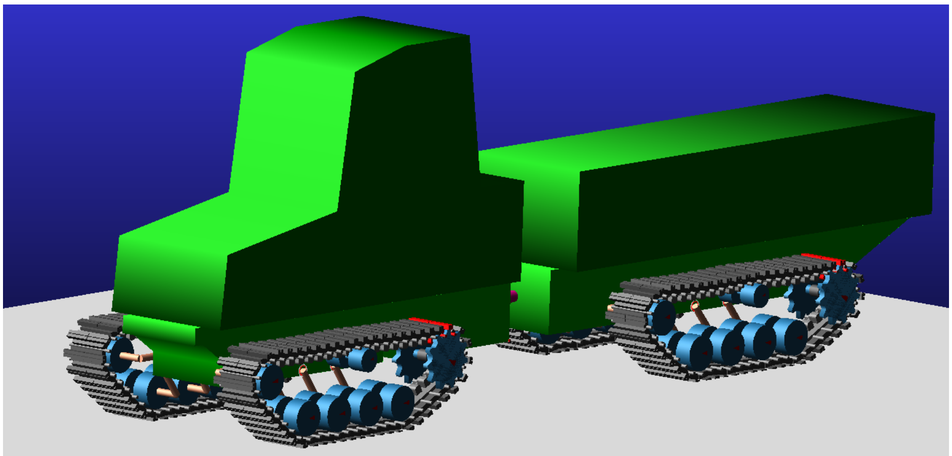

Figure 43: Tracked Forwarder on Hard Flat Ground - Static Equilibrium

The vertical and horizontal of displacement of front chassis is as shown in Figure 44. The stiffness of the torsional spring in the road wheel is so adjusted that the vertical displacement is not highly oscillatory. A less stiff spring will result in rotation of the road wheel and may result in static equilibrium failure. On the other hand a stiffer spring will make the suspension more rigid there by reducing its ability to dampen the vibration. The rotation angle of one of the road wheel suspension springs are shown in the Figure 45.

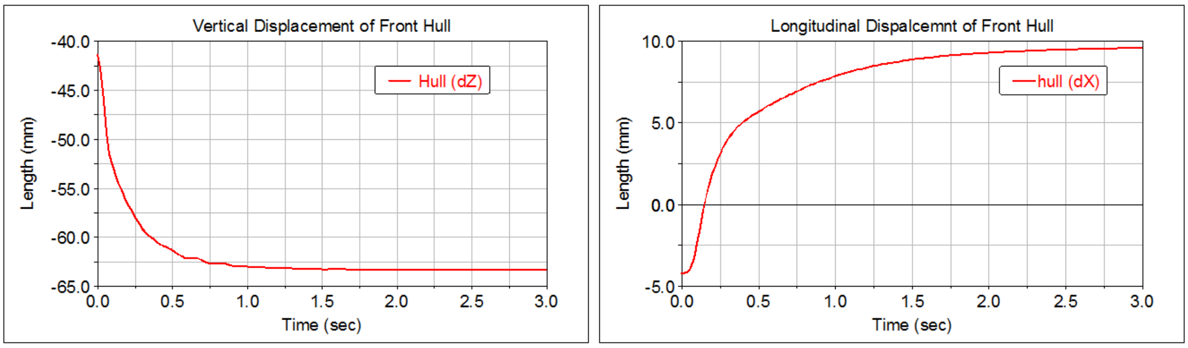

Figure 44: Displacement (Vertical and Horizontal) of front hull in millimetres

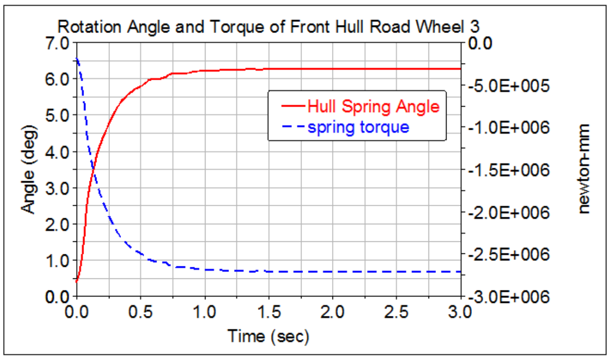

Figure 45: Rotation Angle and Torque of Road wheel 3 of front hull

The tensioner force generated during the simulation is a shown in the Figure 46. In this simulation the ‘design length’ option is used so that the tensioner length does not change and hence the tensioner force remains almost constant.

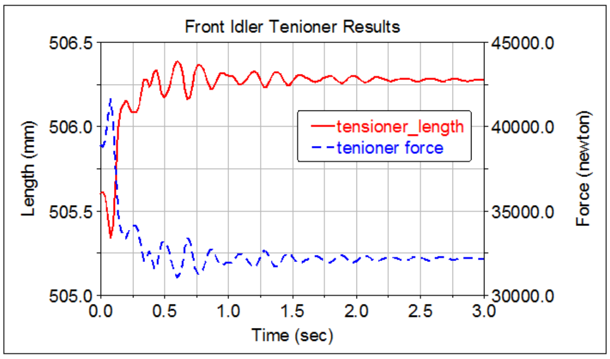

Figure 46: Front Idler Tensioner Results

It is also important to calculate the pressure exerted by the forwarder tracks on the ground. Since its hard soil the pressure can be estimated through the vertical forces between track and ground. Since a standard measure was not available, a macro has been created to generate these custom results. The graph shows that at the track segments from 28 to 39 are in contact in front track segment and 27 to 40 in the rear track segment at the instant time equal to 3 second. The lateral force is shown in Figure 48 and longitudinal force in Figure 49.

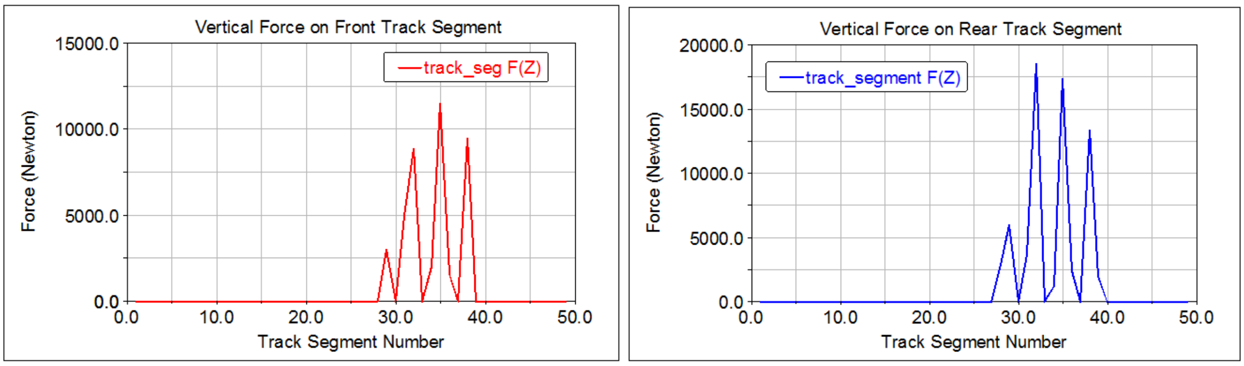

Figure 47: Vertical Track Force on Front and Rear Track Segment

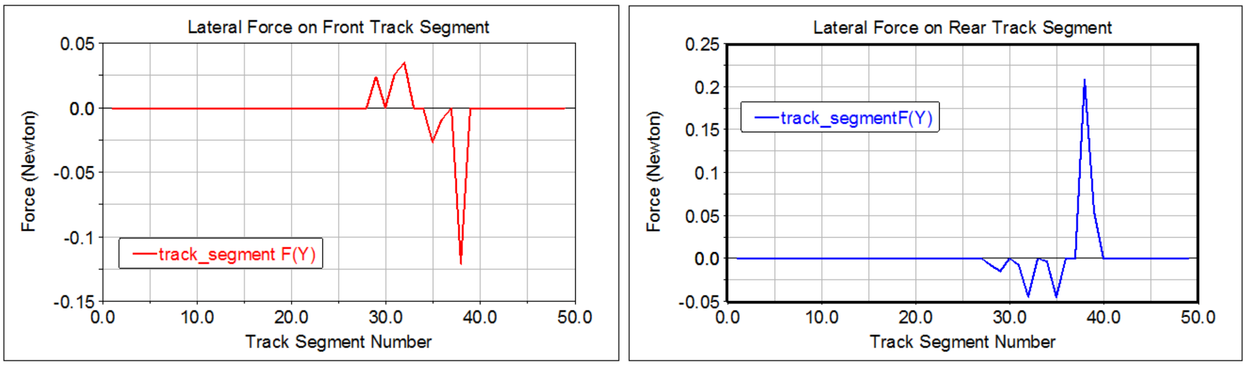

Figure 48: Lateral Track Force on Front and Rear Track Segment

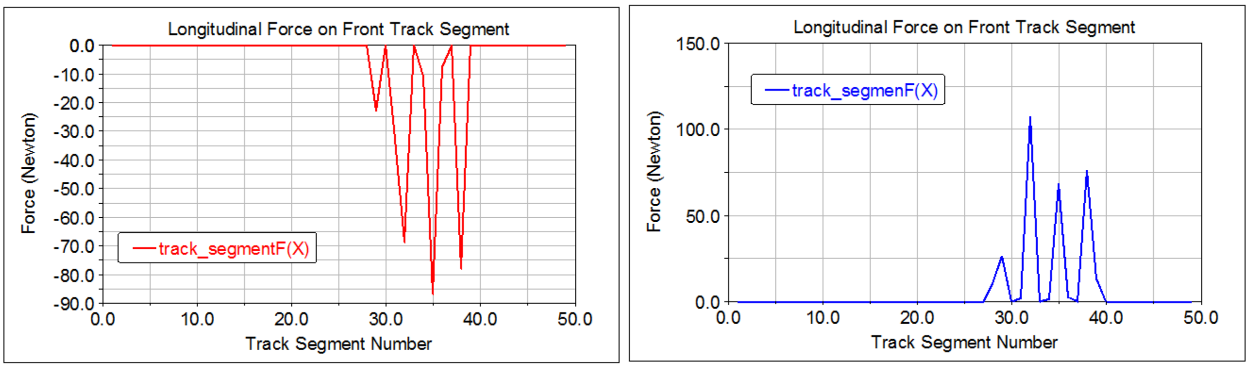

Figure 49: Longitudinal Track Force on Front and Rear Track Segment

The vertical force in the front track segment adds up to 41510 Newton which matches the vertical force due to mass of the front hull. The longitudinal and lateral forces are comparatively negligible since there is no motion in track segment. The longitudinal force on the front hull is in the negative x direction and in the rear segment is positive x direction. This is reasonable due to fact the centre of gravity of the both the hulls are not at the centre resulting in an unbalanced force which results in slight motion of forwarder resulting in the longitudinal forces.

4.3 Hard Flat Ground – In Motion

As the next step an angular velocity of 100 degrees/seconds is applied to the powertrain as shown in the Figure 50 and the simulation is done over a hard flat track. The displacement and velocity obtained is as in Figure 51. It was found out that the RMS value of velocity of the forwarder is 382 mm/s. It is equivalent to 1.4 km/h.

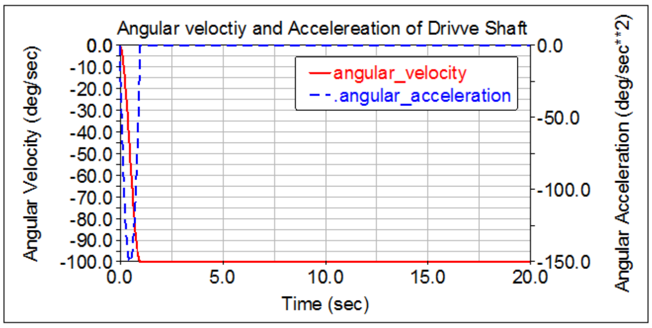

Figure 50: The angular velocity and Acceleration at Drive Shaft

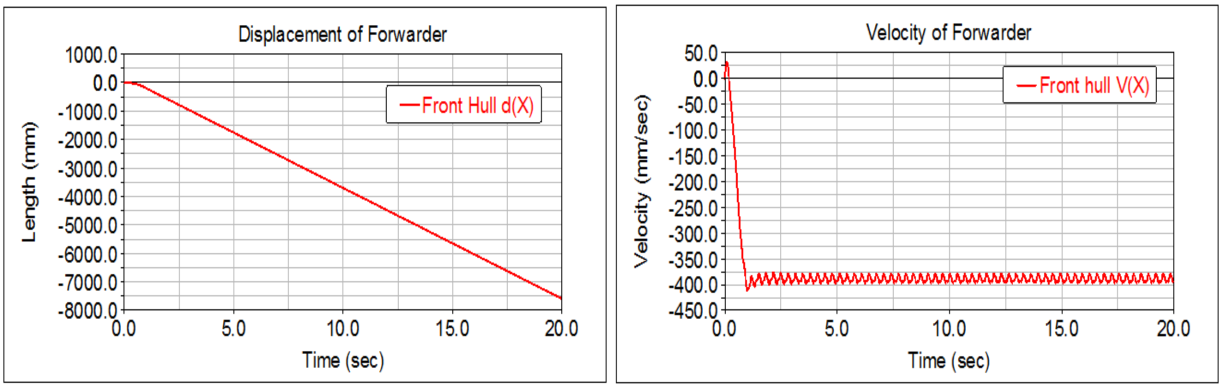

Figure 51: Displacement and Velocity of Forwarder

The torque need to be delivered by powertrain to move the forwarder at a speed of 1.4km/h is shown in Figure 52. The RMS value of the torques to drive on a flat terrain is found out to be $5.7*10^5$ N.mm.

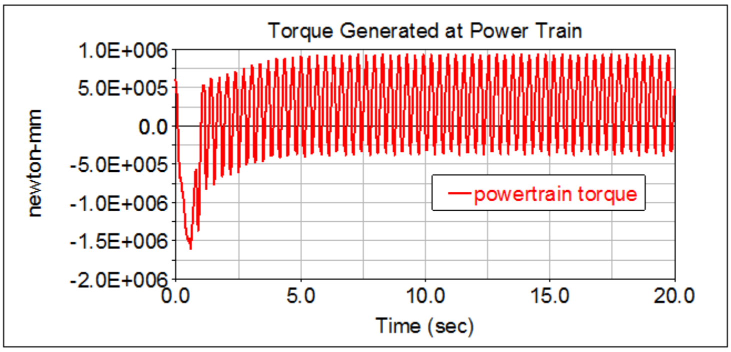

Figure 52: Torque Generated at Front Power Train

The RMS value of the tensioner length and the tensioner force is found out to be 506 millimetres and 31480 Newton respectively. The variation of these values during the simulation is represented in Figure 53 and Figure 54. The angular displacement of the road wheel was found to be 7.5 degrees and the resulting spring torque is $3.2*10^6$ N.mm. This is to support the weight of the vehicle. The variation of these quantities is shown in Figure 55 and Figure 56.

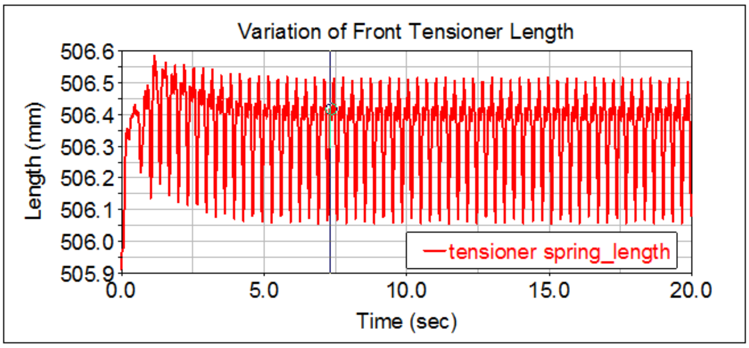

Figure 53: Tensioner Length Vs Time

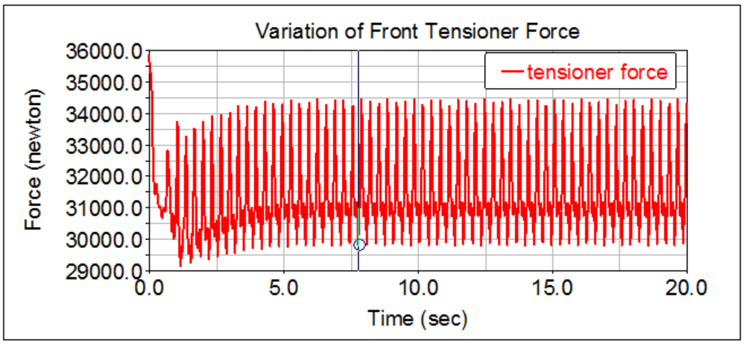

Figure 54: Tensioner Force Vs Time

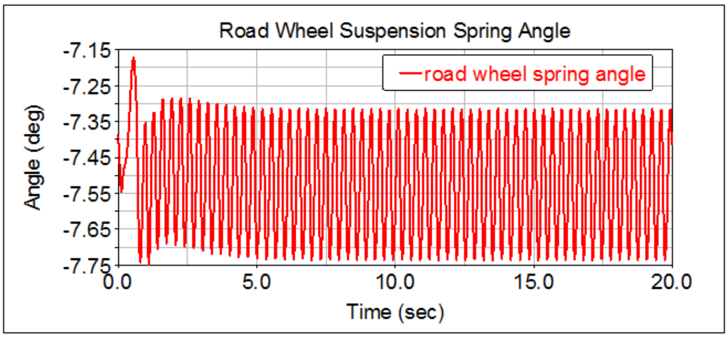

Figure 55: Road Wheel Angle

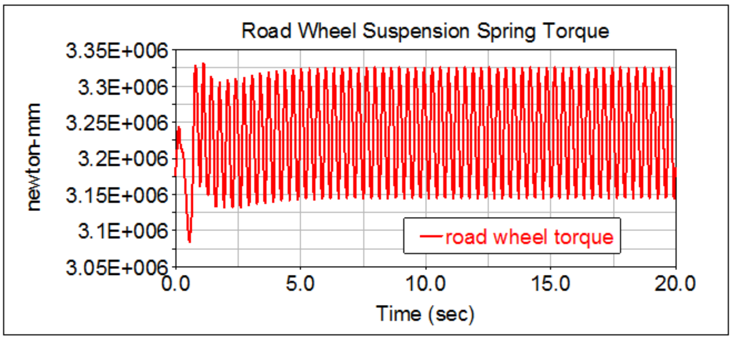

Figure 56: Road Wheel Suspension Torque

The vertical, lateral and longitudinal force exerted by the front and rear track segment on the ground is shown in the Figure 57 Figure 58 Figure 59 respectively. It can be seen that compared to static simulation; there is a large increase in the value of longitudinal force. This predictable since the movement of vehicle forward is due to shearing of soil under the track. This force is significant to predict the shearing force on the ground when moving forward. In a hard ground 3D contact algorithm will govern this force while in a soft soil Janosi shear theory will be the governing factor.

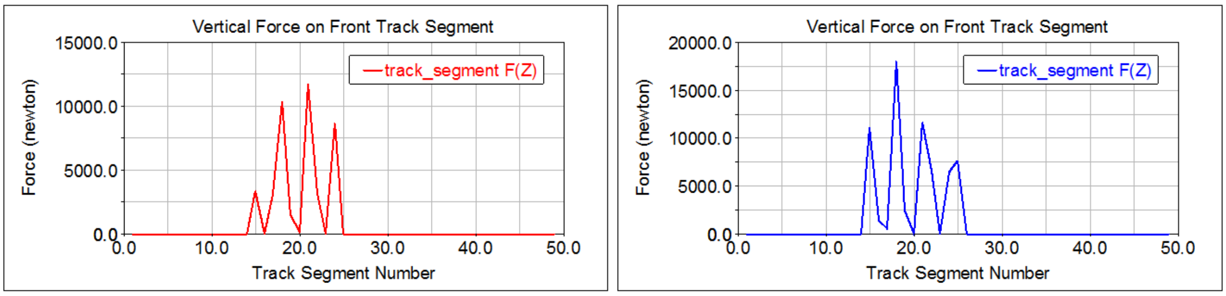

Figure 57: Vertical force on Track Segment

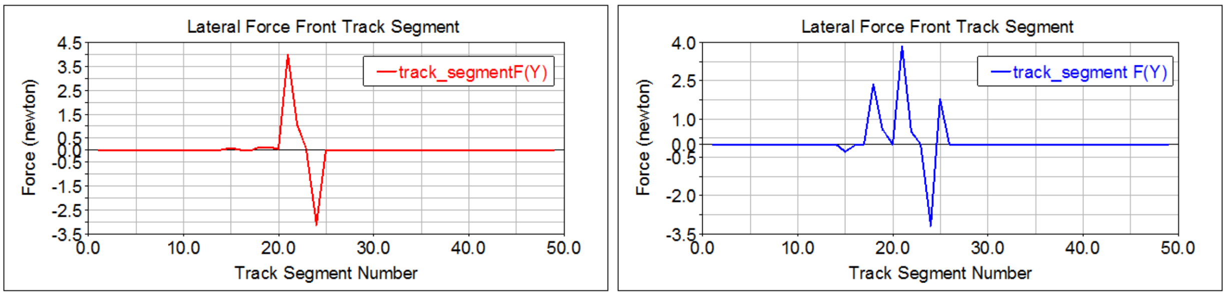

Figure 58: Lateral Force on Track Segment

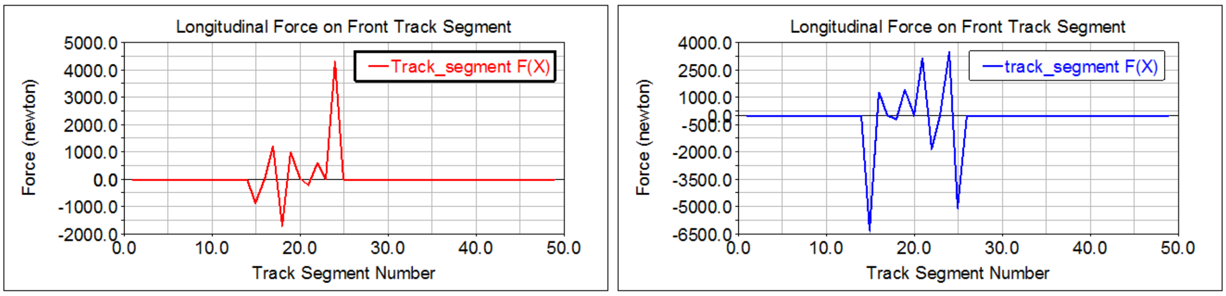

Figure 59: Longitudinal Force on Track Segment

The simulation can be performed under different ground condition for e.g. the flat ground with different slopes and the same measures as described in the report can be used to study the performance of vehicle.

4.4 Hard Ground with Bumps – SKOGFORSK Test Track

The forwarder is set into motion through the Skogforsk test track as shown in Figure 60 and the various dynamics properties where studied. The displacement of forwarder in X, Y and Z direction and the roll pitch yaw angle are measured to understand the motion of the forwarder. The displacement in horizontal direction is given in Figure 61.

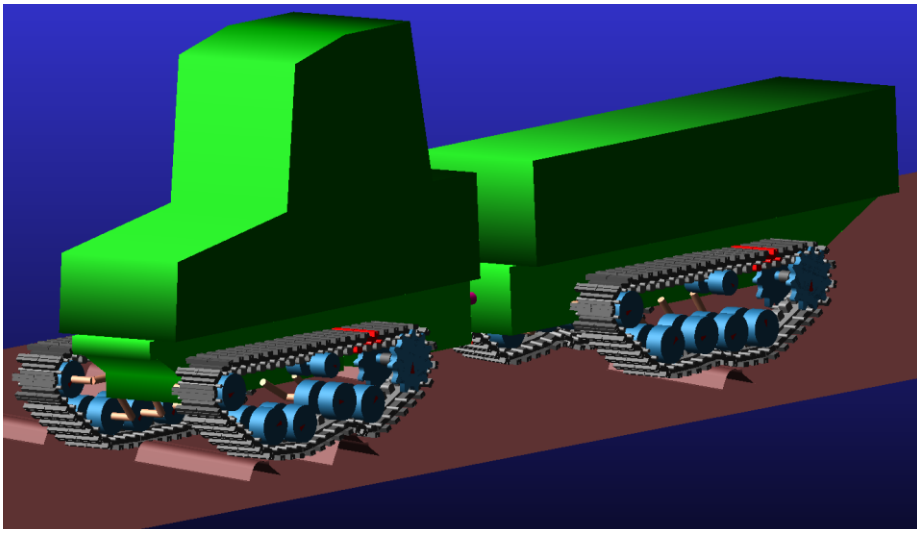

Figure 60: Forwarder Traversing Bump

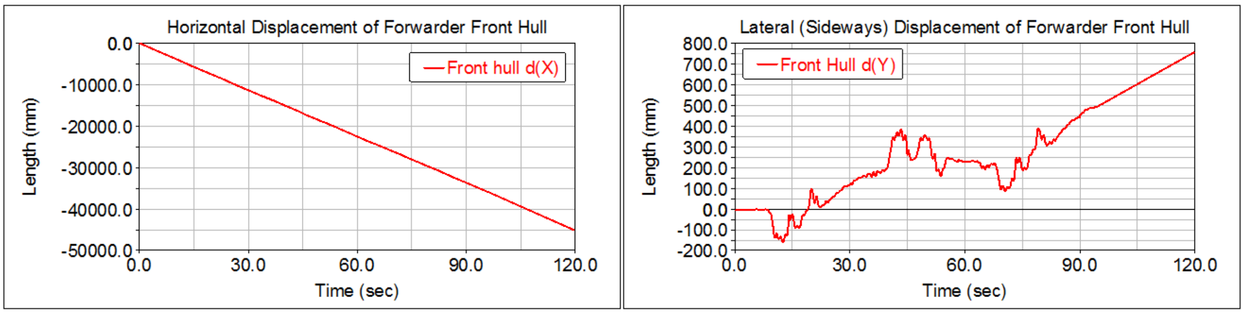

Figure 61: Displacement of Forwarder in Horizontal Direction

The bumps on the road result in motion in vertical direction as represented in Figure 62. In the figure each vertical spike represents the bump motion. It results in swaying motion of the forwarder and it can be visualised as pitch, roll and yaw motion of hull. In this case, since the forwarder was modelled with roll joint only, the roll motion is of importance and can be visualised as in Figure 63.

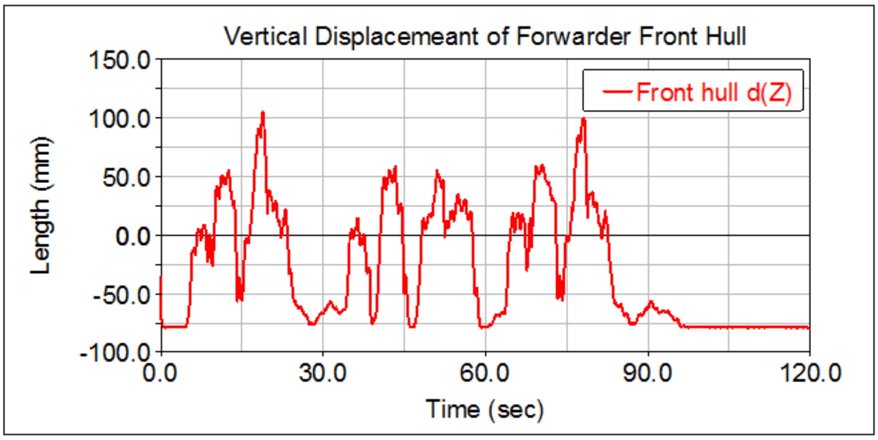

Figure 62: Vertical Displacement of Forwarder

The roll rate and vertical displacement are plotted together in Figure 64 for better visualisation. The roll angle varies from +10 degrees to -10 degrees. The angular velocity in the roll direction is plotted in Figure 65. There are regions in which angular velocity goes up to 20deg/s. Reduction of roll rate can be an objective during future research work to improve ride comfort.

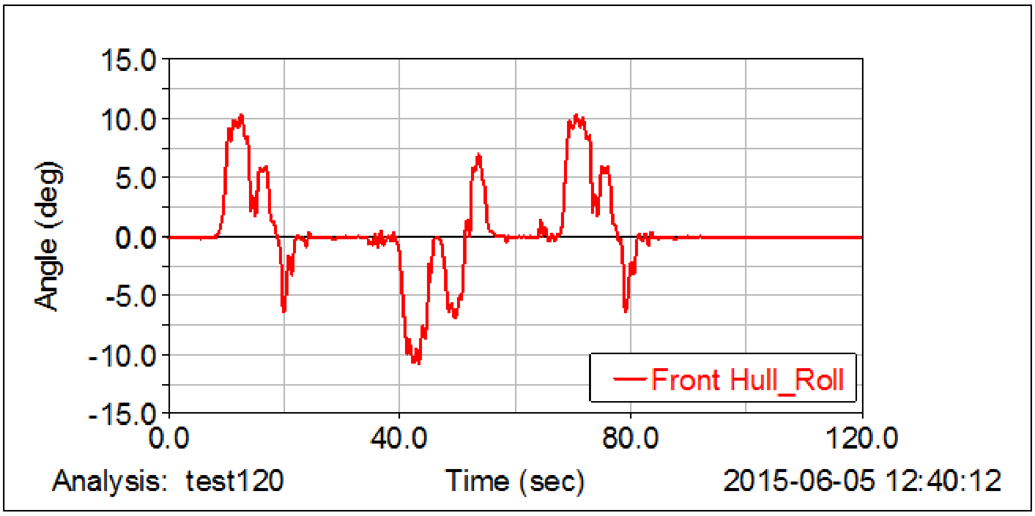

Figure 63: Roll motion of Forwarder

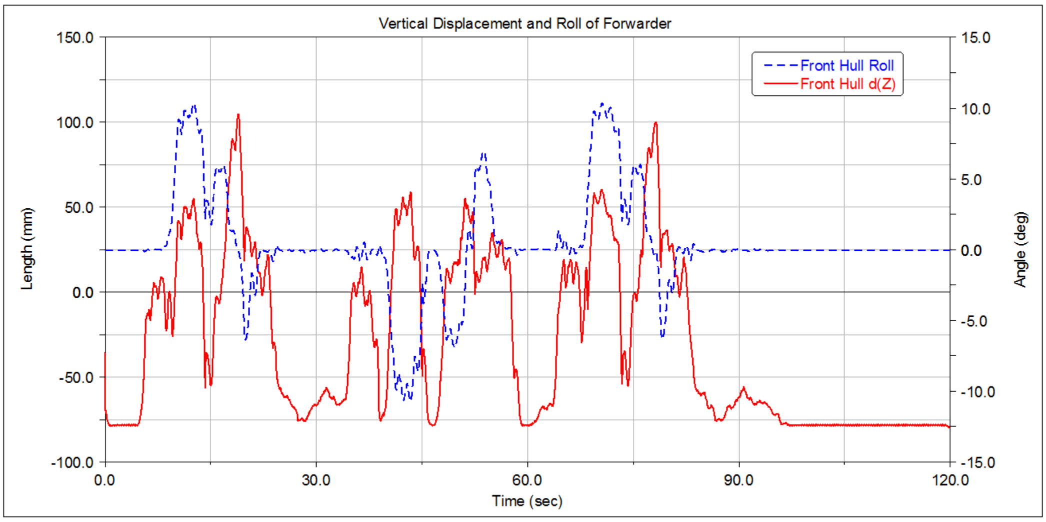

Figure 64: Vertical Displacement and Roll of Forwarder

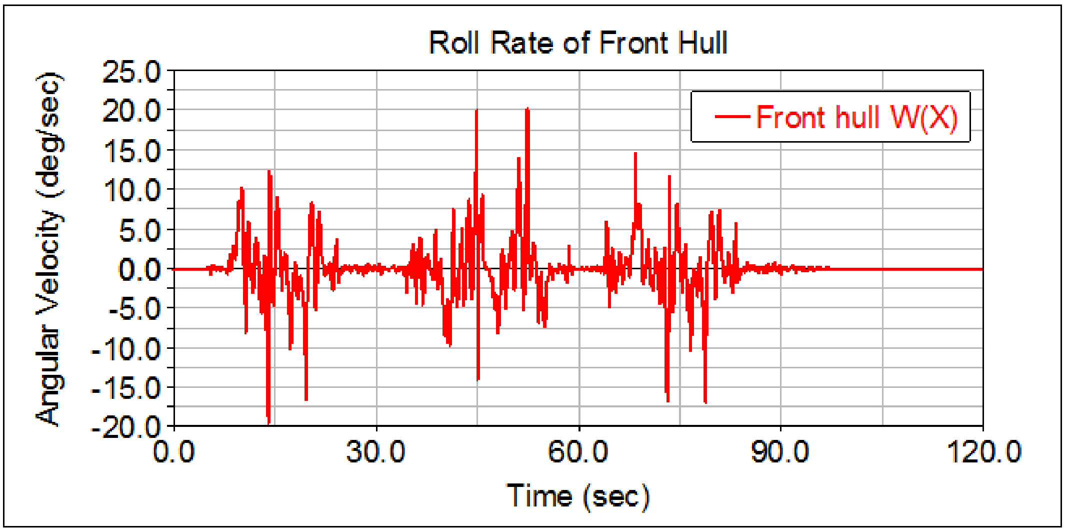

Figure 65: Roll Rate of Front Hull

The motion of the forwarder over a bump is shown in the Figure 66. As can be visualised from the figure the track terrain contact is limited to a few segment. The ground force condition are calculated and the vertical, longitudinal and lateral forces are plotted as in Figure 67 and Figure 68. Thrice the maximum value of vertical force on flat terrain (Figure 47) is genereated when taking a bump. Hence the track unit behaves more like a wheel and its application to protect the soil will be limited. Steps need to be taken to figure out a way to avoid this.

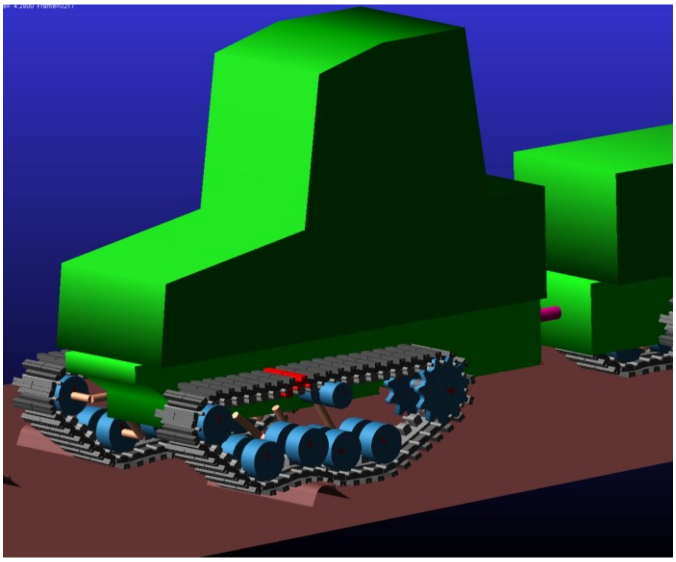

Figure 66: Forwarder Track Unit over a Bump

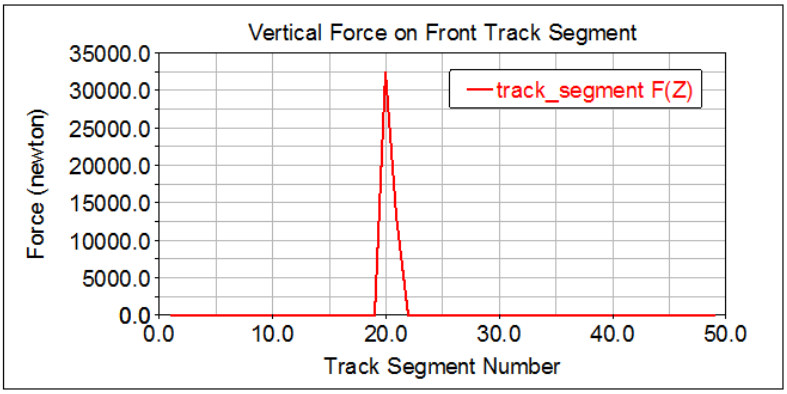

Figure 67: Vertical Force on Track Segment on a Bump

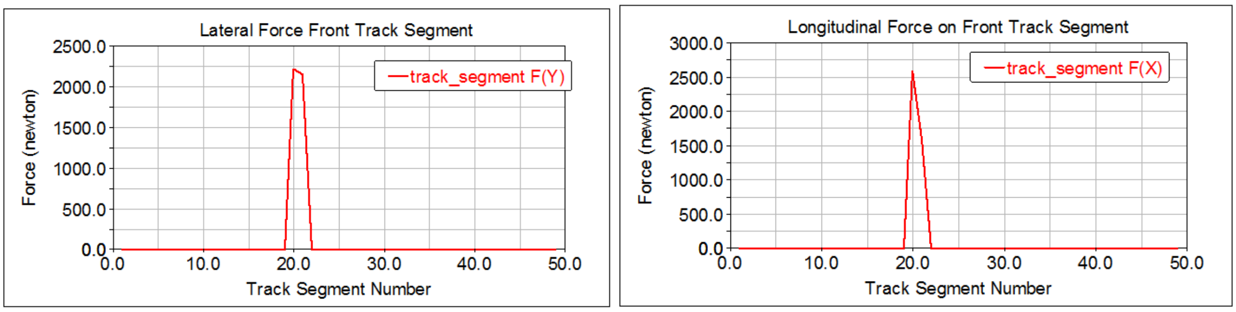

Figure 68: Lateral Force and Longitudinal Forces on Track Segment on a Bump

5 DISCUSSION AND CONCLUSIONS

The conclusions drawn from the master thesis towards the direction of answering the problem statement are presented here.

5.1 Conclusions

The findings from the thesis, discussions and inference from those results are presented in chapter 4. The following conclusions can be made with certainty from the thesis work.

1. It is feasible to remodel the reference forwarder Komatsu Valmet 860.3 to fit a track unit. The developed track unit concept satisfies all the geometrical constrains except the ground clearance. The concept can be further improved by adding a frame that can lower the position of the track unit thereby increasing to the required ground clearance.
2. The concept track unit has been successfully modelled in Adams ATV software using template based modelling and simulated under different road conditions. The test track in Skogforsk has been inputted as a road file and the dynamic properties are studied.
3. The traction performance parameters like vertical and horizontal force exerted on the ground by the track segments and the torque required at the sprocket under different operating conditions have also been studied as part of thesis work
4. The traction of the track unit is modelled using powertrain component. The torque or angular velocity from the power train is controlled based on the user input. Also the track terrain interaction is modelled using the automatic dynamic track wrapping option.
5. The necessary results have obtained from simulation and is plotted and studied using the Adams postprocessor. Custom results is generated by using special macros.

It can be concluded from the thesis that Adams ATV module is good way of modelling tracked vehicles under different operating conditions. Its user friendly and offers several tools to build track units at ease. The simulation results in hard road conditions are reliable and can be obtained at reasonable computing time. The template based ATV model can be used in model based design of tracked forwarders.

However it should be noted that the simulation results are not experimentally verified. Verification has to be done to improve the reliability of results. An experimentally verified simulation model can be used to design and optimise the tracked forwarder for specific forest conditions. It enables cutting cost and time for developing tracked forwarder for sustainable forestry.

6 RECOMMENDATIONS AND FUTURE WORK

In this chapter, recommendations to the company resulting from the master thesis and possible future work and improvements are presented.

6.1 Recommendations

The following recommendations are proposed by the author from the thesis work performed. A multi-body dynamics model of the Tracked forwarder is made in Adams ATV as part of the master thesis.

- The methodology of using virtual prototype and use of multi body simulation to develop new concepts for tracked forwarder is valid. It has several advantages and results in saving valuable time and monetary resources. Multi body dynamics simulation enable researcher to visualise the motion and study the dynamics of machinery over different road conditions. It can be also used to improve and optimise the design.
- It is recommended to use Adams ATV module. Adams ATV is a well-established software. It is user friendly and provides several tools that help to build tracked models. The biggest advantage is the template based modelling which enable the future user to quickly modify and study the models.
- It is recommended to employ a person with knowledge in template based modelling since the template based modelling Adams ATV demands some effort to understand and a beginner in the software will have a steep learning curve if he want to work with templates. But the standard interface is relatively simple can be learned from the tutorial files.
- The performance of the software on hard ground is evaluated as part of this thesis. But it should be noted that, the soft soil capability of the software has not been studied as part of thesis. It is important to develop a soft soil model matching the Nordic forest soil conditions in Adams to develop the thesis further.
- Since the simulation time is high, it will be a good initiative to study how to it by evaluating the parallel processing capabilities of software and investing in more powerful computing resources.
- It should be also note that the simulation models presented in the thesis could not be experimentally verified. It is highly recommended to do experiments to verify simulation results. The ride parameters like roll, pitch, vertical acceleration of chassis and the road wheel angle can be used as the verification parameters. The results from the experiments should be compared with the simulation results presented in thesis. If necessary modification can be made in the simulation results to get results matching.

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6.2 Future work

The future work for the thesis work can be in the directed as per the recommendations made. As the first step the simulation model need to be experimentally verified. New concepts of track unit can be developed and modelled in ATV. The ATV model can be used to evaluate the performance of different concepts. The scope of thesis work can expanded by including the soft soil models also. The final concept can be improved and optimised using in Adams.

7. REFERENCES

Azad, N. L. (2006). Dynamic Modelling and Stability Controller Development for Articulated Steer Vehicles. *Analysis*.

Baez, F. (2014). Multi-objective optimization and performance evaluation of active , semi-active and passive suspensions for forestry machines.

Carroll, E., Stone, M. L., & Smith, D. W. (2006). Traction and Transport, *2003*, 351–382.

Gerasimov, Y., Sokolov, A., & Syunev, V. (2013). Development Trends and Future Prospects of Cut-to-Length Machinery. *Advanced Materials Research*, *705*, 468–473. http://doi.org/10.4028/www.scientific.net/AMR.705.468

Lahtinen, M. (2011). The Global Challenges of Harvesting and how the CTL Method can Respond to Them, (March).

Laughery, S., Gerhart, G., & Goetz, R. (1990). Bekker's Terramechanics Model for Off-Road Vehicle Research, 31. Retrieved from http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA457955

Madsen, J. (n.d.). High Fidelity Modeling and Simulation of Tracked Elements for Off-Road Applications Using MSC / ADAMS. *System*, 1–20.

McCullough, M. K., & Haug, E. J. (1986). Dynamics of High Mobility Track Vehicles. *Journal of Mechanisms Transmissions and Automation in Design*, *108*(2), 189. http://doi.org/10.1115/1.3260801

Mićo, O. V, Rade, R., Miloš, P., Kosta, G., Velibor, S., & Zoran, D. (2013). TRACKS OR WHEELS – PERSPECTIVES AND ASPECTS IN AGRICULTURE, (October), 9–19.

Palaniappan, N. R. (2013). Forest Machine Track-Soil Interaction.

Rubinstein, D., & Hitron, R. (2004). A detailed multi-body model for dynamic simulation of off-road tracked vehicles. *Journal of Terramechanics*, *41*(2-3), 163–173. http://doi.org/10.1016/j.jterra.2004.02.004

Ryu, H. S., Bae, D. S., Choi, J. H., & Shabana, a. a. (2000). A compliant track link model for high-speed, high-mobility tracked vehicles. *International Journal for Numerical Methods in Engineering*, *48*(10), 1481–1502. http://doi.org/10.1002/1097-0207(20000810)48:10<1481::AID-NME959>3.0.CO;2-P

Ryu, H. S., Huh, K. S., Bae, D. S., & Choi, J. H. (2003). Development of a Multibody Dynamics Simulation Tool for Tracked Vehicles (Part I, Efficient Contact and Nonlinear Dynamic Modeling). *JSME International Journal Series C*. http://doi.org/10.1299/jsmec.46.540

Ryu, S., Park, Y., & Suh, M. (2011). Ride quality analysis of a tracked vehicle suspension with a preview control. *Journal of Terramechanics*, *48*(6), 409–417. http://doi.org/10.1016/j.jterra.2011.09.002

Swedish, T. H. E., & Industries, F. (2011). THE SWEDISH FOREST INDUSTRIES Facts and figures 2011.

Wong, J. Y. (1999). Computer-aided methods for design evaluation of tracked vehicles and their applications to product development. *International Journal of Vehicle Design*, *22*(1/2), 73. http://doi.org/10.1504/IJVD.1999.001860

Wong, J. Y. (2010a). Computer-Aided Method NTVPM for Evaluating the Performance of Vehicles with Flexible Tracks. *Terramechanics and Off-Road Vehicle Engineering*, 177–209. http://doi.org/10.1016/B978-0-7506-8561-0.00008-7

Wong, J. Y. (2010b). Performance of Off-Road Vehicles. *Terramechanics and Off-Road Vehicle Engineering*, *129*, 129–153. http://doi.org/10.1016/B978-0-7506-8561-0.00006-3

Wong, J. Y., Garber, M., & Preston-Thomas, J. (2006). Theoretical prediction and experimental substantiation of the ground pressure distribution and tractive performance of tracked vehicles. *ARCHIVE: Proceedings of the Institution of Mechanical Engineers, Part D: Transport Engineering 1984-1988 (vols 198-202)*, *198*(15), 265–285. http://doi.org/10.1243/PIME_PROC_1984_198_155_02

Wong, J. Y., & Huang, W. (2006). “Wheels vs. tracks” - A fundamental evaluation from the traction perspective. *Journal of Terramechanics*, *43*(1), 27–42. http://doi.org/10.1016/j.jterra.2004.08.003

Yin, H. B., & Shao, P. (2005). Dynamic Performance Simulation of a Tracked Vehicle with ADAMS Tracked Vehicle Toolkit Software, 553–558.

The Adams ATV files used for the Master Thesis work is documented in the appendix

A.1 Hull File

Front Hull

```
$--------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    =  'hul'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$--------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'
$-----------------------------------------------------------------HULL_GEOMETRY
[HULL_GEOMETRY]
 UPPER_WIDTH  =  1200.0
 LOWER_WIDTH  =  800.0
$------------------------------------------------------------UPPER_HULL_PROFILE
[UPPER_HULL_PROFILE]
{X        Z}
  82     0
  150    634
  1526   854
  1697   2019
  2321   2171
  3140   2171
  3347   854
  3895   854
  3895   0
$------------------------------------------------------------LOWER_HULL_PROFILE
[LOWER_HULL_PROFILE]
{X        Z}
  0      0
  0     -150
  100   -150
  400   -350
  400   -550
  2200  -550
  2400  -550
  2400  -350
  2600  -350
  2600  -550
  4000  -550
  4000   0
$------------------------------------------------------------SOFT_SOIL_SETTINGS
```

```
[SOFT_SOIL_SETTINGS]
 N_SEGMENTS_LONGITUDINAL  =  10
 N_SEGMENTS_LATERAL       =  3
```

Rear Hull

```
$--------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'hul'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$-------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'
$-----------------------------------------------------------------HULL_GEOMETRY
[HULL_GEOMETRY]
 UPPER_WIDTH  =  1200.0
 LOWER_WIDTH  =  800.0
$------------------------------------------------------------UPPER_HULL_PROFILE
[UPPER_HULL_PROFILE]
{X        Z}
  4600     0
  4600     854
  9100     854
  9100     0

$------------------------------------------------------------LOWER_HULL_PROFILE
[LOWER_HULL_PROFILE]
{X        Z}
  4500    0
  4500   -550
  8000   -550
  9170    0
$------------------------------------------------------------SOFT_SOIL_SETTINGS
[SOFT_SOIL_SETTINGS]
 N_SEGMENTS_LONGITUDINAL  =  10
 N_SEGMENTS_LATERAL       =  3
```

A.2 Road Wheel Suspension File

Torsional Spring

```
$---------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    =  'rsp'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$--------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 ANGLE   =  'degrees'
 FORCE   =  'newton'
 MASS    =  'kg'
 TIME    =  'second'
$-------------------------------------------------------------------------LINEAR
[LINEAR]
 STIFFNESS  =  4.30E+5
$---------------------------------------------------------------------NON_LINEAR
[NON_LINEAR]
{ angle   torque}
-180.0   -7.20E+07
-130.0   -5.20E+07
-100.0   -4.00E+07
 -60.0   -2.40E+07
 -40.0   -1.60E+07
 -10.0   -4.00E+06
  -4.0   -1.60E+06
  -1.0   -4.00E+05
   0.0    0.0
   1.0    4.00E+05
   4.0    1.60E+06
  10.0    4.00E+06
  40.0    1.60E+07
  60.0    2.40E+07
 100.0    4.00E+07
 130.0    5.20E+07
 180.0    7.20E+07
```

Rotational Damper

```
$---------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    =  'rdp'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$--------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 ANGLE   =  'degrees'
 FORCE   =  'newton'
 MASS    =  'kg'
 TIME    =  'second'
$-------------------------------------------------------------------------LINEAR
```

```
[LINEAR]
 DAMPING  =  90000.0
$--------------------------------------------------------------------NON_LINEAR
[NON_LINEAR]
{angular_velocity   torque}
-300.0   -3.50E+07
-260.0   -2.75E+07
-225.0   -2.24E+07
-180.0   -1.62E+07
-130.0   -1.17E+07
-100.0   -9.00E+06
 -60.0   -5.40E+06
 -40.0   -3.60E+06
 -10.0   -9.00E+05
  -4.0   -3.60E+05
  -1.0   -90000.0
   1.0    90000.0
   4.0    3.60E+05
  10.0    9.00E+05
  40.0    3.60E+06
  60.0    5.40E+06
 100.0    9.00E+06
 130.0    1.17E+07
 180.0    1.62E+07
 225.0    2.24E+07
 260.0    2.75E+07
 300.0    3.50E+07
```

Rotational Bumpstop

```
--------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'rbu'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$--------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'
$--------------------------------------------------------------------BUMPSTOP
[BUMPSTOP]
 BUMPSTOP_STIFFNESS      = 1.0E007
 BUMPSTOP_EXPONENT       = 1.1
 BUMPSTOP_DAMPING        = 1.0E005
 BUMPSTOP_PENETRATION    = 1.0
$--------------------------------------------------------------------REBOUNDSTOP
[REBOUNDSTOP]
 REBOUNDSTOP_STIFFNESS   = 1.0E007
 REBOUNDSTOP_EXPONENT    = 1.1
 REBOUNDSTOP_DAMPING     = 1.0E005
 REBOUNDSTOP_PENETRATION = 1.0
```

A.3 Idler File

Tensioner File

```
$---------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE    =  'ten'
 FILE_VERSION  =  1.0
 FILE_FORMAT   =  'ASCII'
$--------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 ANGLE   =  'degrees'
 FORCE   =  'newton'
 MASS    =  'kg'
 TIME    =  'second'
$----------------------------------------------------------------MASS_PROPERTIES
[MASS_PROPERTIES]
 MASS        =  5.0
 CM_LOCATION  =  150.0
 IXX         =  10000.0
 IYY         =  10000.0
 IZZ        =  1000.0
 IXY         =  0.0
 IZX         =  0.0
 IYZ         =  0.0
$--------------------------------------------------------------SPRING_PROPERTIES
[SPRING_PROPERTIES]
 DAMPING              =  30.0
 PRELOAD              =  95000.0
 INITIAL_SPRING_LENGTH  =  500.0
 MIN_SPRING_LENGTH      =  400.0
 MAX_SPRING_LENGTH      =  600.0
 STOP_STIFFNESS        =  1000.0
 STOP_EXPONENT         =  2.0
 STOP_DAMPING          =  1.0
$-------------------------------------------------------------------------LINEAR
[LINEAR]
 STIFFNESS  =  10000.0
$---------------------------------------------------------------------NON_LINEAR
[NON_LINEAR]
{length   force}
-200.0   -2.00E+06
-150.0   -1.50E+06
-100.0   -6.315E+05
 -50.0   -2.00E+05
   0.0    0.0
 100.0    1.00E+05
 200.0    2.00E+05
```

A.4 Road and Soil Property File

Flat

```
$-------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'rdf'
 FILE_VERSION  =  5.0
 FILE_FORMAT   =  'ASCII'
(COMMENTS)
{comment_string)
'ADAMS Tracked Vehicle Toolkit - Flat road'
$------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'meter'
 FORCE   =  'newton'
 ANGLE   =  'radians'
 MASS    =  'kg'
 TIME    =  'sec'
$------------------------------------------------------------------------MODEL
[MODEL]
 METHOD  =  '3D'
$-----------------------------------------------------------------------OFFSET
[OFFSET]
 X  =  0.0
 y  =  0.0
 Z  =  -0.81
$------------------------------------------------------------------------NODES
[NODES]
 NUMBER_OF_NODES    = 4
{ node   x_value   y_value   z_value }
  1  -50.0   -5.0    0.0
  2  -50.0    5.0    0.0
  3   10.0   -5.0    0.0
  4   10.0    5.0    0.0
$--------------------------------------------------------------------ELEMENTS
[ELEMENTS]
 NUMBER_OF_ELEMENTS    = 2
{ node_1   node_2  node_3   mu   }
  1    4     2    1.0    1.0
  1    3     4    1.0    1.0
```

Hard soil

```
$-------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'spf'
 FILE_VERSION  =  2.0
 FILE_FORMAT   =  'ASCII'
$------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'meter'
```

```
 ANGLE  = 'radians'
 FORCE  = 'newton'
 MASS   = 'kg'
 TIME   = 'second'
$------------------------------------------------------------------HARD_PARAMETERS
[HARD_PARAMETERS]
 STIFFNESS   = 2.00E+05
 DAMPING     = 2000.0
 EXPONENT    = 2.0
 PENETRATION = 0.001
 STATIC_FRICTION            = 0.9
 DYNAMIC_FRICTION           = 0.7
 STICTION_TRANSITION_VELOCITY = 0.1
 FRICTION_TRANSITION_VELOCITY = 0.5
 STIFFNESS_VALIDATED_LENGTH_UNIT = 'mm'
$-------------------------------------------------------------SOFT_SOIL_PARAMETERS
[SOFT_SOIL_PARAMETERS]
 SOFT_SOIL_TYPE         = 1
 INTERNAL_SHEARING_ACTIVE = 1
 BULLDOZING_ACTIVE       = 0
 SIDE_FORCE_ACTIVE       = 0
$
 SPECIFIC_WEIGHT = 3000.0
$
 KC   = 6160.0
 KPHI = 1.4935E+05
 n    = 1.53
 K0   = 0.0
 AU   = 4.00E+07
 CC   = 0.00001
$
 SHEAR_EQUATION_TYPE = 1
 CR_LONGITUDINAL   = 120.0
 PHIR_LONGITUDINAL = 0.286
 KR_LONGITUDINAL   = 0.0039
 CI_LONGITUDINAL   = 760.0
 PHII_LONGITUDINAL = 0.405
 KI_LONGITUDINAL   = 0.0424
$
 CR_LATERAL   = 120.0
 PHIR_LATERAL = 0.286
 KR_LATERAL   = 0.0039
 CI_LATERAL   = 760.0
 PHII_LATERAL = 0.405
 KI_LATERAL   = 0.0424
```