CHALMERS
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Traction Control for Off-Road Full Electric Vehicle

Master's thesis in Automotive Engineering

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Cover: L120GZ Volvo Equipment wheel loader and FMX Trucks during loading and unloading cycle.

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Traction control for off-road hybrid or electric vehicle
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Abstract

In this Master thesis a traction control for the construction equipment wheel loader is developed and analysed for the vehicle motion control system. The wheel loader is a articulated vehicle used for different application in various environmental terrains. The machine was undergoing some drawbacks with the current system, this lead to study and development of the new system. There are many research work performed in this industry related to this subject, by considering them as reference the work was initiated. The vehicle considered and studied in the work is an under development vehicle in Volvo Construction Equipment.

The tire is the contact patch of the complete vehicle with the ground. The tire characteristics and the dynamics are very important for the vehicle performance. Study and analysis on tire shows, the tire power efficiency is directly connected with the slip ratio. The slip should be maintained with the optimal value irrespective of the environmental conditions. This optimal value should be maintained in all the wheels to keep the vehicle stable and energy efficient. The input signals are used to maintain the optimal slip value according to the ground condition and the application performed. Study shows that, controlling these values results in the stability and better performance in the vehicle.

During the study of controller it is noticed that, torque and wheel speed at individual wheel plays a major role in the process of control action. By using both the signal together in the PID controller the control strategy to the proposed controller is developed. In this action individual torque and wheel speed controller are designed. They are connected in series. The working cycle of the wheel loader are divided into torque and speed mode depending on the type of driver request. The working of the both the controller also depends on the mode of operation.The simulation are performed in both the modes in different environmental condition on wheel loader model. These results are compared with the current or baseline controller used in the vehicle. Finally along with the development of new controller strategy, it is compared with current controller to obtain the drawbacks during its performance. The comparison includes some limitations considered throughout the project. Hence future work is required to tune the controller for the wheel loader productivity.

Keywords: Wheel loader, Traction control, vehicle model, slip, Modes, Torque controller, Speed controller, Proposed controller, current controller

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Nishanth Bharadwaj, Gothenburg, February 2021 Nithin Pandu, Gothenburg, February 2021

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Introduction

The vehicles designed and intended for use in construction or material handling are known as construction equipments. Wheel loaders is a construction equipment used in different terrain to load materials between locations or to vehicles. It is a tractor type vehicle attached with the lifting arm in the front and it is operated with a bucket or other attachment depending on the type of work. The attachment works on hydraulic system. The idea with the upcoming of new technology, as hybrid or electrical vehicle, new possibilities and solutions can be realized like brake regeneration, better comfort and overall control of the vehicle.

The main focus for this project aims to improve the drivability of the vehicle. A feasibility analysis of a new traction control system is presented. The vehicle performs in different sites and conditions, this in turn effects the control of the vehicle. This thesis is going to utilize the advantages of motors over mechanical driveline in individual wheels to improve the traction control of the vehicle during the maneuvers. It also includes improved control strategy and controller in the vehicle. The final output of the work will improve the overall efficiency of system and equipment.

1.1 Volvo Construction Equipment

Volvo Construction Equipment (Volvo CE) is a subsidiary company of Volvo group. It is one of the top ranked company in the market. They develops, manufactures and markets equipment like Wheel loader, Hydraulic excavators, Haulers, etc for construction and related industries. Volvo CE have their footprints all over the world in terms of manufacturing, service and development, with Sweden as their head quarters. They are in leading position in development of new technologies and features for their equipments.

1.2 Problem definition

Traction control system in off-road vehicles have not seen much improvements, compared to other vehicles. It is necessary for constructional vehicle to not loose vehicle control during performance in different road condition. It is mostly related to tire and vehicle dynamics. As it reduces the traction at the wheels and reducing the tyre life cycle due to slip. Wheel slip is the difference in velocities between the vehicle and driven wheel. This is difficult to estimate as it varies non linearly. Due to the slip in wheel the tyre efficiency and torque required in irregular terrain will be effected. Traction at the wheels can be controlled by two methods. First one is by controlling the engine torque, by providing the required torque at the wheels. Second one by using the brake force, during the slippery road conditions.

Conventional vehicle are driven by shaft and torque is distributed with the differential. Since both the wheels in the front and rear are connected to the same shaft via differential gear, it is difficult to have control over individual wheels. It is also difficult to get instantaneous response for the driver input. But in the hybrid or electric vehicle each wheel or axle have electric motors. This is capable of overcoming the lag, but causing the instability in the vehicle control and yaw movement in the vehicle.

The main aim of the master thesis is developing the traction control system for the wheel loader, by including better wheel slip dynamics and control strategy, this also includes analysing the performance of different control strategies. The hybrid or electric vehicle have better advantages over the conventional in terms of operation different system of the vehicle, off-road performances and energy consumption. Traction control system for wheel loader is verified under certain maneuvers like pilling operation and uneven road. To get good control of the vehicle during these operation, establishing relation between wheels was the challenging task. Right traction can be generated between the wheels and ground to overcome the slip. The motion control system performance, vehicle and yaw stability are better controlled in a systematic way,thus overall vehicle performance is enhanced.

1.3 Objective

- Developing a vehicle model for the electric wheel loader. To create a Simulink model of the vehicle and controller in order to verify and test traction control system in different use cases (maneuvers).
- Designing and implementing PID control strategy in the traction control system.
- To tune the controller and perform the simulation in different operating condition.
- Compare the working and results with current control system in the vehicle simulation.
- To discuss the results based on the graphs and describe the drawbacks.
- To propose future improvements.

1.4 Limitations

- The practical implementation was not be possible in actual machine due to lack of time.
- No integration of electrical and electronic will be done.
- Actual hardware implementations will not be studied.
- Controller software will be build with out any hardware limitations.
- Limited number of test cases are studied in order to limit the topic.

- Different tyre friction conditions will not be studied. Every simulation will be concluded with high friction models.
- Road is flat and surface condition is equal under all wheels.
- Traction on the wheels are controlled by engine torque control and not from the brake forces.
- Vehicle model is considered as two axle single track model. Yaw, pitch and roll are not considered.

2

Methodology

2.1 Overview

In this section an overview of the parallel hybrid electric wheel loaders and distributed electric wheel loaders will be introduced. A description about different power train configuration, driving cycle, baseline or present control system and proposed traction control strategies will be presented.

2.1.1 Hybrid wheel loader

Hybrid power train and electric technology are two efficient energy storage and utilization technologies and are rapidly attracting the attention of off-road vehicle manufacturers to the introduction of both construction and mining machinery technologies. One of the most critical heavy vehicles on construction sites is the wheel loader because it can exhibit high performance.

Based on the power-train design and energy control strategies, the hybrid wheel loader has three design options of power-trains: series, parallel, and series - parallel. With parallel hybrid being of main interest of study and comparison, a brief explanation regarding its layout and working is provided in the below section .

2.1.1.1 Parallel electric hybrid wheel loader

Two different power sources provide a parallel hybrid power-train arrangement that can directly power the loader. In most situations, without energy conversion, the engine can send torque to the wheels directly. The downside of a parallel design is that, since it is still mechanically coupled to the wheels, the engine can not always be operated in its high-efficiency operating area.

2.1.1.2 Distributed electric wheel loader

With limited research and the drawback of hybrid wheel loader power-train design, distributed electric wheel loaders are likely to be one of the next steps in the growth and deployment of off-road vehicle manufacturers. Two types are included in the distributed electric wheel loader: independent front and rear axle drive and independent four-wheel drive, as shown in figure [2.1].Since batteries and super-capacitors have their own faults so that they can not be a single hybrid wheel loader driving source, distributed electric wheel loaders also need to retain the ICE as the primary driving source.The benefit of the distributed electric wheel loader is that the driving force of the front and rear axles or four wheels can not only save energy, but also be regulated in order to improve the operating characteristics of the entire loader.In order to achieve this objective, however, it is first important to define the wheel loader operating environment, which certainly includes state estimation and design of various control strategies to provide optimal driving power, the key parameters for the entire loader.

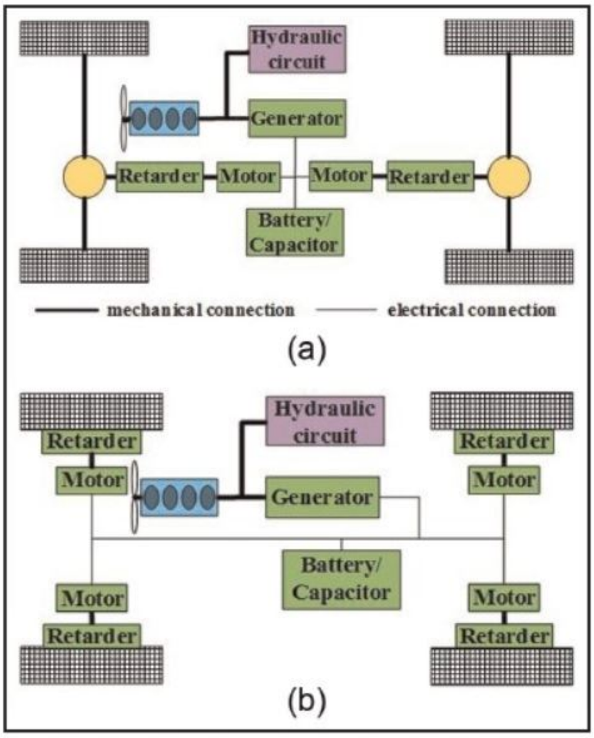

Figure 2.1: Distributed electric wheel loader (a)front and rear axle independent drive wheel loader and (b) four-wheel independent drive wheel loader

2.1.2 Driving cycle

Accordingly, one of the key focuses of this analysis is the Hybrid/Electric wheel loader operating in a V-cycle pattern, where V-cycle-pattern operation is the usual four-cycle work. At the first stage, the wheel loader fills up the bucket with materials and reverses back to the correct point to go to the second stage to the unloading point. The wheel loader reaches the loading point at the third stage to unload the material, and returns to the original point at the fourth stage after unloading the material. As shown in Figure [2.2] below, a standard V-pattern operation of a wheel loader.

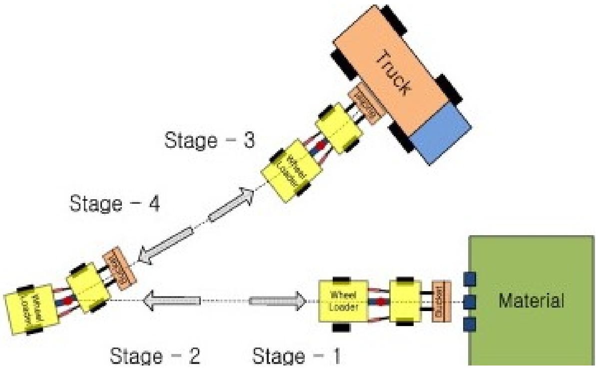

Figure 2.2: V cycle

2.1.3 Baseline control system

The baseline or current controller the most used system in the construction equipment's for generating the required traction force at the contact patch of wheel and the ground. By controlling the torque required at individual wheel depending on the external forces acting on the vehicle and overcome the slip. This approach of the control strategy is open system. It looks like representation done at Figure[2.3]. It is almost as an open-loop system in which torque is applied directly to achieve the requested from the driver combined with limitation of torques in order to not exceed wheel speed limits, or power consumed/generated. Within certain limitations each hub/axle is independent on each other.

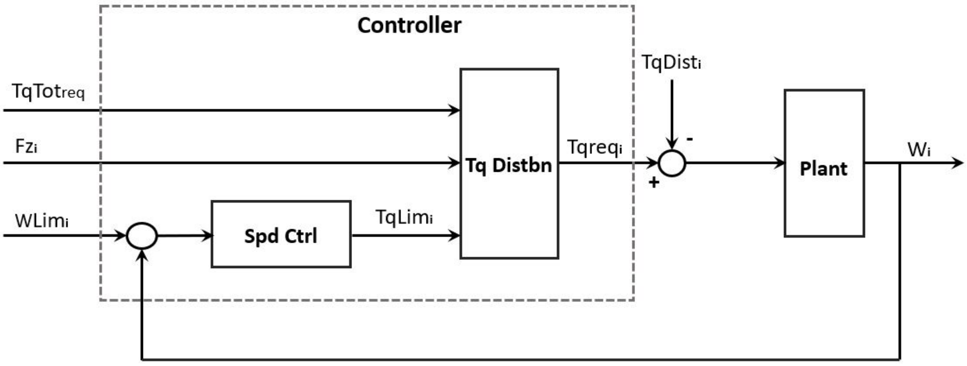

Figure 2.3: Block diagram of current controller

Today the traction control works mostly as an open-loop system by requesting directly the torque to each hub <Tqireq> as function of the total torque requested by the driver <TqTotreq> and a rough estimation of the normal force for each axle <Fzi>. Only, when some of the wheels speed <wi> becomes above an acceptable slip limits, part of the system becomes in a closed loop to control the actual wheel speed to be kept at the speed limits <wiLim>. When the wheel speed returns to be below the speed limits including some hysteresis, the system returns back to be an open system. This make the torque requested to the wheels to become oscillating, especially when the driver request high total torque.

Another existing issue is related to the driver's capability to control low vehicle speed when the terrain has a lot of irregularities. Depending on the chosen pedal map, the driver needs to work hard controlling the pedal position to keep a certain vehicle speed.

2.2 Vehicle model

The vehicle model is used for the studying forces and analysing the controller behaviour during different test cases. The vehicle model along with the chassis, wheels and accessories is based on the important vehicle parameters. It is considered in the mathematical formulation and defining of the forces. One of the important development is addition of the bucket in the model and the forces generated from it are included vehicle model. The traction control includes two major parts known as Torque controller and wheel speed controller, in which vehicle model is used a model based dynamic model for the analysis. The vehicle model development is limited and focused to only wheel loader and its applications.

The wheel loader is an articulated vehicle. The dynamics of the vehicles is considered for equation of motion of the single track model. The test cases considered are straight line motion with different road conditions and different types of vehicle controllable situations is the main point to be considered in the simulations. Another important point considered for the simplification the process of development, analysis and implementation of the traction control system is the lateral forces and yaw movement on the vehicle are neglected. The Test cases includes loading and unloading of work pile cycles in straight line motion. Simulation includes The vehicle approaching the pile in straight line,fills the bucket and returns back in similar motion. It includes only the longitudinal dynamics and lateral dynamics are not considered. The maneuvers are performed with base line controller and the newly designed controller along with the vehicle model. The results are used for the post processing analysis on the basis of traction control behaviour during the maneuvers. Figure[2.4] explains the schematic representation in the form of block diagram of the vehicle model.

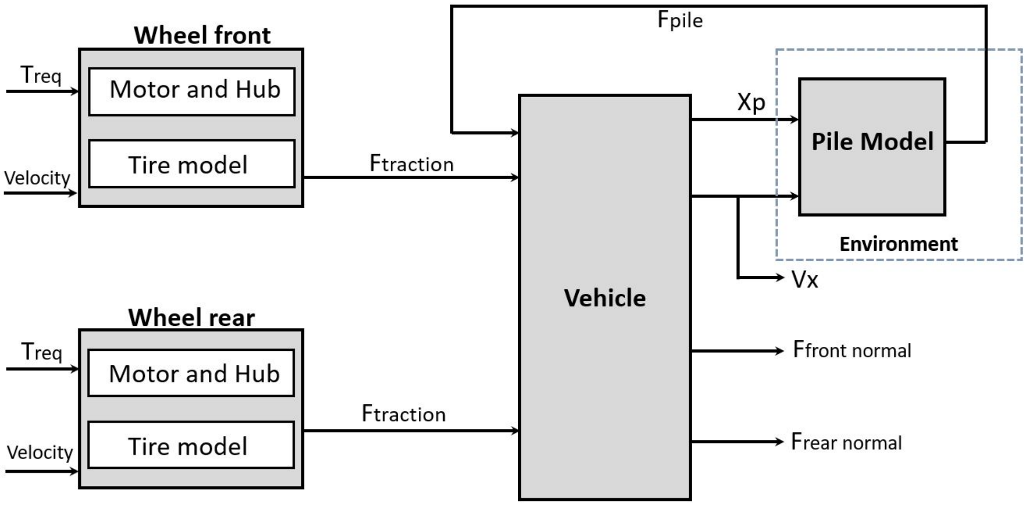

Figure 2.4: Block diagram of Vehicle model

2.2.1 Two Axle vehicle model

As mentioned in the problem definition, the wheel loader during the piling maneuver it is not stable due to slip caused at individual wheels. The controller was not able to control the torque required at the tire to overcome the slip caused by the road condition and disturbances. Studying of Normal forces on individual wheels of the vehicle plays a major role in solving the problem and weight balance of the vehicle during test cases [3].

In our project for better analysis of the normal forces, we considered two-axle model. In this model we assumed the weight of the vehicle and bucket along with the pile load is distributed equally among the right and left wheels. Since the wheel loader operates in different condition involving external forces and depend on the motion and application of the vehicle. This involves change in forces between front and rear wheels, this scenario helped to overview the performance of the controller and its effects on the results [3]. The figure [2.5] below explains the calculation of normal forces individually in front and rear axle, this is done in the presence of external load and weight of the vehicle.

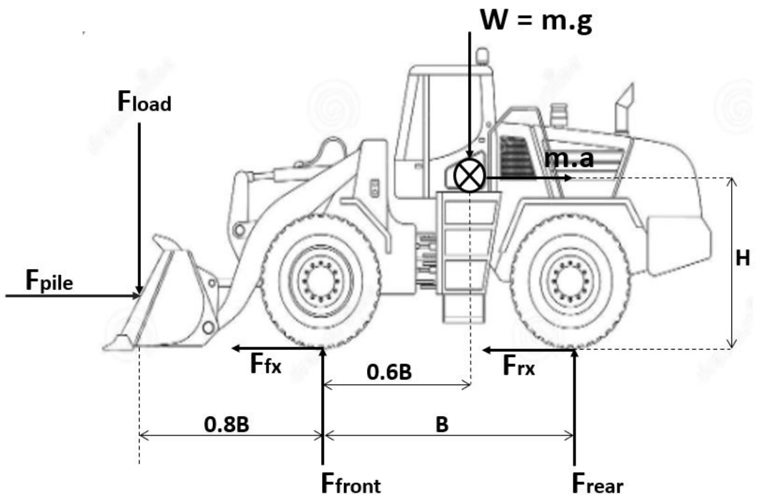

Figure 2.5: Axle model of wheel loader

2.2.2 Forces on a driving wheel

The energy from the engine of the vehicle is transferred through torque to wheel, to initiate the motion in the vehicle. There are many dynamic force acting on the wheel in the wheel loader,the torque generated should overcome all the resistance forces like frictional force, rolling Resistance, aerodynamic resistance and pile resistance force. The dynamic behaviour of forces are explained by using the figure [2.6] below [2].

Figure shows the applied torque T on the individual wheel with radius R0 to produce dynamic motion by overcoming the forces such as, Fp the pile force, Fa aerodynamic force, Fr the rolling resistance, Fx the traction force, Fz the normal force,Vx the velocity of the vehicle, w is the angular velocity and W the vertical load [2].

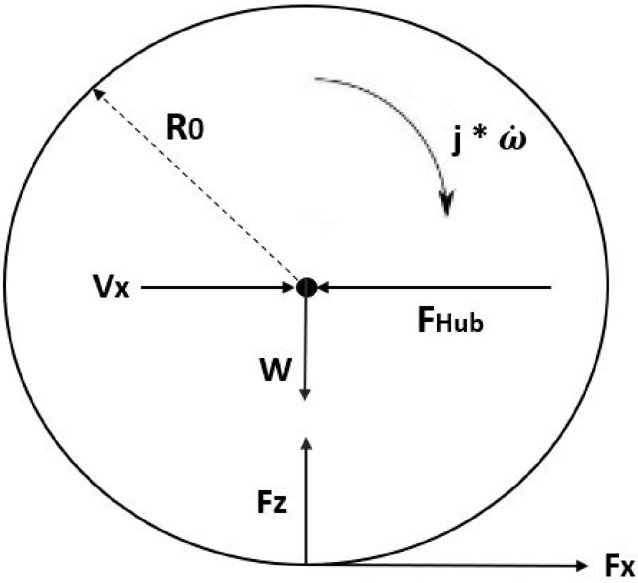

Figure 2.6: Force dynamics of wheel

2.2.3 Tire model

We choose the Pacejka's Magic tire model in the vehicle model, it is most widely used model as it fit a variety of tire constructions and operating conditions. It is developed in a simple and compact model to represent the relation between slip and force. The formula model consists of the different coefficients of the forces(Ex Longitudinal and later forces) at the contact patch between wheel and road, where it plots the general shape of slip-friction curves[4].

The general form of Magic tire model is given by[4],
y = D.sin[C.arctan(Bx E. (Bx - arctan(Bx)))][4]
Where, y is a force or moment resulting from a slip parameter x. B,C,D and E are the coefficients parameters affecting the shape of the slip-friction curve and these parameters are adjusted to bring the curve close to standard form[4].

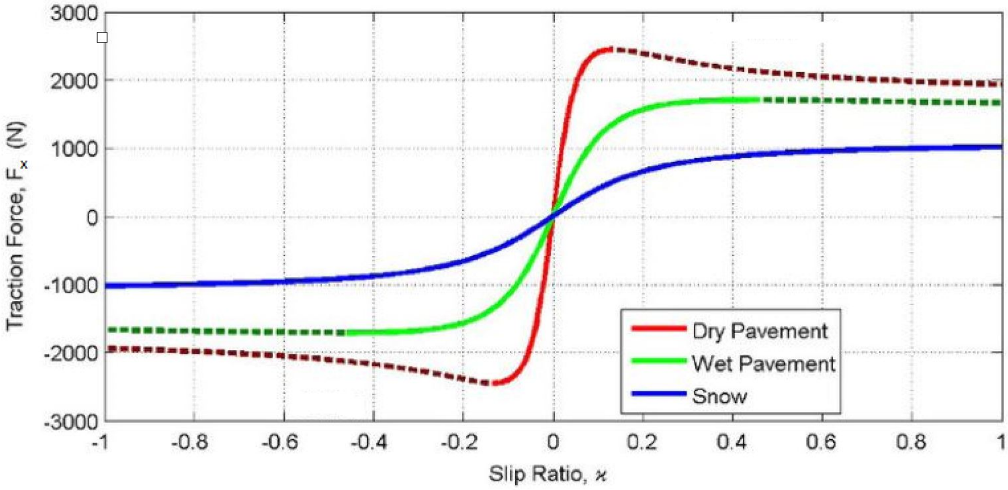

Figure 2.7: Magic tire formula curve in different ground condition[4]

The above graph in the figure [2.7] is an example for changes in the plots of magic tire formula for change in parameters .It is based on real world data for dry, wet and ice conditions. By observing these plots, it can be understood that change in mu results in the changes in slip-force relationship.

2.2.4 Slip

Slip is a important in the longitudinal forces and defined as the difference between the actual longitudinal velocity and rotational velocity to the rotational velocity. It is simply known as ((rw-V)/rw) and it is a friction force with origin from the contact patch between the tire and the ground. The friction coefficient, slip and normal load controls the slip behaviour[4].

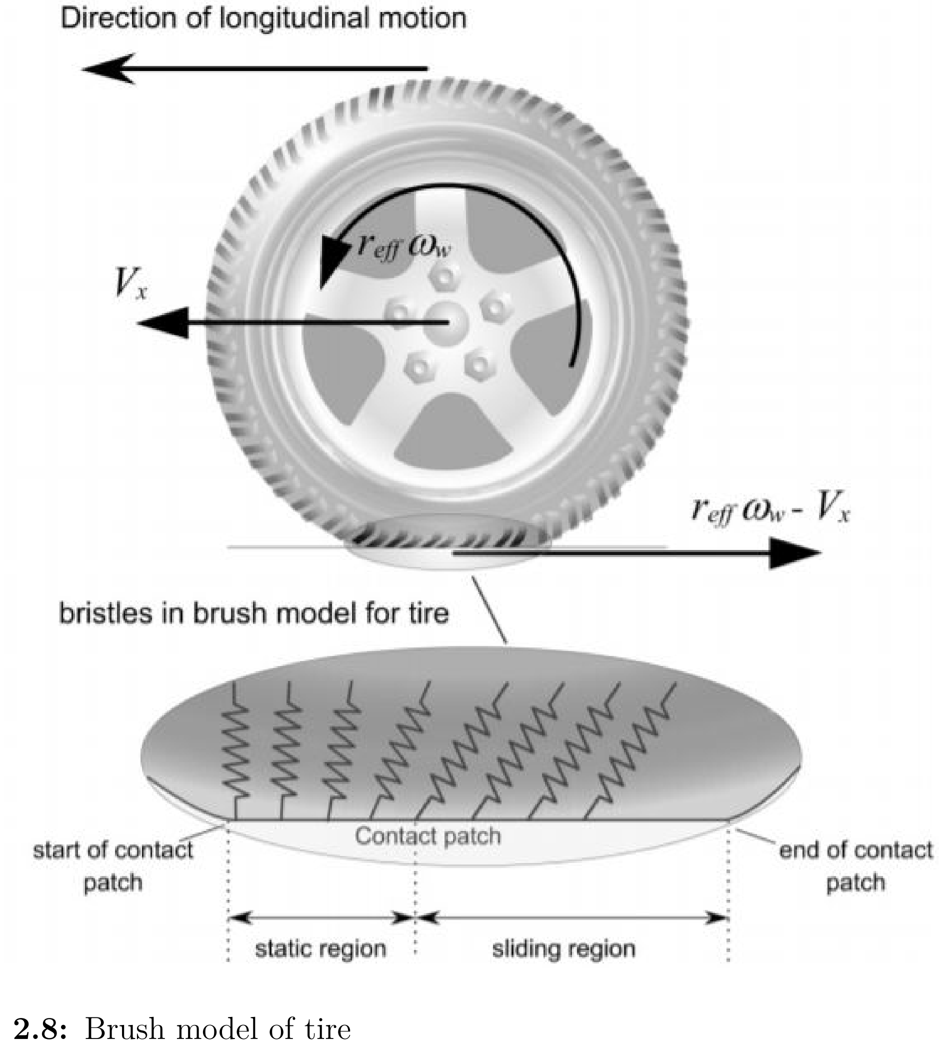

Figure 2.8: Brush model of tire

Figure [2.8] explains schematic representation of deformation of the thread element of the tire. The threads undergoes longitudinal deformation, as they are modelled in the form of series of independent springs. This method of modelling is known as brush model[4]. Let the longitudinal velocity be Vx, the rotational velocity be w and the radius of the wheel be R. Then the net velocity at the threads be rw-V. The tire deforms due the normal load of the vehicle and makes contact with the road is know as contact patch. It is divided into static region, where the thread elements does not slide with respect to ground and the another region thread slides wit respect to ground is sliding region[4].

In the case rw > V, the net velocity is in the opposite direction of longitudinal velocity and assume the rw - V is very small. During the rotation of the wheel the tire is in contact with the ground in the static region must have zero velocity. The top of the thread elements move along with the rw - V and the thread bend forward as shown in the figure[2.8], in the direction of the longitudinal direction of motion of the vehicle[4]. Hence the maximum deflection of the tread is proportional to the ratio of slip to absolute velocity. In the case V > rw, Since the net velocity (rw - V) at the treads is in the forward direction and hence the threads will bend backwards. Hence the tire force on the wheel is in opposite direction to that of the vehicle's longitudinal velocity [4].

2.3 Controller

The important motive of the problem definition and project, it is reduction in the slip in individual wheel and it should payoff in generating better tractive force. Slip at the wheels increase the tire wear and decrease in stability of the system. In order to overcome this problem designing the controller and control strategy is very important. In this system the goal of the traction control is kept simple, First, reduce the amount of slip generated in individual wheel during operating in different condition. Second the most important is increase the stability of the system by maintaining good traction against all the surface irrespective of the condition. Since both these are going to affect the performance of the machine in different application scenarios.

2.3.1 Controller architecture

In this section complete model and all the subsystem are explained. Role of the individual subsystem and its working procedure along with the its limitation are explained in brief. All the subsystem are explained individually in detail in further subsections and its working procedure in the simulations.

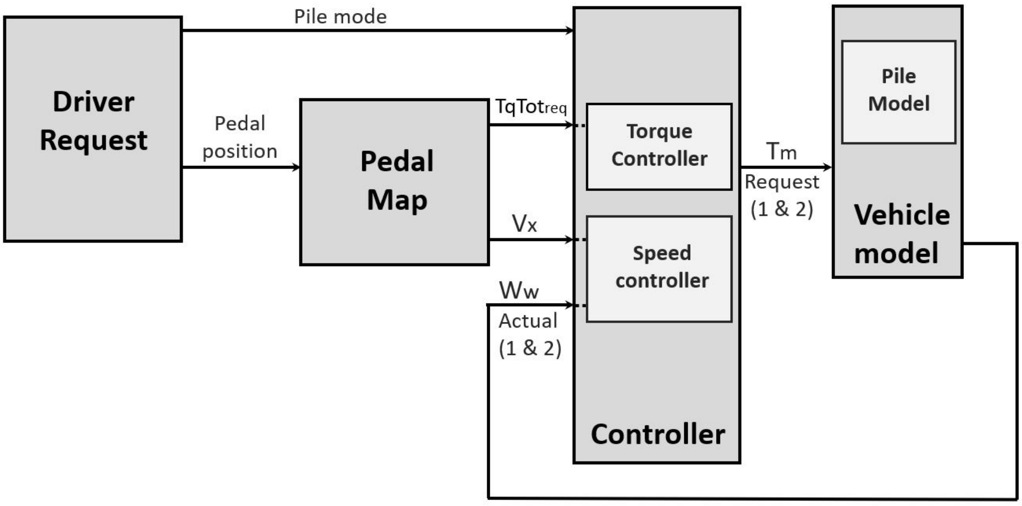

Figure 2.9: Block diagram of wheel loader simulation

In the figure [2.9] the model explains the complete simulation of the wheel loader. Starting with the driver request, depending on the application and conditions the driver requests speed and forces required to perform the maneuver. Based on his request depending on his pedal position and along with the environmental condition such as ground condition, the required velocity and tractive force request is generated from the pedal map. It is the next subsystem and also depending on the tractive force requests total torque and torque at individual wheel request is generated for the controller. The request for the controller will be intended in reducing the slip and increase the stability of the machine in the maneuver, as it results in effective energy utilization and better power efficiency.

The controller input signal will be velocity and total torque requested from driver through pedal map. The values are compared with the actual value to get error value and depending on the control strategy, the output signal is calculated. The output signal is actual torque request for individual wheel of the machine is acting on the wheels in the next subsystem vehicle model. The signals are in continuous form, the difference between the actual value and the requested or previously sent value is the error value. The difference value (error value) is dependent on the ground condition in which the machine is operating.

The design and control strategy of the proposed controller is completely different from the baseline controller. In this controller slip doesnot play an important role and it is also not considered as one of the parameter, it is used only for analysing the simulation results. The test controller is divided in to Torque control and speed control. The division is also dependent on the maneuver condition in which the machine is operating at the instance and the vehicle. All the maneuvers performed by the wheel loader is either torque or speed dependent, so the option to shift the modes depending on the vehicle. The simulations results are analysed and compared with the baseline controller depending on the mode condition. Depending on the mode of operation the role of torque and speed control is decided. For example if the driver is in speed mode and performing velocity based maneuvers, in this condition torque is not important parameter request. The torque control is bypassed to avoid the high acceleration produced when the driver is asking for the speed and speed control plays a major role in control strategy. But in the torque mode both plays major role and , both the parts are explained in detail in future subsections.

2.3.2 Control strategy

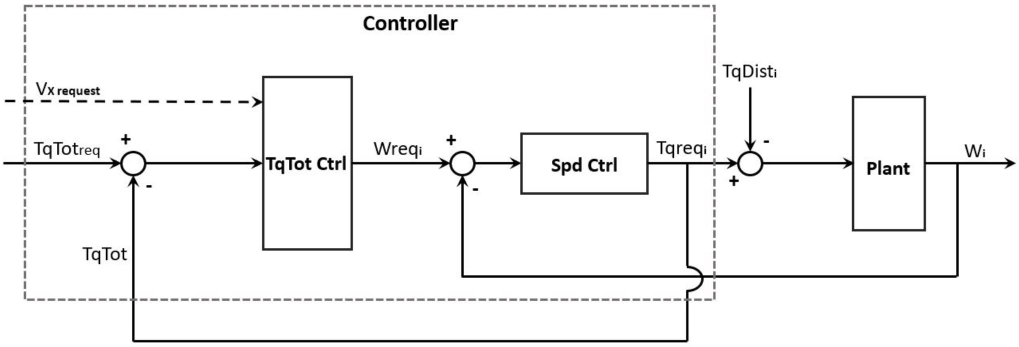

Figure 2.10: Signal flow diagram of controller

Control strategy explains the working procedure and the consideration of the important signals of the system. It also describes the importance of the certain blocks and the feedback signals from vehicle model block, its influence on the input signals. It explains the step by step process followed by the controller in reducing the disturbances caused by the environment for better output. As it will be trying to match the input signal (driver request) and make sure the controller is working in better efficiency mode.

The strategy can be divided in two parts, similar to the type of controls involved in it. The first part is the Torque control block, is known as the outer loop of the controller. The total torque request<TqTotreq> is an input and wheel speed request of individual wheel<Wi> is output. There are many other signals plays role in this block, but based on its impact on the input/output it is not considered in the strategy. The input is the difference of the total torque requested<TqTotreq> by driver and the feedback signal<TqTot>, it is the sum of the torque signal<Tqreqi> of individual wheel sent by the plant model. The feedback is the output of the whole controller or it is also the output of the second part speed control, it is formed by summing up all the torque output to the individual wheel. The output signal<Tqreqi> of this outer loop will be input signal<Wreqi> of the inner loop. Since each inner loop take care of the individual wheel, the output of the outer loop splits into individual speed control.

The second part of the control strategy is speed control and also known as inner loop of the controller. It consists individual wheel speed request from the torque control as input<Wreqi> and torque request of the individual wheel is the output<Tqreqi>. Similar to the first part of the controller, the signals are prioritised over other signal based on their impact on input/output signals. The input is the difference between the individual wheel speed requested from the torque control<Wreqi> and the actual wheel speed<Wi> of the respective wheel. The output signal<Tqreqi> of this speed block is the individual wheel torque request and also the final output on the complete controller. The actual wheel speed of individual wheel obtained from the plant output is the feedback signal of the speed control and impacts on the control process depending upon the working condition. Finally the calculated output signal<Tqreqi> individual torque request is sent to the plant as input with some negative torque disturbances<TqDisti> caused by the environmental forces. The signal flow of both parts explains the detail strategy followed by the controller and working to reduce the errors between input and output signals of the complete/individual systems.

2.3.3 Driving Modes

The Base line controller have some drawbacks in the vehicle system in particular to some of cases in its working condition. It doesnot have different mode to change for wide variety of vehicle and performing different operations. For the betterment of the vehicle performance and for the wide range of its application new controller is designed. The newly designed proposed controller with two segments torque and speed control in its operation, creates an opportunity to operate in all variant of machines. The wheel loader performs maneuvers in different environmental conditions, the vehicle will be requesting torque or speed. This helps to divide most of the maneuvers in torque based or speed based operation, so it can operate torque and speed mode depending on the maneuver performed by the vehicle. By doing this, it helped the system to bypass some subsystem and directly focus on controlling of important signals. This division of two modes of operation in the proposed controller and also freedom for driver as requirement increase the overall performance of the vehicle in difficult conditions. It also supports for analysing of proposed controller and compare it with the current controller. Both the modes of operation comes in to play only in proposed controller and not in the current controller, in some situations it is used to compare between them and its difficult to do in all the situations.

Torque mode is an important mode of operation in constructional vehicles. It includes the operations, in which vehicle is performing and requesting traction force, torque and power based maneuvers. It is the mode used to compare with the proposed and current controller, as the current controller works in similar conditions. During the torque mode both the torque control and speed control operates one after the other in the controlling action.

Speed mode includes the operation, in which vehicle is performing and requesting speed based maneuvers. When it comes to the current controller there is no such as speed mode and it is also not use this mode for comparison of the controller. During this mode of operation, the torque mode is bypassed and only speed control plays major role in the performance of the complete controller.

For analysing and comparing both the current controller and the proposed controller are implemented in the working condition of the vehicle and simulated. The method followed for comparison and the systems involved in the process are explained through the flow diagram in the below.

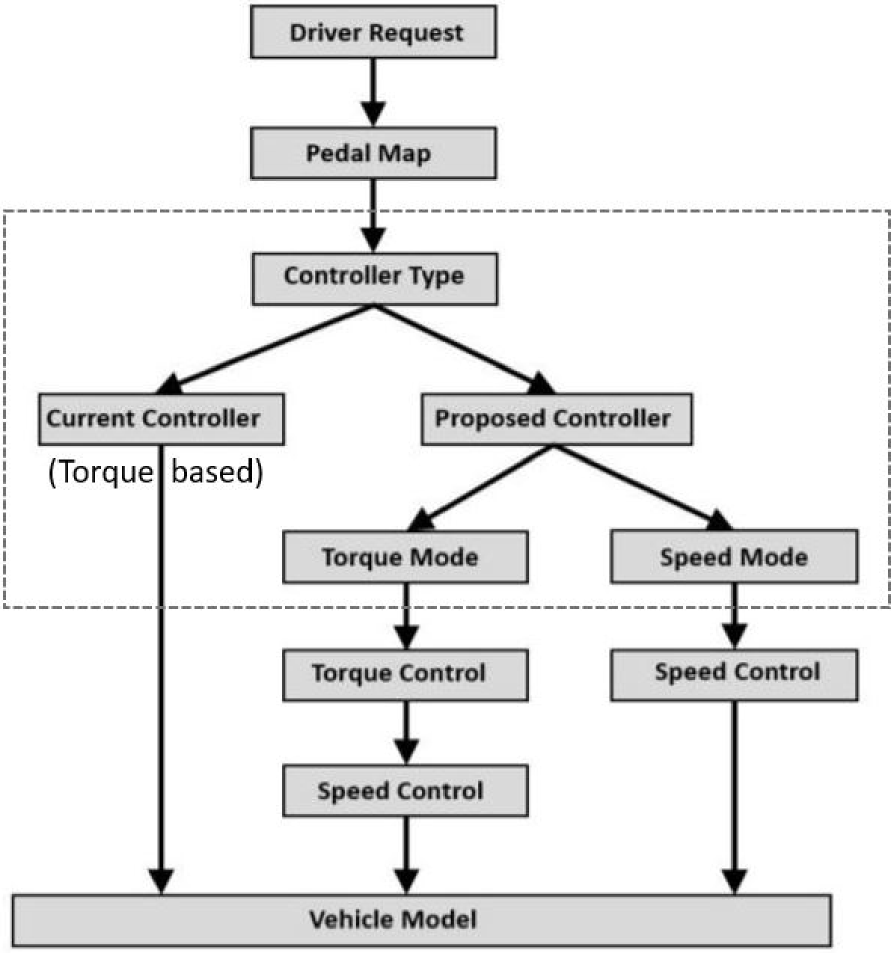

Figure 2.11: Modes used for comparison

Starting from the driver request passing through the pedal map, the signals reaches controller. Here the process can switched between current and the proposed controller and run the simulation. Initially, if we choose the current controller, the signals pass through the this controller and the vehicle model. In this simulation the feedback signals from the vehicle model are connected to the current controller for controlling and reducing the disturbances caused due to the environment conditions. By performing through these steps the results are obtained for the simulation of current controller, which will be used for analysing and comparing.

In the case of proposed controller at the section of controller, if it is chose to run in torque mode based on the operating condition and requirement. In this case, as the controller contains two parts torque and speed control both will take part in the process simultaneously. In the torque mode the signals initially get into torque control, then the speed control. After the controller the signals reaches the vehicle model for the action to be performed to complete the simulation. The feedback signals from the vehicle model returns to the torque and speed control, depending on the signals they are controlling respectively. The changes required for the system depending on the environment conditions are corrected based on the feedback signals to obtain the good results of the simulations. In the speed mode condition, the signals will be based on the driver request signals on operating condition and requirements. The signals from the controller directly connects to the speed control bypassing the torque control. Then the signals from the controller reaches the vehicle model.The feedback signals operates in a similar way to the torque mode and the results are obtained of the simulation. Finally with the results in the form of plots both the controllers are analysed and compared, to discuss the drawbacks.

2.3.4 Torque controller

It is the first part of the controller and it plays a major role in the torque mode. The driver is requesting the torque required by the machine to perform the maneuver and velocity is not a important parameter. If we consider the test case, the wheel loader is performing the piling operation, during this operation torque is important. The torque required at individual wheel irrespective of the ground condition and to perform the operation successfully are calculated by the controller.

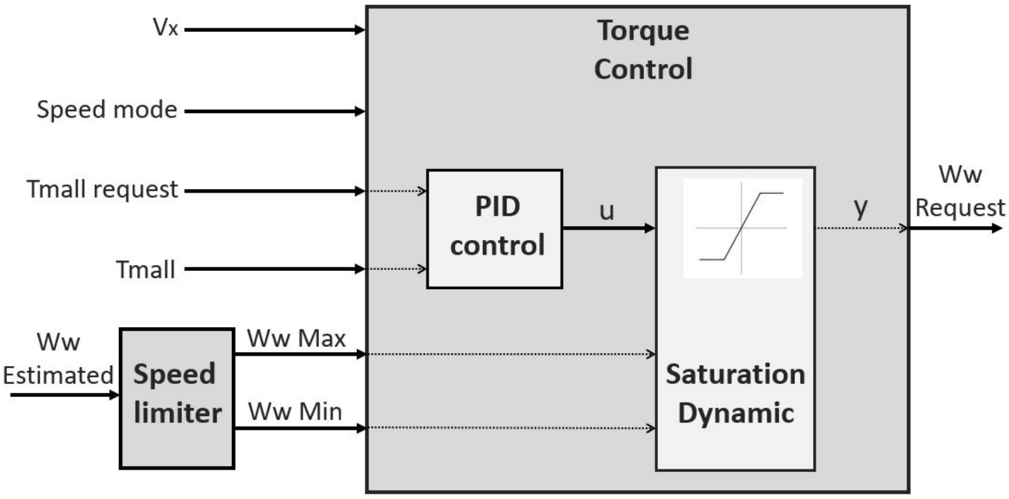

Figure 2.12: Block diagram of Torque controller

The figure [2.12] explains the signal flow diagram of the torque control with input and output signals. The input signals alters according to the mode at which it is performing and vehicle. In the speed mode the controller is bypassed, velocity is important parameter and the output signal wheel speed is directly calculated. This signal is next connected as an input signal to the speed controller. In the case of torque mode, the input signals torque request and torque actual will also be input to the PID controller. PID controller depending on the error generated between the input signals amplifies the output signal. Based on the estimated wheel speed, the speed limiter calculates the maximum and minimum values. These values are also in continuous form and varies depending on the operating condition. The limiting values defines the operating region of the controller, the values cannot be out of the region in any operating condition. The output signal (u) of the PID is subjected to these limiting values in the saturation dynamics and the final output signal wheel speed request(y) is calculated, it is input signal to the second part speed controller. Depending on the driver torque request the wheel speed request is calculated, the torque control conclude its role in the operation of the controller. Then further actions are taken care by the speed control to overcome the irregularities.

2.3.5 Speed controller

It is second part of the controller and it is most important section, it works on both the torque mode and speed mode. Irrespective of the driver request and operating condition, the controller works. The working procedure is similar to torque control with minimal changes. In this section the wheel speed is compared with the request from torque control and actual value, this gives idea about the slip. IT will take the necessary action to overcome the disturbances and to carryout the maneuver.

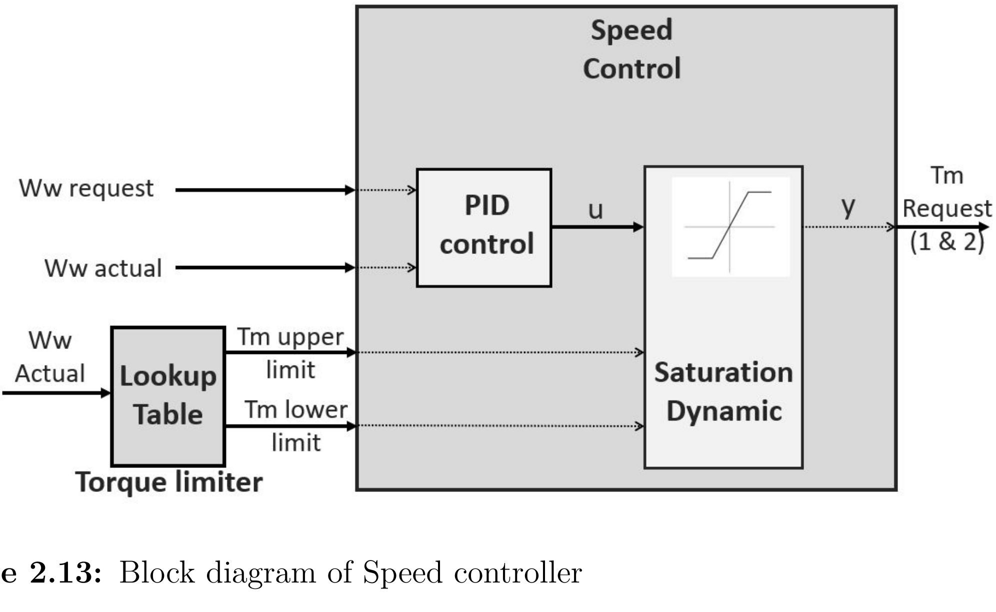

Figure 2.13: Block diagram of Speed controller

The figure [2.13] explains the final stage of controller, depending on the condition it provides the correct values for the wheel loader to work. Here the output signal wheel speed request of torque control will be the input signal and it is compared with the actual wheel speed to calculate the error. These signals will also be the input to the PID controller, it calculates the output value to overcome the disturbances and it is depending on the error value calculated in the PID controller.

The actual wheel speed is used to calculate the torque upper and lower limit. The operating region is obtained by the lookup table, by comparing the values in the lookup table the limiting values are obtained. The limiting values as input to the saturation dynamics defines the operating region of the controller for the torque signal(u) and always keeps the output torque signal(y) within the range of working. The torque output signal is based on the driver request and the disturbances, it will be one of the input and acting to the vehicle model. As mentioned in the problem definition, this signal is the final part and plays major role in reducing the slip and increasing the stability of the vehicle in different operating condition. After this step, the vehicle model performs on the basis of signals provided from controller and pedal map. The working procedure during performing maneuver can be observed and these simulation results helps to compare with baseline controller.

3

Results

In this section the results of the simulations are analysed through the graphs,by selecting some of the important signals. The comparison between current controller and the proposed controller are analysed and explained in detail. The section is organised starting with the current controller, Torque mode of the proposed controller and Finally speed mode of the proposed controller.

3.0.1 Current controller

In the current controller the results are based on the some important signals and in this controller there is no division of modes. The controller is working in a manner close to torque dependent in the maneuvers. By selecting the each and every important signal, in which major difference can be identified between the controller are explained individually below.

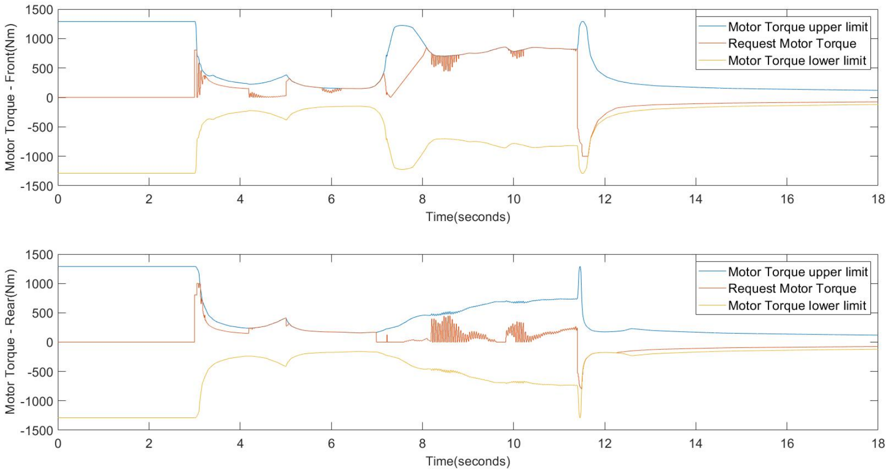

Figure 3.1: Torque signal in current controller

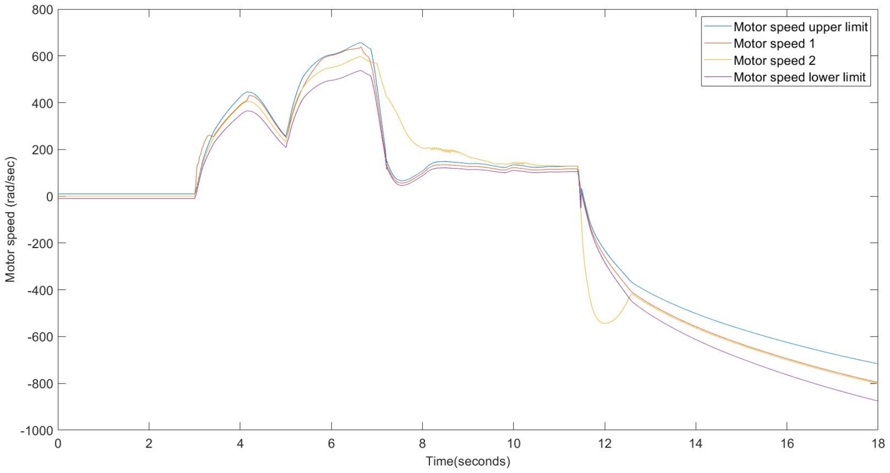

Figure 3.2: Wheel speed signal in current controller

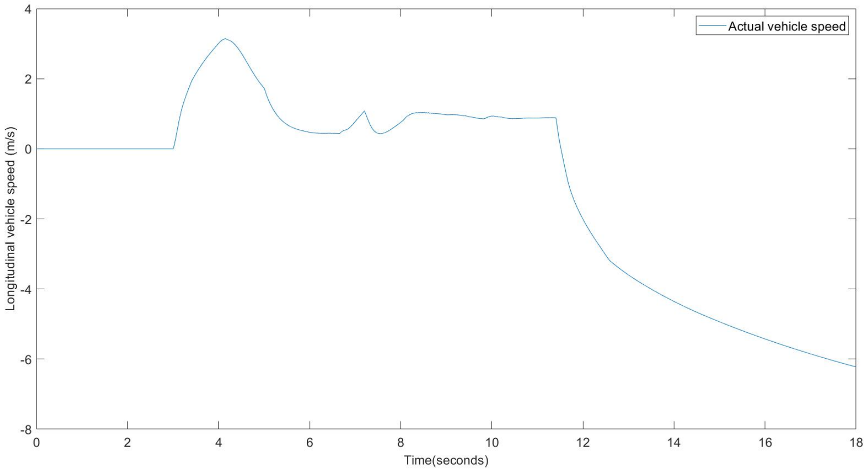

Figure 3.3: Vehicle speed signal in current controller

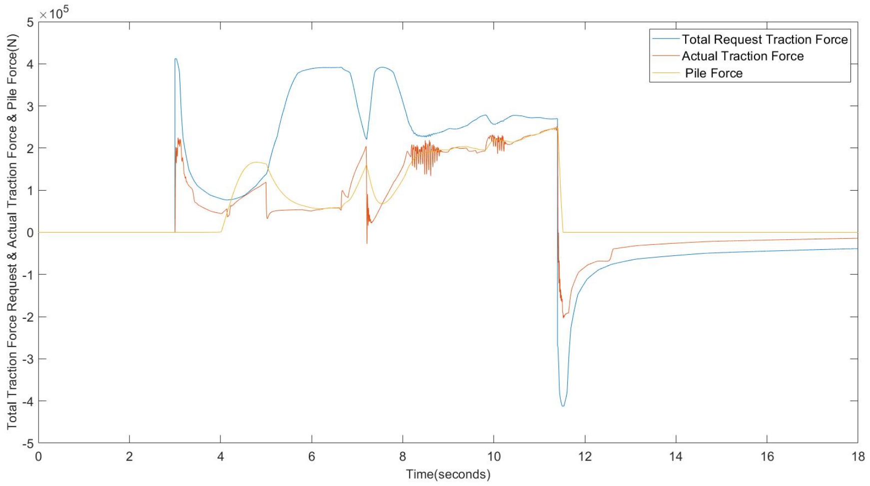

Figure 3.4: Traction force and Pile force signal in current controller

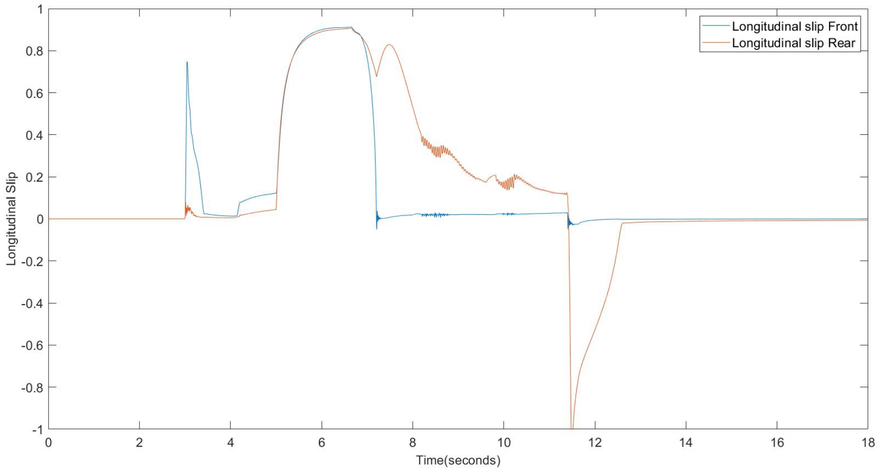

Figure 3.5: Slip signal in current controller

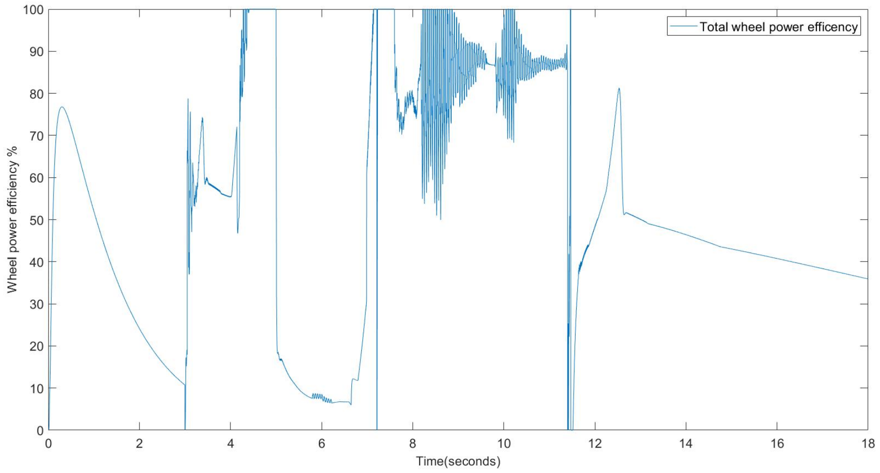

Figure 3.6: Wheel power efficiency signal in current controller

In the first graph the signal considered is Torque in Figure [3.1]. There are separate graphs for the front and the rear wheel, along with the limitation signals. The limitation signals helps to define the working region of the controller the driver can request. The torque request signal always will be with in the range during the operation irrespective of the demand. In the graph it can be observed that, during the piling operation the controller is not able to generate constant torque signal.During the piling operation there is lot of disturbance, which leads to instability and down performance in the vehicle. Always the driver request the constant torque signal in the operation, but the controller depending on the external forces it should be able to fulfill the request..

At the start of the piling maneuver, there will a step up request from driver in torque demand intends tractive force at wheel to overcome the external forces and ground conditions. The controller needs to match the request, but in the current controller in Figure [3.4] the signal total tractive force there is disturbances and it is also not able to match the requested signal. It can also be observed that, after the maneuver there will be step down in the tractive force request. During this step down process the change is taking place in short duration, which should not be in this case. It needs to follow the smooth curve path for not effecting the vehicle performance.

In the figure [3.5] the slip at front and rear wheel during the piling operation. As the slip is the focus point, it should be reduced by correct torque signal to over come external forces. The controller with the feedback signals need to reduce the slip, as it leads to instability of the vehicle. During the operation in practical there will be higher value of slip at the rear than front, it is because of the bucket load generates normal force at the front wheel. But in this controller the signal are far from the reality. In the figure [3.6] it is the power efficiency at the wheel, the controller is trying difficult to maintain its efficiency in the highest efficiency points. It can also be observed huge variation with respect to time.

3.0.2 Proposed controller in torque mode

In this section, the results of the torque mode in proposed controller are discussed and as its working procedure is similar to the current controller, they are compared based on some signals. The signal selection are kept constant in all the controller, to have comparison in a simple manner. The torque mode is based on torque request operation, so the controller will be trying to match the requested torque throughout the operation to overcome the external forces.

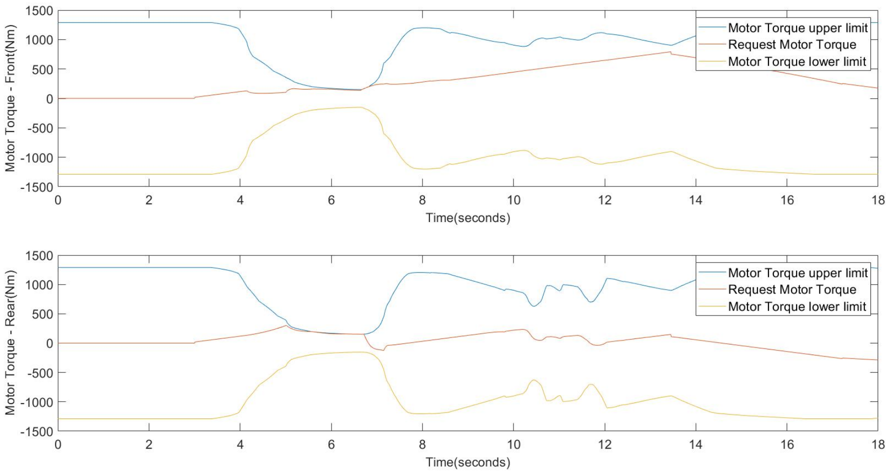

Figure 3.7: Torque signal in Proposed controller Torque mode

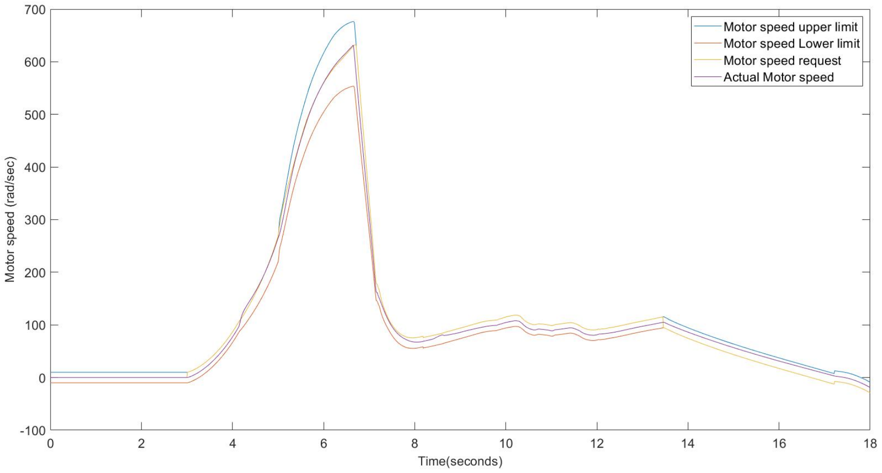

Figure 3.8: Wheel speed signal in Proposed controller Torque mode

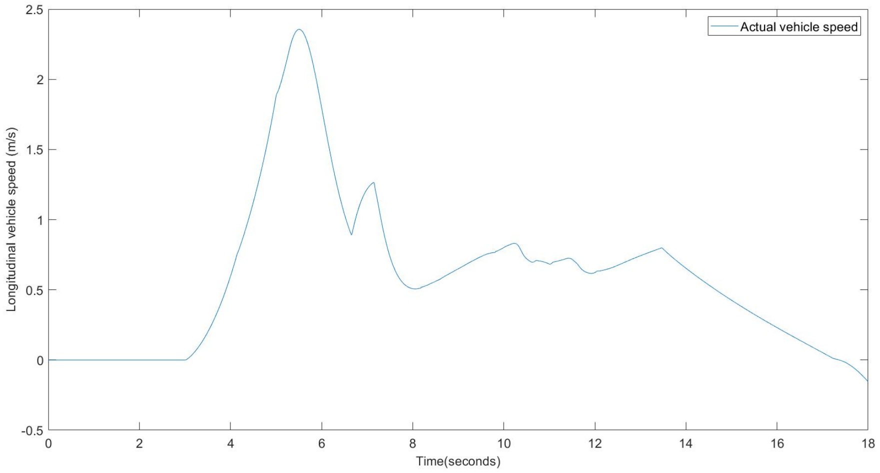

Figure 3.9: Vehicle speed signal in Proposed controller Torque mode

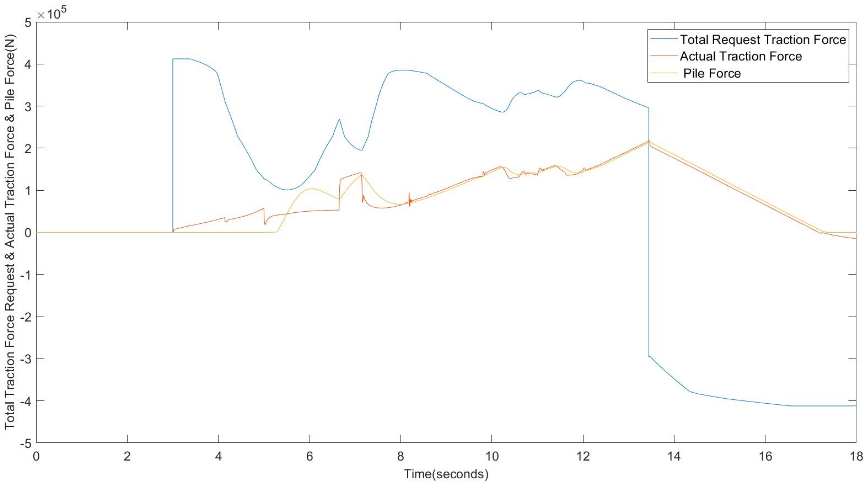

Figure 3.10: Traction force and Pile force signal in Proposed controller Torque mode

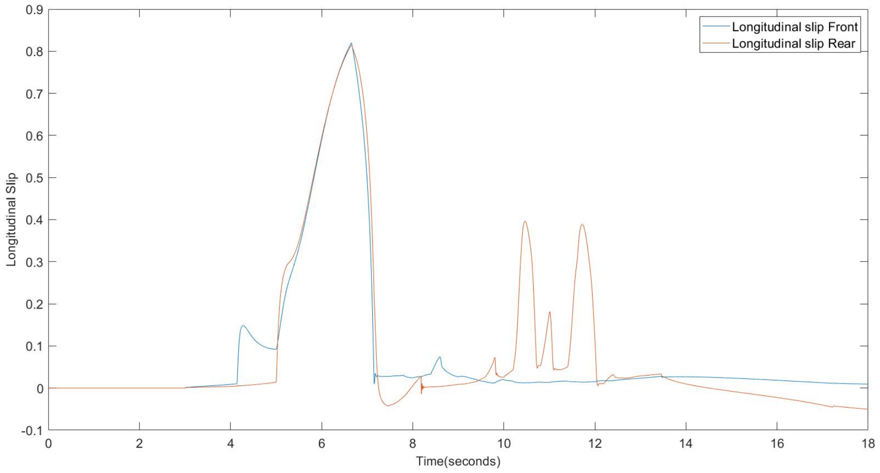

Figure 3.11: Slip signal in Proposed controller Torque mode

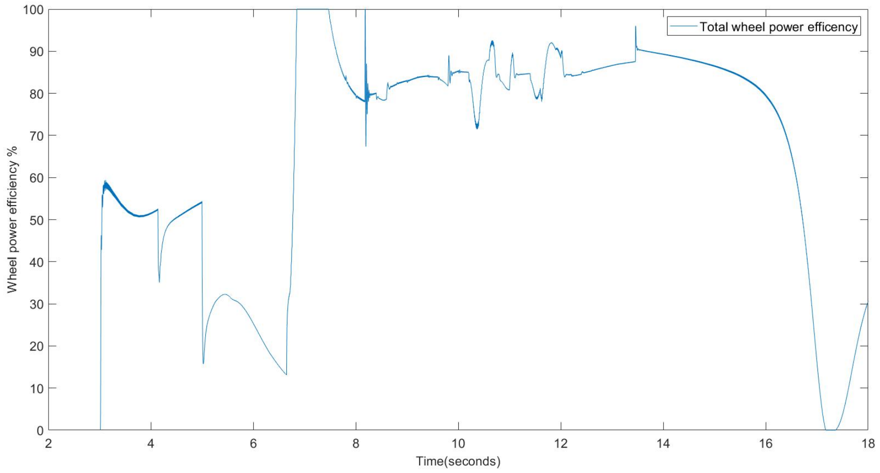

Figure 3.12: Wheel power efficiency signal in Proposed controller Torque mode

In figure [3.7] the signals of front and rear wheel with the limitation and the request signals. The limitation signals are based on the maximum and minimum values of the estimated wheel speed and it also sets the operating region. The requested torque signal of individual wheel are within the range and are in smooth manner. In these signals there are no disturbances like present in the current controller.

In the graph of traction and pile force in figure [3.10], starting from the piling maneuver it is trying to match the torque request from the driver. There are some fluctuation in tractive force signal, but very less compared to the current controller tractive force signal. It is also trying to maintain constant in the region and also operating with the limitation in which the controller can operate. But in this graph one important variation can be noticed, after the piling operating during the negative velocity, there is a delay in time of the tractive force to reach the normal value. It is following the pile force pattern ,so it needs to be more tuned for better performance and results.

The slip signal at individual wheel in figure [3.11], at the start of pile operation both the wheels are slipping because of the external forces and reduce in the normal force. But in the short duration, due to the feedback signals, the proposed controller in the torque mode reduces the slip by generating required normal force in the wheels. In this condition the work load at the bucket helps to reduce the slip in the wheels. Slip occurs in the rear wheel during the negative velocity because of the improper weight distribution along with the pile in the bucket. In the figure [3.12] the power efficiency at the wheels is operating in better efficiency region than the power efficiency region of the current controller. This explains the difference in the performance of both the controller.

3.0.3 proposed controller in speed mode

In this section the results of the another part of the proposed controller in speed mode are discussed and this part is dependent on the speed request based on operations. This part cannot be compared with the current controller, because the is no such as speed dependent operation in the current controller. It is explained its different way of working from the torque mode from the graphs.

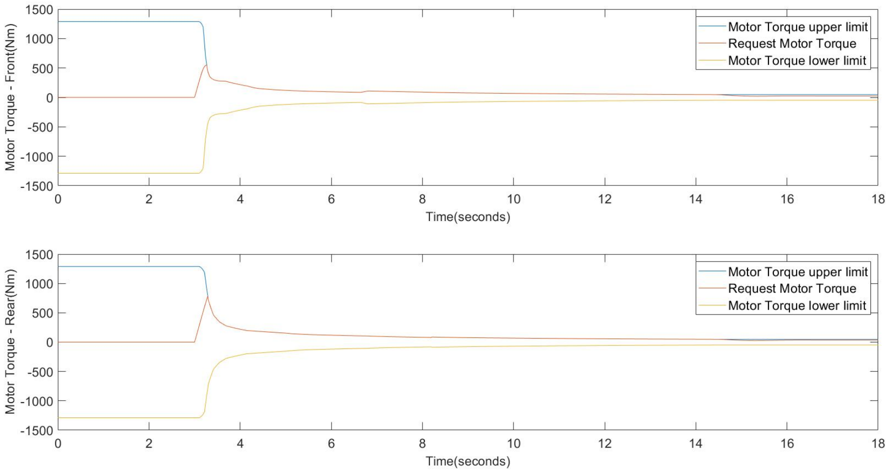

Figure 3.13: Torque signal in Proposed controller speed mode

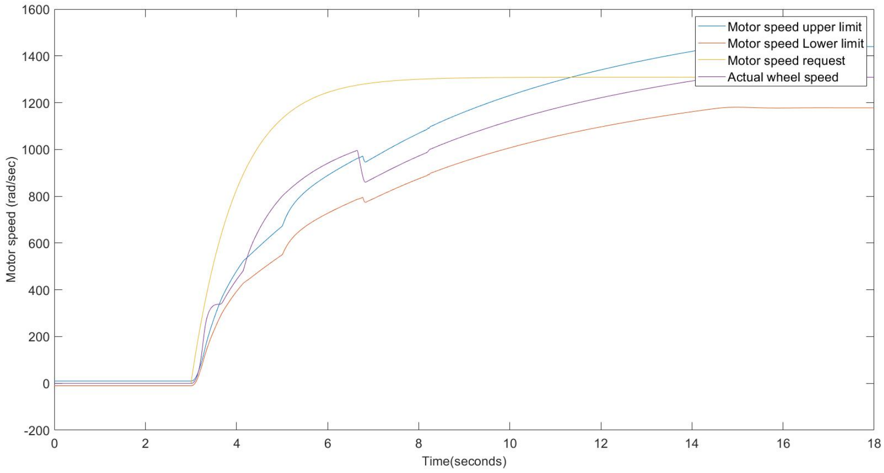

Figure 3.14: Wheel speed signal in Proposed controller speed mode

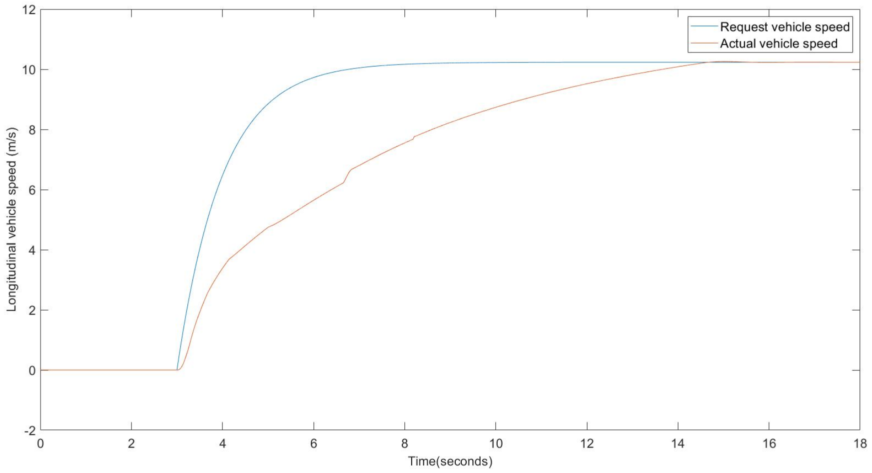

Figure 3.15: Vehicle speed signal in Proposed controller speed mode

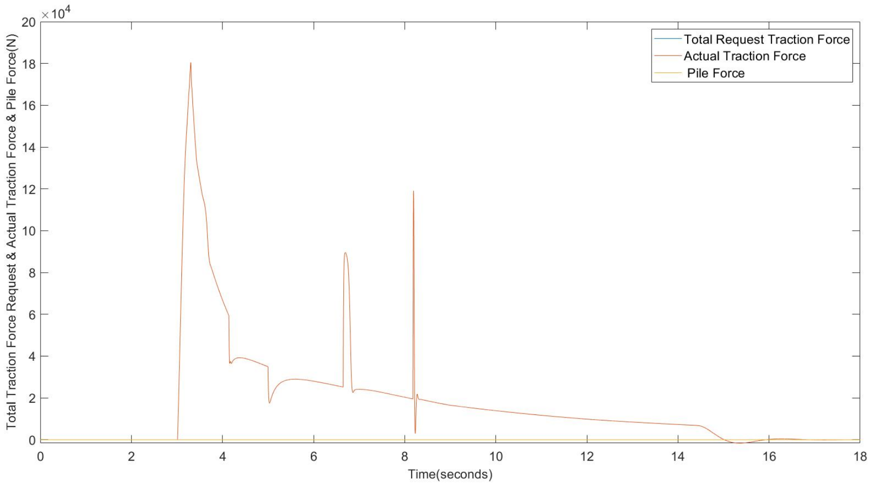

Figure 3.16: Traction force and Pile force signal in Proposed controller speed mode

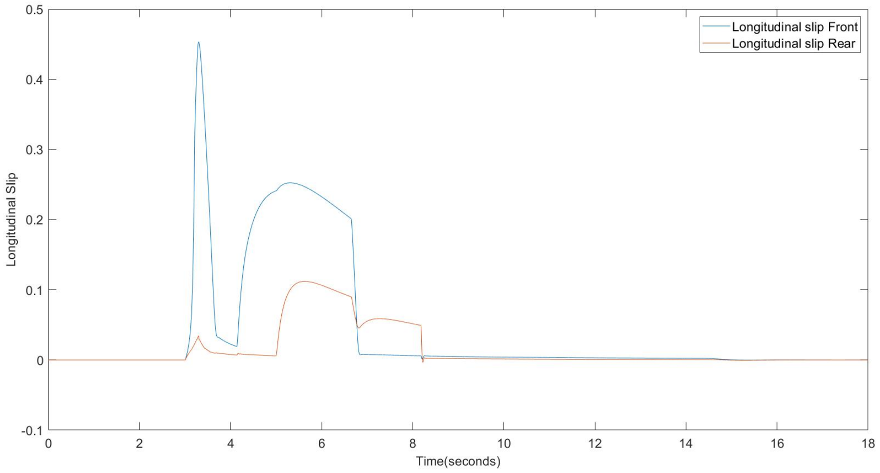

Figure 3.17: Slip signal in Proposed controller speed mode

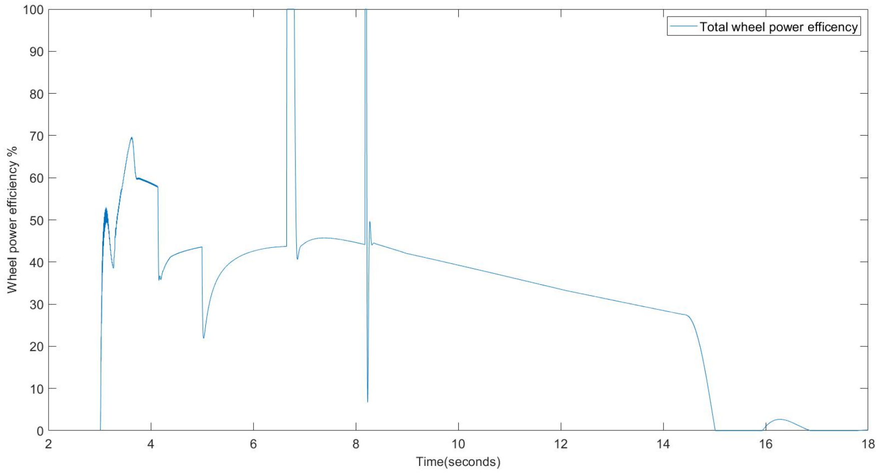

Figure 3.18: Wheel power efficiency signal in Proposed controller speed mode

In the figure [3.14] graphs are based on wheel speed signal and the actual wheel speed is trying to match the requested signal in the presence of limiting signals. The limiting signals are based on the upper and lower torque signals at the wheels and also defines the range of working. The actual wheel speed even tough it not able to meet the requested value, it is following the patter of the requested signal in the controller operating range and also in the presence of the external forces. In the figure [3.15] as it it speed based maneuver, the driver is requesting the speed signal and the actual speed signal with proposed controller in the speed mode is able to follow the path of the requested signal.

The slip signal at both the wheel in the figure [3.17] are very low and the values is due to the absence of the opposing force/pile force in figure [3.16]. these signals are due to the actual wheel speed is trying to match the requested signal. In the figure [3.18] the power efficiency at the wheel are low compared to the torque mode. This is because, as the vehicle is not operating in torque mode and in speed mode there is difference in the actual and requested wheel speed in the presence of the proposed controller with the limiting values.

4

Discussions

In the segment of automotive engineering the construction equipment plays predominant role in adaptability to terrain and wide variety of application it performes. In these vehicle traction control systems aim is not only to meet the operational requirements, it should also improve the dynamic performance in various operating conditions. Due to the presence of the limitations the problem complexity is reduced, the work provided freedom for analysis in simple way and study the process.

In the study of the current control system, it is mainly based on the slip based control. This lead to effect the performance of the various system in the vehicle and also towards the solution to enhance the performance in electric vehicle segment. This idea lead to think about the speed type control and resulted in development of the proposed controller with two modes of operation. The wheel loader operates in difficult environmental condition, which challenges its operation capabilities and performance. By studying its operating maneuvers, they are divided into two mode of operation and also driver has the option to switch between them. The division of two modes was also based on the control strategy and simplifies the controller action to enhance the performance of the vehicle.

Depending on the mode selected and the driver requests to the torque or speed signal for the performance of the vehicle in presence of the external forces. To generate the external force and the vehicle working environment, bucket filling operation in the pile is considered as the test maneuver with different ground condition. It also helped to compare the current controller and the proposed controller with respect to the graphs of the important signals.

The newly proposed controller is still in the preliminary stage it needs to be tuned better and test its operation capabilities in different and complex conditions. In this thesis the simulations are performed with certain limitations and its area of operation should be increased to match the real-time scenario. In the comparison between current controller and the proposed controller in the thesis work, the proposed controller is better than the current controller in the piling operation maneuver. The proposed controller tries to match requested signal in different operating condition and environmental forces in the operating limiter range. In some sections there are some drawbacks in the proposed controller, to overcome this the controller must be tuned and more signals affecting the operation and performance should be included in the analysis.

5

Conclusion

In this chapter final comments are stated based on the results obtained. Focusing on the problem definition of the baseline controller, the development of proposed controller was done with certain limitations. For the betterment of the low speed controlability, reduction of Wheel speed and idea to obtain the common controller irrespective of the machine the analysis are performed. The comments on the simulation results are stated below.

- Based on the proposed controller results, the wheel slip at the individual wheel are reduced. This leads to obtain more stability and reduction in yaw movement of the vehicle.
- During the process of comparison between baseline and proposed controller, in some cases baseline controller performes better than the proposed one. so, the proposed controller to be tuned more by considering better sensor signals, estimators and observers.
- The whole process of comparison was based on limitations,few test cases and with consideration of only few important signals. In this situation it is difficult to conclude proposed controller is better than baseline controller.
- since the proposed controller is in the initial stage of development and testing, it is important to study, integrate and implement subsystems to see its overall performance.
- The proposed controller can be installed in all variant of machines irrespective of size and type used in different operations.

6

Future Work

The complete master thesis was carried out with limitations to make the process simple and make it easy to understand. The wheel loader undergoes many challenges during its performance in different conditions and its difficult to resemble similar condition in the simulation. So the process was carried out by considering important factors, which plays major role in analysing and comparing with the current controller. To take the work to next level and also make it more complex to resemble the real time scenario, some points can be added to current work in future for better analysis. The points are stated below,

- The two axle model can be upgraded to complete vehicle with four wheels.It increases the complexity of the work, but it will be close to the real time scenario.
- In the four wheel case there will be slip at individual wheel, this will lead to the yaw movement and instability in the vehicle. Yaw and yaw rate should also be included in the controller.
- Addition of articulation angle in the work and analysing its behaviour in the simulations and effects the results.
- Increasing the number of test with different scenarios and complex maneuvers in the simulation.
- During the start of thesis the initial focus was to build a controller in common to all construction equipment, but the work was completed by considering only the wheel loader. In future implementation of proposed controller in different construction equipment can be done.
- Addition of the electrical, hydraulics and many more system in the simulations.
- In the vehicle model implementation of all the resistance forces and trying with different tire models can be considered.
- Different control system can be used in the control strategy for more robust controller and difference can be analysed.
- The pile model is kept simple in the work, it can be upgraded by considering different materials and complex situation in bucket filling operation.

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A

Appendix 1

A.1 Baseline controller

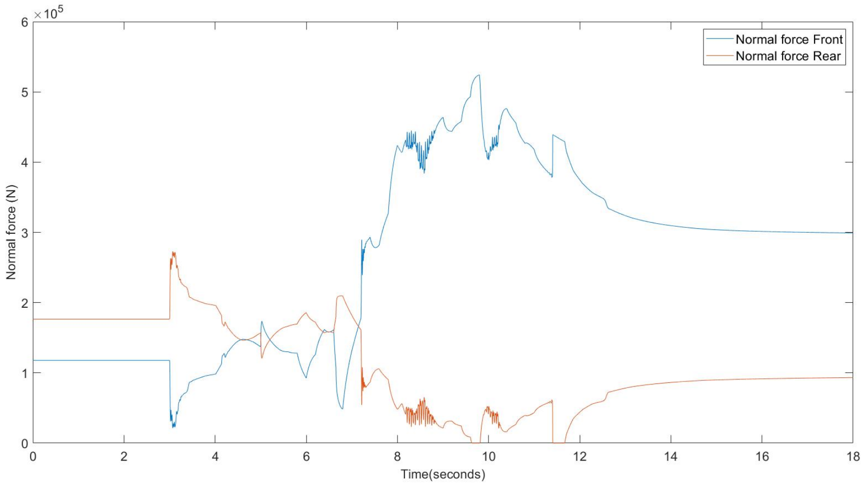

Figure A.1: Normal forces on front and rear wheel

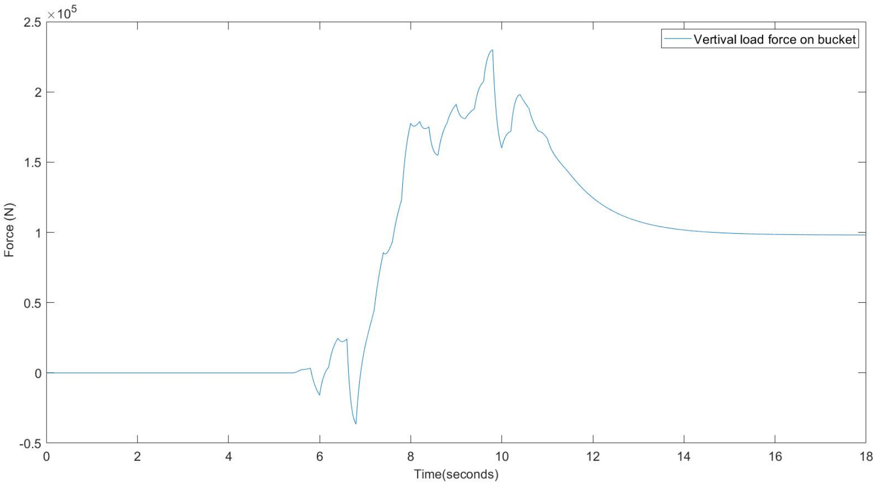

Figure A.2: Vertical load force on bucket

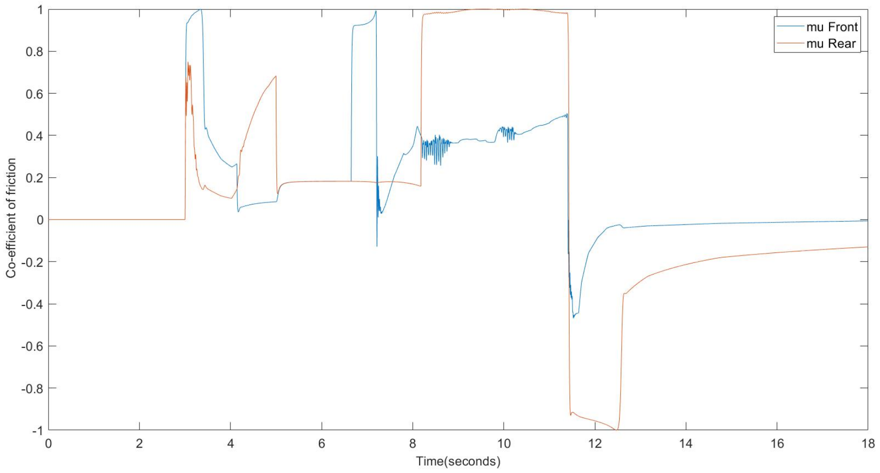

Figure A.3: Co-efficient of friction on front and rear wheel

A.2 Proposed controller in torque mode

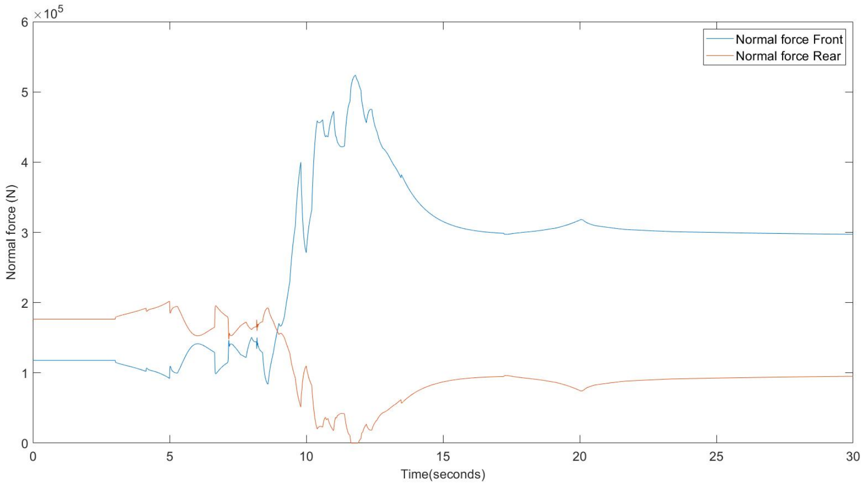

Figure A.4: Normal forces on front and rear wheel

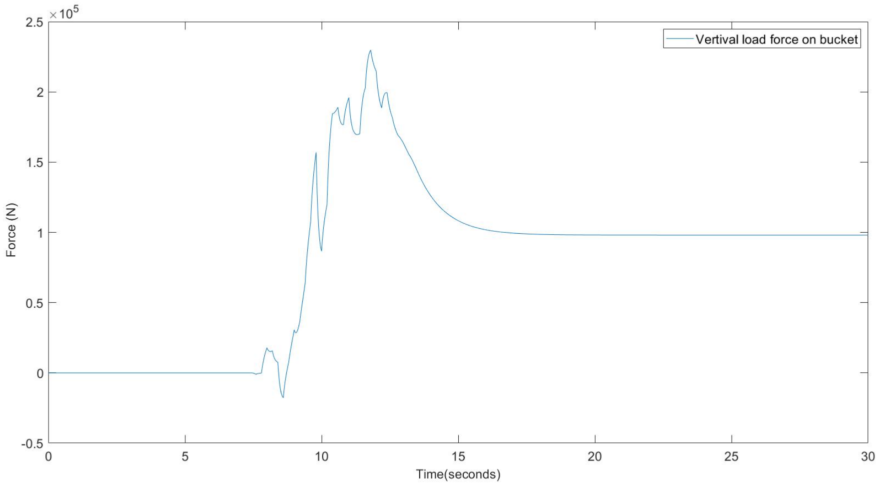

Figure A.5: Vertical load force on bucket

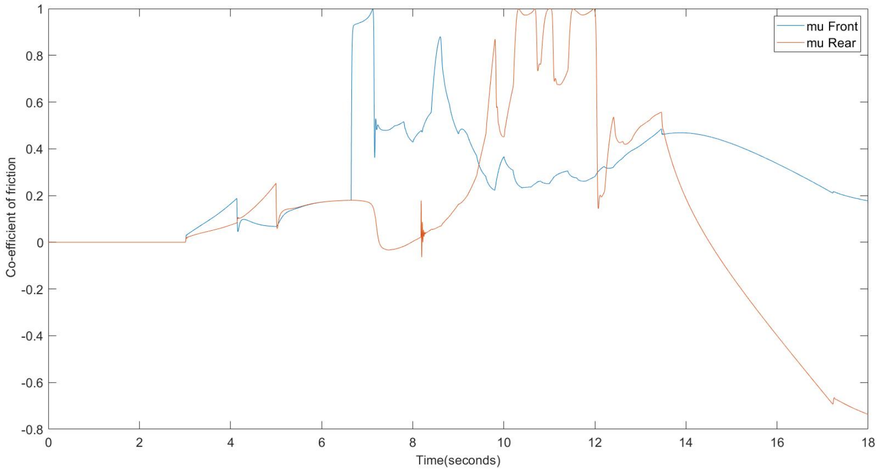

Figure A.6: Co-efficient of friction on front and rear wheel

A.3 Proposed controller in speed mode

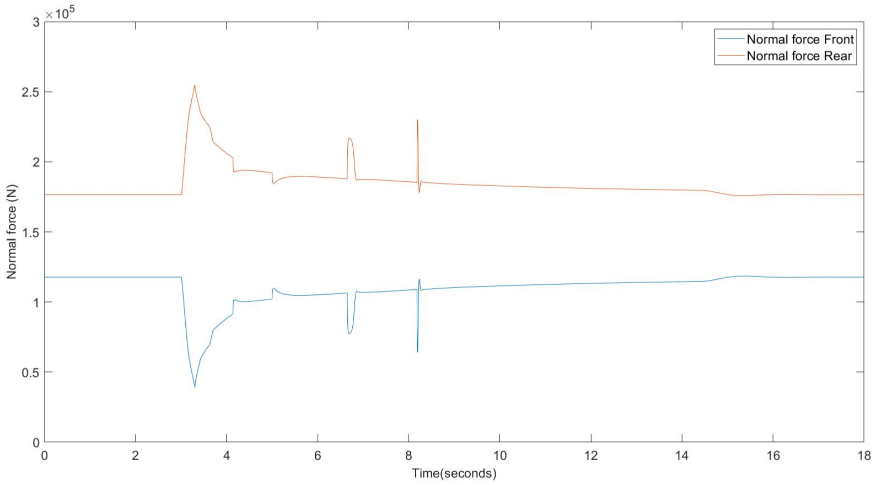

Figure A.7: Normal forces on front and rear wheel

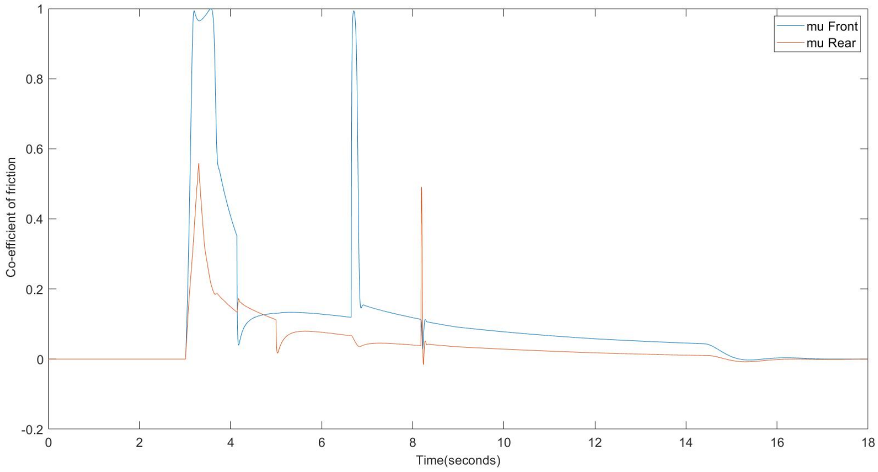

Figure A.8: Co-efficient of friction on front and rear wheel