Automation and synchronization of traction assistance devices to improve traction and steerability of a construction truck

MEET DABHI

KARTHIK RAMANAN VAIDYANATHAN
Abstract

Automotive development has always been need-based and the product of today is an evolution over several decades and a diversified technology application to deliver better products to the end users. Steady increase in the deployment of on-board electronics and software is characterized by the demand and stringent regulations. Today, almost every function on-board a modern vehicle is either monitored or controlled electronically.

One such specific demand for AB Volvo arose out of construction trucks in the US market. Users seldom have/had a view of the operational boundaries of the drivetrain components, resulting in inappropriate use causing damage, poor traction and steering performance. Also, AB Volvo’s stand-alone traction assistance functions were not sufficiently capable to handle the vehicle use conditions. Hence, the goal was set to automate and synchronize the traction assistance devices and software functions to improve the traction and steerability under a variety of road conditions.

The first steps in this thesis involved understanding the drivetrain components from design and operational boundary perspective. The function descriptions of the various traction software functions were reviewed and a development/integration plan drafted. A literature survey was carried out seeking potential improvement in traction from differential locking and also its effects on steerability. A benchmarking exercise was carried out to identify competitor and supplier technologies available for the traction device automation task.

The focus was then shifted to developing and validating the traction controller in a simulation environment. Importance was given to modeling of drivetrain components and refinement of vehicle behavior to study and understand the effects of differential locking and develop a differential lock control strategy. The modeling also included creating different road segments to replicate use environment and simulating vehicle performance in the same, to reduce test time and costs. With well-correlated vehicle performance results, a differential lock control strategy was developed and simulated to observe traction improvement. It was then implemented on an all-wheel drive construction truck using dSPACE Autobox to test, validate and refine the controller.

Periodic test sessions carried out at Hällered proving ground, Sweden were important to refine the control strategy. Feedback from test drivers and inputs from cross-functional teams were essential to develop a robust controller and the same was tested for vehicle suitability and repeatability of results. When comparing with the existing traction software functions, the integrated differential lock and transfer case lock controller showed significantly better performance under most test conditions. Repeatable results proved the reliability of developed controller. The correlation between vehicle test scenarios and simulation environment results indicated the accuracy of software models and control strategy, bi-directionally.

Finally, the new traction assistance device controller function was demonstrated within AB Volvo to showcase the traction improvement and uncompromising steerability.

Keywords: All-wheel drive, Control strategy, Differential lock control, Drivetrain, Modeling, Simulation, Steerability, Traction, Vehicle performance
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We wish to thank our friends and family for their support and encouragement. Once again, we would like to thank all those associated directly or indirectly with this thesis.

We perceive this opportunity as a big milestone in our career development and shall strive to use the gained skills and knowledge in the best possible way.

Thank you.

Karthik Ramanan Vaidyanathan and Meet Dabhi

Gothenburg, Sweden
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Anti-lock braking system</td>
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<tr>
<td>ADAS</td>
<td>Advanced driver assistance system(s)</td>
</tr>
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<td>ADAS-RP</td>
<td>Advanced driver assistance system(s) - Research protocol</td>
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<tr>
<td>ADM</td>
<td>Automatic Drivetrain Management</td>
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<td>ATC</td>
<td>Automatic traction control</td>
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<tr>
<td>AWD</td>
<td>All-wheel drive</td>
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<tr>
<td>CAN</td>
<td>Controller area network</td>
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<td>CCIOM</td>
<td>Central chassis input output module (ECU)</td>
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<td>CIOM</td>
<td>Cab input output module (ECU)</td>
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<tr>
<td>DLC</td>
<td>Differential lock control</td>
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<tr>
<td>EBS</td>
<td>Electronic braking system (ECU)</td>
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<td>ECU</td>
<td>Electronic control unit</td>
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<td>EMS</td>
<td>Engine management system (ECU)</td>
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<td>FDL</td>
<td>Front (inter-wheel) differential lock</td>
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<tr>
<td>GCW</td>
<td>Gross combination weight</td>
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<tr>
<td>GPS</td>
<td>Global positioning system</td>
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<tr>
<td>HMIIOM</td>
<td>Human machine interface input output module (ECU)</td>
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<tr>
<td>IAL</td>
<td>(Rear) Inter-axle differential lock</td>
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<tr>
<td>IMU</td>
<td>Inertial measurement unit</td>
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<tr>
<td>IWL</td>
<td>(Rear) Inter-wheel differential lock</td>
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<tr>
<td>RAS</td>
<td>Rear axle steering (ECU)</td>
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<td>RCIOM</td>
<td>Rear chassis input output module (ECU)</td>
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<tr>
<td>SIL</td>
<td>Software in the loop</td>
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<tr>
<td>TCL</td>
<td>Transfer case lock</td>
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<tr>
<td>TCS</td>
<td>Traction control system</td>
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<td>TCS-BC</td>
<td>Traction control system - Brake control</td>
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<td>TCS-EC</td>
<td>Traction control system - Engine control</td>
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<tr>
<td>TEA2+</td>
<td>Truck electronic architecture version 2.0+</td>
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<td>TECU</td>
<td>Transmission electronic control unit</td>
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<tr>
<td>VMCU</td>
<td>Vehicle master control unit (ECU)</td>
</tr>
<tr>
<td>VTM</td>
<td>Virtual transport model</td>
</tr>
</tbody>
</table>
## Contents

1 Introduction .......................... 1  
1.1 Heavy commercial vehicles .................................. 1  
1.2 Automotive lexicons ..................................... 1  
1.3 Vehicle architecture ..................................... 2  
1.4 Software-controlled traction functions ...................... 3  

2 Scope ......................................... 5  
2.1 Automatic inter-axle differential lock engagement ............. 5  
2.2 Synchronization of traction assistance devices ................. 6  

3 Methodology .................................... 7  

4 Literature survey .................................. 8  
4.1 Automatic Drivetrain Management .................................. 8  
4.2 Reverse Method for Differential Engagement and Disengagement ........................................ 8  
4.3 Differential Braking ....................................... 9  
4.4 Software-controlled traction functions .......................... 9  
4.4.1 Traction Control System .................................. 9  
4.4.2 Differential Lock Control ................................ 10  

5 Simulation environment .................................. 12  
5.1 Virtual Transport Model simulation environment ................. 12  
5.2 Organization in simulation environment .......................... 12  
5.3 Differential modeling ...................................... 14  
5.3.1 Concept of automotive differential .......................... 14  
5.3.2 Simscape modeling ...................................... 15  
5.4 Transfer case modeling ...................................... 18  
5.4.1 Concept of automotive transfer case ......................... 18  
5.4.2 Simscape modeling ...................................... 20  
5.5 Vehicle motion support devices ................................ 22  
5.6 Road friction variation in vehicle plant model ................. 25  
5.7 Road modeling ........................................ 26  

6 Vehicle behavior study .................................. 32  
6.1 Traction study ......................................... 32  
6.1.1 Scenario 1 ........................................... 32  
6.1.2 Scenario 2 ........................................... 36  
6.2 Steerability study ....................................... 39  
6.2.1 Scenario 1 ........................................... 39  
6.2.2 Scenario 2 ........................................... 41  
6.3 Summary ............................................. 43  

7 Differential Lock Control .................................. 44  
7.1 Torque Limitation ....................................... 45  
7.2 Steering Wheel Angle Estimation .............................. 46  
7.2.1 Method 1 ............................................ 48  
7.2.2 Method 2 ............................................ 49  
7.3 Inter-axle Differential lock .................................. 50  
7.3.1 Engagement .......................................... 50  
7.3.1.1 Pre Conditions ..................................... 50
7.3.2 Disengagement .................................................. 52
    7.3.2.1 Pre Conditions ........................................... 52
    7.3.2.2 Trigger Conditions ...................................... 52
7.4 Transfer Case Lock ............................................. 53
    7.4.1 Engagement .................................................. 53
    7.4.1.1 Pre Conditions ........................................... 54
    7.4.1.2 Trigger Conditions ...................................... 54
    7.4.2 Disengagement .............................................. 55
    7.4.2.1 Pre Conditions ........................................... 55
    7.4.2.2 Trigger Conditions ...................................... 55
7.5 Inter-wheel Differential Lock .................................. 55
    7.5.1 Engagement .................................................. 56
    7.5.1.1 Pre Conditions ........................................... 56
    7.5.1.2 Trigger Conditions ...................................... 56
    7.5.2 Disengagement .............................................. 57
    7.5.2.1 Trigger Conditions ...................................... 57
7.6 Results in VTM .................................................. 58
7.7 Implementation Strategy ........................................ 60

8 Test Results ...................................................... 61
    8.1 Road with Disturbances ...................................... 61
    8.2 Slippery Gravel Road ......................................... 62
    8.3 Hill Climb on Rough Terrain ................................ 63

9 Conclusion .......................................................... 65

10 Future Scope ...................................................... 66
    10.1 Sensor Configurations ....................................... 66
    10.2 Validation for Different Load Conditions .................. 66
    10.3 Pro-Active Engagement ...................................... 66
    10.4 Synchronization with Other Systems ......................... 67
        10.4.1 Traction Control System ............................... 68
        10.4.2 Front Inter-wheel Differential Lock .................... 68

References ............................................................ 69
List of Tables

1  Traction study - scenario 1 - results ............................................. 33
2  Traction study - scenario 2 - results ............................................. 38
3  Steerability study - scenario 1 - results ....................................... 41
4  Steerability study - scenario 2 - results ....................................... 42
5  Vehicle behaviour study - summary .............................................. 43
6  Synchronization Condition ........................................................... 45
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>6 x 6 vehicle architecture</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>6 x 6 vehicle power flow</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>6 x 4 construction truck in a steep wedged slope getting stuck</td>
<td>5</td>
</tr>
<tr>
<td>5.1</td>
<td>A typical control system arrangement</td>
<td>13</td>
</tr>
<tr>
<td>5.2</td>
<td>Arrangement of blocks in VTM</td>
<td>13</td>
</tr>
<tr>
<td>5.3</td>
<td>Automotive differential</td>
<td>14</td>
</tr>
<tr>
<td>5.4</td>
<td>2-speed AWD transfer case</td>
<td>18</td>
</tr>
<tr>
<td>5.5</td>
<td>AB Volvo VT2501TB transfer case</td>
<td>19</td>
</tr>
<tr>
<td>5.6</td>
<td>VTM engine model - speed torque curve</td>
<td>23</td>
</tr>
<tr>
<td>5.7</td>
<td>D13K460 engine model - speed torque curve</td>
<td>23</td>
</tr>
<tr>
<td>5.8</td>
<td>VTM engine model - throttle map</td>
<td>24</td>
</tr>
<tr>
<td>5.9</td>
<td>D13K460 engine model - throttle map</td>
<td>24</td>
</tr>
<tr>
<td>5.10</td>
<td>Road friction input to vehicle plant tyre model</td>
<td>25</td>
</tr>
<tr>
<td>5.11</td>
<td>Road definition</td>
<td>26</td>
</tr>
<tr>
<td>5.12</td>
<td>Road track definition</td>
<td>27</td>
</tr>
<tr>
<td>5.13</td>
<td>Road information to vehicle plant model</td>
<td>28</td>
</tr>
<tr>
<td>5.14</td>
<td>Road information visualisation</td>
<td>29</td>
</tr>
<tr>
<td>5.15</td>
<td>Road information visualization in VTM Virtual Reality environment</td>
<td>30</td>
</tr>
<tr>
<td>5.16</td>
<td>Vehicle simulation information</td>
<td>31</td>
</tr>
<tr>
<td>6.1</td>
<td>Traction study - scenario 1 - road information</td>
<td>33</td>
</tr>
<tr>
<td>6.2</td>
<td>Traction study - scenario 1 - vehicle lateral velocity for differential lock combinations</td>
<td>35</td>
</tr>
<tr>
<td>6.3</td>
<td>Traction study - scenario 1 - steering wheel angle for differential lock combinations</td>
<td>36</td>
</tr>
<tr>
<td>6.4</td>
<td>Traction study - scenario 2 - road information</td>
<td>37</td>
</tr>
<tr>
<td>6.5</td>
<td>Traction study - scenario 2 - steering wheel angle for differential lock combinations</td>
<td>39</td>
</tr>
<tr>
<td>6.6</td>
<td>Steerability study - differential spinout</td>
<td>40</td>
</tr>
<tr>
<td>6.7</td>
<td>Steerability study - differential spinout on rear axle</td>
<td>40</td>
</tr>
<tr>
<td>7.1</td>
<td>The primary strategy for Differential Lock Control</td>
<td>44</td>
</tr>
<tr>
<td>7.2</td>
<td>Torque Limitation Strategy</td>
<td>46</td>
</tr>
<tr>
<td>7.3</td>
<td>Calculation of Curve radius based on wheel speeds</td>
<td>47</td>
</tr>
<tr>
<td>7.4</td>
<td>Validation of Steering wheel angle Estimation</td>
<td>49</td>
</tr>
<tr>
<td>7.5</td>
<td>Automatic Engagement and Disengagement lock strategy for Inter-axle Differential</td>
<td>50</td>
</tr>
<tr>
<td>7.6</td>
<td>Automatic Engagement and Disengagement lock strategy for Transfer Case</td>
<td>53</td>
</tr>
<tr>
<td>7.7</td>
<td>Automatic Engagement and Disengagement lock strategy for Inter-wheel Differential</td>
<td>56</td>
</tr>
<tr>
<td>7.8</td>
<td>Introduction of icy patch on one side of the road</td>
<td>58</td>
</tr>
<tr>
<td>7.9</td>
<td>Activation of Inter-axle Differential lock after detection of icy patch</td>
<td>59</td>
</tr>
<tr>
<td>7.10</td>
<td>Unsteered driven rear axle speed difference</td>
<td>59</td>
</tr>
<tr>
<td>7.11</td>
<td>Unsteered driven rear axle speed difference</td>
<td>60</td>
</tr>
<tr>
<td>8.1</td>
<td>Test data for a Scenario of the vehicle entering a road with Disturbances</td>
<td>61</td>
</tr>
<tr>
<td>8.2</td>
<td>Test data for a Scenario of the vehicle entering a slippery road with Gravel</td>
<td>62</td>
</tr>
<tr>
<td>8.3</td>
<td>Test data for a Scenario of the vehicle starting to climb a hill on a rough terrain</td>
<td>63</td>
</tr>
<tr>
<td>10.1</td>
<td>Advanced Driver Assistance System Research Protocol</td>
<td>67</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Heavy commercial vehicles

The motor vehicle of today is a product of evolution of road vehicles over several decades and a multi-disciplinary approach to application of technology in diversified fields. Such has been the unparalleled growth in this domain that has attracted much investment and spurred a great deal of competition to deliver the best products. Topics such as mobility, efficiency, safety, dynamics and sustainability have taken center stage in this era of development, only to be fueled by ever-stricter regulations to create conscious products, consciously.

Road vehicles are classified based on their purpose - passenger or commercial. The gross combination weight (GCW) is representative of the load capacity of the vehicle and is the basis for classification dictated by the regulation ECE/TRANS/WP.29/78. As per the definition in mentioned regulation, a heavy commercial vehicle is defined as a power-driven vehicle having at least four wheels, used for the carriage of goods with GCW exceeding 12 tonnes. This includes rigid trucks and tractor units, with semi-trailers and full trailers.

In the present context, the discussion has been confined to rigid trucks used for construction purpose.

1.2 Automotive lexicons

Before advancing into detailed discussions on the subject of importance, it is essential to define the key terms related to a commercial vehicle that shall be referred to hereafter.

- A rigid truck or tractor unit is denoted $A \times B$ where $A$ denotes the number of wheels on the unit and $B$, the number of driven or powered wheels. For instance, a $6 \times 4$ vehicle refers to a truck unit with 6 wheels, out of which 4 are powered. This report deals with $6 \times 6$ or all-wheel driven rigid trucks.

- The engine along with the clutch and transmission is together referred to as the Powertrain.

- The auxiliary gearbox or transfer case as it shall be referred hereafter, along with the propeller shaft and differentials is referred to as the Drivetrain.

- Differential is a gear arrangement with one input and two shafts that allows for differential output shaft speeds during cornering.

- A differential lock mechanically locks together the driven shafts of a differential to maintain same rotational speeds.

- Traction is the adhesive friction or force delivered by the wheels to rolling surface.

- Steerability is the quality or degree to which a vehicle can be steered.

- Traction Assistance Device refers to any mechanical component deployed with/without any electronic/software control to improve vehicle traction.
1.3 Vehicle architecture

As mentioned in sections 1.1 and 1.2, the discussion about vehicle architecture shall be confined to $6 \times 6$ rigid trucks used for construction purposes.

Figure 1.1 is representative of the vehicle architecture for a $6 \times 6$ rigid truck. The key components are marked and described below.

- $PP$ refers to the vehicle powertrain.
- $C$ refers to the front axle inter-wheel differential. When it receives a drive input, the differential splits driving torque between front left and right wheels.
- $D$ refers to the transfer case. It receives drive input from the powertrain $PP$ and provides driving torque to the certain drivetrain components dependent on the transfer case construction.
  - In a non-permanent all-wheel drive (AWD) transfer case, only the rear axle is driven under normal conditions. The drive to front axles is disconnected and the operating torque split ratio front-to-rear is 0:100. Under demanding conditions such as a rear wheel slip, a dog clutch engages and provides driving torque to one or more front axles thereby equalizing axle speeds between the front and rear axles.
  - In a permanent AWD transfer case, all axles are driven. The operating torque split ratio front-to-rear is dependent on gear ratio inside the transfer case.
- $F$ refers to the rear inter-axle differential. It receives the drive input from the transfer case and distributes the driving torque to the first and second rear axles, $E$ and $G$. The differential action permits for speed differences between the driven rear axles and also assists during cornering. Locking the inter-axle differential equalizes the axle speed of the first and second rear axles.
- $E$ and $G$ are the inter-wheel differentials on the first and second rear axles. They allow for rotational differences between the left and right wheels on each axle and also transfer the rotational speeds between the wheels during cornering. Locking the inter-wheel differential equalizes the wheel speed between left and right wheels.

The power flow in a $6 \times 6$ truck is shown in figure 1.2.
1.4 Software-controlled traction functions

Disclaimer: The following section describes the software-controlled traction functions proprietary of AB Volvo and Knorr-Bremse AG. Description is limited to the functionality and not the technical details of each function. The terminology defined here shall be used for interpretation in all subsequent instances as these differ from the commonly used terms.

Software-controlled traction functions improve the vehicle traction performance by monitoring input parameters to control one or more vehicle actuators. Inputs such as wheel speeds, IMU signals, driver requests form a part of the computational logic for vehicle state and sensor signals from actuators form a part of the decision logic to control the actuators. A few such functions are described below.

- **Differential Lock Control**: This function assists the driver demanded differential lock engagement and protects them against operating error. The differential lock engagement occurs only when the speed difference between driven wheels is below a programmable threshold value, accomplished through passive or active synchronization.

- **Differential Lock Synchronization**: Developed as a sub-function to assist Differential Lock Control, this function performs active synchronization of the driven wheels or axles when the driver requests to engage the differential lock(s). The synchronization process is carried out by engine maximum torque limitation until the differential lock(s) requested by the driver are engaged.

- **AutoDiff**: This function automatically locks the rear axle inter-wheel differentials when a rear wheel slip condition is detected. The differential lock engagement is accomplished through passive or active synchronization and occurs only when the difference speed of driven wheels is below a programmable threshold value.
Introduction

- **Traction Control System:** The objective of this function is to avoid the spinning of driven wheels, in order to increase traction during acceleration and to gain vehicle lateral stability while driving. This is achieved through Brake Control (TCS-BC) and Engine Control (TCS-EC).
  
  - **Brake Control** is done by individually applying brake pressure to specific wheels so that the driven wheels spin synchronously. The target is to increase the traction when driving on surfaces with different friction coefficient between left and right.
  
  - **Engine Control** regulates the engine torque to avoid spinning wheels, in a way that the slip of the driven axle remains within desired limits. The target is to provide traction on straight forward driving and vehicle stability on curves.

- **Automatic Traction Control:** This function engages the front wheel drive by locking the transfer case, when a rear wheel loses traction on a slippery or soft surface. The dog clutch in the transfer case is engaged while the vehicle is still moving, as a result of which the vehicle can continue to move without losing torque or speed. The drive to front axle remains engaged until the driver no longer requests traction.
2 Scope

2.1 Automatic inter-axle differential lock engagement

The company focus for the work presented here was for the segment trucks operating in construction sites carrying heavy load to and from the destination. The working area for these trucks can vary a huge extent from asphalt road to a heavy muddy terrain with steep slopes. One such truck segment from US market was receiving some complaints with regards to the truck performance in steep slopes. The truck specifications include 3 axle trucks with either 6 × 6 or 6 × 4 drive.

A construction truck with two driven axles encountering a steep wedged slope (a typical scenario at construction sites in US) can be seen in figure 2.1a. Without any differential lock engaged, the first driven axle gets in air and the truck is unable to climb the slope due to open differential properties.

![Figure 2.1: 6 × 4 construction truck in a steep wedged slope getting stuck](image)

(a) Encountering a steep slope  
(b) First driven axle in the air

The ideal solution to this problem is to engage the inter-axle differential lock before encountering the slope. Certain drivers do not take this solution into account and engage the differential lock after getting stuck, which reduces the life span of gears due to aggressive engagement of differential.

As mentioned above in the chapter 1, the inter-axle differential lock is not automatic unlike transfer case and inter-wheel differential lock. The driver has complete control over the differential lock engagement switch of inter-axle differential. It is interesting to note that this problem could be solved by using the traditional Brake and Engine controls (TCS-BC, TCS-EC), but it required extra sensors and actuators for brake actuation on all the driven wheels. In comparison to that, the engagement of inter-axle differential lock can solve this with existing sensors and actuators.

To overcome this problem described in figure 2.1 and as a step towards automatic engagement of differentials, the first scope of this thesis work was to make the inter-axle differential lock engagement automatic.
2.2 Synchronization of traction assistance devices

With a shifting focus towards efficiency and safety, automotive manufacturers have adopted techniques to reduce human factors within their systems of operation. This is due to that end users seldom have a view of the operational boundaries and are more influenced by environmental factors. Automation of individual automotive systems is seen as the first step towards autonomous driving.

With a macro perspective of removing the driver from vehicle control loop, individual powertrain and drivetrain elements have been automated presently. As standalone entities, these systems perform to expectations of the end user. With multiple non-interacting standalone systems on-board, the vehicle control architecture increased in complexity. This was evident with the introduction of Automatic Traction Control and Differential Lock Control functions on separate modules of the truck.

With the planned introduction of the automatic inter-axle differential lock function, it was apparent that the individual functions had to be synchronized for collective efficiency in terms of traction improvement and steerability. This was the prime objective for synchronization of traction assistance devices and the functions - to create a controlled interaction between standalone functions eliminating the driver from the control loop.

The objective was also defined for the safe use of traction assistance devices. Differentials and transfer cases comprise of gears and clutches with a certain mechanical strength and the life cycle of these components is influenced by the peak stresses they undergo when used. This is of particular importance when differential lock is engaged or when the dog clutch in the transfer case is engaged, as subjecting them to higher stresses can reduce their operating cycle tremendously and also cause excessive wear and tear. When drivers request differential locking or front-wheel drive under non-demanding conditions, these components could be damaged.

Hence, it was equally important that the synchronization of traction assistance devices factored mechanical safety aspects of these elements as well. Also by removing the driver from vehicle control loop, the timing, duration and operating cycles of these elements could be optimized, thereby significantly improving traction, steerability and life of components.
3 Methodology

The objectives set for the thesis were:

- Automate inter-axle differential lock engagement
- Synchronize traction assistance devices and functions
  - Automate and synchronize inter-axle differential lock, inter-wheel differential lock and transfer case lock within same function
  - Synchronize automatic inter-axle differential lock with Automatic Traction Control software function

A literature study was carried out to understand the boundaries of required functionality. A review of the software-controlled traction functions and vehicle electronic architecture (TEA2+) was conducted. Vehicle CAN topology was studied to identify the signals required for vehicle state assessment and controller development.

Benchmarking was carried out to identify competitor technologies and for goal-setting against previously developed functions. This aimed at performance measurement of the new function and also to determine the viability for implementation in production trucks.

For simulations, a vehicle plant model was created using predefined blocks with the cab, chassis and vehicle dynamics attributes and it required definition of the drivetrain, powertrain, controller and vehicle environment elements. The elements were developed in MATLAB/Simulink and Simscape software and the vehicle parameters tuned to match with the test vehicle.

The automation of inter-axle differential lock required creating vehicle condition observers and development of control logics based on vehicle state and requirements. For the synchronization objective, vehicle behavior study and plant model refinement was prioritized. The vehicle response to conditions such as slip, steer, combinations of slip and steer and behavior with locked differentials was planned and studied. Based on the vehicle behavior study, control logics for differential lock engagement were developed, studied and refined.

The simulation of vehicle plant model along with the controllers was vital for implementation on a test vehicle and the simulation environment development included creating a road information block to simulate real-life scenarios. The results from simulation were carefully studied and controllers refined.

Yet another target was to carry out a hardware-in-loop simulation of the developed controllers, along with the vehicle ECU’s. This was planned as a confidence approach to implement on test vehicle, however owing to time and resource constraints was later dispensed with.

The implementation of developed functions and validation on a test truck was agreed upon as satisfactory completion of the objectives. dSPACE Autobox was the software-hardware platform for implementation and validation. A cable breakout was done to monitor CAN signals, implement the developed function and vehicle trial runs were carried out to ensure functionality of controllers.

As an advancement, features such as curve compensation, torque reduction and steering wheel angle estimation were planned and added to refine the controllers. Pro-active engagement of differential locks based on road condition data from ADASRP is being discussed for extending the scope of developed function.
4 Literature survey

A literature survey was carried out prior to the development work during the thesis. This focused on existing software-controlled traction functions, exploring similar technologies available and on strategies for differential lock control. Traction functions were reviewed to gage the level of integration possible, strategies were reviewed for differential lock sequencing and differential locking was studied to understand the effects on traction and steerability.

4.1 Automatic Drivetrain Management

The system described in the literature [2] was the closest thing found to the idea of the presented literature in this thesis. The Automatic Drivetrain Management (ADM) described here controls the traction of the vehicle using the engagement of different Differential gear locks. The system described in the literature about ADM [2], however does not consider the Inter-axle Differential lock engagement and disengagement, which was the primary requirement of the company.

The ADM concept describes the idea of checking the engine speed and vehicle air pressure before the process of shifting a gear takes place. The similar concept was used for reducing the engine torque momentarily before locking of Differential with high torques on output side. The automation for Inter-wheel Differential lock in ADM is primarily based on the wheel speed differences, which is one of the factors that is looked upon in the system described in this thesis as well. The ADM concept also inspired the idea of compensation in Wheel Speed differences while cornering and that resulted in development of steering detection and compensation for the same. The idea of pre conditions for engagement of a differential lock was partly based on this literature along with numerous additions to the same to ensure the smooth engagement of a differential lock. the order of the Differential lock in order to gain traction also resembles the order of Differential lock which was calculated based on extensive simulations in Virtual environment in the presented thesis, with addition of Inter-axle Differential lock. However, the Locking of Front Differential is not taken into account in this thesis unlike this literature about ADM.

The effects of various Differential locks are also described in the literature mentioned here about ADM. The Front wheel drive often results in stabilizing of the vehicle, which is what was found out after the simulations as well. The various limits on speed upto which the Differential locks stays engaged are also described in this literature. However, these speeds for exit conditions were tuned after several test sessions in the test vehicle based on driver inputs and data analysis. These issues are addressed later in this thesis in subsequent chapters. Another similar concept is the exit condition of Disengagement of Differential lock while braking indicating the non-requirement of traction. One of the key findings of this literature suggests the benefits of using the All-wheel drive systems only, which supports the outcome of this thesis suggesting, majority of additional traction can be covered by engagement of Transfer Case lock making the vehicle Add-wheel driven.

4.2 Reverse Method for Differential Engagement and Disengagement

The literature [3] describes a strategy of increasing traction which is quite unique and opposite to what was discussed in literature [2] and the one which will be discussed in this thesis later on. The All-wheel Drive systems are always switched on unless the road conditions are good, in which case, there is a periodic shutdown of driven axles to save fuel. The shutdown of driven axles are dependent on vehicle speed and the slippage of wheels which has different thrash-holds. The activation of Traction Control systems to reduce slippage takes place on rough roads. The
primary focus of this literature was on power distribution, unlike the Automation, which was the primary focus based on the targets of this thesis.

4.3 Differential Braking

The literatures [4] and [5] describes the concept of Differential Braking in order to gain traction. In this method, if one of the wheel is slipping, instead of Braking the slipping wheel in Traction Control Systems, the shaft of the differential is braked in order to transfer the power to the wheel with capability to utilize the friction. This is one of the several means to gain traction in a vehicle. The possibility to extend the automation of engagement and disengagement of differential braking including the differential braking can be explored in future.

4.4 Software-controlled traction functions

Disclaimer: The following section contains extracts from software-controlled traction function descriptions, proprietary of AB Volvo and Knorr-Bremse AG. Description is limited to the functionality of each function. The terminology defined here shall be used for interpretation in all subsequent instances as these might differ from the commonly used terms.

4.4.1 Traction Control System

The objective of this function is to avoid the spinning of driven wheels, in order to increase traction during acceleration and to gain vehicle lateral stability while driving. This function is integrated in braking system of the vehicle (EBS) and utilizes common brake system components. It consists of three independent working control loops:

- Brake Control (BC)
- Engine Control (EC)
- Drag Torque Control (DTC)

The purpose of the brake control loop is to synchronize the wheel speeds of the driven axle(s). This is done by individually applying brake pressure to specific wheels. The target is to increase the traction when driving on surfaces with different friction coefficient between left and right. If the driven wheels spin synchronously no pressure is applied to the wheels.

An axle differential always distributes the output equally 50:50. It behaves like a torque balance. When driving off on a split friction surface without enabling TCS, the maximum drive torque achieved on the high friction side of the road is limited by the effective drive torque on the low friction side. An additional increase of the drive torque will only lead to a spinning up of the wheel on the low friction side. When driving with TCS enabled, by braking the spinning wheel, additional torque is applied to the system which increases drive torque on the high friction side.

The purpose of engine control is to control the engine torque in a way that the slip of the drive axle remains within desired limits and to avoid spinning wheels. Generic data received from the EMS includes actual engine torque, actual engine speed, driver demand torque and accelerator pedal position based on which an engine torque limitation request is sent back to the EMS.

The target is to provide traction on straight forward driving and to provide vehicle stability when driving through curves. This is achieved by a method termed as adaptive slip control (ASC).
To achieve best traction the target slip should be in the range of the maximum coefficient of friction. During cornering the target slip has to be reduced in order to increase the side force for better vehicle stability. In ASC, to achieve an optimal vehicle behavior the traction slip is adapted dynamically to the momentary driving situation.

Depending on vehicle speed, curve rate and estimated slope, the target slip is reduced to increase the available side force and to improve vehicle stability. By additionally considering the estimated slope, the function can be tuned in a way that will allow less target slip reduction when driving uphill, hence providing more traction. Depending on the accelerator pedal position, the target slip is increased according a programmed characteristic. Thus, the driver can demand higher wheel slip (and engine torque) by pressing the accelerator pedal above a certain position.

The final composition of the target slip range is based on the curve and accelerator pedal position dependency. The target slip is calculated from the wheel speed difference between steered axle and drive axle. To start engine control, the speed of the drive axle has to exceed above a certain threshold, which is defined as an offset to the target slip.

When the driveline is engaged, the moment of inertia of the driven wheels is increased by the dynamic mass of the engine. This can lead to big wheel slip during down shifting on low friction surface thereby reducing the side force and the lateral stability of the vehicle. The purpose of drag torque control is to control the wheel slip of the driven axles in the described situations. This is done by sending a torque request to EMS to overcome the engine inertia.

### 4.4.2 Differential Lock Control

The task of the function is to assist the driver demanded differential lock engagement and to protect the differential lock(s) and/or transfer gearboxes from operating error by:

- only permitting the differential lock engagement, when the difference speed of driven wheels and/or axles is smaller than a programmable threshold value
- actively support to synchronize the driven wheel speeds before engaging the differential lock(s), if necessary
- **Differential Lock Synchronization** where at differential lock ordering, the driven wheels are synchronized by engine torque intervention to force engagement of the differential lock(s)
- **Automatic Differential Lock Control** (*AutoDiff*), means automatic engagement and disengagement of the differential lock(s) if a spinning drive wheel is detected via TCS-BC
- **Differential Lock Inhibit** where the driver is prevented passively to engage the differential lock(s)

This function controls the inter-wheel differential locking of the rear driving axles. The function observes the actual difference of revolutions by supervising the connected wheels and their wheel speeds. The differential lock(s) can be activated by the driver manually with or without synchronization of drive axle wheel speeds, depending on differential lock variant. The differential lock(s) can also be automatically engaged as a starting aid at low speeds. The feature then automatically engages the differential lock when necessary and disengages it again at a specific speed threshold.
**Differential Lock Synchronization** is a function for active synchronization of the driven wheels when the driver requests to engage the inter-wheel, inter-axle and/or transfer case differential lock(s). The synchronization process can be assisted actively with engine torque reduction until the differential lock(s) are not engaged but are requested by the system/driver. If the differential lock switch is pressed, the function reduces/limits the engine torque until the speed difference of the affected driven wheels is below the parameterized limit for a definite time until the differential lock engages.

The main tasks are:

- mechanical protection of the differential lock and drivetrain components against wrong operation
- assist the driver demanded engagement of differential lock(s)
- time reduction until differential lock engagement

The **Automatic Differential Lock** function performs autonomous engagement and disengagement of differential locks. The function calculates the optimum turn on and turn off time of the differential lock concerning actual vehicle conditions and actively tries to synchronize the driven wheels and with inter-wheel differential lock equipped axles by manipulating engine torque and by individual driven wheel braking.

The **Differential Lock Inhibit** function supports the driver to protect the mounted differential locks. The function calculates the optimum turn on and turn off time of the differential lock(s) in the background regarding actual vehicle environmental conditions and switches ON/OFF the differential lock power stage depending on connected and itself synchronized axles. The ECU is not able to switch on the differential lock without a driver demand, but the driver is not able to switch on the differential lock(s), if the ECU prohibits its engagement.
5 Simulation environment

Essential to the development of differential lock controller was a simulation environment capable of aptly defining vehicle characteristics, usage scenarios and producing accurate simulation results. MATLAB/Simulink was chosen as software for controller development, whilst the simulation could be carried out on programs such as IPG CarMaker, TruckSim and few others.

However, it was decided to develop and simulate on the Virtual Transport Model (VTM) simulation platform developed by AB Volvo. The primary reason for adopting VTM was that it included inbuilt vehicle plant, actuator models along with vehicle parameters, the capabilities to add newer functionality and simulate a variety of scenarios. VTM was a network-driven platform and hence, any major changes to vehicle elements could be reflected via server-host communication thereby improving model updation and validation.

5.1 Virtual Transport Model simulation environment

VTM is a simulation platform developed by AB Volvo for the purpose of analysis, advanced technology development and simulation. It is a complete environment in itself along with a visualization and data logging interface. VTM offers flexibility to add and test newer functionalities and systems, thereby reducing the testing time on a vehicle and saving costs.

VTM is constructed as a modular platform with well-defined parameter and model blocks for most vehicle components and controllers. It also features black box controllers such as Electronic Braking System (EBS), which can be used for software-in-loop simulations. VTM offers the flexibility to define and add newer components and the physical signal based platform also represents system interactions accurately.

VTM is extensively used for vehicle analysis purposes and to create vehicle and actuator controllers whose dynamic effects can be studied in detail within the simulation environment. Also, the virtual environment within VTM allows to load, record, save and compare multiple test scenarios, to arrive at meaningful decisions in regard to vehicle behavior.

Pre-defined blocks within VTM to control vehicle steer and to define road information offer end users the choice to create real life scenarios and to observe vehicle response under such conditions. The vehicle plant models within VTM incorporate most aspects of cabin, chassis and overall vehicle dynamics and are beneficial for analysis and development purposes.

5.2 Organization in simulation environment

As explained in chapter 5.1, VTM comprises of vehicle model and its dynamic characteristics which was the basis of whole project plan. The VTM block hereafter would be named as vehicle plant model.

A typical control system arrangement is shown in figure 5.1. It consists of a plant which can either be a physical system or a model of the physical system (usually mathematical). The actuators control the way this plant model will react. The controller is then developed based on the requirements and plant sensors or feedback which controls the actuators.
Similar approach was chosen for the controller development in virtual environment. As seen from figure 5.2, the common driven input parameters like steering wheel angle, accelerator pedal position and brake pedal position were fed into controller, actuator and plant blocks.

![Figure 5.2: Arrangement of blocks in VTM](image)

Each block were renamed according to the function performed by them.

- **Vehicle Motion Management:** This block controls the actuator inputs i.e. which differential lock to engage and at what time along with any input for torque limitation to powertrain. This is where the major scope of this thesis work lies on. This block uses the driver inputs and plant model output signals or physical sensor signals to compute the actuator inputs. The strategy developed here would be described in subsequent chapters.

- **Motion Support Devices:** This block resembles the actuators part of the common control strategy blocks. Motion support devices in this case relate to various differential models for inter-wheel, inter-axle and transfer case. This block also includes a powertrain model which acts as an actuator to the plant model. Each modeling is described in detail in subsequent chapters.

- **Vehicle Plant model:** The vehicle plant model is the mathematical representation of a $6 \times 6$ construction truck tire model developed by AB Volvo. The input to this model are the driver-controlled parameters and the actuator (differentials and powertrain) outputs. It is a two-track vehicle dynamics model with lateral and longitudinal load transfer taken into account with PAC2002 Magic Formula tire model according to Tyre and Vehicle Dynamics [H.B. Pacejka, *Tire and Vehicle Dynamics*, Butterworth-Heinemann, Elsevier, ISBN 9780750669184, 2006][1].
5.3 Differential modeling

5.3.1 Concept of automotive differential

The automotive differential is a gear arrangement with one input and two output shafts related by the property that angular velocity of the input shaft is a fixed multiple of the average angular velocities of the output shafts. This property of the differential allows for angular velocity transfer between the output shafts during a turn. The increase in speed of one output shaft is balanced by a corresponding decrease in speed of the other output shaft. This is referred to as open differential.

In commercial vehicles, differentials are equipped with an additional feature termed as the differential lock that locks together the two output shafts as a single shaft and thus, rotating with same angular velocities. This is referred to as locked differential.

To understand the differential modeling, it is essential that all elements within the differential are understood. Figure 5.3 shows the internal construction of an automotive differential.

![Figure 5.3: Automotive differential](image)

The power flow within the differential begins with the drive shaft which is coupled to the drive pinion. The drive pinion is mated to the ring gear, the ratio between ring gear and drive pinion known as the final drive ratio. The ring gear is also known as the planet carrier.

The planet carrier contains a gear housing within which are assembled differential side gears and differential pinions. The side gears connect to the axle half shafts, which are directed to the left and right wheels. The differential pinions, also knowns as spider gears are responsible for the transfer of rotation between the differential side gears.

In an open differential, torque entering the differential assembly through the drive shaft, is transmitted by the ring gear to the carrier housing. By virtue of the differential pinion ratio, the carrier housing torque is split equally between the left and right axle shafts, only to be limited by the wheel with lower friction. In the scenario when wheels have equal adhesion, the differential pinions revolve together around the carrier axis, with no rotation about their own axis.

When one of the wheels enters a lower friction region, the torque received by the wheel causes it to rotate at a speed greater than the wheel on higher friction region, thereby causing the differential pinions to simultaneously revolve around the carrier axis and rotate about their own axis. This rotation of the differential pinions causes the torque limitation in an open differential.
When the differential is locked, the axle shafts can no longer rotate at different angular velocities, as the rotation of differential pinions about their own axis is blocked. This results in an unequal torque distribution between the axle shafts, depending upon the available friction at wheels and the normal loads. Hence in an open differential, axle shafts can rotate at different angular velocities at the wheels, but always receive equal torque only to be limited by the wheel on lower friction surface. In a locked differential, axle shafts rotate at same angular velocity and receive unequal torque.

The above concept and in-depth analysis of torque limitation and differential locking was used in the Simscape modeling of the differential. The reason to use a Simscape model, instead of a differential equation based model was to avoid singularity errors during simulation and to accommodate the interaction effects of the differential with other vehicle drivetrain and dynamics elements.

5.3.2 Simscape modeling

A Simscape model of a component is a physical definition model, unlike differential equation based models which use solvers. Hence, all physical quantities need to be conserved within the model unless energy losses are specified. For the case of differential, a torque loss could occur if the differential is open and this is defined through the rotation of spider gears.

Certain rules to defining a Simscape component are listed below:

- Every component parameter shall be defined with their corresponding unit, for instance, torque variable shall be defined with (Nm)
- All parameters or variables relating to a component shall be defined, for instance, a rotating component shall be defined with both torque and angular velocity
- There can exist only one governing equation per parameter or variable
- In cases of multiple operating conditions, each condition shall define exactly the same amount of states or variables
- The number of equations defined shall not exceed the number of variables defined and vice-versa

With the above set of rules, the differential was defined as a torque component with one input torque variable and two output torque variables. The input torque to the differential was provided as a physical signal output from the vehicle powertrain and the output torques were provided to the tire models.

Within the Simscape model, the physical signal input was converted to a torque signal for calculation purpose, using a spring-damper system. The deformation rate or damper velocity was provided as the speed difference between the input shaft and average of output shaft speeds. The deformation \( \kappa \) was provided as the integration of damper velocity.

\[
\frac{d\kappa}{dt} = \left( N_{dr} \times \frac{(\omega_{s1} + \omega_{s2})}{2} \right) - \omega_d
\]  

(1)
Here,

\[ N_{dr} = \text{Final drive ratio} \]
\[ \omega_{s1} = \text{Angular velocity of output shaft 1, in rad/s} \]
\[ \omega_{s2} = \text{Angular velocity of output shaft 2, in rad/s} \]
\[ \omega_d = \text{Angular velocity of input shaft, in rad/s} \]

\[ \tau_d = -(k \times \kappa) - (c \times \frac{d\kappa}{dt}) \tag{2} \]

\[ \tau_c = -(\tau_d \times N_{dr} \times \eta) + \left( \frac{J_i}{N_{dr}} \times \frac{d\omega_d}{dt} \right) \tag{3} \]

Equation 2 shows the conversion of physical input signal to a pure torque signal within Simscape. Equation 3 calculates the carrier torque from the drive torque.

Here,

\[ k = \text{Stiffness of drive gear, in N*m/rad} \]
\[ c = \text{Damping of drive gear, in N*m*s/rad} \]
\[ \eta = \text{Overall efficiency of differential} \]
\[ J_i = \text{Internal inertia of differential components} \]
\[ \frac{d\omega_d}{dt} = \text{Input shaft acceleration} \]

The open differential equations are written as follows:

\[ \omega_{sp} = |\omega_{s2} - \omega_{s1}| \tag{4} \]

\[ \kappa_{s1s2} = 0 \tag{5} \]

\[ \tau_{sp} = (0.99 \times \tau_c \times \frac{\omega_{sp}}{\omega_d}) - (N_{tr} \times J_{ii} \times \frac{d\omega_{sp}}{dt}) \tag{6} \]

\[ \tau_{s1} = \frac{\tau_c - \tau_{sp}}{2} \tag{7} \]

\[ \tau_{s2} = \frac{\tau_c + \tau_{sp}}{2} \tag{8} \]

Here,

\[ \omega_{sp} = \text{Angular velocity of the differential pinion, in rad/s} \]
\[ \tau_{sp} = \text{Torque utilized in differential pinion rotation about its own axis, in N*m} \]
\[ N_{tr} = \text{Number of tires on the entire axle} \]
\[ J_{ii} = \text{Mass moment of inertia of each tire} \]
Equation 4 describes the differential pinion rotation. The angular velocity of the differential pinion about its own axis is the difference of speeds between the output shafts. Equation 5 implies that the angular deformation between the two output shafts need not be considered as these can rotate independently.

Equation 6 calculates the torque lost due to differential pinion rotation about its own axis. The product of tire inertia, number of tires on axle and the angular acceleration of pinion is subtracted from this calculated quantity so as to allow the wheel to spin up, in case it enters a lower friction region. Equations 7 and 8 are the output torques to the axle shafts and are equal in magnitude.

In a locked differential, the unequal torque distribution between the output shafts is brought about calculating the difference in speeds between output shafts before locking and trying to equalize the difference to zero, using a spring-damper system. The equations for a locked differential are as follows:

\[ \omega_{sp} = \omega_{s2} - \omega_{s1} \]  
\[ \kappa_{s1s2} = \int \omega_{sp} \]  
\[ \tau_{sp} = (c g \times \omega_{sp}) + (k g \times \kappa_{s1s2}) - (N_{tr} \times J_{ii} \times \frac{d\omega_{sp}}{dt}) \]  
\[ \tau_{s1} = \frac{\tau_{c}}{2} + \tau_{sp} \]  
\[ \tau_{s2} = \frac{\tau_{c}}{2} - \tau_{sp} \]

Here,

\( kg \) = Stiffness at the output of differential pinion, in N*m/rad  
\( cg \) = Damping at the output of differential pinion, in N*m*s/rad

Equation 9 describes the differential pinion rotation. Notice that the difference is not an absolute value, but a real magnitude. This speed difference is integrated to provide as a deformation between the output shafts, as in equation 10. The differential pinion torque, to hold it without rotation about its own axis is calculated similar to equation 2 as a pure torque signal. This is the equalization torque from the differential pinion, and this is added to one output shaft, as in equation 12 and is subtracted from the other output shaft, as in equation 13. This creates an unequal torque distribution and the differential pinion torque achieves this by equalizing the speeds of output shafts.

The stiffness and damping constant of the drive gear and differential pinion are tunable parameters. These need to be adjusted depending upon the vehicle response during simulations. Also, the tire inertia and number of tires is specified within the Simscape model because the vehicle plant model is not a physical signal based model, instead it is equation and actuator based. Hence, inertias cannot be sensed by the differential model. For a rear axle inter-wheel differential, \( N_{tr} = 4 \) and for a front axle inter-wheel differential, \( N_{tr} = 2 \). For inter-axle differentials, \( N_{tr} = 0 \).
5.4 Transfer case modeling

5.4.1 Concept of automotive transfer case

The transfer case forms a part of the driveline of all-wheel drive and multiple powered axle vehicles. It is also referred to as transfer box, auxiliary gearbox or center differential. The main functions of the transfer case are:

- Transfer the power received from the transmission to front and rear axles by means of drive shafts
- Synchronize the rotational difference between front and rear wheels
- Allow for differential action between front drive shaft and rear drive shaft, thereby preventing torsional windup due to different final drive ratios

The power transmission to the front and rear drive axles can be done with gears, hydraulics or a chain drive. The transfer case operation in RWD (rear wheel drive) mode or AWD is controlled by the driver and a shifter unit accomplishes switching between the different drive modes. In transfer cases where the drive mode is not selectable, the transfer case is permanently locked into AWD mode.

To understand the transfer case modeling, it is essential that all elements within the transfer case are understood. Figure 5.4 shows the internal construction of an AWD transfer case. This is a manually shifted 2-speed transfer case and can be operated in four positions.

![Figure 5.4: 2-speed AWD transfer case](image)

- When the shift lever is in neutral position, the power through input shaft drives the main drive gear. The main drive gear drives the idler shaft and the high-speed gear that is free running on the front output shaft. However, no power will be delivered to the front or rear shafts because the shaft sliding gears are slid out of contact with the shaft drive gears.
- When the shift lever is in 4-wheel low gear position, the front and rear output sliding gears are slid into engagement with the idler shaft low speed gear. Power flows from the main drive gear through the idler shaft gear into the front and rear output sliding gears which drive the respective output shafts, with speed reduction.
When the shift lever is in 2-wheel high gear position, the front and rear output sliding gears are pulled out of engagement with the idler shaft low speed gear. This corresponds to the neutral position of the shift lever. The rear output sliding gear is pulled further to engage with the clutch teeth of the main drive gear which locks the input main shaft directly to the rear wheel output shaft. The power flows from the transmission directly to the rear axle without any reduction in speed. The front output sliding gear remains in neutral position and is free running on the front output shaft. Hence, no power is directed to the front axle.

When the shift lever is in 4-wheel high position, the front and rear output sliding gears are pulled into engagement with the clutch teeth of the high speed gear and main drive gear respectively. This locks the front output shaft to the high speed gear and rear output shaft directly to the input shaft from the transmission. The power flows from the transmission through main drive gear in two directions. The front axle receives drive power through the idler shaft drive gear, high-speed gear and front output shaft. The rear axle receives direct drive from the rear output shaft coupled to the input shaft by the main drive gear.

The transfer case developed by AB Volvo is a single-stage design, operated through a driver-controlled switch or by software function ATC. The simple and reliable design gives small transmission losses resulting in higher vehicle productivity. Figure 5.5 shows the construction of VT2501TB transfer case.

![AB Volvo VT2501TB transfer case](image)

The transfer case consists of a primary drive shaft that continually drives the rear drive output shaft 1. On the primary drive shaft, the gear 2 via an idler gear 3, drives the gear 4, which via a dog clutch 6 is connected to the front drive output shaft 5.

In transfer case open mode, the driving force is transmitted directly to the rear axles via the rear drive output shaft 1. The front drive gear 4 is driven simultaneously, since it is continually engaged with the primary drive shaft via the idler gear 3. However, no drive is transmitted to the front drive output shaft 5 as the dog clutch 6 is not engaged to transmit the drive from front drive gear to front drive output shaft. This corresponds to the 2-wheel high position of the AWD transfer case.
In transfer case locked mode, the gear 4 engages with the front drive output shaft 5 with the aid of the pneumatic dog clutch 6 and the driving force is transmitted to the front drive axle(s) via the front propeller shaft. This corresponds to the 4-wheel high position of the AWD transfer case.

The front wheel drive is engaged/disengaged from the driver’s seat with the switch 7 on the dashboard or via the ATC software function. On transfer case lock request, the solenoid valve 8 is operated which supplies compressed air to the control cylinder 9 in the transfer case. When the cylinder is pressurized, the front wheel drive is engaged. The drive is disengaged through spring-return action of the control cylinder when de-pressurized.

5.4.2 Simscape modeling

The Simscape modeling of the transfer case was carried out using a similar methodology as that of the differential. The transfer case was defined as a "torque" component with one input torque variable and two output torque variables. The input torque to the transfer case was provided as a physical signal output from the vehicle powertrain and the output torques were provided to the front and rear drive shafts for the axles.

Within the Simscape model, the physical signal input was converted to a torque signal for calculation purpose, using a spring-damper system. The deformation rate or damper velocity was provided as the speed difference between the input shaft and average of output shaft speeds. The deformation $\kappa$ was provided as the integration of damper velocity.

$$\frac{d\kappa}{dt} = \frac{(\omega_f + \omega_r)}{2} - \omega_{ls}$$  \hspace{1cm} (14)

Here,

$\omega_f$ = Angular velocity of the front drive output shaft, in rad/s
$\omega_r$ = Angular velocity of the rear drive output shaft, in rad/s
$\omega_{ls}$ = Angular velocity of the input shaft, in rad/s

$$\tau_{ls} = -(k \times \kappa) - (c \times \frac{d\kappa}{dt})$$ \hspace{1cm} (15)

$$\tau_d = -(\tau_{ls} \times \eta) + (J_i \times \frac{d\omega_{ls}}{dt})$$ \hspace{1cm} (16)

Equation 15 shows the conversion of physical input signal to a pure torque signal within Simscape. Equation 16 calculates the drive torque.

Here,

$k$ = Stiffness of drive shaft, in N*m/rad
$c$ = Damping of drive shaft, in N*m*s/rad
$\eta$ = Overall efficiency of transfer case
$J_i$ = Internal inertia of transfer case components
$\frac{d\omega_{ls}}{dt}$ = Input shaft acceleration
The transfer case open mode equations are as follows:

\[ \kappa_{fr} = 0 \]  
\[ \tau_f = 0 \]  
\[ \tau_r = \tau_d \]  

Equation 17 implies that the angular deformation between the two output shafts need not be considered as these can rotate independently. Equations 18 and 19 are the output torques to the axle shafts and indicate that the entire drive torque \( \tau_d \) is transmitted to the rear axle(s) and no drive torque is provided to the front axle(s).

In a locked differential, the unequal torque distribution between the output shafts is brought about calculating the difference in speeds between output shafts before locking and trying to equalize the difference to zero, using a spring-damper system. The equations for a locked differential are as follows:

\[ \omega_{diff} = \omega_f - \omega_r \]  
\[ \kappa_{fr} = \int \omega_{diff} \]  
\[ \tau_{diff} = (cg \times \omega_{diff}) + (kg \times \kappa_{fr}) \]  
\[ \tau_f = \frac{\tau_d}{2} - \tau_{diff} \]  
\[ \tau_r = \frac{\tau_d}{2} + \tau_{diff} \]  

Here,

\( kg \) = Stiffness of the dog clutch, in \( N \cdot m/\text{rad} \)  
\( cg \) = Damping of the dog clutch, in \( N \cdot m \cdot s/\text{rad} \)

Equation 20 describes the rotational difference between output shafts. This speed difference is integrated to provide a deformation between the output shafts, as in equation 21. The dog clutch torque in equation 22, is the equalization torque and is added to one output shaft, as in equation 24 and is subtracted from the other output shaft, as in equation 23. This creates an unequal torque distribution and thus achieves output shaft speed equalization in transfer case locked mode.
5.5 Vehicle motion support devices

As discussed in section 5.2, the vehicle motion support devices block in VTM comprises of the motion actuators - powertrain and drivetrain elements of the vehicle. Essential to the development of controllers was to aptly define the vehicle characteristics and the environment within VTM. This meant accurate modeling of characteristics and response of the systems and refining the same for system interactions. The modeling of drivetrain elements such as the differentials and transfer case has been discussed in sections 5.3 and 5.4. This section deals with the refinement of powertrain and drivetrain components.

- The powertrain model in VTM comprised of a gearbox and a simple engine model. The gearbox model included a delay timer to match the clutch operation and featured a shift strategy to skip gears when vehicle reached higher speeds. The control input to the gearbox was a vehicle speed reference which would control the gear selection. However, this was found to be not appropriate and hence, the control input to the gearbox was changed to the gearbox output shaft speed multiplied by a gain value to match with engine speed. The gain value was dependent on the gear number and the gear ratio.

- The clutch activity in the gearbox model was included as a delay timer and the clutch operation time found to be more than on the actual vehicle. Hence, the clutch engagement and disengagement time was reduced to 0.3s from 0.7s through iterations for vehicle response. This reduction in clutch operation time improved the acceleration and gradeability performance of the vehicle in simulation environment and matched closely with the actual vehicle.

- The engine model available in VTM was constructed based on lookup tables of engine data. The engine torque output was based on the accelerator pedal position. The engine speed dependent friction torque was modeled as a lookup table. A torque limitation feature was available to limit maximum engine torque under fault conditions. An engine retarder was also modeled to simulate engine brake torque based on a lookup table.

- The identified deficiencies in the engine model were that the torque-speed curve did not match with the engine model on test vehicle. The low-end torque was approximately 20% lesser in VTM than that of the vehicle. Also, the flat torque region was available at a higher engine speed in VTM than that of the test vehicle, thereby affecting the acceleration performance during simulation. Hence, the engine lookup tables for speed torque curve and engine brake curve were modified to match with a Volvo D13K460 13-liter 460HP engine, that was available on the vehicle. The original and modified speed torque curves of the engine model in VTM can be seen in figures 5.6 and 5.7.

- The throttle pedal response curve also required fine adjustment as the dead pedal region and the throttle pedal gain needed to be more realistic to simulate driver behavior. Hence, a non-linear throttle pedal gain was incorporated and dead limit region changed. The original and modified throttle pedal response curves for the engine model in VTM can be seen in figures 5.8 and 5.9.

- For the drivetrain refinement, the front and rear drive shafts, intermediate drive shafts and wheel drive shafts were added. The stiffness and damping coefficients for the gears inside were tuned for transmitting requested torque and to damp fluctuations in torque output due to gear changes or differential locking. This response was particularly important as incorrect damping resulted in torque fluctuations or response lag.
Figure 5.6: VTM engine model - speed torque curve

Figure 5.7: D13K460 engine model - speed torque curve
Figure 5.8: VTM engine model - throttle map

Figure 5.9: D13K460 engine model - throttle map
5.6 Road friction variation in vehicle plant model

Modeling the vehicle environment within VTM was equally as important as modeling vehicle plant model, vehicle actuators or vehicle behavior controllers. This was for the vehicle behavior study, development of a controller, verification of controller and also to create a simulation environment with good correlation to real driving conditions. The main environment input required to describe the vehicle interaction and response was the road friction.

Figure 5.10 below shows the road friction definition within VTM.

The road friction input $LMUX$ shown in figure 5.10a was provided as a constant input to the Pacejka Tire Model shown in figure 5.10b. The road friction could be varied individually for the left and right wheels of the truck and this definition was applicable to individual axles. Hence, a realistic road friction variation could be simulated by a time-series friction input replacing $LMUX$ parameter for each wheel.

This simple method could be extended to a realistic case by defining progressive friction variation instead of the same time instant. This is because individual axles progressively move through a particular friction zone in a road and not at the same time instant. However, the simulation time dependence for friction variation meant more difficulty in simulating actual road conditions. Also, it was more relevant to include the road friction definition within the vehicle environment definition instead of vehicle tire definition. Hence, the time-dependent friction variation model was replaced by a road profile and friction model block, as discussed in section 5.7.
5.7 Road modeling

As discussed in section 5.6, it was important to model the vehicle environment accurately within VTM as well to provide a demarcation between vehicle parameters and environment parameters. Hence, a road segment builder program was developed and linked to the vehicle plant model and VTM for providing environment information and simulation purposes.

The objective was to define a road segment comprising of different zones with the following information:

- Segment / Zone length
- Road gradient (positive and negative)
- Road camber (positive and negative)
- Road friction (uniform, split and patch)
- Road curvature (left and right)
- Road disturbances (random excitation, sine excitation, pothole excitation)

The information would then be passed on to individual axles and thus the axle motion responses would be progressive instead of occurring at the same time instant. This was essential to recreate test conditions from vehicle use environments and observe vehicle behavior.

The road segment was defined comprising of five different zones, as shown in figure 5.11. Zones numbered 1 through 3 could be defined individually and the zones were defined as continuous to observe vehicle response during transition from a particular set of conditions to another. Two dead zones, one at the beginning and one at the end of the road segment were defined as uniform friction zones with a \( \mu = 1 \) and without disturbance, curvature, gradient or camber to initialize vehicle parameters and to obtain normal vehicle response at start and end of simulations.

![Figure 5.11: Road definition](image)

The road segment definition within VTM was defined as comprising of 20 individual tracks arranged as shown in figure 5.12. Each track was defined individually with all zone parameters. Also, road track boundaries, road track width and road track centerline were defined individually to create a realistic road profile.
The following variable descriptions were used to define each zone in the road segment created:

- **inputposition** described the track y-position of the 20 road tracks.
- **inputextraposition** contained the definition for road width.
- **inputdistance** defined the length of each zone. This was incremented in steps of 1 m have optimal resolution for road definition. Higher resolution in distance meant unrealistic road conditions and lower resolution in distance meant poor road definition.
- **inputcurvature** defined the curvature of the road segment. This user input was read into the program as curve radius and the curvature calculated as given in equation 25. The curvature was limited to a minimum of 100 m as vehicle overturning behavior was observed with lesser curve radii. Also, the angle of curvature was set at 45°.
  \[
  \text{curvature} = \left(\frac{45}{r_c}\right) \ast \left(\frac{\pi}{180}\right) \tag{25}
  \]
  where, \( r_c \) is the radius of curvature, in m.
- **inputcamber** defined the road camber as the ratio of road elevation to road width.
  \[
  \text{camber} = \frac{dz}{dy} \tag{26}
  \]
- **inputslope** defined the local gradient as the ratio of road elevation to road length.
  \[
  \text{slope} = \frac{dz}{dx} \tag{27}
  \]
- **inputprofile** defined the overall gradient of the road. This was defined as degree gradient.
• *inputfriction* defined the road friction within each zone. The minimum value was set to 0.001 correlating to zero contact with road. Also, with the road builder program GUI, the friction variation within each zone could be configured to uniform friction zone, split friction zone or friction variation in patches.

• *inputdisturbance* defined the road disturbance pattern. This was an enable/disable option from the road builder GUI and could be done so for each zone. Invoking the disturbance created a sine excitation by changing the parameters of the local gradient and camber. This was configurable to create other types of road variations as well.

All these defined parameters were created as a look-up table within the MATLAB workspace. An axle position block provided the current axle x-y position during simulation and this information was passed onto the road profile information block and road friction information block to provide the appropriate road inputs to the wheels. This is shown in figure 5.13.

![Figure 5.13: Road information to vehicle plant model](image)

With this detailed definition of the road, it was possible to re-create most vehicle use environments and quite accurately observe vehicle behaviour. The visualizations created for one such road definition using the road builder program is shown in figure 5.14. The equivalent visualization from the truck cabin during simulation in VTM, using the *VTM Virtual Reality* toolbox can be seen in figure 5.15.

The road segment defined in figure 5.14 comprises of the following zone definitions.

• **Dead Zone 1** extends from 0m to 5m. Here, \( \mu = 1 \) and is uniform throughout the zone. The road camber and gradient are zero. No disturbances are defined in this zone.

• **Zone 1** extends from 5m to 55m. Here, \( \mu = 0.3 \) occurs in patches throughout the zone, alternated by \( \mu = 1 \). The road camber and gradient are zero. No disturbances are defined in this zone.

• **Zone 2** extends from 55m to 100m. This is a split friction zone with \( \mu = 1 \) on and Tracks 1 to 10 and \( \mu = 0.6 \) on Tracks 11 to 20. The road camber is zero and gradient is 10°. No disturbances are defined in this zone.

• **Zone 3** extends from 100m to 155m. Here, \( \mu = 1 \) and is uniform throughout the zone. The road camber and local gradient values are set to define the disturbances in this zone.

• **Dead Zone 2** extends from 155m to 165m. Here, \( \mu = 1 \) and is uniform throughout the zone. The road camber and gradient are zero. No disturbances are defined in this zone.
Figure 5.14: Road information visualisation
Figure 5.16 shows the vehicle parameters from the simulation for the road definition in figure 5.14. It is observable from the wheel speed plots that in zone 1, friction patches are not sufficient to cause a wheel spin up. This is because the inertia of the wheels as well as the tire normal loads prevents the spin up condition. In zone 2, the road gradient causes a sharp fall in vehicle speed. When the vehicle enters zone 3, the road disturbances cause lateral movement of the vehicle as indicated in the vehicle lateral velocity plot. The path follower block within the vehicle plant model adjusts the steering wheel position so that the vehicle follows the track centerline, as can be seen from the steering wheel angle block. Also, within the disturbance zone, due to varying tire contact forces with the road, the vehicle acceleration is comparitively reduced as that to a flat road. When the vehicle exits zone 3, the vehicle motion parameters reach a steady state due to the dead zone 2.
Figure 5.16: Vehicle simulation information
6 Vehicle behavior study

In line with the thesis objectives to automate differential locks and synchronize with traction assistance software functions, the improvement in traction through differential locking as well as its effect on steerability had to be studied. This section deals with two different entities on the study of differential locking, listed below:

- Traction improvement through different locking
- Effect of differential locking on steerability

Section 6.1 discusses about the improvement in traction by various differential lock combinations. Two vehicle use scenarios are defined and discussed to identify the most suitable differential lock combination for maximum traction. Section 6.2 highlights the effect of differential locking on steerability. The steering response of the vehicle to open and locked differentials is discussed, with special mention about wheel spinout conditions. Section 6.3 summarizes the results from the traction and steerability study to define the differential lock control strategy that was developed and implemented on the test vehicle. All results are from VTM simulations and have been verified through vehicle testing. The vehicle parameters used for simulation can be found under Appendix.

6.1 Traction study

It is a well-established fact that by means of differential locking, vehicle traction can be obtained or improved when conditions demand. However, a quantification is unavailable on the traction improvement as well to define the limit of obtainable traction through differential locking. This section discusses two most common vehicle use scenarios and studies the traction improvement through differential locking. The methodology adopted for simulation is all simulations are run for the same duration and the last time step vehicle parameters are recorded. Traction change will be reflected by a variation in final vehicle position along x-axis and vehicle longitudinal velocity at last time step.

6.1.1 Scenario 1

The first vehicle use case is a gradient road segment with non-uniform friction. This is an equivalent of gravel slope where the tire contact with the ground is continuous, yet not uniform, thereby resulting in different normal forces being transmitted to the ground. The road segment created can be seen in figure 6.1 and the road definition is as follows:

- Total road segment length: 165m
- Dead zone length: 15m
- Non-uniform friction zone length: 150m
- Lower friction value: 0.4
- Higher friction value: 0.6
- Gradient: 6°

Table 1 shows the vehicle simulation results for the first scenario.
Figure 6.1: Traction study - scenario 1 - road information

Table 1: Traction study - scenario 1 - results

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>X-position (m)</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>181.1</td>
<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>183.1</td>
<td>1.10</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>183.4</td>
<td>1.27</td>
</tr>
<tr>
<td>TCL + IAL</td>
<td>186.1</td>
<td>2.76</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>186.4</td>
<td>2.93</td>
</tr>
<tr>
<td>FDL + TCL + IAL + IWL</td>
<td>186.2</td>
<td>2.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>Longitudinal velocity (kph)</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>30.69</td>
<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>31.49</td>
<td>2.61</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>31.62</td>
<td>3.03</td>
</tr>
<tr>
<td>TCL + IAL</td>
<td>32.4</td>
<td>5.57</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>32.46</td>
<td>5.77</td>
</tr>
<tr>
<td>FDL + TCL + IAL + IWL</td>
<td>32.41</td>
<td>5.60</td>
</tr>
</tbody>
</table>
The results from table 1 can be summarized as follows:

- Without any differential locks, the vehicle is able to traverse the defined road segment. The vehicle x-position and longitudinal velocity at the last time step is our baseline for traction percentage change calculations.

- With the rear inter-axle differential locked (IAL), the vehicle covers 1.1% more in distance. The corresponding increase in longitudinal velocity is 2.6%. This can be attributed to the fact that locking the inter-axle differential equalizes the axle speeds on the first and second rear axles. This results in a torque re-distribution between the driven rear-wheels with reduced torque being applied on the rear axle with lesser traction. Hence, there is a considerable reduction in wheel slip on the rear axles, thereby improving vehicle traction.

- When the rear inter-wheel differentials (IWL) are locked on conjunction with rear inter-axle differential (IAL), all available traction is utilized by the driven rear axles. This translates to a corresponding 1.27% increase in distance covered and 3.03% change in longitudinal velocity. Similar to inter-axle differential locking, the inter-wheel differential locking re-distributes the torque between the left and right wheels on the driven axle in such a manner that the wheel with higher traction receives more driving torque. Hence, wheel slip tendency is further reduced compared to inter-axle differential locking thereby improving vehicle traction.

- Transfer case locking (TCL) engages the front wheel drive in a non-permanent AWD vehicle. This results in speed equalization between front and rear driven axles of the truck. The transfer case is always locked in conjunction with rear inter-axle differential to prevent torque wind up on the driveline. With the transfer case locked alongside the rear inter-axle differential, torque is re-distributed between all driven axles of the truck. Hence, all wheels have a reduced tendency to slip compared to rear differential locking (IAL and IWL) and hence, the vehicle covers 2.76% more in distance compared to the baseline. Also, lesser wheel slip tendency translates to better vehicle traction performance and hence, the vehicle longitudinal velocity attained at last time step is 5.57% higher compared to baseline.

- Transfer case locking in conjunction with rear axle inter-wheel differential locking results is utilization of almost all available traction, with the only possibility of front axle driven wheels slipping. This differential lock combination results in 2.9% increase in distance covered and 5.77% increase in vehicle longitudinal velocity compared to baseline. This is once again attributed to torque re-distribution between driven front axle and individual rear wheels of the truck.

- When all the longitudinal differentials (TCL and IAL) and cross differentials (FDL and IWL) are locked, all available traction is utilized. However, with little or no allowance for driveline windup torque release, the vehicle covers the equivalent distance of the case without front differential locking. The vehicle covers 2.82% more distance and achieves 5.6% higher longitudinal velocity compared to baseline. However, since the automation of front differential lock is outside the scope of this thesis, the differential lock control strategy employing the same is not developed. Also, locking all differentials can result in poor steerability of the vehicle which will be discussed in further sections.

A hint about the impact of differential locking on the steerability of the truck can be obtained by viewing the time history of the vehicle lateral velocity and steering wheel angle for different lock combinations. This is so because the simulation model contains a path follower block that attempts to follow the track centerline. When differentials are locked, torque re-distribution between axles and wheels can produce yaw moments, thereby causing small vehicle lateral velocity variations.
Figure 6.2: Traction study - scenario 1 - vehicle lateral velocity for differential lock combinations

Figure 6.2 shows the vehicle lateral velocity time history for the differential lock combinations. Of prime importance is the trend in lateral velocity variation as well as peak amplitudes of lateral velocity in different cases. Three trends can be generally observed.

- Rear inter-axle differential locking (IAL) and its conjunction with transfer case locking (TCL and IAL) have a similar effect on steerability.

- Rear inter-wheel differential locking (IWL) in all cases reduces the trend variations from inter-axle differential locking. This is because the left and right wheels are not allowed to rotate independently to be steered and hence, reduces lateral velocity variation trend. Hence, inter-wheel differential locking could affect steerability to a greater extent than inter-axle differential locking or transfer case locking.

- Front axle differential locking (FDL) reduces the trend variations in vehicle lateral velocity significantly and even higher than rear inter-wheel differential locking. This is because the steered wheels of the truck cannot rotate independently any longer and hence, are constrained to follow a straight line. Hence, front axle differential locking could have the maximum effect on steerability.
Figure 6.3 shows the vehicle steering wheel angle time history obtained from the path follower block. The trends correlate with the description of differential lock effect on steerability provided from vehicle lateral velocity time history.

6.1.2 Scenario 2

The second vehicle use case is a road segment with disturbances and uniform medium friction. This is a construction zone with a gravel road and high amplitude disturbances such as mounds and potholes. The road segment created can be seen in figure 6.1 and the road definition is as follows:

- Total road segment length: 90m
- Dead zone length: 15m
- Friction zone length: 75m
- Friction value: 0.6
- Disturbance zone length: 75m
Figure 6.4: Traction study - scenario 2 - road information
The results from table 2 show the similar trend in traction improvement for the differential lock combinations. Figure 6.5 shows the vehicle steering wheel angle time history obtained from the path follower block. No significant pattern is observable from the plots and hence, a steerability study with a steering input needs to be carried out to understand the effect of differential locking on steerability.

Based on the test scenarios 1 and 2, the traction study can be summarized as follows:

- Rear inter-axle differential locking (IAL) improves the traction sufficiently above open differential traction. Hence, inter-axle differential locking can be considered as a first step in the differential lock control strategy.

- Transfer case locking (TCL) in conjunction with rear inter-axle differential locking improves traction significantly by re-distributing torque between all driven wheels of the truck. Hence, under demanding conditions that traction is not sufficient with rear inter-axle differential locking alone, the transfer case can be locked to provide drive to front axles thereby reducing wheel slip tendency and improving traction.

- Under most severe conditions that the vehicle continues to slip with rear inter-axle differential and transfer locked, shall the rear inter-wheel differential (IWL) be locked as this will utilize all available adhesion and provide maximum traction.

- The sequence of differential locking shall be derived only after a steerability study is carried out on the differential lock combinations.

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>X-position (m)</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>105</td>
<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>106.1</td>
<td>1.05</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>106.4</td>
<td>1.33</td>
</tr>
<tr>
<td>TCL + IAL</td>
<td>106.4</td>
<td>1.33</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>106.7</td>
<td>1.62</td>
</tr>
<tr>
<td>FDL + TCL + IAL + IWL</td>
<td>106.8</td>
<td>1.71</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>Longitudinal velocity (kph)</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>43.71</td>
<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>44.05</td>
<td>0.78</td>
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<tr>
<td>IAL + IWL</td>
<td>44.14</td>
<td>0.98</td>
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<tr>
<td>TCL + IAL</td>
<td>44.16</td>
<td>1.03</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>44.27</td>
<td>1.28</td>
</tr>
<tr>
<td>FDL + TCL + IAL + IWL</td>
<td>44.34</td>
<td>1.44</td>
</tr>
</tbody>
</table>
6.2 Steerability study

As discussed in section 6.1, it is evident that differential locking affects vehicle steerability. But, equally like traction improvement, it lacks a quantification to define the change in steerability. This section discusses two most common differential lock use scenarios and analyses the vehicle steerability as a consequence of differential locking. The methodology adopted for simulation is all simulations are run for the same duration and the vehicle parameters from a particular time instant are compared. Differential locking effect on steerability will be reflected by a variation in vehicle position along y-axis and vehicle lateral velocity at compared time instant.

6.2.1 Scenario 1

The first scenario is a case of vehicle steer and wheel spinout. Wheel spinout is a condition when a particular driven wheel loses contact with the ground and thereby spins up. This results in spinout of the corresponding inter-wheel differential and in case of multiple driven axles, the inter-axle differential as well. One such spinout condition is illustrated in figure 6.6.
In this case, the right side wheels on the first driven rear axle have lost tire contact with ground causing an inter-axle differential spinout and the corresponding inter-wheel differential spinout. If the transfer case is locked, differential spinout can occur on driven front axles as well.

![Figure 6.6: Steerability study - differential spinout](image)

The analysis carried out in this scenario was to study the effect of locking the rear inter-axle differential and rear inter-wheel differentials in case of wheel spinout. A constant left steer input was provided to the vehicle model. Wheel spinout condition was created by defining a split friction road element. The condition is illustrated in figure 6.7. Differential locking effect was studied when left wheels 'A' and 'C' are on low friction surface and when right wheels 'B' and 'D' are on low friction surface causing rear inter-axle and rear inter-wheel differential spinout.

![Figure 6.7: Steerability study - differential spinout on rear axle](image)

The results of the analysis are summarized in table 3. The simulation results can be interpreted as follows:

- Firstly, on a split friction surface with low friction value ($\mu < 0.3$), there is usually a complete loss of traction. Hence, the vehicle can cover very low distance and extrapolation of the results cannot be done. Therefore, this cannot be used as a reference to study the effect of differential locking.

- Secondly, the objective is to study the effect of differential lock combinations on steerability on a relative basis. Hence, we use the simulation results for locked rear inter-axle differential as our reference.
In the first test case, we compare the result of vehicle y-position and lateral velocity for a locked inter-axle differential when wheel spinout occurs on rear left and right wheels. With a locked rear inter-axle differential, when the vehicle is provided a left steer input and wheel spinout occurs on left rear wheels, the vehicle reaches a final y-position of 31.65m at the end of simulation. The corresponding lateral velocity at the time instant is 1.94kph. However, when spinout occurs on right rear wheels, locking the rear inter-axle differential results in a torque re-distribution between the rear driven axles providing more torque to the axle with greater normal load. This results in a greater forward driving torque and lesser steering forces. This results in a lower final y-position at 29.5m. The counter-effect on steering is indicated by a lower lateral velocity of 1.9kph at the final time step.

When the rear inter-wheel differential is locked in conjunction with the rear inter-axle differential, there is a significant drop in the vehicle y-position. For the test case of left wheel spinout, the change is 11% and for the right wheel spinout case, the change is 18% compared to inter-axle differential locking results for the same test cases. This is attributed to the fact that locking the inter-wheel differentials equalizes the speed between the left and rear wheels thereby restricting them from differential speed essential for cornering. Hence, it is clearly understandable that locking an inter-wheel differential can lead to great loss in steerability.

Table 3: Steerability study - scenario 1 - results

<table>
<thead>
<tr>
<th>Y-position (m)</th>
<th>Lateral velocity (kph)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Differential lock</strong></td>
<td><strong>Wheel spinout</strong></td>
</tr>
<tr>
<td></td>
<td>Left</td>
</tr>
<tr>
<td>IAL</td>
<td>31.65</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>27.92</td>
</tr>
</tbody>
</table>

6.2.2 Scenario 2

Scenario 2 is the study of differential locking on vehicle steerability on surfaces with maximal traction. In this section, we compare and analyse the effect of differential lock combinations with a constant left steer input, by comparing vehicle final x-position and y-position. Then, the differential lock combinations are rated for best steerability and compared along with the traction improvement to derive a differential lock control strategy. Table 4 shows the results of the simulation for differential locking on dry asphalt surface with constant left steer input.

The simulation results can be interpreted as follows:

- Locking the rear inter-axle differential (IAL) affects the vehicle steerability to a certain extent. However, when the percentage change is translated to a steering effort, this can be considered as minimal effect.

- When the rear inter-wheel differentials (IWL) are locked in conjunction with the rear inter-axle differential, it has a pronounced effect on the steering. The 9% improvement in traction is offset by a 16% reduction in steerability and hence, it is conclusive that inter-wheel locking differential can affect steering greatly. The cause of this effect is that the individual wheels on left and right side of the vehicle are not allowed to rotate independently.
• When the transfer case (TCL) is locked in conjunction with the inter-axle differential, improved traction and minimal effect on steering is observed. This is because of torque re-distribution between the front and rear driven wheels of the truck and hence, this is an ideal lock combination for good traction and steerability.

• Locking the rear inter-wheel differential combined with the rear inter-axle differential and transfer case results in poor steering. But, a considerable increase in traction is achieved making this a combination ideal for maximum traction requirement.

• Locking the front inter-wheel differential (FDL) provides little or no scope for vehicle steering as it locks all driven wheels of the truck. Hence, this is the poorest combination in regards to steerability, though it provides maximum traction.

• All effects in traction distance increase (x-position) can be viewed as a steerability decrease (y-position).

With this study, we have now quantified the effect of differential locking on steerability. The necessary parameters to summarize and derive a differential lock control strategy are now available and are discussed in the following section.

Table 4: Steerability study - scenario 2 - results

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>X-position (m)</th>
<th>Percentage change</th>
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</thead>
<tbody>
<tr>
<td>No differential locks</td>
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<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>48.68</td>
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<td>IAL + IWL</td>
<td>50.21</td>
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<td>TCL + IAL</td>
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<td>TCL + IAL + IWL</td>
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<td>9.71</td>
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<td>FDL + TCL + IAL + IWL</td>
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<thead>
<tr>
<th>Differential lock combination</th>
<th>Y-position (m)</th>
<th>Percentage change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>25.71</td>
<td>-</td>
</tr>
<tr>
<td>IAL</td>
<td>23.94</td>
<td>-6.88</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>21.57</td>
<td>-16.10</td>
</tr>
<tr>
<td>TCL + IAL</td>
<td>24.11</td>
<td>-6.22</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>21.66</td>
<td>-15.75</td>
</tr>
<tr>
<td>FDL + TCL + IAL + IWL</td>
<td>19.45</td>
<td>-24.35</td>
</tr>
</tbody>
</table>
6.3 Summary

The results of traction and steerability study are subjectively summarized in table 5 for the differential lock combinations considered for automation and synchronization.

Table 5: Vehicle behaviour study - summary

<table>
<thead>
<tr>
<th>Differential lock combination</th>
<th>Traction rating</th>
<th>Steerability rating</th>
<th>Overall rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>No differential locks</td>
<td>-</td>
<td>-</td>
<td>Reference</td>
</tr>
<tr>
<td>IAL</td>
<td>Sufficient</td>
<td>Good</td>
<td>Better traction</td>
</tr>
<tr>
<td>IAL + IWL</td>
<td>Good</td>
<td>Poor</td>
<td>Not recommended</td>
</tr>
<tr>
<td>TCL + IAL</td>
<td>Very good</td>
<td>Good</td>
<td>Good traction</td>
</tr>
<tr>
<td>TCL + IAL + IWL</td>
<td>Excellent</td>
<td>Poor</td>
<td>Only when needed</td>
</tr>
</tbody>
</table>

Based on the ratings, the differential lock control strategy was derived:

- Locking the rear inter-axle differential (IAL) provides sufficient traction increase and also has no significant undesirable effects on the vehicle steering. Hence, this can considered as the first level of automation and engagement.

- Locking the rear inter-wheel differential (IWL) along with the rear inter-axle differential provides for maximum traction, however, affects steerability greatly. Hence, this lock combination is not the recommended choice for transition after inter-axle differential locking.

- Locking the transfer case (TCL) subsequent or in conjunction with rear inter-axle differential provides a very good increase in traction with less effect on steerability. Hence, this is a good choice for transition from inter-axle differential locking.

- Locking the rear inter-wheel differential (IWL) after the transfer case lock utilizes maximum available adhesion and this combination can be used only under demanding conditions. Hence, this can be the final level of differential lock control strategy.

The differential lock control, developed based on the vehicle behaviour study is discussed in subsequent chapters.
7 Differential Lock Control

The contents of Chapter 6 explained the effects of various Differential locks on the vehicle behavior. In account to the Company requirements for Inter-axle Differential lock automation as the primary task as well as the harmless nature of Inter-axle Differential lock alongside providing more traction, it was an obvious choice to automate this Differential lock. The complete strategy of Differential lock control for all the three Differential locks in the scope of this thesis was developed subsequent to Inter-axle Differential lock control.

For creating the control strategy for automatic engagement of Differential locks, two approaches were taken into account.

- **Reactive**: Engagement of the Differential locks by detecting the conditions when it is required
- **Pro-Active**: Engagement of the Differential locks by predicting the conditions when it would be required

The company’s focus was to get this work implemented on a test vehicle as soon as possible. The first strategy of Reactive engagement was thus focused on, in the beginning of the project. The Pro-active strategy and its usefulness is described in Chapter 10.

The primary strategy to engage Differential locks is described in figure 7.1 below, the reason of which was described in Chapter 6.

![Figure 7.1: The primary strategy for Differential Lock Control](image)

All the Differential locks are in Disengaged state initially. If the Lock conditions for engagement of Inter-axle conditions (described later in this section) are met, it is engaged. In the same manner, if the conditions get worse and Lock conditions for Transfer case are met, the engagement
of Transfer Case lock takes place. On the other side, during Inter-axle Differential lock was engaged, if the road condition has improved or the vehicle does not need extra traction anymore, which means activation of Disengagement condition (described later in this section) for Inter-axle Differential lock, the lock gets disengaged. The similar logic can be followed for transition from Transfer Case lock to Inter-wheel lock and back as it is clearly seen in figure 7.1

### 7.1 Torque Limitation

The Differential is a mechanical component which makes the two output shaft’s speeds equal by meshing the gears when it is locked. The functionality and the purpose is same as a normal Differential as explained in Chapter 5. This component can be severely damaged if the shafts whose speed it is trying to equalize are rotating at a vast speed difference. Thus, a strategy to keep the output shafts’ speed difference under a Synchronizing limit was necessary taking mechanical properties of the component into account.

Before engagement of any differential lock, the difference in speed for output shafts for the differentials should not be too high. Certain measures needed to be taken to keep the difference under the synchronizing limit. It was possible to achieve this by two different measures:

- **Brake Control**: Also known as Differential braking in which, the axle with higher speed is braked either by Differential output or by braking the individual wheels. This concept is currently used by “Traction Control System” as described in chapter 1. This function is developed by Knorr-Bremse AG and a very limited access to this function block was available. As the development of Individual or axle brake control was out of scope of this project, this idea was dropped.

- **Engine Control**: Whenever required, the Engine Torque is limited in order to get the desired torque limit to achieve the functionality. This functionality is also used in “Traction Control System”. It was decided to adopt this strategy to get speed difference under Synchronizing limit due to non-complex control nature of engine torque.

The Synchronizing condition for different Differential locks are varied depending on the type of Differential lock engagement taking place. As seen in Table 6, the activating condition for Torque Limitation for Inter-axle Differential lock is dependent on Rear Drive shaft connecting the Gearbox and Drive axles. On the other side, for Transfer Case and Inter-wheel Differential lock, the Torque limitation activation is carried out whenever any of the Differential lock request is requested. This is done for safety reasons for Mechanical gear engagements.

<table>
<thead>
<tr>
<th>Differential Lock</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-axle</td>
<td>Rear Drive Shaft speed</td>
</tr>
<tr>
<td>Transfer Case</td>
<td>Lock Request</td>
</tr>
<tr>
<td>Inter-wheel</td>
<td>Lock Request</td>
</tr>
</tbody>
</table>

Table 6: Synchronizing Condition

The Torque Limitation logic, with Synchronizing limits taken into account can be seen in Figure 7.2.
Whenever any Differential lock is requested, the Synchronizing condition depending upon the type of Differential lock is checked as shown in Table 6. It is also made sure that the Differential lock is disengaged before putting any limitation on Engine Torque. When these conditions are met, the maximum torque output is limited to a user defined value reduced_torque_lim. This torque limitation is activated for AT LEAST user defined time \( tr_{min\_timer} \). After this minimum timer, the Differential lock request is sent. This torque limitation is kept activated until EITHER the Differential lock has been engaged OR the Torque limitation is active for more than a user defined time \( tr_{max\_timer} \). After this stage, the Torque limitation request is stopped.

The Torque limitation is very critical in deciding the Life of the component due to Mechanical damage and high induced stresses during engagement of Differential lock at high speeds.

### 7.2 Steering Wheel Angle Estimation

The Differential lock strategy to put up on vehicles was targeted for almost all major segments of the company trucks in Europe. A vast number of truck variants are not equipped with certain Sensors and Actuators. The basic functionality included wheel speed sensors on rear first driven axle and front axle. This meant unavailability of speed sensors on last axle and the Steering wheel angle sensor. The compensation for the last axle speed sensors is given subsequently while describing the Control strategy. Moreover, the estimation for Steering wheel angle had to be
done in order to get that value, which is important for curve velocity compensation due to speed difference between outer and inner wheel while turning. So, the Estimation for Steering wheel angle was carried out based on the available wheel speeds.

Before Estimation of Steering wheel angle, it is important to estimate the Radius of Curvature in which the vehicle is cornering. That was the base for carrying out the estimation of Steering wheel angle Estimation.

A two top view of a two axle vehicle in a left curve is shown below in figure 7.3. Similar calculation is also valid for a three and four axle vehicle. The description of the figure is given below the figure.

![Figure 7.3: Calculation of Curve radius based on wheel speeds](image)

Here,

\[ \delta \] = Wheel angle while taking a turn  
\[ FL \] = Front left wheel  
\[ FR \] = Front right wheel  
\[ R1L \] = Rear left wheel  
\[ R1R \] = Rear right wheel  
\[ R_i \] = Curve radius of inner wheel  
\[ R_o \] = Curve radius of outer wheel  
\[ l \] = Wheelbase of the vehicle  
\[ b \] = Trackwidth of the vehicle  
\[ R \] = Turning radius of the vehicle  
\[ O \] = Instantaneous center of Steering geometry  
\[ V_{rl} \] = Speed of the rear left wheel  
\[ V_{rr} \] = Speed of the rear right wheel

Based on the geometry, it can be said that:
\[
\frac{V_{rr}}{V_{rl}} = \frac{R_o}{R_i} = \frac{R + \frac{b}{2}}{R - \frac{b}{2}} \quad (28)
\]

Solving for R,

\[
R = \frac{\frac{b}{2}(1 + \frac{V_{rr}}{V_{rl}})}{\left(\frac{V_{rr}}{V_{rl}} - 1\right)} \quad (29)
\]

For a specific test vehicle, considering the minimum turn radius it can overcome is \(R_{\text{min}}\), the ratio of outer to inner wheel can be simplified and written as:

\[
\frac{V_{rr}}{V_{rl}} = 1 + \frac{2R_{\text{min}}}{b} \left(\frac{V_{rr}}{V_{rl}} - 1\right) \quad (30)
\]

Theoretically, the ratio of outer to inner wheel speeds cannot exceed \(V_{\text{curve}}\), unless any of the wheel has lost traction, in which case, the controller will give lock engagement request to Differential. So, whenever a curve is detected and the ratio of outer to inner wheel speed is less than \(V_{\text{curve}}\), the limit of speed difference is increased because in account of curve compensation.

The steering wheel angle estimation was carried out by two ways described below:

### 7.2.1 Method 1

Referring to figure 7.3 with the same notations and similar calculations, the turning radius using the wheel speeds was calculated as:

\[
R = \frac{\frac{b}{2}(1 + \frac{V_{rr}}{V_{rl}})}{\left(\frac{V_{rr}}{V_{rl}} - 1\right)} \quad (31)
\]

Where,

\(R = \) Curve radius of the vehicle
\(b = \) Trackwidth of the vehicle
\(V_{rr} = \) Speed of the outer rear wheel while turning
\(V_{rl} = \) Speed of the inner rear wheel while turning

The wheel angle \(\delta\) can thus be given by:

\[
\sin \delta = \frac{L}{R} \quad (32)
\]

Where,

\(\delta = \) Wheel angle while turning
\(L = \) Wheelbase of the vehicle

The wheel angle can then be converted to Steering wheel angle with the help of Steering ratio depending the vehicle.
7.2.2 Method 2

According to same figure 7.3 and similar definition of terms, not taking the curve radius into account and Wheel speed difference instead of wheel speed ratios to avoid undefined conditions, the wheel angle was given by:

\[
\sin \delta = \frac{L}{b} \frac{V_{rr} - V_{rl}}{V_{rl}}
\]

The wheel angle can again be converted to Steering wheel angle with the help of steering ratio.

Both the above methods were then computed in Virtual tool for the comparison with the simulations. This was done for validation of Steering wheel estimation logic and to compare the accuracy of Steering wheel Estimation of each method. The figure 7.4 below shows the comparison of two methods of Estimation based on wheel speeds with the actual steering wheel angle from VTM.

![Figure 7.4: Validation of Steering wheel angle Estimation](image)

As it can be seen in figure 7.4, the nature of all the three curves is much similar. The high oscillations at around 6th and 8th second corresponds to gear shifts and their adverse effect on the vehicle model and thus, wheel speeds. Such type of oscillations are not expected in reality due to smooth gear shifts in account of sophisticated Gearbox. Thus, the steering wheel angle Estimation was validated and used for vehicles wherein the Steering wheel angle sensor was not present.

The Controller for Automatic Differential lock control was developed in the virtual environment, VTM. It was included in the “Vehicle Motion Management” block as described in chapter 5.2.
The input to this controller block is the various sensor signals from “Vehicle Plant Model” like Wheel Speeds, Vehicle Speeds, Rear axle Drive shaft speed and Driver parameters like Throttle percentage, Brake percentage and Steering Wheel position. Based on the logic described below, the controller output is the signal for Actuators i.e. Differential and Powertrain to Engage/Disengage and Torque Limitation respectively.

7.3 Inter-axle Differential lock

The conditions for automatic Engagement and Disengagement of Inter-axle Differential lock can be seen in figure 7.5. It contains a set of Pre conditions and Trigger conditions for Engagement as well as Disengagement. Pre conditions are the pre-requisites for triggering blocks which decides the engagement and Disengagement.

Figure 7.5: Automatic Engagement and Disengagement lock strategy for Inter-axle Differential

7.3.1 Engagement

Engagement request of Inter-axle Differential lock is sent when Pre-conditions AND Trigger conditions, BOTH are satisfied. Those conditions are described below:

7.3.1.1 Pre Conditions

These are several conditions which needs to be satisfied as pre-requisites in order to be active engagement of Inter-axle Differential lock. These conditions are described here:

- **Vehicle Speed**
  
  The vehicle Speed should be less than a used defined vehicle speed \( engagement_{lim}_{IA} \). The Differential lock should only be engaged at low vehicle speeds. The chances of vehicle getting stuck requiring extra traction is only at lower speeds. If the vehicle speed is high and a low friction region is encountered, the vehicle is bound to move due to its inertia, not requiring extra traction. So, when the Vehicle speed is high, the engagement of Inter-axle Differential lock is not required/expected.
• **Throttle**
  The throttle pedal should be depressed i.e. The driver should demand the traction. If the driver is not requesting any torque from engine, the driver probably does not need traction. There is no need for Differential lock activation if driver is not requesting propulsion. So, the throttle pedal should be depressed.

• **Brake**
  The brake pedal should not be depressed. If the driver has pressed the brake pedal, it signifies the interest in stopping the vehicle, which in turn shows that the traction is not needed. Another reason for this condition is Preventive Safety reasons with respect to Brake functionalities. For example, the Differential lock should be disengaged when there is ABS(Anti-lock Braking System) intervention, for better controllability of wheel speeds. So, as long as the brake pedal is not depressed, the Automatic engagement of Differential lock can take place.

### 7.3.1.2 Trigger Conditions

The trigger condition for Automatic Inter-axle Differential lock Engagement is activated when EITHER of the following conditions are activated:

• **Axle Speed Difference**
  The axle speed is calculated by the average of the wheel speeds on that particular axle. The axle speed difference here corresponds to the difference in axle speeds of first Rear driven axle speed and the front Axle speed. When this Axle speed difference exceeds a user defined value `axle_speed_diff_condition_IA`, this condition gets activated. A difference in axle speeds above this value corresponds to the loss of traction on one or several wheels, in which case, the Inter-axle Differential plays a role and can help in improvement of traction. Also, this user defined value is increased twice its value when the Steering Wheel angle is above a user defined value `steer_axle_IA`. In case of the vehicles with sensors on the last driven axle, this axle speed difference definition can be changed to the axle Speed difference between two rear driven axles between whom, the Inter-axle Differential exists.

• **Wheel Speed**
  Similar to the previous condition, this is a triggering condition, but it takes wheel speed differences into account. If the difference between any of the wheels on the first rear axle and the front axle speed exceeds a user defined value `wheel_speed_condition_IA`, the condition is activated. This condition depicts the excessive spinning of any of the wheels and loss of traction. This condition signifies the need of traction as well. Also, this user defined value is increased twice its value when the Steering Wheel angle is above a user defined value `steer_wheel_IA`. When the sensors for wheel speeds on the last axles are available, they can also be included in this condition, making it 4 wheel conditions instead of 2 wheel conditions in the current program.

• **Rear Drive Shaft Speed**
  This condition was included to compensate for the absence of wheel speed sensors on the last axle. The knowledge of slipping of any of the wheels on that axle could not be gained due to this absence. If the difference between the propeller shaft (output of Transmission) speed in km/h and the front axle speed in km/h exceeds a certain user defined value `prop_shaft_condition_IA`, the condition for engagement is activated. This condition suggests any wheel spin without enough traction. If the propeller shaft speed is increasing, but the vehicle is not moving (front wheel speeds), it clearly implies the loss of traction in any of the wheels. In that condition, there is requirement of engagement of Inter-axle lock.
Differential lock to enhance the traction properties. Similar speed difference was also used for Torque limitation and defining the synchronization limit as described above. Moreover, this propeller shaft speed difference would increase inherently at higher vehicle speeds. In order to correct that problem, the prop_shaft_condition_IA limit was increased at higher speeds. Also, the information about Road Inclination was useful in modifying this limit. If the vehicle detects a steep slope, the limit for prop_shaft_condition_IA was reduced. This was done for more sensitive engagement of Differential lock in higher gradient slopes. Whenever the driver encounters a slope, there is an obvious need of more traction. Hence, this condition was also included.

If the Pre condition AND Trigger condition is satisfied, the algorithm will send the Inter-axle Differential lock Engagement request, which will enter the “Torque Limitation” block described above.

7.3.2 Disengagement

The Disengagement of the Inter-axle Differential lock at appropriate time is equally important as the engagement procedure. After the Engagement of the Differential lock with or without Torque Limitation, the disengagement takes place when the following Pre conditions AND Trigger Conditions are activated.

7.3.2.1 Pre Conditions

The following Pre condition should be fulfilled and checked in order to send a Disengagement request to the Inter-axle Differential lock.

- **Transfer Case Status**

  The Transfer Case should not be locked in order to Disengage the Inter-axle Differential lock. The engagement of Transfer Case lock without engagement of Inter-axle Lock is not preferred by majority of the drivers. That can also cause mechanical wear and tear of the dog clutch in Transfer Case. The engagement of Inter-axle Differential lock while the Transfer Case engagement takes place helps the traction as well as Mechanical fatigue is less. The similar logic can be followed to justify this condition of Inactive Transfer Case lock for Disengagement of Inter-axle Differential lock.

7.3.2.2 Trigger Conditions

The Trigger conditions for Disengagement of Inter-axle Differential lock is activated when EITHER of the following conditions are achieved.

- **Vehicle Speed**

  When the Vehicle speed has reached a user defined value disengagement_lim_IA, the Differential lock is disengaged. At such a high speed, the vehicle does not need more traction. Even for small patches of low friction appears, the vehicle should be able to overcome those with the help of a large momentum (Mass \times Velocity) similar to the engagement condition reasoning. This value is kept at a bit higher side compared to engagement_lim_IA in account of extra Hysteresis to avoid unnecessary switching between Activation and Deactivation.

- **Brake**

  Similar to other functions in the company, like “Traction Control System” and “Automatic Traction Control”, the condition of brake signal for disengagement remains as it is. With
Differential Lock Control

concerns of safety, when the driver brakes, there is absolutely no need of traction. In this case, the Differential lock should be disengaged.

- **Lock Engagement time**
  When the Inter-axle Differential lock is engaged state for maximum of a certain user defined time $autoIA_{disengagement \_ time}$ AND the Throttle pedal is not depressed, the Differential lock is disengaged. This condition is to make sure to compensate for any wrong engagement of excessive engagement of Differential lock due to some errors. This timer is kept a bit on higher side due to the harmless nature of Inter-axle Differential lock as described in the beginning of this chapter. The lifting of the foot from throttle pedal suggests the end of traction requirement and thus, it needs to be disengaged. Even after this timer, if the throttle is depressed, the Differential lock will keep in engaged state because of the requirement of traction. The disengagement will only take place after this timer, when the throttle is not depressed.

### 7.4 Transfer Case lock

The Transfer Case lock Engagement and Disengagement strategy can be seen in the figure 7.6. Similar to Inter-axle Differential Lock control, this also has its own Engagement and Disengagement conditions. For Engagement or Disengagement, the Pre conditions AND Trigger conditions needs to be satisfied in order to execute any action.

![Figure 7.6: Automatic Engagement and Disengagement lock strategy for Transfer Case](image)

At the first glance, the logic for Inter-axle Differential lock and Transfer Case lock seems to be the same with a couple of changes in Pre conditions. The major changes from the previous logic includes a set of Pre conditions as well as the Trigger values. The changes are described here.

#### 7.4.1 Engagement

Engagement request of Transfer Case lock is sent when Pre-conditions AND Trigger conditions, BOTH are satisfied. Those conditions are described below:
7.4.1.1 Pre Conditions

The pre conditions for Transfer Case engagement remains the same as Inter-axle Differential Lock apart from two changes:

- **Vehicle Speed**
  
The Speed below which the Engagement can take place was reduced to $engagement_{lim \_TC}$. This reduction of speed limit is due to the fact that the Transfer Case lock is not required at too high speeds.

- **Inter-axle Differential Lock Request**
  
  This condition requires the Inter-axle Differential lock request to be in Active state as a pre condition for possibility of engagement of Transfer Case lock. If the Inter-axle Differential Lock is not requested, it suggests enough available traction. The Inter-axle engagement conditions are at a sensitive side compared to Transfer Case values. So, in the extra traction requirement condition, the Inter-axle Differential request would always be active, after which, this logic can calculate the requirement of Engagement of Transfer Case lock and send the appropriate request.

The rest of the conditions like “Throttle” and “Brakes” remain the same.

7.4.1.2 Trigger Conditions

The trigger conditions are also similar to what described for Automatic Engagement of Inter-axle Differential lock. Although the way they are triggered is a bit different, which is described here. This condition is active when **EITHER** of the following conditions are activated.

- **Axle Speed Difference**
  
The axle speed difference definition is the same as described above for Inter-axle Differential lock. The reason for inclusion of this condition is also same with regards to traction. When this Axle speed difference exceeds a user defined value $axle\_speed\_diff\_condition\_TC$, this condition gets activated. Unlike taking Steering wheel angle as an affecting parameter as Inter-axle Differential lock control, the road inclination was used in case of Transfer Case locking. The reason was to have a sensitive engagement of Front wheel drive on harsh conditions like Hill climb and comparatively, less sensitive Engagement on flat roads. So, this value of $axle\_speed\_diff\_TC$ was reduced when a gradient was detected.

- **Wheel Speed**
  
The wheel speed difference definition is also same as described above for Inter-axle Differential lock. The reason for inclusion of this condition is also same with regards to traction. When any of the wheel speed difference exceeds a user defined value $wheel\_speed\_diff\_condition\_TC$, this condition gets activated. Similar to Axle Speed condition described just above, this value is also dependent on the the road inclination and the value $wheel\_speed\_diff\_condition\_TC$ is reduced when a steep slope is encountered giving a sensitive engagement of Transfer Case lock in conditions where a greater traction is demanded.

- **Rear Drive Shaft Speed**
  
The condition definition is similar to the Inter-axle Differential lock control. But, in case of Transfer Case locking, this can be considered a safety condition. In most of the cases, the two trigger conditions mentioned above are usually enough for activation of Transfer Case lock. This condition makes sure that the Front wheel drive gets engaged in case of excessive speed difference between the propeller shaft and the Front axle. When it exceeds a certain user defined value $prop\_shaft\_condition\_TC$, the condition for engagement is activated.
If the Pre condition AND Trigger condition is satisfied, the algorithm will send the Transfer Case lock Engagement request, which will enter the “Torque Limitation” block described above.

### 7.4.2 Disengagement

The Disengagement of Transfer Case lock is requested when the Pre conditions AND Trigger conditions are met.

#### 7.4.2.1 Pre Conditions

Similar to the logic explained above for Inter-axle Differential lock, the Pre condition involved the Disengaged state of Inter-wheel Differential lock, which is the next and last step for achieving more traction in this dissertation.

#### 7.4.2.2 Trigger Conditions

The Trigger conditions for Transfer Case Differential lock contains the similar conditions as the one for Disengagement of Inter-axle Differential lock in terms of “Accelerator Pedal” and “Brake Pedal”. Although, there are two changes in parameter values.

- **Vehicle Speed**
  
  Vehicle Speed for Disengagement is reduced to \( \text{disengagement\_lim\_TC} \). This is due to the operating conditions of Transfer case lock at lower Vehicle speeds.

- **Lock Engagement Time**
  
  The Differential Lock time is also reduced to \( \text{autoTC\_disengagement\_time} \). The use of Front wheel drive is usually to get out of the harsh condition where it requires extra traction. As explained in Vehicle behavior Study in Chapter 6, Transfer Case has a higher effect on Steerability, compared to Inter-axle Differential lock. So, it is not completely harmless in that sense. So, the timer for Disengagement was kept at a lower side.

### 7.5 Inter-wheel Differential lock

The Inter-wheel lock Engagement and Disengagement strategy can be seen in the figure 7.6. Similar to Inter-axle Differential and Transfer Case Lock control, this also has its own Engagement and Disengagement conditions. For Engagement or Disengagement, the Pre conditions AND Trigger conditions needs to be satisfied in order to execute any action.

Inter-axle Differential Lock is a very special Differential lock in a sense that it is the most effective means of increasing the traction. This is because of its ability to equalize the speeds of all the driven wheels. Although, it comes with a huge side effects of a great loss in Steerability as described in Chapter 6. This is also one of the reason, why this was kept as a last part in the automation process because it is a kind of system, driver usually activated in a very harsh driving conditions.
7.5.1 Engagement

Engagement request of Inter-wheel Differential lock is sent when Pre-conditions AND Trigger conditions, BOTH are satisfied. Those conditions are described below:

7.5.1.1 Pre Conditions

The pre conditions for Transfer Case engagement remains the same as Inter-axle Differential Lock apart from two changes:

- **Vehicle Speed**
  
The Speed below which the Engagement can take place was reduced to $engagement_{lim, IW}$. This reduction of speed limit is due to the fact that the Inter-wheel Differential lock is not required at too high speeds and only in very bad conditions.

- **Transfer Case Lock Request**
  
  This condition requires the Transfer Case lock request to be in Active state as a pre condition for possibility of engagement of Inter-wheel Differential lock. The reasoning is similar to what is described for Transfer Case Pre condition. If the Transfer Case lock is not requested, it suggests enough available traction. The Transfer Case engagement conditions are at a sensitive side compared to Inter-wheel values. So, in the extra traction requirement condition, the Transfer Case request would always be active, after which, this logic can calculate the requirement of Engagement of Inter-wheel Differential lock and send the appropriate request.

The rest of the conditions like “Throttle” and “Brakes” remain the same.

7.5.1.2 Trigger Conditions

The trigger conditions in case of Inter-wheel Differential lock engagement is a bit different from the other two Differentials mentioned above. This trigger condition is active when the condition “Driven Axle L-R Speed” AND EITHER of the other two Trigger conditions are satisfied.
• **Driven Axle L-R Speed**

  If the speed difference between the Left and Right wheel of the First Rear driven axle exceeds a user defined value $driven_{LR,IW}$, this Trigger condition for Engagement of Inter-wheel Differential lock is activated. These wheels are the ones amongst which, the Inter-wheel Differential is located. As described above, both the other Differential locks are the Pre-requisites for this engagement, this condition of Left to Right wheel speed Difference ensures detection of any wheel in slipping condition.

• **Left Front-Rear Speed**

  This and the next Trigger condition ensures the detection of any of the front wheel slip. If the speed difference between the Front and Rear (the one on the first Driven axle) Left wheels exceeds a user defined value $front_{rear_{left},IW}$, this Trigger condition for Engagement of Inter-wheel Differential lock is activated. **EITHER** of this and next condition ensures slipping of any of the wheels, in which case, the excessive traction is required for which, the Inter-wheel Differential lock is essential.

• **Right Front-Rear Speed**

  Similar to what described above for second Trigger condition, if the speed difference between the Front and Rear (the one on the first Driven axle) Right wheels exceeds a user defined value $front_{rear_{left},IW}$, this Trigger condition for Engagement of Inter-wheel Differential lock is activated. Just having the first trigger condition “Driven Axle L-R Speed” makes the Engagement of Inter-wheel Differential lock too sensitive, which is not required in many cases.

If Pre condition **AND** Trigger condition is satisfied, the algorithm will send the Inter-wheel Differential lock Engagement request, which will enter the “Torque Limitation” block described above.

### 7.5.2 Disengagement

As this was the highest level of Differential lock control developed in this work, there was no Pre conditions required for Disengagement of Inter-wheel Differential lock. Thus, if ANY of the following Trigger conditions for Disengagement of Inter-wheel Differential lock gets activated, the request for Disengagement is sent immediately.

#### 7.5.2.1 Trigger Conditions

The Trigger conditions for Inter-wheel Differential lock contains the similar conditions as the one for both the above strategies terms of “Accelerator Pedal” and “Brake Pedal”. Although, there are two changes in parameter values.

• **Vehicle Speed**

  Vehicle Speed for Disengagement is reduced to $disengagement_{lim,IW}$. This is due to the operating conditions of Inter-wheel lock at very low Vehicle speeds.

• **Lock Engagement Time**

  The Differential Lock time is also reduced to $auto_{IW\_disengagement\_time}$. The use of Inter-wheel Differential Lock is usually in very bad conditions where there is absolute chance of one or more wheels in slipping condition and it requires extra traction to get out of those situations. As explained in Vehicle behavior Study in Chapter 6, the Inter-wheel Differential lock has a a very adverse effect on Steerability, compared to the rest of the Differential locks described above. So, it is harmful in that sense. So, it is advised to keep
it engaged for a very less time and Disengage it as soon as it is not required. thus, the timer for Disengagement was kept at even more lower value.

7.6 Results in VTM

After the Modeling of Motion support devices and the controller development, it was important to test the controller in the virtual environment before its implementation on the test vehicle. Certain conditions were created in the virtual environment to check the proper automatic engagement and disengagement of Inter-axle Differential lock which includes:

- One rear driven wheel starting on low friction surface
- One rear driven axle starting on low friction surface
- Three rear driven wheels starting on low friction surface
- Split Mu starting condition with low friction surface on one side
- One rear driven wheel encountering low friction surface while driving
- One rear driven axle encountering low friction surface while driving
- Three rear driven wheels encountering low friction surface while driving
- Split Mu condition with low friction surface on one side encountered while driving

Out of the cases described, the last one, Split Mu condition with low friction surface on one side encountered while driving is described below along with automatic engagement and disengagement of Inter-axle Differential lock. A $6 \times 6$ truck was simulated for 16 seconds on this condition, where an icy patch was introduced on one side of the road (Split Mu) from 5th second to 9th seconds of the simulation. This icy patch activation is shown in the figure 7.8 below.

![Figure 7.8: Introduction of icy patch on one side of the road](image)

The figure 7.9 below shows the time of the simulation during which, the Inter-axle Differential lock was engaged. As it is seen here, the Inter-axle Differential got engaged as soon as the icy patch was detected and the traction requirement was increased. As the driver inputs were constant and the vehicle speed did not reach too high values, the disengagement condition of
time for Inter-axle Differential lock got activated, which was 10 seconds, which is also seen in figure 7.9, with activation occurring between 5th and 15th seconds.

![Interaxle Difflock switch activation w.r.t time](image)

Figure 7.9: Activation of Inter-axle Differential lock after detection of icy patch

After the engagement of the Differential lock, it was also important to observe the speed difference between the axles amongst which, the Inter-wheel Differential exists. The plot for the Unsteered driven axle speed difference is shown in figure 7.10. The huge axle speed difference in the initial part of the simulation (less than 3 seconds) occurs due to numerical errors in the initial part due to division by very small values. If that is neglected, the axle speed difference is close to zero from 3rd second to 5th second. When the icy patch is detected and the Differential lock is engaged, the speed difference between the axles is in oscillatory nature with very small amplitude, which is close to zero, which is the allowable speed difference after the lock engagement. This also proves the correctness of Differential model whose idea is to have the equal speeds on the output shafts of the differential when it is locked.

![Unsteered Axle Speed Difference](image)

Figure 7.10: Unsteered driven rear axle speed difference
An oscillation behavior with a bit more amplitude can be seen at around 9 seconds, which is due to the vehicle leaving the icy patch and starting to move on a road with high friction. This simulation result shows working of Automatic Inter-axle Differential lock engagement and disengagement in the virtual environment VTM. Similar simulations were also performed for other cases mentioned before to verify the robustness of the controller.

### 7.7 Implementation strategy

After development and verification of controller in the virtual environment, the same controller was then implemented on the test truck, following the methodology as described in chapter 3. The idea was to assist and support the driver in harsh driving conditions with the help of a controller deciding the engagement and disengagement of the Differential lock as described in chapter 2.

Similar to many developments in Advanced Engineering field in automobiles, the algorithm for Automatic Inter-axle Differential lock was implemented on the AutoBox platform from dSPACE using their tool ControlDesk. CAN (Controller Area Network) is a vehicle bus standard designed to allow Controllers such as AutoBox and ECUs (Electronic Control Units) to communicate internally as well as with each other.

The AutoBox arrangement within the CAN network is showed in the schematic diagram which is described below in figure 7.11.

![Figure 7.11: Unsteered driven rear axle speed difference](image)

The above figure 7.11 shows a part of CAN topology used in a VOLVO AB truck. The blue boxes represents ECUs and the red and blue lines represent the CAN networks. The AutoBox was placed between VMCU (Vehicle Master Control Unit) and other ECUs. A breakout was created at that place and AutoBox was inserted there as seen from the figure 7.11. The Driver operated activation switch of Inter-axle Differential lock was disconnected and with the help of Controller in AutoBox, a request for Differential lock was send automatically from the AutoBox to respective ECUs and VMCU.
8 Test Results

This section will describe the test data results from a few testing sessions carried out at test track in the test vehicle after the controller implementation was done. To see the individual differential lock behavior as well as synchronized behavior for Differential locks, the tests were carried out in the conditions where slight extra traction was required, conditions where a decent amount of extra traction was required as well as the conditions where a large amount of extra traction was required. These test cases are described below:

8.1 Road with Disturbances

This test case is the condition where the vehicle encounters disturbances on the road. In such conditions, extra traction is not necessarily, the requirement. Although, extra traction would definitely support the driver to drive with more control. The graph below in figure 8.1 shows some of the parameters logged from the test session on the road with Disturbances.

As it is seen in the test data, as soon as the vehicle enters a disturbance patch on road at around 27.5th second, the Rear Drive Shaft speed and Front axle speed difference increases shown by Green line in figure 8.1, which Triggers the Differential lock. The Axle and wheel speed differences do not trigger any conditions for lock activation because of very small values. Because of the Rear Shaft speed difference, which is also the Synchronizing condition for Torque limitation block, a Torque limitation request can be observed in figure 8.1. The Disengagement of Inter-axle Differential lock was triggered by detection of Brake signal, which can also be visible.
at the time of Disengagement. It is also interesting to note that the Transfer Case lock as well as Inter-wheel Differential lock did not get activated in this condition. This was due to decent traction available from road, and Inter-axle lock was activated as a support function to have a smoother ride in Disturbance without any loss of traction.

8.2 Slippery Gravel Road

This test case is the condition in which the vehicle encounters a slippery gravel road. The vehicle typically has a tendency to lose traction due to low friction in certain region. The vehicle probably can surpass this situation without added traction support, but the driver usually do not prefer this because the loss of friction is quite obvious as far as the drive feel is concerned. So, extra traction is definitely required when such condition is encountered. The test data of a test vehicle can be observed in figure 8.2 along with Differential requests made by the controller.

Figure 8.2: Test data for a Scenario of the vehicle entering a slippery road with Gravel

In the described test case, the vehicle enters the gravel road at about 211\textsuperscript{th} second. As it is seen from figure 8.2, the Inter-axle Differential lock gets activated instantly due to increasing axle and wheel speed difference. As the Rear Drive shaft and Front axle speed difference is not too high, which is the Synchronization condition, the Torque Limitation does not take place while Engagement of Inter-axle Differential lock occurs. After driving for about three seconds, the gravel road becomes worse and slippery conditions are encountered. At that instant, the front wheel drive request is carried out by Engagement of Transfer Case lock. As the Torque Limitation occurs every time there is Front wheel drive request, Torque Limitation request can be seen during engagement of Transfer Case lock. After the maximum engagement time for Transfer
Case lock, the throttle position can be seen to be dropping at around 221\textsuperscript{st} second, which satisfies the disengagement condition for Transfer Case lock. About 4 seconds later, the driver requests Brakes, suggesting no requirement of traction anymore, resulting in Disengagement of Inter-axle Differential lock as well at about 225\textsuperscript{th} second.

8.3 Hill Climb on Rough Terrain

In this test case, the vehicle encounters a very steep slope of about 12 Degrees (24 \%) on a Construction track without asphalt. This was the worst possible scenario on the test track and the vehicle absolutely needs the maximum available traction to climb in such harsh conditions. One such scenario can be seen in figure 8.3, where the vehicle successfully climbs the Construction hill.

As soon as the vehicle starts climbing the Construction segment gradient, it detects a rise in Wheel and axle speed difference resulting in activation of Inter-axle Differential lock. A few fraction of seconds later, it still detects a rise in those speed difference resulting in Transfer Case lock request. As it is seen in the figure 8.3, even after Front wheel drive engagement, the Different between wheel speeds of First rear Drive axle keeps on increasing. This scenario suggests any of the wheel spinning (In the air probably due to bumps on track) hence requiring Engagement of Inter-wheel Differential lock. The Torque Limitation activation can be seen for a rather extra time due to requirement of Torque Limitation in Engagement of Transfer Case lock as well as Inter-wheel Differential lock. Soon after the engagement of all three Differential locks, the speed differences seems to be dropping suggesting the vehicle on top of the hill and which can be seen by the Throttle pedal position. The Inter-wheel Differential lock Disengagement request is sent after encountering the Maximum engagement timer and driver taking foot off the throttle at around 5\textsuperscript{th} second. Similarly, Disengagement of Transfer Case lock takes place after the Maximum timer of Differential lock and encountering the drop in Throttle signal at

Figure 8.3: Test data for a Scenario of the vehicle starting to climb a hill on a rough terrain
around 24th second. As soon as the Inter-axle Controller receives the Transfer Case status as “Inactive”, the Disengagement of Inter-axle Differential lock also takes place.
9 Conclusion

Chapters 2 through 8 have discussed the work done during the thesis in entirety and it is now essential to discuss on the quality of work and to summarize. A review of the methodology followed will detail the milestones and key results from this work.

Revisiting the objectives, the main tasks were:

- Automate inter-axle differential lock engagement
- Synchronize traction assistance devices and functions
  - Automate and synchronize inter-axle differential lock, inter-wheel differential lock and transfer case lock within same function
  - Synchronize automatic inter-axle differential lock with Automatic Traction Control software function

The understanding of drivetrain components from design and functional perspective was the key to identification of traction improvement. Traction software function descriptions detailed on the methods of traction improvement through electronic control. Literature survey and benchmarking showed that by means of a refined differential lock control strategy, significant improvement in traction is achievable.

Simscape modeling of components and simulation using vehicle plant models helped understand vehicle behavior and response in traction and steerability due to differential locking. Well-correlated models and simulation environment helped reduce development and test time. The vehicle behavior study was key to development of the differential lock control strategy.

The implementation of differential lock control strategy on a test vehicle was carried out using dSPACE Autobox platform. The test runs of the vehicle with developed control algorithm highlighted improvements to control strategy and also for implementation of the same across different vehicle configurations.

Test results show that the differential locks are engaged only under demanding conditions and the differential lock combination is determined by the severity of the condition. Also when traction is no longer requested by the driver, differential locks are disengaged in a sequential manner, to minimize drivetrain losses, reduce wear and tear of components and to minimize transient response of the differentials.

Two key results from the thesis are:

- Inter-axle differential lock, inter-wheel differential lock and transfer case lock have been automated and integrated within same function and verified through vehicle testing
- Automatic inter-axle differential lock and Automatic Traction Control software function have been synchronized, refined and improved through vehicle testing

The objectives of the thesis work have thus been met, within the stipulated time. Plentiful scope exists for the improvement of the developed functions, as discussed in chapter 10.
10 Future Scope

This thesis was developed as a part of bigger project and bigger vision for the development of autonomous drives. Automatic Engagement of the Differential locks is a major step towards that. Although, a lot of things can be done in new way or improve in the current developed algorithm. A few of them are listed below.

10.1 Sensor Configurations

The whole function development was carried out in the test vehicle without the speed sensors on the last axle and without the Steering wheel angle sensor. This is good in a way that, this strategy can be applicable to almost all the variants of the company vehicles. But, if this Differential lock control strategy can be tested and modified to be applicable on a vehicle with the sensors on last axle wheels for detecting their speed as well as the steering wheel angle sensor, the accuracy of detection can be vastly improved. Many conditions were added in the developed logic to compensate for absence of these sensors. But, if the sensors are present, the engagement of all the differentials can be done in a better and smoother manner. To name a few example,

- The Rear Axle Drive shaft speed difference condition can be replaced by the actual axle speed difference between two driven axles, between whom, the Inter-axle Differential is present.

- The sensitivity of Inter-wheel Differential lock can be decreased and even better Engagement can be achieved with the help of wheel speed sensors on last driven axle.

- The Steering wheel angle Estimation is based on the wheel speed difference and it is not accurate at low speeds. The accurate measurement of Steering wheel angle, and thus, a more sophisticated system can be obtained with the help of Steering wheel angle sensor.

10.2 Validation for Different Load conditions

The development was carried out on a vehicle with constant load. The Normal load variation affect the traction positively. Thus, the normal load dependency can be included in the Differential lock control strategy.

10.3 Pro-Active Engagement

As mentioned before in Chapter for Differential lock Control 7, the Pro-active Engagement of Differential lock can also take place instead of the developed Reactive system. This system can be developed in such a manner that, the Differential lock engagement can take place even before the harsh condition has been detected. This can be done by continuously observing the surroundings and as soon as such conditions are predicted, the Differential lock can be activated. Pro-active Engagement can be combined with developed Reactive algorithm as well.

The basic feasibility of this method was looked upon. There is a Windows software from “HERE” company, which VOLVO AB already has access to. This software is an Advanced Driver Assistance System Research Protocol (ADASRP) developed for Advanced Engineering and Prototype purpose. It is currently used by Powertrain group in the company for Pro-active Engine and Gearbox Control. The user Interface for this software can be visible in figure 10.1.
This software, when connected to Global Positioning System (GPS), can create an electronic Horizon around the vehicle and the Most Probable path according to complex Probability calculations. Currently, it includes the Map data of most of the Europe. Based on the horizon, it can give information such as:

- Curve Warning
- Speed Limit
- Curve Radius
- Slope
- Road Class
- Road Attributes

Based on these informations, specifically Slope and Road attributes, the Differential lock can be automated. If it detects a bad road condition ahead, the controller can engage appropriate Differential lock even before encountering such conditions.

Furthermore, a lot of research work is currently going on for estimation of Road-tire friction. If such information is available in future, it can directly be used in conditions for activation of Differential lock Engagement.

10.4 Synchronization with Other Systems

The developed function can be more advanced if there is interaction with other traction assistance systems as described below:
10.4.1 **Traction Control System**

The Engine and Brake control is traditionally proved to be a very successfully method to increase traction in a vehicle. The Brake control specifically, which can also be Differential Braking can be a very important function which can be looked upon, for synchronization with Differential lock Control.

10.4.2 **Front Inter-wheel Differential Lock**

The Front Inter-wheel Differential lock currently stays in Driver’s control because of very adverse effects on Steerability of the vehicle. This Front Inter-wheel Differential Lock can be a part of Differential lock strategy as an extension in future. This can be seen as one of the last steps towards fully autonomous Traction Assistance Devices.
References


