



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

MSc - Motorsport Engineering

**Investigating Vehicle Dynamic Effects of Passive and
Active Limited Slip Differentials.**

Sean Doyle

University of Wales Trinity Saint David
School of Engineering
2024-2025

Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:



Date: 06/09/2025

Abstract

This project utilises a multibody simulation-based vehicle model to investigate the vehicle dynamic effects active and passive limited slip differentials have on the performance of a front wheel drive vehicle. Physical network modelling and Vi-CarRealTime are utilised alongside Simscape Multibody to assess vehicle locking effects, performance, and to ensure result validity and accuracy. The results of this project determined that FWD vehicles experience high yaw moments and as a result, are very susceptible to torque steering. LSDs such as the torque sensing, eLSD and clutch pack present a greater controllability challenge than alternatives such as the viscous and MRF LSD which respond with a larger delay period. During extreme events (split μ), the LSDs resulted in velocity gains of over three times higher than the open differential but also experiencing up to 6 times the yaw rate. During lateral dynamic events, LSDs are observed to perform best during high driveline torque applications and events where reasonable quantities of load transfer occur (for example cornering – demonstrated by ramp steer investigation).

Contents

Abstract	2
Acknowledgements	5
Table of Figures	6
Table of Graphs.....	9
Table of Tables.....	13
Nomenclature.....	14
Introduction	15
Industrial Relevance	16
Aims and Objectives	16
Project Plan.....	17
1 Literature Review.....	18
1.1 Drivetrain Configurations.....	18
1.2 Vehicle Dynamics Fundamentals.....	20
1.2.1 Physical Network Modelling	21
1.2.2 Multibody Vehicle Modelling.....	22
1.3 Tyre Dynamics and Modelling.....	23
1.4 Differentials.....	25
1.4.1 Open Differential – Traction Problem	26
1.4.2 Limited Slip Differential Fundamentals.....	27
1.4.3 Passive Limited Slip Differentials.....	28
1.4.4 Active Limited Slip Differentials	34
1.4.5 Magnetorheological Fluid Limited Slip Differential	36
2 Methodology and Testing	38
2.1 Simscape Driveline Modelling.....	39
2.1.1 Simscape Driveline Differential Modelling.....	39
2.1.2 Simscape Driveline Vehicle Model	48
2.1.3 Simscape Driveline Active Differential Control Systems.....	52
2.2 Simscape Multibody Vehicle Modelling.....	60

2.2.1	Multibody Powertrain	63
2.2.2	Multibody Chassis and Suspension	64
3	Results and Analysis	67
3.1	Open Differential Results.....	67
3.2	Clutch Pack LSD Results	69
3.3	Torque Sensing LSD Results.....	71
3.4	Viscous LSD Results	73
3.5	eLSD Results	75
3.6	MRF Results	77
3.7	Validation of Results: Split Mu.....	79
3.8	Results Comparison and Analysis	82
4	Further Development.....	95
5	Conclusion.....	97
	References	98

Acknowledgements

The author would like to mention and thank the following personnel for their support and guidance for this project:

Mark Sandford – for your guidance, knowledge and time invested into assisting and supporting this project.

Ryan James – for sharing knowledge and feedback in regard to vehicle control systems.

Table of Figures

Figure 1: Project Plan Gantt Chart.....	17
Figure 2: Conventional Drivetrain Configurations (AutoPivot, 2023).	18
Figure 3: BEV Drivetrain Architecture. (a) ICE Based, (b) Fixed Gear no Clutch, (c) Integrated Fixed Gear, Motor and Differential, (d) Dual Motors with Fixed Gears, (e) Dual Motors, Geared in Wheel Drives, (f) Gearless Dual Motor In-Wheel Drive (Zhou, et al., 2023).....	19
Figure 4: 14-DOF Vehicle Dynamic Signing Convention (Blundell & Harty, 2015).	20
Figure 5: (a) RWD Vehicle Schematic Diagram, (b) Physical Network for RWD Lumped Parameter model (Rahnejat, et al., 2002).....	21
Figure 6: Simscape Driveline Representation of RWD Physical Network.	21
Figure 7: Domain Variables Diagram for Simscape Physical Network Model (Mathworks [1], 2025).	22
Figure 8: (Left) Longitudinal Tyre Model Diagram (Mathworks [2], 2025), (Right) Pacejka Longitudinal Force Against Slip Angle Graph Demonstration- Modified from (Vogel, 2021).	24
Figure 9: (Left) Pacejka Tyre Model Signing Convention and Labelling (Right) Parameter Inputs and Outputs (Pacejka, et al., 2010).	24
Figure 10: Comparing Open (left), and Locked (right) Differentials where (top) Absence of Drive Torque and (Bottom) with Driveline Torque (Blundell & Harty, 2015).....	25
Figure 11: Open Differential Diagrams, (Left) Component Schematic Diagram (Mathworks [4], 2025), (Right) Traction Problem - Equal Torque Split where Left Wheel Slips and Spins Faster (AuburnGear, n.d.).....	26
Figure 12: LSD Cornering Characteristics (Polyphony Digital Inc, 2025).	27
Figure 13: Viscous Coupling Limited Slip Differential (Left) Schematic Diagram (Jin, et al., 2021), (Right) Viscous Coupling Unit Clutch Plates (Z1 Motorsports, 2018).....	28
Figure 14: Clutch Pack LSD (Left) Component Diagram (Guiggiani, 2018), (Right) Bevel Gear Separation Forces Diagram (Sharma & Purohit, 2004).	29
Figure 15: Cone Clutch LSD Internal Diagram (Stone & Ball, 2004).....	30
Figure 16: Cone Clutch LSD Operation (Autodata Training, 2019).	30
Figure 17: Clutch Pack and Ramp LSD Diagram, (Left) Components (Guiggiani, 2018), (Right) Cutaway Section of Ramp Block Design (Alferink, 2019).	31
Figure 18: Clutch Pack LSD Ramp Block Configuration Diagram (Turner Motorsport, n.d).	32

Figure 19: Torque Sensing Differential, (Left) Internal Components Diagram (Wenbourne, 2007), (Right) Locking Effects of Torque Sensing Differential (Bruls, et al., 2011).	33
Figure 20: Eaton 'IntelliTrac' Electronic LSD (Eaton, 2016).	35
Figure 21: Schematic Diagram of Active Electronic LSD (Rubin & Arogeti, 2015).....	35
Figure 22: Schematic Diagram of MRF LSD (Russo, et al., 2016).....	36
Figure 23: Project Modelling and Testing Flowchart Methodology.	38
Figure 24: Simscape Driveline Open Differential Model.	39
Figure 25: Simscape Driveline Clutch Pack LSD Model.....	40
Figure 26: Simscape Driveline Clutch Pack LSD Torque to Pressure Subsystem.....	40
Figure 27: Simscape Driveline Torque Sensing LSD Model.	41
Figure 28: Simscape Driveline Viscous Coupling LSD Model.	42
Figure 29: Simscape Driveline eLSD Model.....	43
Figure 30: eLSD Setup Parameters, (Left) Clutch Data, (Right) Torsional Spring-Damper Data for Compliance.....	43
Figure 31: Simscape Driveline Magnetorheological Fluid LSD Model.	44
Figure 32: Simscape MRF Clutch Component Written in Simscape Language.	47
Figure 33: Simscape Driveline FWD Vehicle Model.....	48
Figure 34: Simscape Driveline Vehicle Driveline Model - Open Differential.	48
Figure 35: Simscape Driveline Throttle Control Stateflow Chart.....	49
Figure 36: (Top) Simscape Vehicle Model, (Bottom Left) Vehicle Parameters, (Bottom Right) Tyre Parameters.	50
Figure 37: Vehicle Road Condition Control System, (Left) Road Conditions Subsystem Block Mask, (Right) Linked Constant Blocks to Road Conditions Subsystem Mask Parameters.	51
Figure 38: Switch Controller of MF Vector Values.	51
Figure 39: Simscape Driveline eLSD Variant Control Systems and Signal Examples. Graphs: X-Axis is Simulation Time (seconds) and Y-axis Represent Logic Control Value (Unitless).....	52
Figure 40: PID Influential Parameters Diagram (NI, 2025).	58
Figure 41: Simscape Multibody Vehicle Model.	60
Figure 42: Signal Controls (Left) Driveline Torque, (Right) Steering Angle.....	60
Figure 43: Vehicle Model Subsystem Categories.	62

Figure 44: Simscape Driveline Vehicle Model Ideal Torque Source.	62
Figure 45: Simscape Driveline Drivetrain Subsystem within Multibody Vehicle Model.....	63
Figure 46: Simscape Multibody Driveshafts and Multibody/Driveline Connection Interface. Subsystem Right is the contents of ‘Revolute Transaxle’.....	63
Figure 47: Multibody Vehicle Chassis Subsystem.....	64
Figure 48: Multibody Front Left Double Wishbone Suspension Model Block Diagram and Virtual Model.	64
Figure 49: Simscape Multibody Vehicle Spring Settings and Block Diagram.....	65
Figure 50: Simscape Multibody Damper and Bump Stop Settings and Block Diagram (Mathworks [10], 2025).	65
Figure 51: Multibody Tyre Model Longitudinal and Rotational Axis Diagram (Mathworks [13], 2025).	66
Figure 52: Multibody Vehicle Tyre Model.	66
Figure 53: Setup Data for Split Mu Scenario (Top) Vi-Road Surface Friction Data, (Bottom) Vi- EventBuilder for Event Control System.....	79
Figure 54: Simscape Multibody Lane Change Manoeuvre Demonstrating Key Time Frames of Right Steering (Top), Left Steering (Middle) and Straight Steering (Bottom) for the Following Differentials: Open (Blue), Torsen (Orange), Viscous (Purple) and MRF (Light Blue).....	84
Figure 55: Simscape Multibody Ramp Steer Manoeuvre Demonstrating Key Time Frames of Initial Left Turn-in (Top), Favourable Torque Transfer (Middle) and Final Effects (Bottom) for the Following Differentials: Open (Blue), Torsen (Orange), Viscous (Purple) and eLSD (Green).	91
Figure 56: Multibody Suspension System Example (Archut & Burkhard, 2025).....	96
Figure 57: Electromagnetic Field Analysis Results Example from (Park, et al., 2022).	96

Table of Graphs

Graph 1: Locking Torque Faces of Clutch Pack and Ramp LSD (Tremlett, et al., 2014).	31
Graph 2: Comparing Ramp Block Configurations on Locking Effects (DSport, 2022).	32
Graph 3: MRF LSD Current and Locking Torque Graph (Abd elhafiz & Metered, 2018).	37
Graph 4: MRF-140CG Data Sheet Plots, (Left) Shear Stress as a Function of Shear Rate with no Magnetic Field Applied at 40 Degrees Celsius, (Right) Yield Stress against Magnetic Field Strength (Parker Lord, 2024).	45
Graph 5: Simscape Driveline Engine Power and Torque Curves.	49
Graph 6: Simscape Driveline Dry Tarmac Simulation Data for Active LSD Validation, (Top) Vehicle Velocity Data, (Bottom Left) Axle Angular Velocity Data, (Bottom Right) Axle Torque Data.	53
Graph 7: Simscape Driveline Split Mu Simulation Data for Active LSD Validation where Left Tyres Contact Ice and Right Tyres Contact Dry Tarmac, (Top) Vehicle Velocity Data, (Bottom Left) Axle Angular Velocity Data, (Bottom Right) Axle Torque Data.	54
Graph 8: eLSD Parameter Study of Clutch Logic Control Values Effect on Vehicle Wheels Angular Velocities.	55
Graph 9: MRF LSD Parameter Study of MMF Effect on Vehicle Wheels Angular Velocities.	56
Graph 10: eLSD PID Controller Gain Parameters Study using Monte Carlo Simulation Impact on Maximum Wheel Speed Difference, (Top Left) Proportional Gain Parameter, (Top Right) Integral Gain Parameter, (Bottom Left) Derivative Gain Parameter, (Bottom Right) Filter Coefficient Parameter. .	57
Graph 11: MRF PID Controller Gain Parameters Study using Monte Carlo Simulation Impact on Maximum Wheel Speed Difference, (Top Left) Proportional Gain Parameter, (Top Right) Integral Gain Parameter, (Bottom Left) Derivative Gain Parameter, (Bottom Right) Filter Coefficient Parameter. .	59
Graph 12: Statistics Analysis of Gain Parameter Influence on Maximum Wheel Speed Difference. .	59
Graph 13: Torque Signal Configurations.	61
Graph 14: Steering Angles for Vehicle Testing Manoeuvres, a Positive Value Refers to a Right Turn and Negative Left.	61
Graph 15: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Engine Speeds, (Right) Propeller Shaft Torque.	67
Graph 16: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.	68
Graph 17: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.	68

Graph 18: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.....	68
Graph 19: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Engine Speed, (Right) Propeller Shaft Torque.....	69
Graph 20: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.	70
Graph 21: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.....	70
Graph 22: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.....	70
Graph 23: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Torsen Engine Speed, (Right) Propeller Shaft Torque.	71
Graph 24: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.	72
Graph 25: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.....	72
Graph 26: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.	72
Graph 27: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Engine Speed, (Right) Propeller Shaft Torque.....	73
Graph 28: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.	74
Graph 29: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.....	74
Graph 30: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.	74
Graph 31: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Top Left) Engine Speed, (Top Right) Propeller Shaft Torque, (Bottom) eLSD Control Signals.	75
Graph 32: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.....	76
Graph 33: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.....	76

Graph 34: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.	76
Graph 35: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Top Left) Engine Speed, (Top Right) Propeller Shaft Torque, (Bottom) Magnetomotive Force Control Signal. 77	
Graph 36: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.....	78
Graph 37: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.	78
Graph 38: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.	78
Graph 39: Vi-CarRealTime Vehicle Longitudinal Velocity Results for Split Mu Simulation for Open and Torsen Differentials.....	80
Graph 40: Vi-CarRealTime Driveshaft Torque Results for Split Mu Simulation for Open and Torsen Differentials.	81
Graph 41: Vi-CarRealTime Driveshaft Angular Velocity Results for Split Mu Simulation for Open and Torsen Differentials.....	81
Graph 42: Vi-CarRealTime Vehicle Yaw Rate Results for Split Mu Simulation for Open and Torsen Differentials.	81
Graph 43: Simscape Driveline Comparing Differential Percentage Locking Effects on split mu surface.	82
Graph 44: Comparing Vehicle Position Results for Simscape Multibody Lane Change Manoeuvre. .	83
Graph 45: Comparing Vehicle Longitudinal Velocity Results for Simscape Multibody Lane Change Manoeuvre.....	85
Graph 46: Comparing Vehicle Driveshaft Torque Results for Simscape Multibody Lane Change Manoeuvre.....	85
Graph 47: Comparing Vehicle Driveshaft Axle Angular Velocity Results for Simscape Multibody Lane Change Manoeuvre.....	86
Graph 48: Comparing Vehicle Pitch Rate Results for Simscape Multibody Lane Change Manoeuvre.	87
Graph 49: Comparing Vehicle Roll Rate Results for Simscape Multibody Lane Change Manoeuvre. 87	
Graph 50: Vi-CarRealTime Vehicle Longitudinal Velocity Results for Double Lane Change Simulation for Open and Torsen Differentials.....	88

Graph 51: Vi-CarRealTime Driveshaft Torque Results for Double Lane Change Simulation for Open and Torsen Differentials.....	89
Graph 52: Vi-CarRealTime Driveshaft Axle Angular Velocity Results for Double Lane Change Simulation for Open and Torsen Differentials.....	89
Graph 53: Vi-CarRealTime Vehicle Yaw Rate Results for Double Lane Change Simulation for Open and Torsen Differentials.....	89
Graph 54: Comparing Vehicle Position Results for Simscape Multibody Ramp Steer Manoeuvre. ...	90
Graph 55: Comparing Vehicle Driveshaft Torque Results for Simscape Multibody Ramp Steer Manoeuvre.....	92
Graph 56: Comparing Vehicle Driveshaft Axle Angular Velocity Results for Simscape Multibody Ramp Steer Manoeuvre.....	92
Graph 57: Comparing Vehicle Longitudinal Velocity Results for Simscape Multibody Ramp Steer Manoeuvre.....	93
Graph 58: Comparing Vehicle Pitch Rate Results for Simscape Multibody Ramp Steer Manoeuvre.	94
Graph 59: Comparing Vehicle Roll Rate Results for Simscape Multibody Ramp Steer Manoeuvre. .	94

Table of Tables

Table 1: MRF LSD Components and Materials (Russo, et al., 2016).	36
Table 2: Magic Formula Coefficients for Various Road Conditions (Mathworks [2], 2025).	51
Table 3: PID Gain Parameters Effect on Control Signal. T_i - Rise Time, T_s - Settling Time, OS - Overshoot and SSE - Steady State Error (Hussien, et al., 2015).....	58

Nomenclature

<i>4WD</i>	4 Wheel Drive
<i>ABS</i>	Anti-Lock Braking System
<i>AWD</i>	All Wheel Drive
<i>BEV</i>	Battery Electric Vehicle
<i>CAD</i>	Computer Aided Design
<i>DOF</i>	Degrees-of-freedom
<i>FWD</i>	Front Wheel Drive
<i>eLSD</i>	Electronic Limited Slip Differential
<i>LSD</i>	Limited Slip Differential
<i>ICE</i>	Internal Combustion Engine
<i>MF</i>	Pacejka Magic Formula
<i>MMF</i>	Magnetomotive Force
<i>MRF</i>	Magnetorheological Fluid
<i>PID</i>	Proportional-Integral-Derivative
<i>RWD</i>	Rear Wheel Drive
<i>SMD</i>	Spring-mass-damper
<i>TBR</i>	Torque Bias Ratio
<i>YSC</i>	Yaw Stability Control
<i>A</i>	Area (m ²)
<i>α</i>	Lateral slip
<i>d</i>	Distance between friction plates (m)
<i>F</i>	Force (N)
<i>H</i>	Magnetic field strength (A/m)
<i>I</i>	Intertia (Kg.m ²)
<i>l</i>	Length of magnetic path (m)
<i>k</i>	Longitudinal slip
<i>mmf</i>	Magnetomotive force (AT – Ampere-turn)
<i>n</i>	Number of friction surfaces
<i>n_{vc}</i>	Number of plates in viscous coupling unit
<i>η</i>	Viscosity coefficient (Pa.s)
<i>P_s</i>	Silicon oil density (kg/m ³)
<i>r</i>	Radius of disc, subscript 1 is inner and 2 is outer (m)
<i>r_e</i>	Rolling radius (m)
<i>R</i>	Distance from rotation axis to force applied (m)
<i>u</i>	Ratio between diff housing and first (1), and second (2) auxiliary links
<i>V_s</i>	Kinematic viscosity of silicon fluid (St - Stokes)
<i>V_x</i>	Wheel hub longitudinal velocity (m/s)
<i>V_y</i>	Wheel lateral velocity (m/s)
<i>T</i>	Torque (Nm)
<i>σ</i>	Stress (Pa)
<i>γ</i>	Shear rate (s ⁻¹)
<i>τ</i>	Shear stress (Pa)
<i>τ_y</i>	Yield stress (Pa)
<i>ω</i>	Angular velocity, denotated as Ω during tyre dynamics (rad/s)

Introduction

The vehicle dynamic influence of limited slip differentials (LSDs) is frequently underappreciated within the broader vehicle dynamics discipline. The wide array of LSD configurations available today has led to persistent misconceptions regarding their operational principles and performance characteristics. Given that the UK automotive market is predominantly composed of front-wheel drive (FWD) vehicles, and that FWD platforms are widely used in competitive racing series such as the British Touring Car Championship; it is both relevant and necessary to investigate the impact of LSDs on FWD vehicle behaviour. While performance-oriented drivers and racing teams may actively seek LSD setups, many other consumers remain unaware of the substantial effects these devices have on handling (Gadola, et al., 2021), particularly in relation to steering dynamics. This lack of awareness can contribute to serious safety risks, including loss of vehicle control.

This project aims to address the gap in knowledge by providing both consumers and motorsport teams with operational insights and simulation-based performance data for suitable selection of mainstream LSD types. Project research explores the general benefits of LSD integration and examines the mechanical behaviour of both passive and active variants, including: open differentials, clutch-type (clutch pack, cone clutch, and Salisbury), torque-sensing, viscous coupling, electronic LSDs, and magnetorheological LSDs (Palazzolo, 2009). All simulation data presented in this study has been generated using Vi-Grade, MATLAB Simscape Driveline and Multibody simulation platforms. A comprehensive results analysis compares the different characteristics these devices exhibit, with special attention given to torque transfer and locking effects.

Industrial Relevance

The differential is a vital component within most drivelines for road and track cars today. The standard open differential performs sufficiently for the majority of road car applications, however, those seeking higher end performance on and off the track recognise the traction benefits of LSDs. Whilst the basic understanding of traction improvements is often understood, the large variety of these devices available (some with adjustable parameters) often causes misconceptions in terms of how the devices operate and their influence on vehicle dynamic response. Blundell & Harty (2015), state that the most misinterpreted aspect of these devices is torque distribution, a vital aspect when considering the performance of LSDs.

With a lack of published literature in this domain, this study seeks to investigate, compare, and contrast the mechanical operation, adjustability, torque distribution and related performance characteristics of these devices. The primary objective is to educate consumers with a comprehensive understanding, thus enabling informed decisions when either adjusting internal parameters or acquiring a new differential. Given that differential selection depends on factors such as terrain, road/racing applications, drivetrain configuration, budgetary constraints, and racing regulations, a thorough understanding of each device's operation and capabilities is therefore vital to the consumer (Team O'Neil, 2020).

Aims and Objectives

The project aims are therefore:

- Provide the motorsport and automotive industry with comprehensive comparison of different LSDs mechanical workings and vehicle dynamic effects.
- Fill in gaps within industry knowledge (motorsport and vehicle dynamics industry).
- Provide a guide to race teams/customers for selecting the appropriate LSD based on requirements and desired handling.
- Define overall handling implications and positive/negative effects of each LSD investigated.

Project objectives are:

- Investigate both passive and active LSDs.
- Build vehicle dynamics models in Simulink that assess handling characteristics due to LSDs.
- Model a suitable controller for active LSDs.
- Use simulated data and published literature to analyse result validity.
- Conduct a comprehensive analysis comparing the different effects.

Project Plan

The project plan timeline is detailed in the Gantt chart shown in Figure 1.

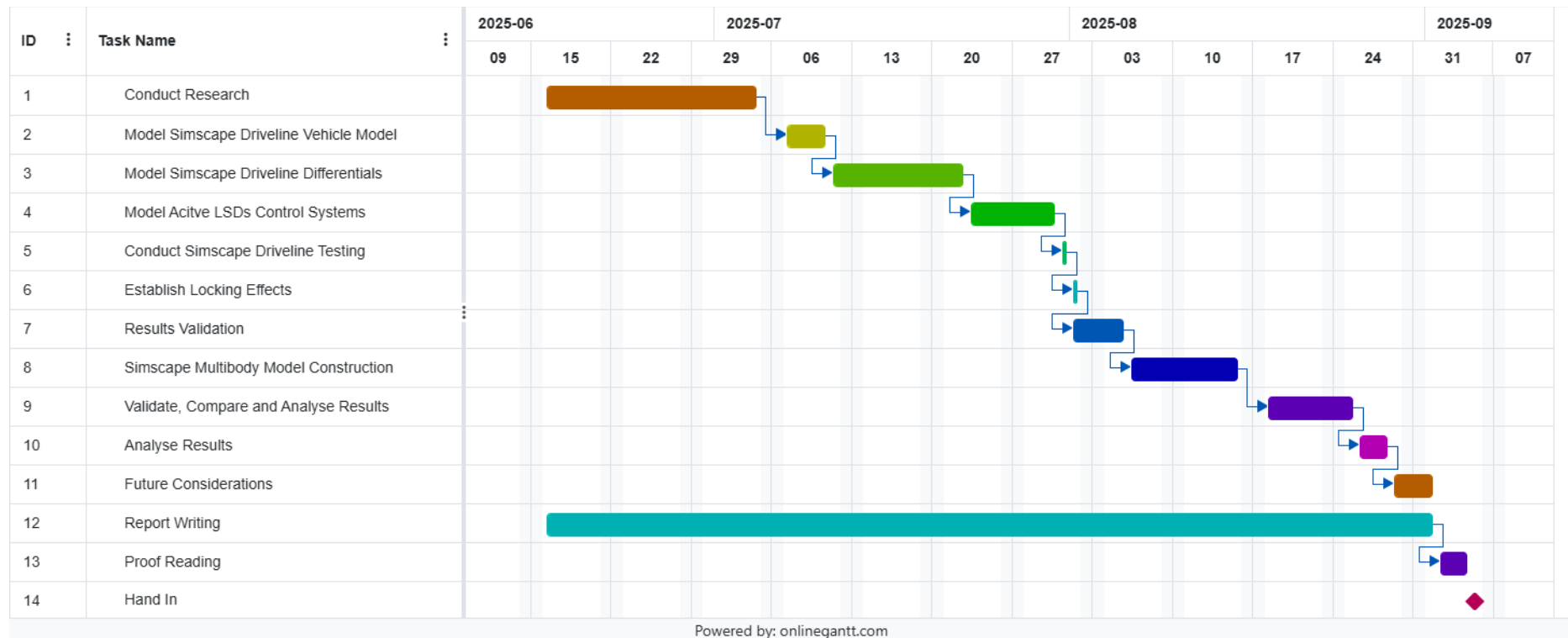


Figure 1: Project Plan Gantt Chart.

1 Literature Review

The following literature review investigates the operation of popular passive and active LSDs. In addition to LSD research, an understanding of vehicle dynamics modelling and fundamentals are also required to accurately model and validate the results. Certain aspects of research within this literature review are based on information gathered within ‘research proposal report’ (Doyle, 2025).

1.1 Drivetrain Configurations

Conventionally, vehicles would utilise at least one differential within the drivetrain. However, with the development of alternative drivetrains and powertrains this quantity varies (Ansys, 2024). Traditional ICEs utilise one of the following configurations: FWD, RWD, AWD and 4WD (Figure 2), whilst a BEV or hybrid does not strictly require a differential (dependant on design). In essence, if a singular motor is used to power the front or rear axle, a differential is required; if instead an individual motor is applied to each desired drive wheel, a differential is then no longer required, Figure 3 (Zhou, et al., 2023).

An additional factor to consider when study differentials and drivelines is drivetrain losses. Each component within the drivetrain contributes to a reduction in power transmitted from the powertrain to the wheels; certain components such as gearboxes and differentials have higher losses than others due to their design. Whilst drivetrain losses depend on each drivetrain component and drive cycle, rough estimates for manual transmission drivetrains are 87-91% efficient and automatics as low as 80% (Crolla & Mashadi, 2011). For differentials, the key contributing factors are considered to be: lubricant/lubricant condition, gear: temperatures, geometry and type (Radzevich, 2021).

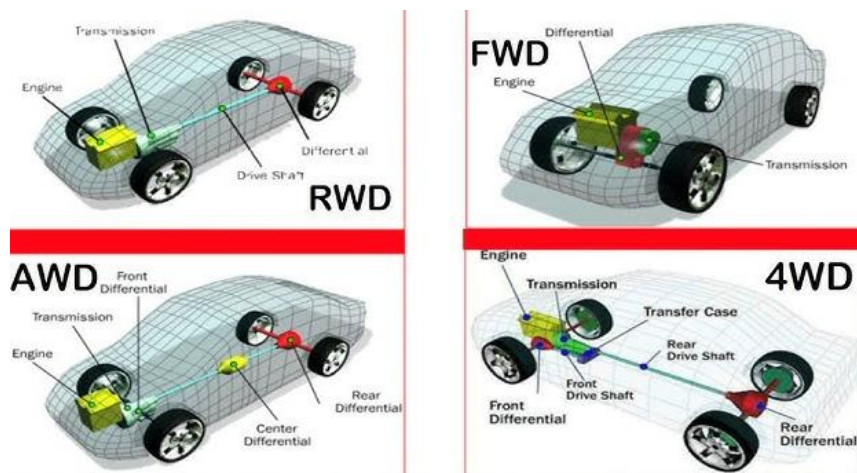


Figure 2: Conventional Drivetrain Configurations (AutoPivot, 2023).

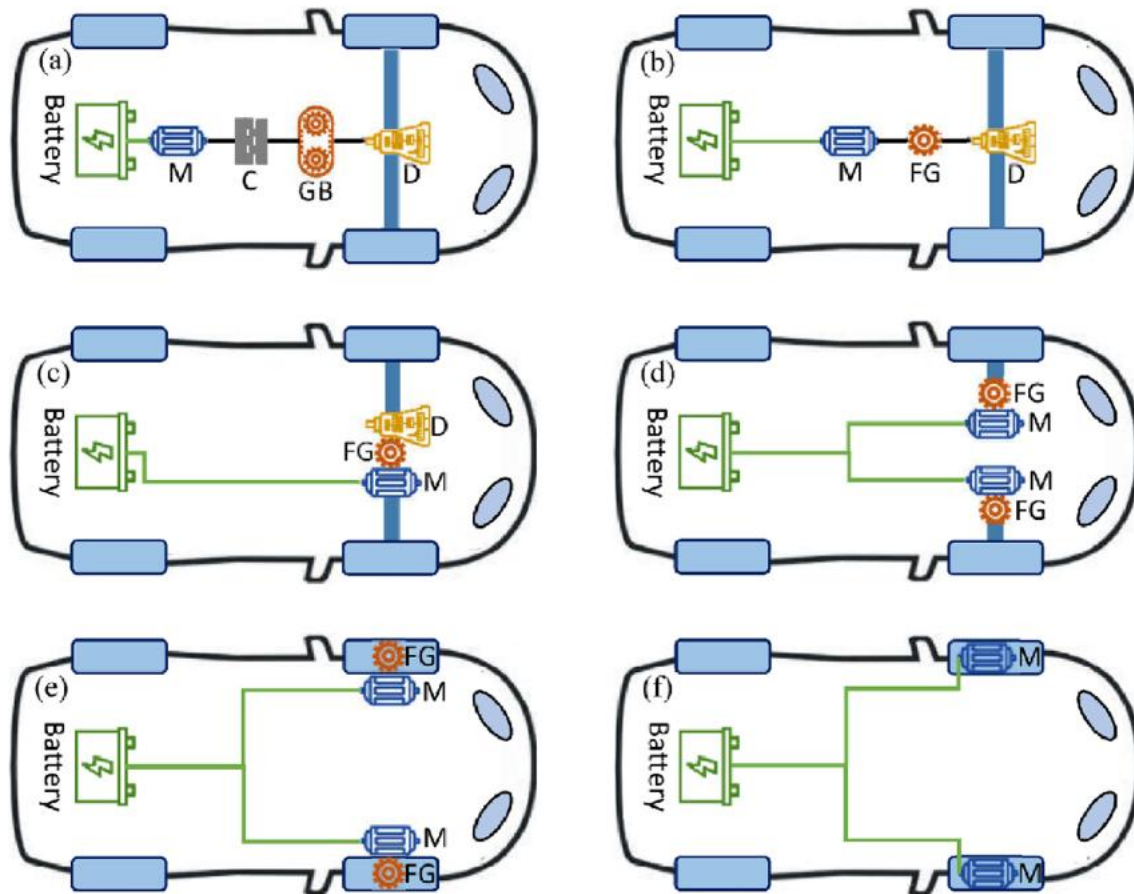


Figure 3: BEV Drivetrain Architecture. (a) ICE Based, (b) Fixed Gear no Clutch, (c) Integrated Fixed Gear, Motor and Differential, (d) Dual Motors with Fixed Gears, (e) Dual Motors, Geared in Wheel Drives, (f) Gearless Dual Motor In-Wheel Drive (Zhou, et al., 2023).

Due to the vast quantity of drivetrain configurations available, and the opportunity to implement numerous differentials into these drivetrain configurations, FWD will be the focus of this project due to the implications LSDs can have on vehicle safety, handling and performance characteristics. In comparison to RWD vehicles, additional considerations are required for FWD vehicles fitted with LSDs due to the impact of asymmetric drive forces on steering and vehicle control. Key factors effecting these steering characteristics are differential locking effects, suspension layout, tyre parameters and more; each to be considered within this project.

1.2 Vehicle Dynamics Fundamentals

Vehicle dynamics studies the response of a vehicle in relation to the road surface during a cornering, acceleration or braking event (Gillespie, 2021). Crucial data aspects to capture during vehicle dynamic modelling for LSDs effects include tyre response/data, driveline torque and data, suspension kinematics, load transfer (roll, yaw and pitch), and more. To capture the essential LSD data, a comprehensive vehicle dynamics model is required. The modelling methods selected for this project are therefore a lumped parameter model (a SMD system) and multibody system.

In accordance with the vehicle dynamics sector, the ISO 8855:2011 and SAE J670 (SAE, 2022) provide clear standards for communication in which vehicle dynamic systems follow a specified positive direction (ISO, 2011). The 14-DOF vehicle coordinate system in Figure 4 demonstrates the positive signing convention of rotational and translational movements as specified by the ISO 8855:2011 standard. Figure 4 illustrates the key vehicle dynamic movements, which are essential when analysing differential performance.

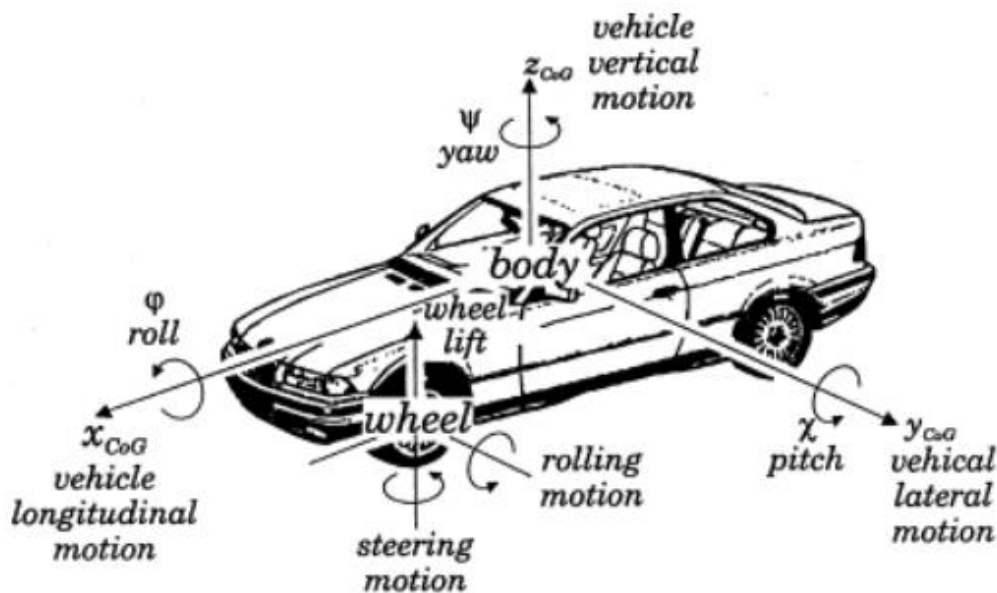


Figure 4: 14-DOF Vehicle Dynamic Signing Convention (Blundell & Harty, 2015).

1.2.1 Physical Network Modelling

Differential and driveline modelling can be completed using a physical network of lumped parameter models within Simscape Driveline (MATLAB/Simulink) allowing for driveline testing of different LSDs in a longitudinal 1-dimension environment (Mathworks, 2025). The physical network model is constructed using some of the following aspects/components: inertias, springs, dampers, friction and governing equations. This method is suitable for mechanical modelling where the image in Figure 5 (a) represents a schematic diagram of a RWD drivetrain system (Rahnejat, et al., 2002), this can then be represented as a lumped parameter model in Figure 5 (b) and modelled in Simulink as demonstrated in Figure 6. This example can therefore be adapted to represent a FWD configuration.

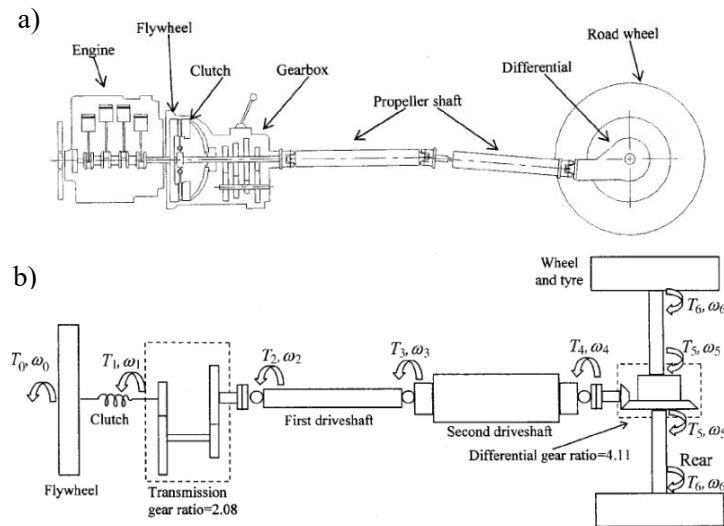


Figure 5: (a) RWD Vehicle Schematic Diagram, (b) Physical Network for RWD Lumped Parameter model (Rahnejat, et al., 2002).

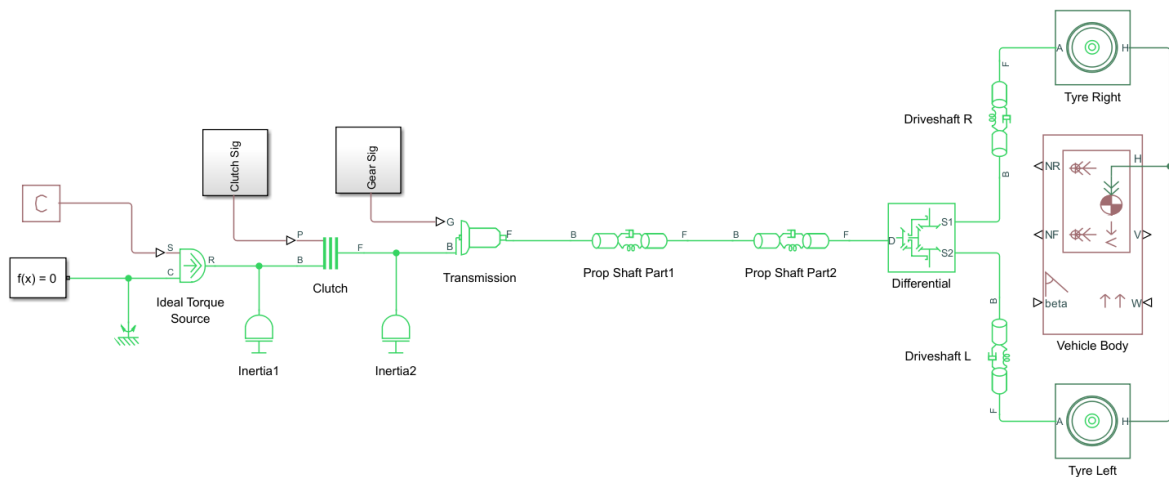


Figure 6: Simscape Driveline Representation of RWD Physical Network.

The physical model uses two variable types referred to as ‘across variable’ and ‘through variable’ within the mechanical rotational domain. The across variable (angular velocity) is measured with a gauge connected in series to an element, whilst the through variable (torque) is measured with a gauge connected in parallel to an element (Mathworks [1], 2025). The through variable (TV) – torque, is cited to ‘flow’ from node ‘A’ to ‘B’ whilst the across variable (AV) refers to the difference between the values at each node, demonstrated in equation 1 and Figure 7.

$$AV = AV_A - AV_B \quad (1)$$

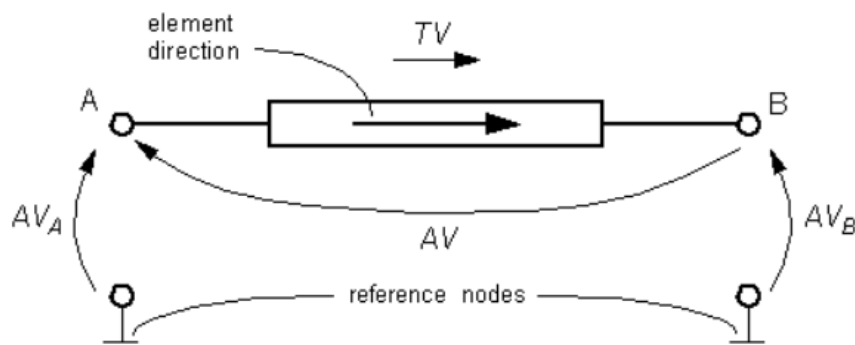


Figure 7: Domain Variables Diagram for Simscape Physical Network Model (Mathworks [1], 2025).

1.2.2 Multibody Vehicle Modelling

Multibody vehicle modelling is an alternative approach to lumped mass modelling and physical world testing. This approach can consist of many interconnected components in a system all undergoing changing states of motion (Blundell & Harty, 2015). Depending on the desired outcomes, components can be modelled as rigid or flexible bodies, adding to the complexity and realism of the solution. The benefit of a multibody systems approach is the ability to observe all components transient dynamics within a model, allowing for design adaptations and performance assessment (ANSYS, 2023). The fundamentals of multibody modelling are the formation and solving of the equations of motion in matrix form, Blundell & Harty (2015) example the details of constructing a multibody system using vector algebra. The model develops from geometry analysis (e.g. suspension component points) to velocity analysis, acceleration analysis, angular momentum and integration of inertia. MATLAB’s Simscape Multibody addon provides a block set interface to model and simulate the complex equations of motion behind a mechanical multibody system. Thus, making this software ideal for use within this project.

1.3 Tyre Dynamics and Modelling

Tyre dynamics and modelling are fundamental to the study of vehicle dynamics. Given the critical importance of an accurate tyre model, this project adopts the Pacejka Magic Formula (MF) due to its demonstrated reliability and its integration within the required software platforms: Vi-CarRealTime, MATLAB Simscape Driveline, and Simscape Multibody (Mathworks [2], 2025). Developed by renowned tyre modelling expert Hans Pacejka, the latest iteration of the MF incorporates between 60 and over 100 parameters. For the Simscape Driveline implementation, a simplified version of the MF will be employed, reflecting both the absence of real-world tyre data and the constraints of the model's one-dimensional network. Conversely, the Simscape Multibody network will leverage more sophisticated tyre data scripts provided by MathWorks and the Raghupati Singhania Centre of Excellence for Tyre and Vehicle Mechanics (RPSCO), enabling the use of a more comprehensive model (Mathworks [3], 2025). This advanced model captures longitudinal, lateral and normal forces, as well as slip characteristics, aligning moments, and numerous additional parameters. These elements are essential for the accurate analysis and evaluation of various differential configurations.

Due to tyre modelling complexity, the author of this project has researched the fundamentals to provide a basic understanding for use within testing software. Initial investigation into longitudinal dynamics for 1-dimensional driveline modelling is demonstrated in Figure 8 with the following parameters: normal force (F_z), angular velocity (Ω), wheel hub longitudinal velocity (V_x) and longitudinal force exerted on tyre at contact patch (F_x) (Mathworks [2], 2025). Calculations for the longitudinal tyre force are demonstrated in equations 2-4 with the additional parameters: rolling radius (r_e) and longitudinal slip (k) (Pacejka & Besselink, 2012). The MF uses 4 fundamental coefficients to describe force generation capacity of a tyre, these being 'B', 'C', 'D' and 'E'. They are "defined as a function of pressure, camber angle, tyre load, temperature, and more" (Vogel, 2021). The effects of these coefficients are demonstrated in Figure 8 (right).

$$r_e = \frac{V_x}{\Omega_o} \quad (2)$$

$$k = -\frac{V_x - r_e \Omega}{V_x} = -\frac{\Omega_o - \Omega}{\Omega_o} \quad (3)$$

$$F_x = F_z \times D \times \sin(C \times \tan^{-1}\{B_k - E[B_k - \tan^{-1}(B_k)]\}) \quad (4)$$

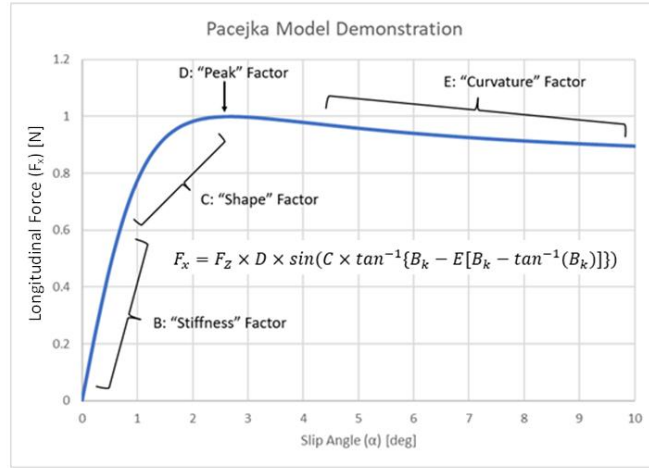


Figure 8: (Left) Longitudinal Tyre Model Diagram (Mathworks [2], 2025), (Right) Pacejka Longitudinal Force Against Slip Angle Graph Demonstration- Modified from (Vogel, 2021).

Progressing onto a more complex model as shown in Figure 9, an increased number of input and output parameters enable a broader understanding of the tyre's performance during a range of different manoeuvres that are not limited to longitudinal and vertical motion. The additional parameters include but are not limited to: lateral forces, slip and moments, inclination angle (camber), tyre deflection, and more (Pacejka, et al., 2010). Equation 5 is used to define the lateral wheel slip (α) which is a ratio of the lateral and forward velocity of the wheel (Pacejka & Besselink, 2012). With additional input parameters also demonstrated in Figure 9 (right), the model complexity and accuracy can be increased.

$$\tan \alpha = -\frac{V_y}{V_x} \quad (5)$$

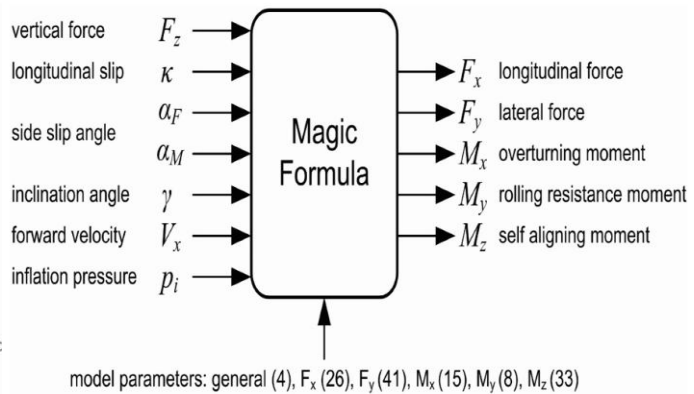
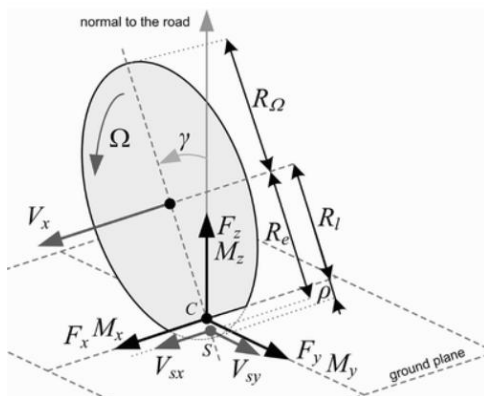


Figure 9: (Left) Pacejka Tyre Model Signing Convention and Labelling (Right) Parameter Inputs and Outputs (Pacejka, et al., 2010).

1.4 Differentials

The differential serves three purposes within a vehicle (Smith, 2013), the first is to provide power and torque to the drive wheels, second is to allow variations in wheel speeds on the driven axle when cornering, and finally, to act as a final drive gear within the drivetrain system. The conventional open differential is suitable for standard driving conditions, however, those requiring additional performance for applications such as motorsport demand a higher performing device such as an LSD. Blundell and Harty (2015) describe the parameters that influence speed and torque characteristics of a vehicle: “How these speeds turn into torques is governed entirely by the wheel to which they are attached - it is a function of vertical load, friction coefficient and slip state. The latter is influenced by vehicle states and, of course, the differential locking conditions. These comments apply whichever differential is under consideration” (Figure 10). By conducting driveline analyses across different LSD configurations, insights into each device’s locking behaviour can be leveraged to model and assess the individual impact on vehicle dynamic performance.

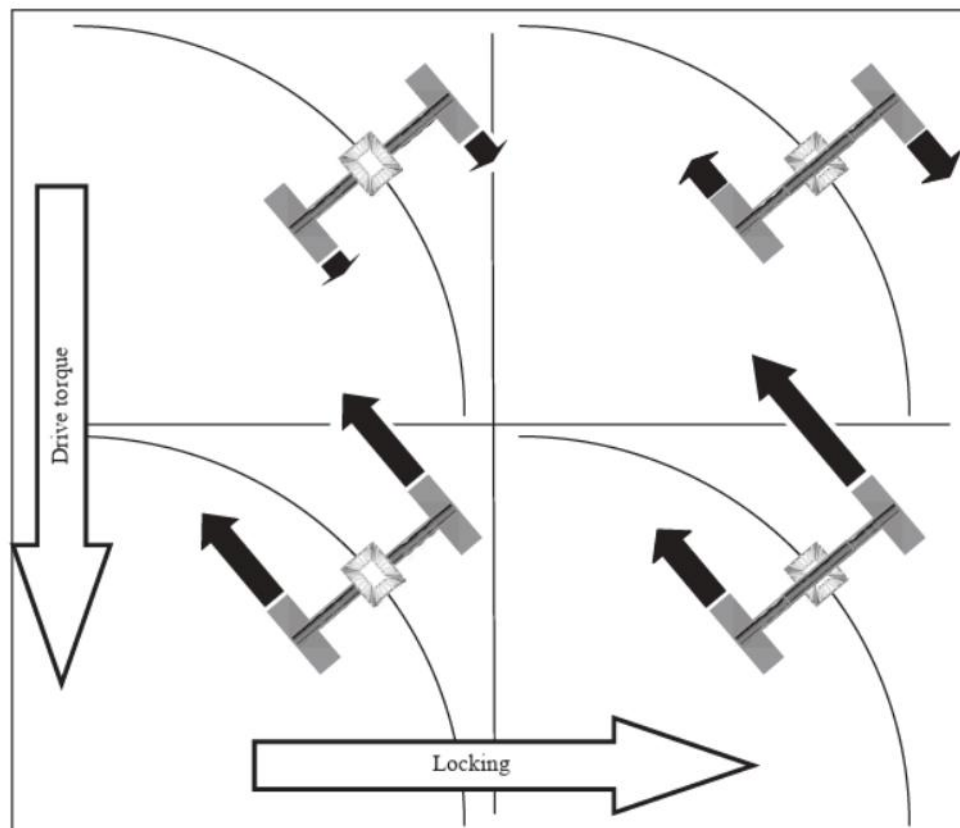


Figure 10: Comparing Open (left), and Locked (right) Differentials where (top) Absence of Drive Torque and (Bottom) with Driveline Torque (Blundell & Harty, 2015).

1.4.1 Open Differential – Traction Problem

The open differential (Figure 11) is constructed with the use of a ring gear, differential case, shaft, drive pinion, 2 pinion gears, 2 differential side gears and connecting axles (Crouse & Anglin, 1983). The torque path in an open differential is as follows: torque is transmitted from the drive pinion to the ring gear, from the ring gear to the carrier and pinion shaft, from here to the pinion gears, then to the side gears, axles and wheels (Crolla, 2015). Due to this torque path - referred to as the primary torque path in differentials, torque is distributed evenly (50-50) between the left and right axles, mathematically represented in equations 6 and 7. Whilst torque remains equal in both left and right axles, the primary purpose of an open differential being the ability to vary wheel speeds, dictates that angular velocity left does not always equal angular velocity right (equation 8). As a consequence of design, the open differential exhibits suboptimal performance during slip events. In such scenarios, the loss of traction in one wheel limits the maximum traction application of both wheels. This inherent limitation is commonly referred to as the traction problem (Figure 11).

$$T_{Left} = T_{Right} \quad (6)$$

$$T_{In} = T_{Out} \quad \therefore \quad T_{In} = T_{Left} + T_{Right} \quad (7)$$

$$\omega_{In} = \frac{(\omega_{Left} + \omega_{Right})}{2} \quad (8)$$

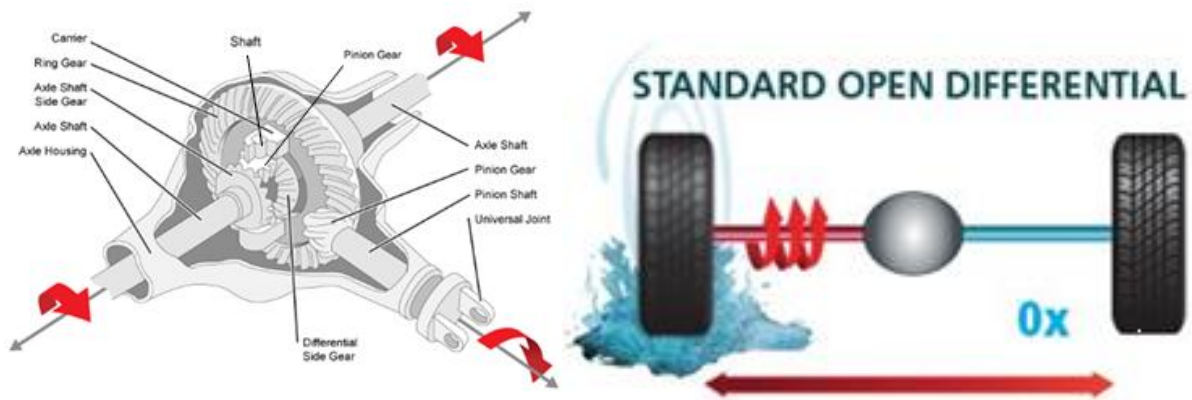


Figure 11: Open Differential Diagrams, (Left) Component Schematic Diagram (Mathworks [4], 2025), (Right) Traction Problem - Equal Torque Split where Left Wheel Slips and Spins Faster (AuburnGear, n.d.).

1.4.2 Limited Slip Differential Fundamentals

Considering the LSD as a generic device, the fundamental objective of this component is to enhance traction and performance of a vehicle over the standard open differential by limiting tyre slip and driven axle wheel speed differences (VanGelder, 2022). Within the LSD grouping, there are two subcategories: passive and active. Passive LSDs refer to devices that rely solely on mechanical forces and systems to transfer torque between wheels and limit wheel slip (Figure 12); on the other hand, active differentials utilise electronic controllers to manage the device (Forstinger, et al., 2015). The secondary ‘pathing’ for torque transfer to the wheel with most traction is unique to each LSD and their mechanical configuration (Palazzolo, 2009). This secondary torque path is the focus of this project as each device exhibits unique characteristics and effects on vehicle dynamics. A key parameter in LSD investigations is percentage locking effect (equations 9 and 10), this terminology refers to the amount of torque transferred from the wheel with least traction to the wheel with greater traction (Chocholek, 1988). When considering an open differential, the percentage locking effect is 0%, this is due to the differential being unable to bias torque and having a constant torque split of 50-50. On the other hand, a fully locked differential (or spool axle) can achieve 100% locking effect (Allen, 2009). Regarding LSDs, percentage locking effect varies for each device, in the case of front wheel drive vehicles, limitations to maximum percentage locking effect are sometimes implemented for safety purposes due to the significant effect these devices can have on steering and vehicle control. A device often carefully designed for FWD vehicles is the torque sensing LSD (sometimes referred to as Torsen), this devices ability to instantaneously bias torque can lead to uncontrollable vehicles when the device outperforms human response capabilities (Bruls, et al., 2011).

$$\text{When } T_{\text{Left}} > T_{\text{Right}} : \quad LE = \frac{T_{\text{Left}} - T_{\text{Right}}}{T_{\text{Ring Gear}}} \times 100 \quad (9)$$

$$\text{When } T_{\text{Left}} < T_{\text{Right}} : \quad LE = \frac{T_{\text{Right}} - T_{\text{Left}}}{T_{\text{Ring Gear}}} \times 100 \quad (10)$$

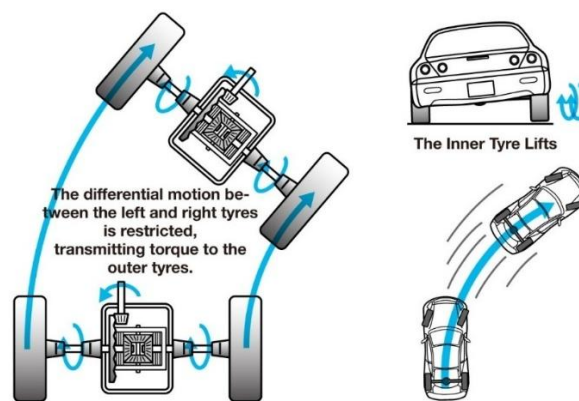


Figure 12: LSD Cornering Characteristics (Polyphony Digital Inc, 2025).

1.4.3 Passive Limited Slip Differentials

This section investigates 3 common passive LSDs, detailing mechanical operations and characteristics.

1.4.3.1 Viscous Coupling Limited Slip Differential

The speed sensing viscous coupling limited slip differential consists of an open differential connected to a viscous coupling unit (Figure 13). The viscous coupling unit consists of a multi-plate clutch pack and a highly viscous fluid such as silicon. One set of this clutch pack is splined to the connected axle, and the other half splined to the casing. It is important to note that the two clutch sets are not in contact with each other. Regarding the silicon type fluid within this unit, it is the fundamental reason behind torque transfer; as one wheel begins to slip and the wheel speed difference increases, the shearing fluid generates friction on the clutch discs, reducing wheel speed difference (Frömmig, 2023). However, the effectiveness of this type of LSD is reduced by temperature increases caused by shearing friction, this temperature increase causes the fluids viscosity to decrease and as a result, reduces locking effect and torque transferring capabilities, shown in equations 11 and 12 (Jin, et al., 2021). Where: t_e current temperature, $V_{t=298}$ absolute viscosity at 298K, ' A_{VC} ' constant related to silicone oil viscosity, $\Delta\omega$ angular velocity difference of input and output shafts. A final factor to consider regarding the viscous coupling unit is the requirement for angular velocity differences between the driven wheels, whilst not necessarily a disadvantage, the delayed response time in preventing wheel slip and transferring torque can lead to a less responsive vehicle when compared to torque sensing LSDs.

$$T_q = \frac{n_{VC} \pi \rho_s V_s \Delta\omega (r_2^4 - r_1^4)}{\lambda} \quad (11)$$

$$V = V_{t=298} \left(\frac{t_e}{298} \right)^{A_{VC}} \quad (12)$$

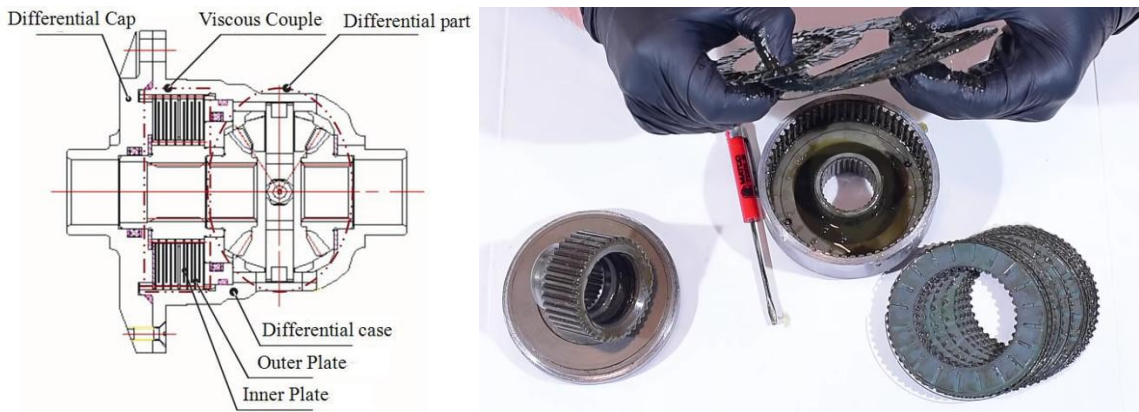


Figure 13: Viscous Coupling Limited Slip Differential (Left) Schematic Diagram (Jin, et al., 2021), (Right) Viscous Coupling Unit Clutch Plates (Z1 Motorsports, 2018).

1.4.3.2 Clutch Type Limited Slip Differentials

The clutch plate LSD is available in various configurations, within this document three of the main types are researched with one taken forward for further testing. The three investigated in this document are: clutch pack, cone clutch type and Salisbury (clutch pack and ramp) (Guiggiani, 2018). Each use clutches within the design; however, actuation of each clutch set varies.

Clutch Pack LSD:

Figure 14 demonstrates a clutch pack LSD that is fitted with either four springs or a single S-shaped spring. Compressive forces on the clutch pack cause the LSD to lock/begin to lock; these compressive forces occur due to the inherent design of bevel gears which generate high axial thrust separation forces between the gears. Equations 13-16 demonstrate calculations for separation forces with Figure 14 highlighting the vectors of each force (Sharma & Purohit, 2004). Preload on this device is configured using the springs within the centre of the device; by increasing the number of springs and/or spring rate, the amount of preload applied can be increased. By altering the clutch material and changing the number of clutch plates used within the device, the locking characteristics can be altered.

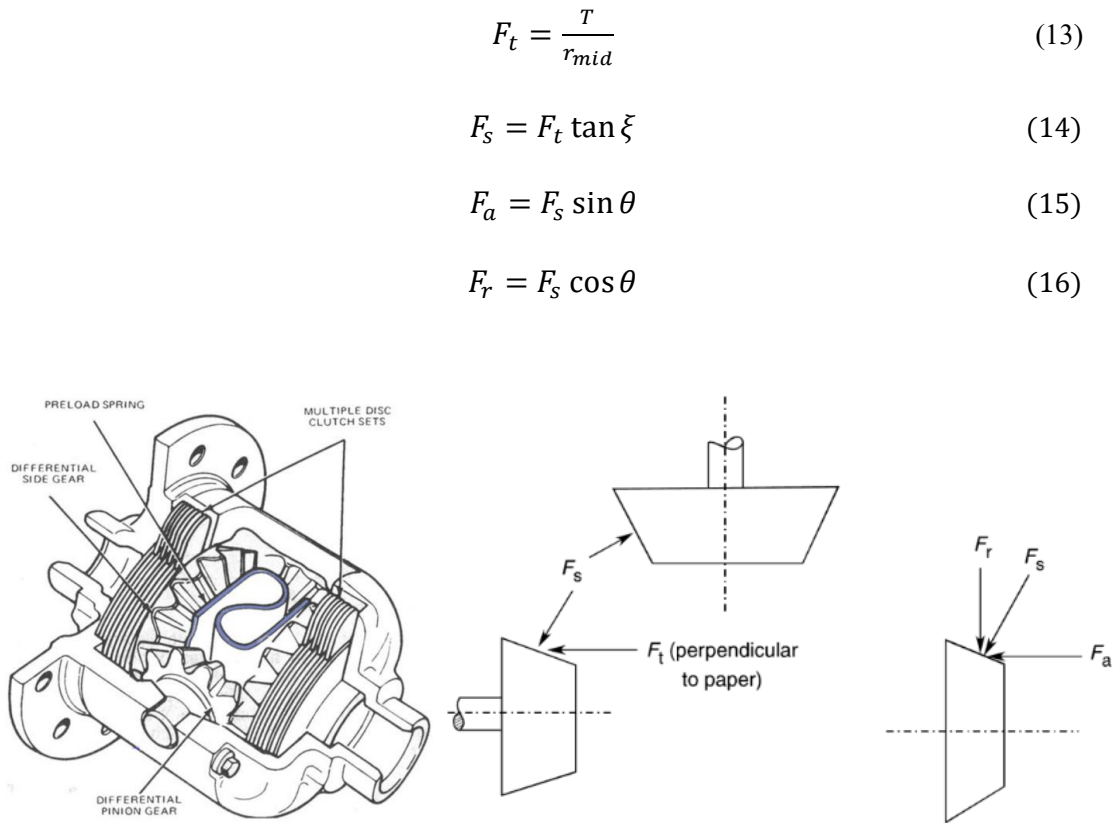


Figure 14: Clutch Pack LSD (Left) Component Diagram (Guiggiani, 2018), (Right) Bevel Gear Separation Forces Diagram (Sharma & Purohit, 2004).

Cone Clutch LSD:

The cone clutch LSD is an alternative clutch device to the multipack clutch styles detailed previously. Instead of utilising multiple clutch plates, the cone clutch LSD consists of: a differential case - cap half, differential case – flange half, two cone clutches and a preload spring system (either multiple smaller springs or a singular S-shaped spring) (Stone & Ball, 2004). The construction of a cone clutch is demonstrated in Figure 15. Clamping of the cone clutch is achieved in a similar manner to the multipack LSD by again relying on the axial thrust forces generated by the bevel gears (demonstrated previously Figure 14 Right). Friction within the cone clutch limits the driven wheels angular velocity difference during a slip event (Figure 16).

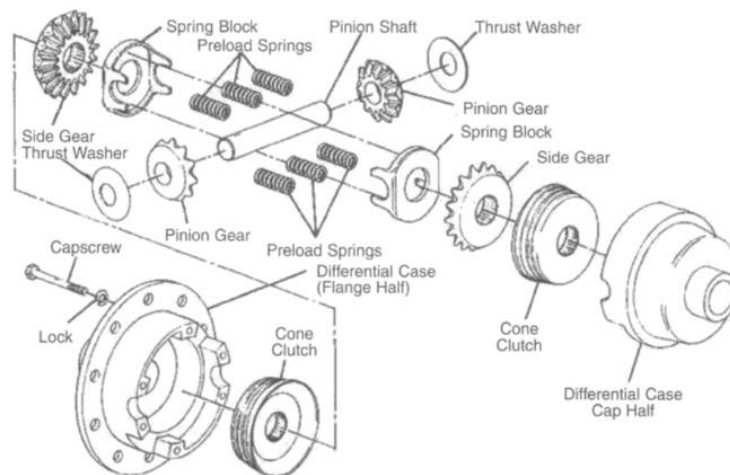


Figure 15: Cone Clutch LSD Internal Diagram (Stone & Ball, 2004).



Figure 16: Cone Clutch LSD Operation (Autodata Training, 2019).

Clutch Pack and Ramp ('Salisbury') LSD:

The clutch pack and ramp LSD is a commonly used device in motorsport. The device consists of a Belleville spring for preload, a shaft encased by two ramp blocks, inner and outer clutch discs and the main components found within a standard open differential (Figure 17). The purpose of preload in all of these devices is to apply a slight amount of pressure on the clutch plates to support torque transfer in low torque situations such as jacking (preload effects are demonstrated in Graph 1); increasing preload results in larger amounts of torque transfer (Tremlett, et al., 2014). The Salisbury LSD locking effect is caused by acceleration or deceleration forces (depending on ramp block design), which cause the shaft to separate the ramp blocks and compress against the clutch packs (Tremlett, et al., 2014).

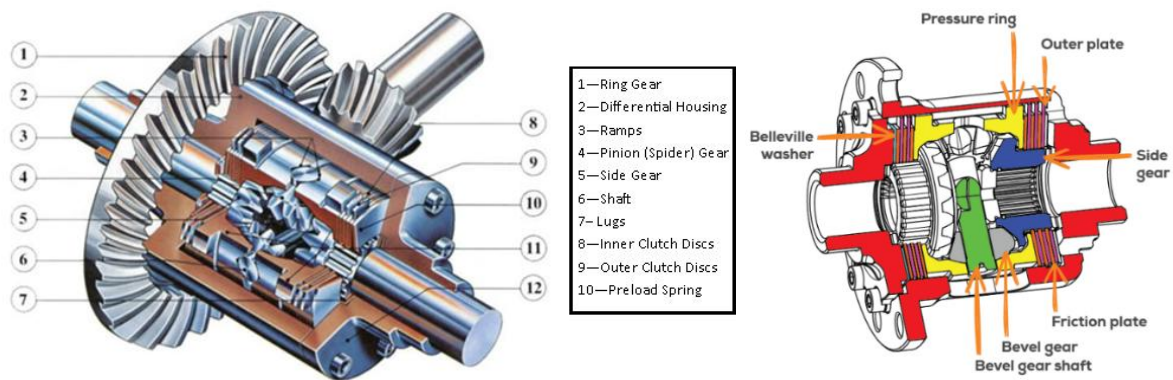
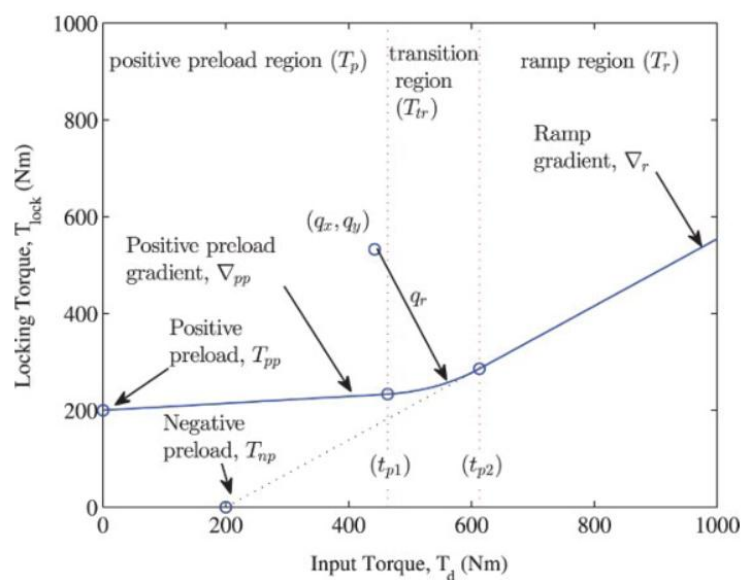


Figure 17: Clutch Pack and Ramp LSD Diagram, (Left) Components (Guiggiani, 2018), (Right) Cutaway Section of Ramp Block Design (Alferink, 2019).



Graph 1: Locking Torque Faces of Clutch Pack and Ramp LSD (Tremlett, et al., 2014).

For this style of clutch type LSD, there are three main configurations available: 1-way, 1.5-way and 2-way. These configurations refer to the design of the ramp block implemented within the device (Figure 18). The 1-way ramp block is used when differential effects are required for acceleration effects/events only, 1.5-way for acceleration and slight braking and 2-way for acceleration and braking, these affects can be seen in Graph 2 (Crouse & Anglin, 1983). Additionally, adjustments to the ramp block angles alter the locking characteristics of the LSD, increasing or decreasing locking rate.

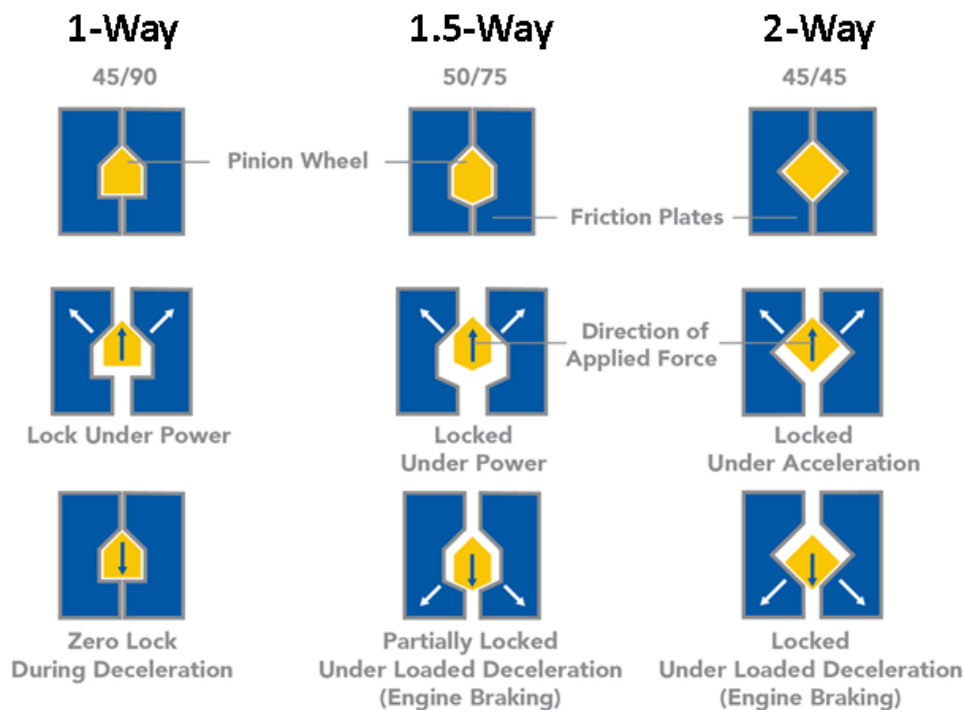
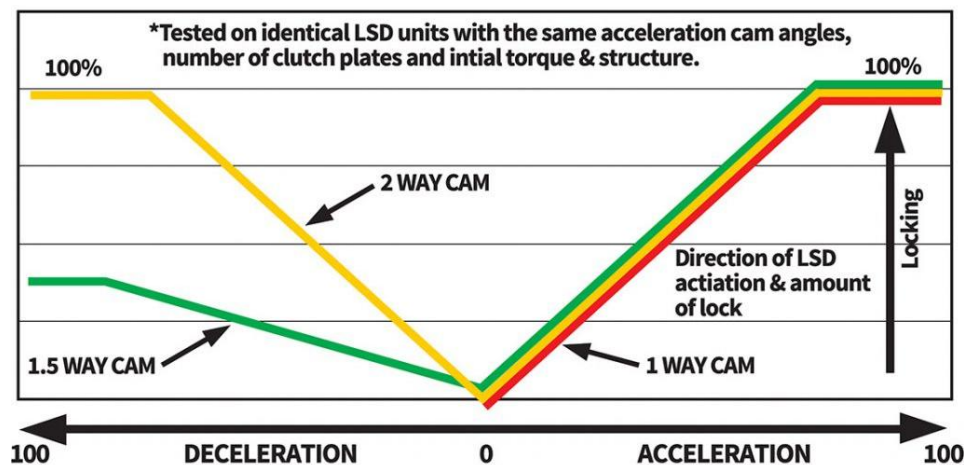


Figure 18: Clutch Pack LSD Ramp Block Configuration Diagram (Turner Motorsport, n.d).



Graph 2: Comparing Ramp Block Configurations on Locking Effects (DSport, 2022).

1.4.3.3 Torque Sensing ('Torsen'):

The torque sensing LSD (commonly referred to as 'Torsen') consists of worm gears, worm wheels and spur gears, instead of a bevel gear design (Figure 19). The fundamental principle underlying the torque sensing differential is that a worm wheel cannot rotate a worm gear, causing instantaneous locking (VanGelder, 2022). The ratio of torque transferred from the wheel with low traction to the wheel with greater traction is referred to as the torque bias ratio, where the formula is demonstrated in equation 17. The torque bias ratio is dictated by frictional forces within the device, typically these friction forces are generated due to contacting surfaces between the side gear and housing, between the two side gears and at the "6 gear meshes at the crossed-axis-helical side gear and element gear" (Shih & Bowerman, 2002). Benefits of this device are: reduced service intervals due to the absence of clutches and viscous fluids, instantaneous torque biasing (not always beneficial), various torque biasing ratios are available dependent on vehicle applications. On the contrary, a disadvantage of this device occurs during jacking events when torque biasing effects are reduced.

$$TBR = \frac{T_{High}}{T_{Low}} \quad (17)$$

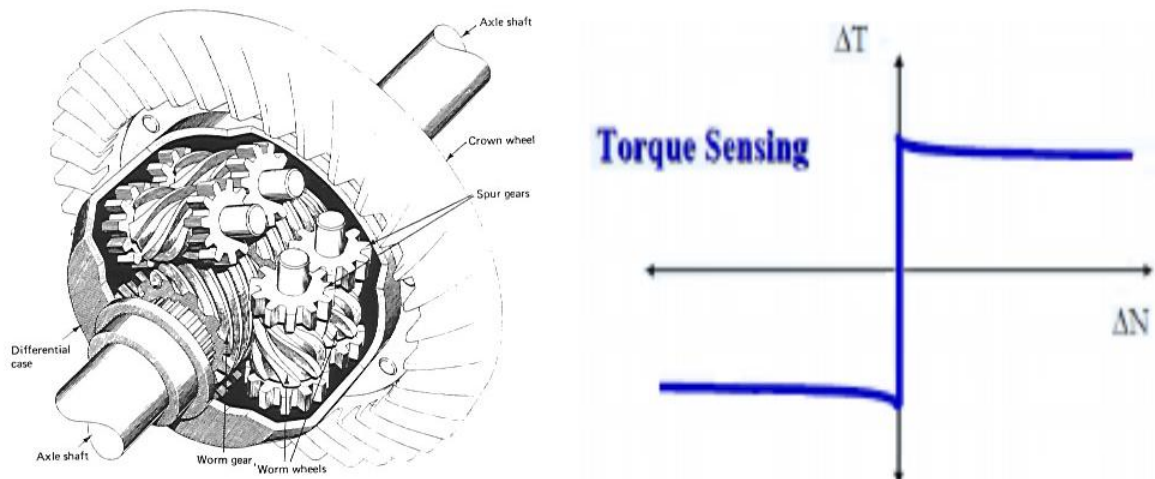


Figure 19: Torque Sensing Differential, (Left) Internal Components Diagram (Wenbourne, 2007), (Right) Locking Effects of Torque Sensing Differential (Bruls, et al., 2011).

1.4.4 Active Limited Slip Differentials

The following section details a semi-active differential and an active electronic LSD (this section refers to the research proposal document (Doyle, 2025)).

1.4.4.1 Electronic Limited Slip Differential

The eLSD is a variation of the active differential. This project investigates a generic actuator with a single clutch pack design (Figure 20 and Figure 21). Main actuator types include electromechanical, electromagnetic, electric motor, and pneumatic (Rubin & Arogeti, 2015). These actuators are controlled by an electronic control module such as YSC. The signal from the control module causes the actuator to compress or decompress the clutch pack, determining the differentials locking effect and torque transferring capacity (Eaton, 2016). The following equations 18-22 are fully derived and available at Rubin and Arogeti (2015):

Considering Figure 21 and the driveline components, the input torque to the differential ring gear is denoted as T_d with subscript g: transmission outputs in equation 18:

$$\bar{I}_{in}\dot{\omega}_g = T_g - n^{-1}T_d \quad (18)$$

Equation 19 is used to calculate the equivalent drive shaft and differential inertia:

$$\bar{I}_{in} = I + n^{-2}I_d \quad (19)$$

Equation 20 calculates transmission output speed as:

$$\omega_g = \frac{n}{2}(\omega_{2l} + \omega_{2r}) \quad (20)$$

Whilst individual wheel velocities are calculated from half shaft dynamics in equations 21 and 22:

$$I_l\dot{\omega}_{2l} = \frac{1}{2}T_d - \frac{1}{2}T_c - T_{2l} \quad (21)$$

$$I_r\dot{\omega}_{2r} = \frac{1}{2}T_d - \frac{1}{2}T_c - T_{2r} \quad (22)$$

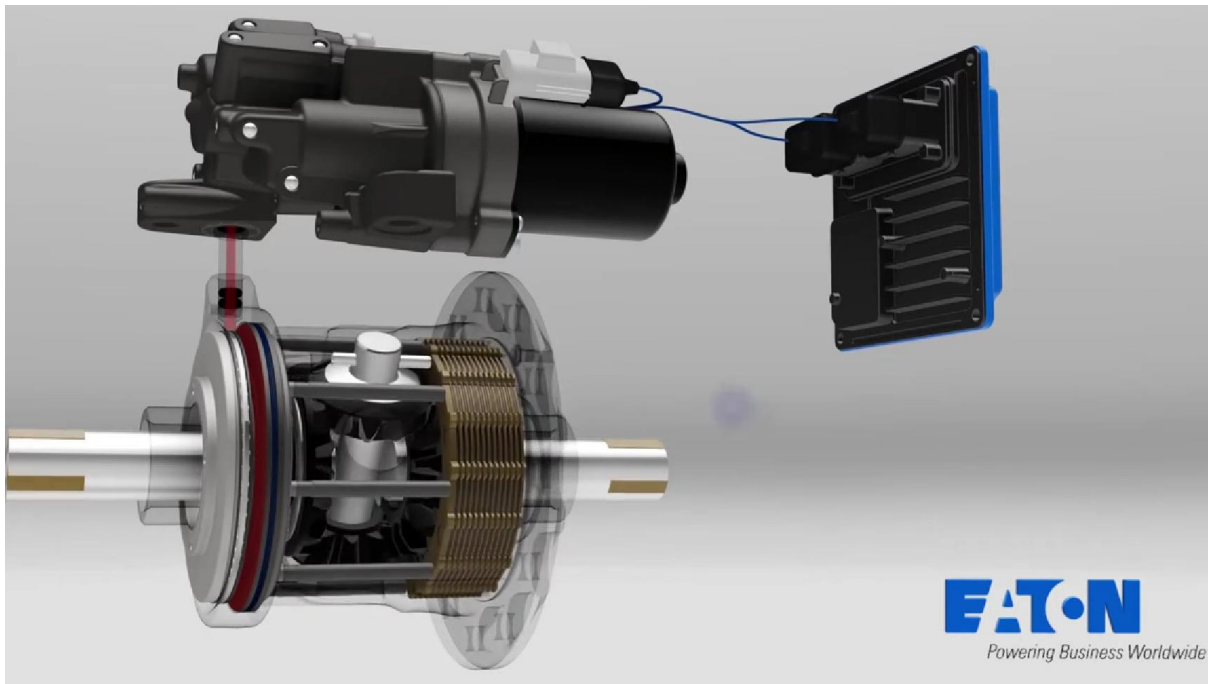


Figure 20: Eaton 'IntelliTrac' Electronic LSD (Eaton, 2016).

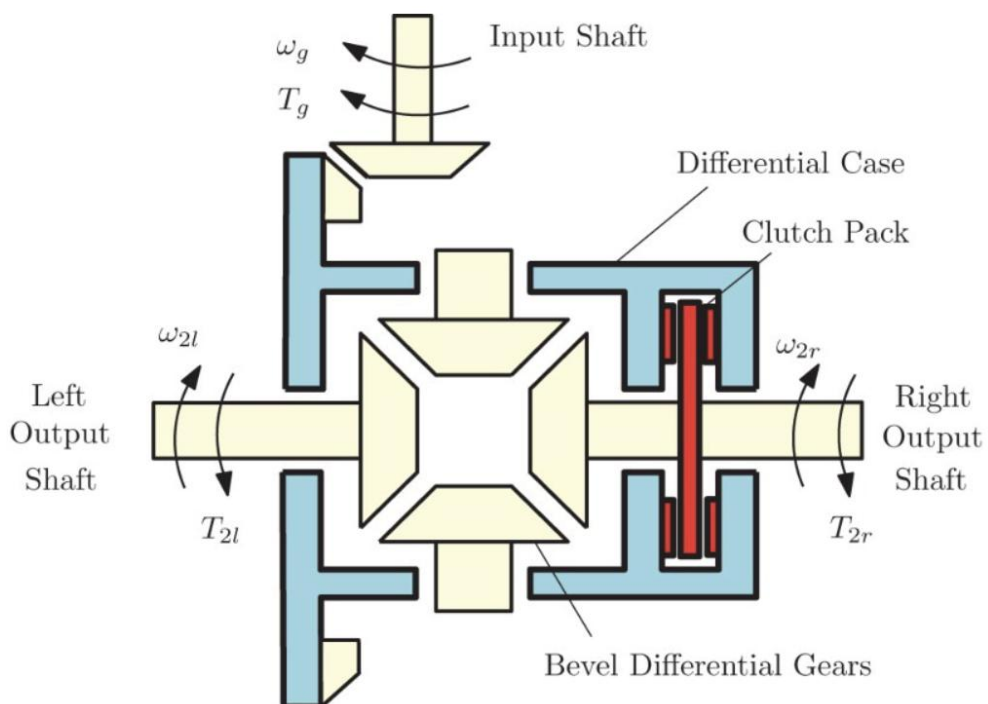


Figure 21: Schematic Diagram of Active Electronic LSD (Rubin & Arogeti, 2015).

1.4.5 Magnetorheological Fluid Limited Slip Differential

A relatively new device in semi-active differential technology is the MRF LSD. MRF contains micron-sized ferrous particles. By applying a magnetic field, the shear stress and rate of the fluid are altered, changing locking torque (Russo, et al., 2016). Due to low viscosity of MRF, the LSD behaves close to open differentials when magnetic fields are absent. Table 1 lists the notations used in Figure 22, which demonstrates a proposed schematic diagram of this LSD.

Table 1: MRF LSD Components and Materials (Russo, et al., 2016).

Number	Description	Material
1	Side Gear A	Standard Steel
2	Side Gear B	Standard Steel
3	Planetary Gear	Standard Steel
4	Differential Case P	Low Carbon Steel
5	Differential Gear	Low Carbon Steel
6	Inner Disk	Low Carbon Steel
7	Outer Disk	Low Carbon Steel
8	Spacer Element	Austenitic Stainless Steel
9	Disk Shaft	Austenitic Stainless Steel
10	Disk Housing	Austenitic Stainless Steel
11	Coil Outer Housing	Low Carbon Steel
12	Coil Inner Housing	Austenitic Stainless Steel
13	Coil	Copper
14	Sealing	Steel
15	Sealing	Steel

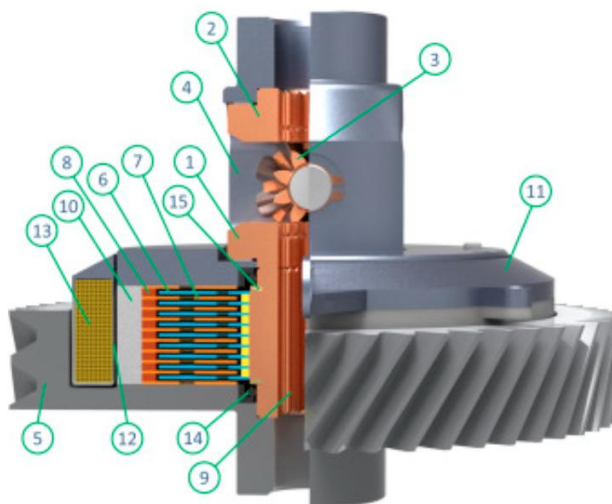
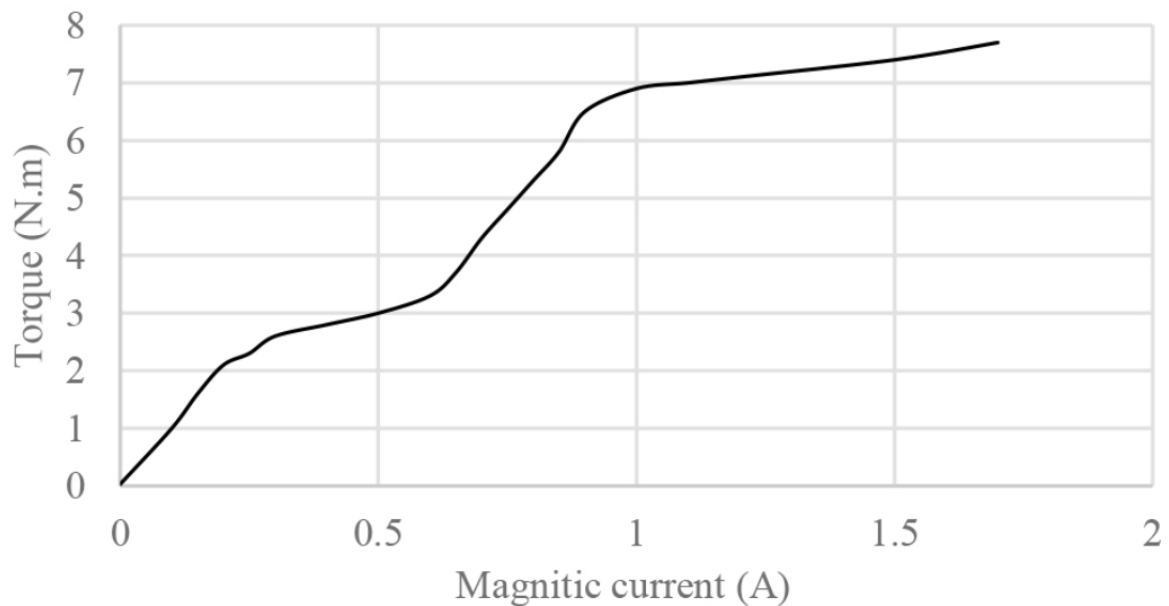


Figure 22: Schematic Diagram of MRF LSD (Russo, et al., 2016).

To control the LSD in slip events, an electromagnetic field requires a calculated supply voltage to the coil, dependent on the LSD controller output. In real-world applications, understanding supply voltage effect on clutch torque and differential locking torque is essential. Graph 3 from Abd elhafiz, & Metered, (2018) shows that higher current increases differential locking torque, with significant effects at lower currents (0-1 Amps). A relationship exists between clutch torque, coil voltage, and shaft relative rotary speed, expressed as a function in equation 23 (Abd elhafiz & Metered, 2018). The angular velocity of the differential case can be calculated as an average of the left and right axle angular velocities (Russo, et al., 2016).

$$M = \frac{n\omega}{g}AR^2 - 0.0264u^2 + 0.3538u + 0.105 \quad (23)$$



Graph 3: MRF LSD Current and Locking Torque Graph (Abd elhafiz & Metered, 2018).

2 Methodology and Testing

Due to this project being theoretical and simulation based, no physical testing is conducted. With the lack of real-world data to compare and verify results, a carefully devised testing methodology is created to ensure result validity (Figure 23). Limitations of these modelling techniques will inevitably introduce certain assumptions into the models; these will be stated throughout model construction and included in results analysis.

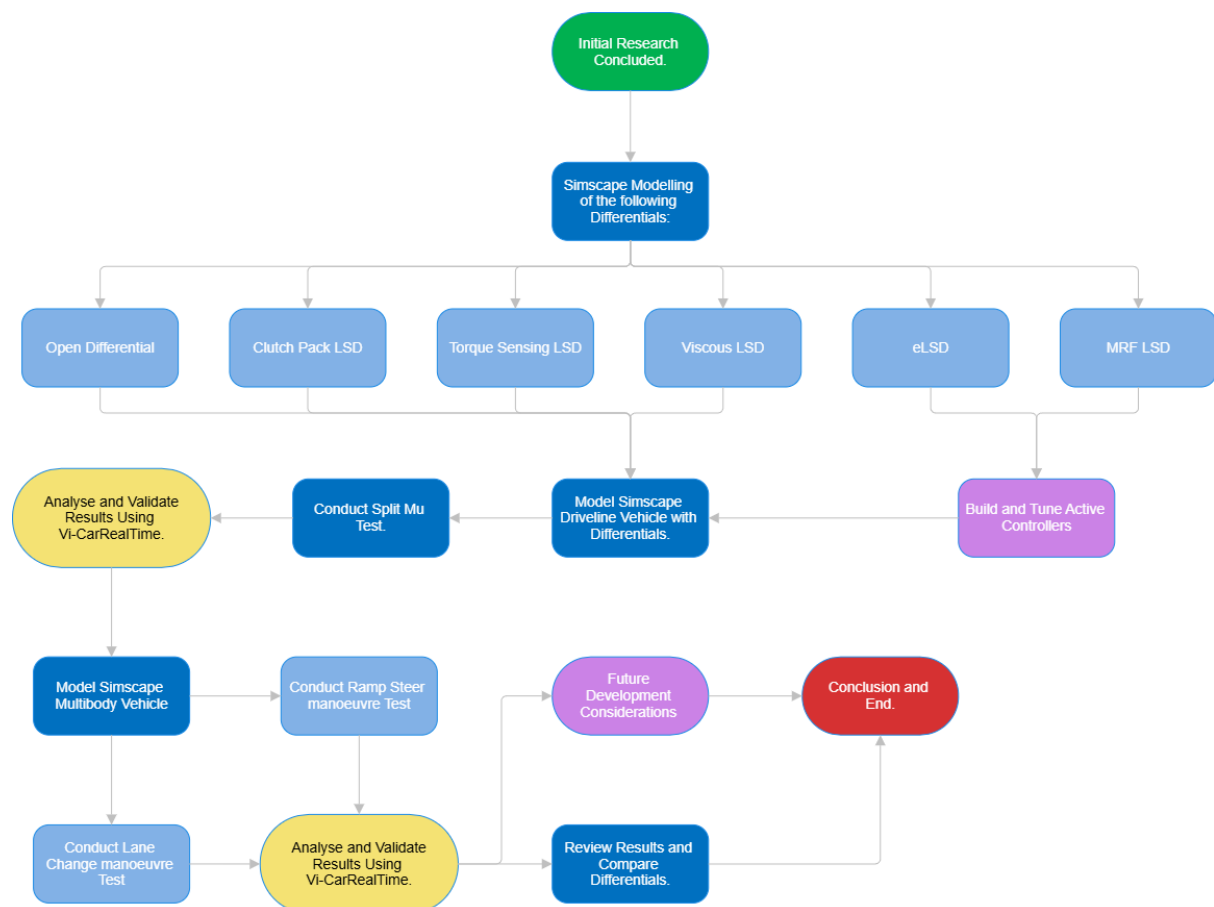


Figure 23: Project Modelling and Testing Flowchart Methodology.

2.1 Simscape Driveline Modelling

Initial modelling was conducted using Simscape Driveline to gain a better understanding of the differential behaviours and characteristics. This section details the principles behind the model, building of the model and any input signals/control systems.

2.1.1 Simscape Driveline Differential Modelling

Prior to construction of the full vehicle model, each differential is modelled using Simscape blocks within Simulink. Custom components are also created using the Simscape Language to integrate new features within the models (Mathworks [5], 2025). MATLAB examples built into the software have been used as a reference and baseline for building the differentials detailed below.

2.1.1.1 Simscape Driveline Open Differential

The open differential (Figure 24) is modelled using three Simscape blocks: ‘simple gear’ and 2 ‘sun planet bevel gears’ (Mathworks [6], 2025). The simple gear is used to model the differential ring gear which accounts for the final drive ratio where the teeth ratio is set as follower/base: 1.33, and a meshing losses efficiency set as 85% to represent driveline losses. The 2 ‘sun planet bevel gears’ are used to model the spider gear and side gear of each respective axle. The driveline connection to the rest of the model is made from input connection port (‘DRV’) whilst the left and right driveshaft connection ports are labelled ‘FL’ and ‘FR’. An ideal torque sensor is implemented to monitor ring gear torque.

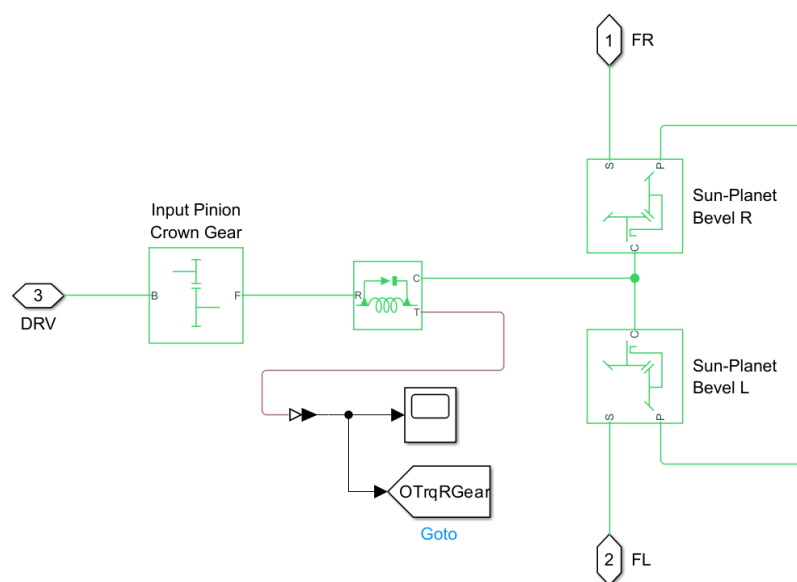


Figure 24: Simscape Driveline Open Differential Model.

2.1.1.2 Simscape Driveline Clutch Pack LSD

Modelling of the clutch pack LSD is completed by developing the open differential model. The model (Figure 25) consists of the same previously mentioned Simscape blocks with the addition of 2 ‘disk friction clutches’, a ‘torsional spring damper’ and a torque to pressure subsystem (Mathworks [7], 2025). Ideal torque sensor 1 is used to analyse the torque input to the differential from the driveline, allowing for a driveline-based pressure application to the clutch packs. The subsystem ‘Torque to Pressure’ is demonstrated in Figure 26 where the input torque signal is converted to pressure per unit torque and summed with the preload constant (500 Pa) used to represent the preload springs within the LSD. Small amounts of lag are added to account for compliance within the model. The disk friction clutches respond to the pressure input signal, when this value exceeds a specified threshold, the clutch plates lock together. If the torque input into the clutch pack exceeds the maximum torque transferring capabilities, the clutch pack unlocks and friction surfaces slip. A torsional spring-damper is added to reduce model stiffness and allow for small amounts of compliance within the model, assisting the solver.

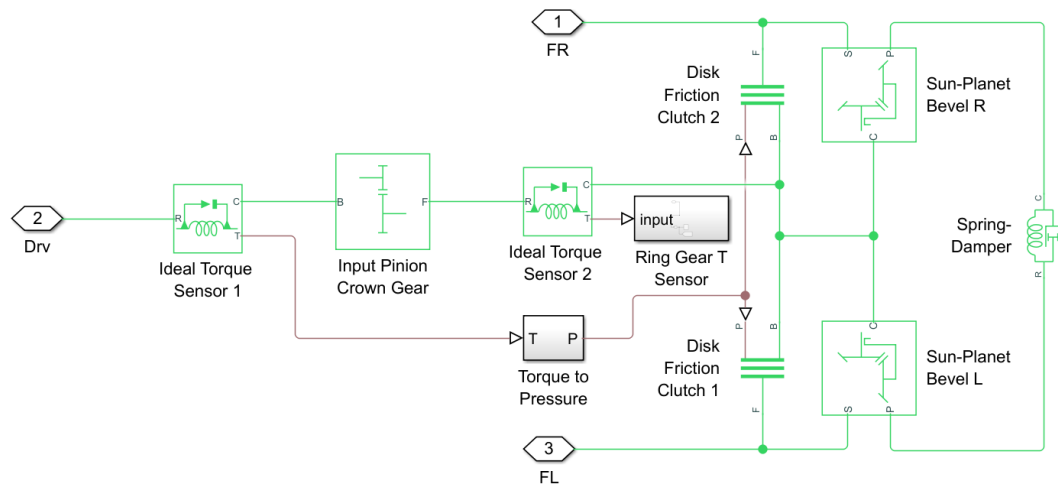


Figure 25: Simscape Driveline Clutch Pack LSD Model.

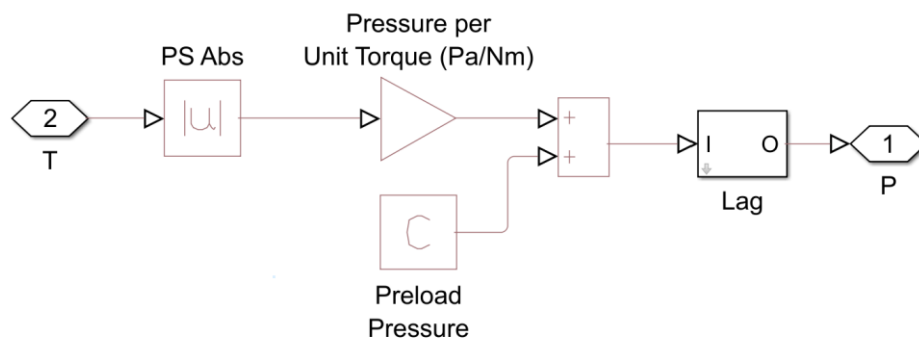


Figure 26: Simscape Driveline Clutch Pack LSD Torque to Pressure Subsystem.

2.1.1.3 Simscape Driveline Torque Sensing LSD

The torque sensing LSD is modelled using the following fundamental Simscape blocks: 2 ‘simple gears’ and 2 ‘sun-planet worm gears’ Figure 27. Due to the design of the torque sensing LSD, this model replaces the sun planet bevel gears with sun-planet worm gears, a simple gear is used to represent the worm wheel. Due to the design of this LSD, a worm wheel cannot rotate a worm gear (VanGelder, 2022).

As a torque sensing LSD is dependent on frictional forces between the gearing, casing and other components to bias torque, frictional meshing losses are implemented into the worm gear as 74% efficient and 92% efficient for the worm wheels (Mathworks [8], 2025). The current model utilises a TBR of 9:1, where torque transferred is equal to the maximum applicable torque to low friction side without slipping - multiplied by the TBR (Torsen Traction, n.d.). Whilst this is unfeasible for a FWD torque sensing LSD, it does accurately depict the locking characteristics of a torque sensing LSD, as detailed in the results section. This high of a TBR is selected for testing purposes, to ensure the vehicle is on an equal/similar performance level to all other devices tested in this project.

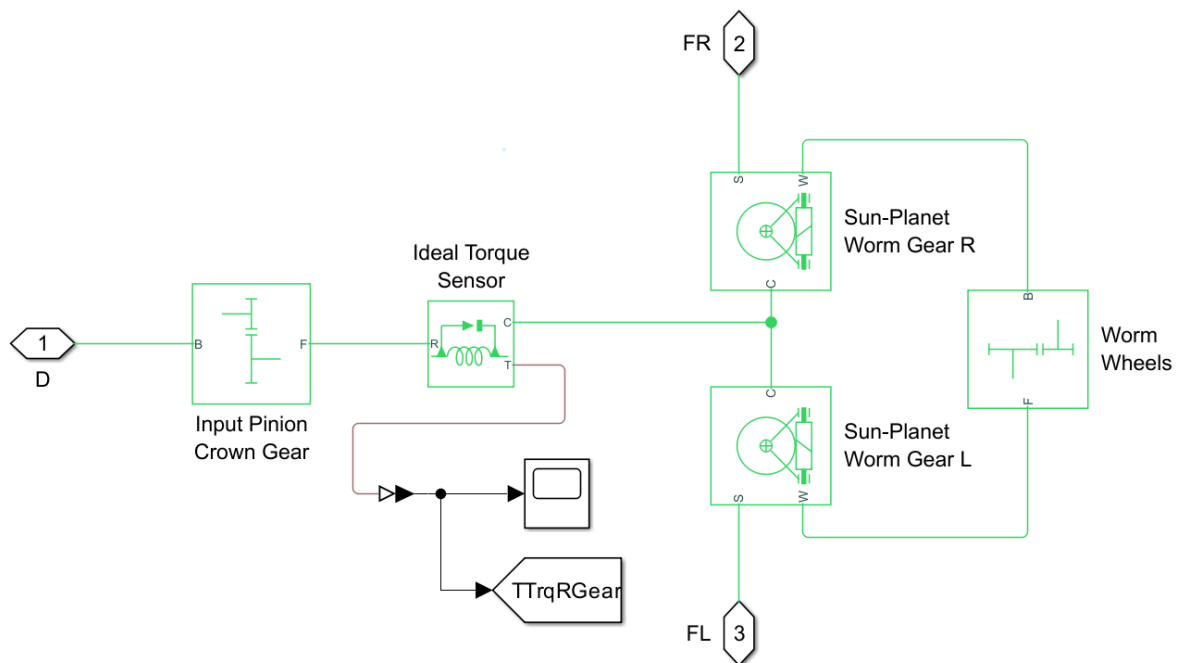


Figure 27: Simscape Driveline Torque Sensing LSD Model.

2.1.1.4 Simscape Driveline Viscous LSD

The modelling of a Simscape driveline viscous LSD is demonstrated in Figure 28, this system is again based on the open differential with the addition of a rotational damper to replicate the effects of a viscous coupling unit. Due to the implementation of a rotational damper, the model is therefore dependent on the wheel speed difference to transfer torque which is true for the real-world variant. Properties of this differential can be altered by adjusting the damping coefficient, within this exemplified model, the damping coefficient is set at 2000 N*m*s/rad. As a real-world viscous coupling unit is connected to the differential case and one of the axle half shafts, the model is configured to replicate this by connecting one port of the rotational damper to the centreline signal (essentially the differential case), and the other port to the right-side sun planet bevel gear output signal (axle shaft).

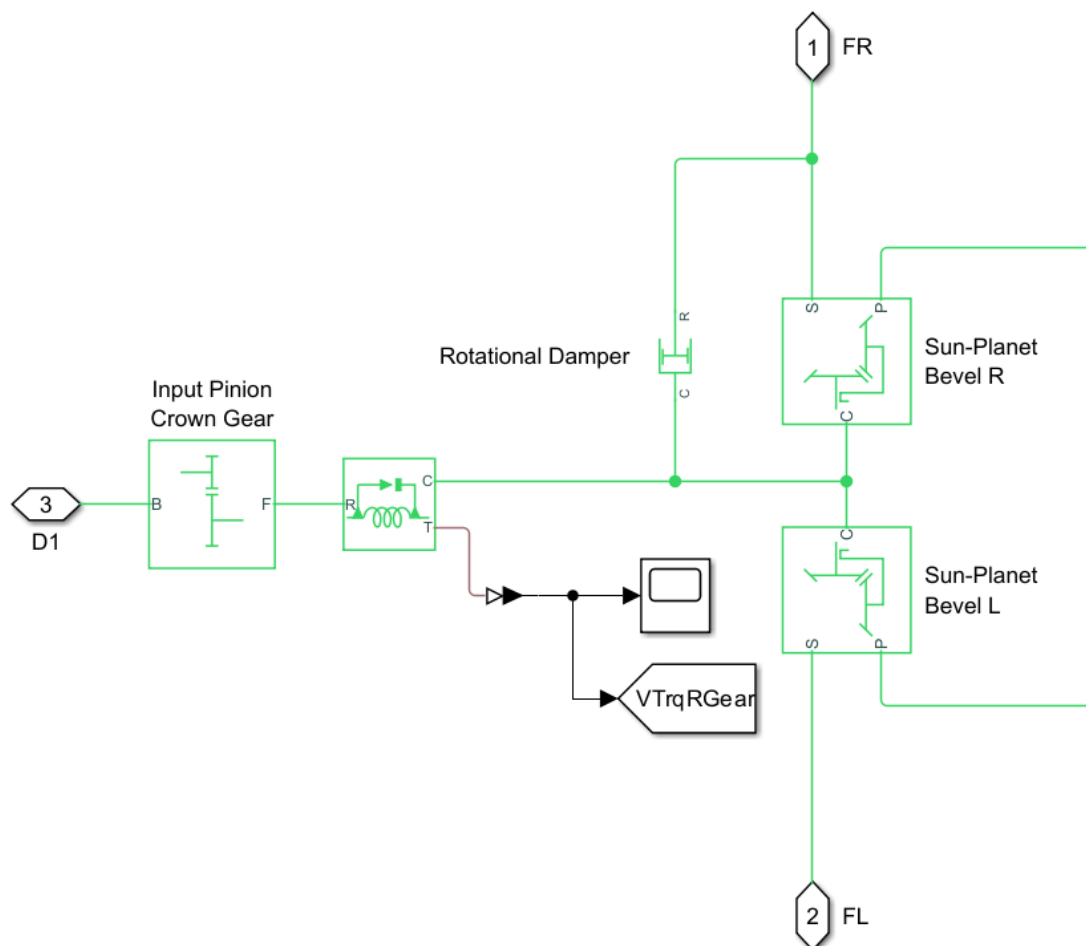


Figure 28: Simscape Driveline Viscous Coupling LSD Model.

2.1.1.5 Simscape Driveline Electronic LSD

The eLSD model is based on the Eaton clutch type demonstrated in Figure 20 (Eaton, 2016). Due to the eLSD having similar mechanical components to the clutch pack LSD (excluding actuation method and control system), most of these components within the two differentials are similar. For control system implementation within the Simscape model, two ‘Logic-Controlled Clutch’ blocks (Figure 29) replace the pressure actuated ‘Disk Friction Clutch’ used within the clutch pack LSD. To reduce simulation duration, electronic and hydraulic physical domain modelling of the eLSD actuation control system are excluded; this assumption does reduce model accuracy in respect to eLSD response time. It should therefore be anticipated that a true eLSD will exhibit a marginally longer delay in response time, this demonstrates the downside to virtual testing without hardware in the loop experimentation. Gearing parameters remain the same as previous differential models to act as a control variable, thus ensuring only differential characteristics are the focus of this investigation. A torsional spring-damper block is connected to the model to reduce stiffness and add compliance (Pena, et al., 2020). The spring and damper rates are set to high values to minimise effects on simulation results. Details of the control system are mentioned in section 2.1.3.

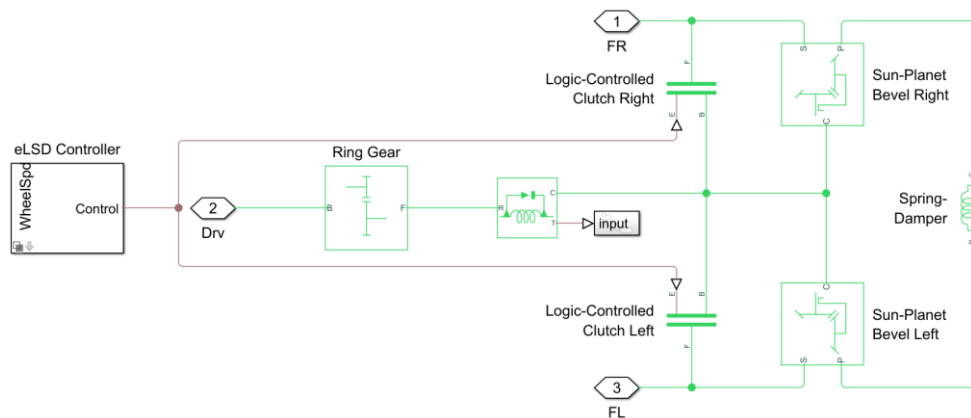


Figure 29: Simscape Driveline eLSD Model.

Logic-Controlled Clutch			Torsional Spring-Damper		
Settings	Description		Settings	Description	
NAME	VALUE		NAME	VALUE	
Parameters			Spring-Damper		
Transition model	First-order lag		Spring stiffness	50000	N*m/rad
> Transition time constant	0.1	s	> Viscous friction coefficient	10000	N*m/(rad/s)
> Kinetic friction torque	300	N*m	Coulomb friction torque	0	N*m
> Static friction torque	1500	N*m	> Ratio of static to kinetic friction	1.1	
> Clutch velocity tolerance	0.001	rad/s	> Velocity tolerance	0.001	rad/s
Initial state	Unlocked		Hard Stops		
			Initial Conditions		

Figure 30: eLSD Setup Parameters, (Left) Clutch Data, (Right) Torsional Spring-Damper Data for Compliance.

2.1.1.6 Simscape Driveline Magnetorheological LSD

Modelling of the MRF LSD within Simscape required construction of a custom Simscape block, demonstrated in Figure 31 with the ‘MRF Clutch Pack Left/Right’ blocks. The remaining aspects of the differential are consistent with that of the open differential, with the addition of torsional spring damper block for reduced model stiffness and increased compliance within the developed Multibody model.

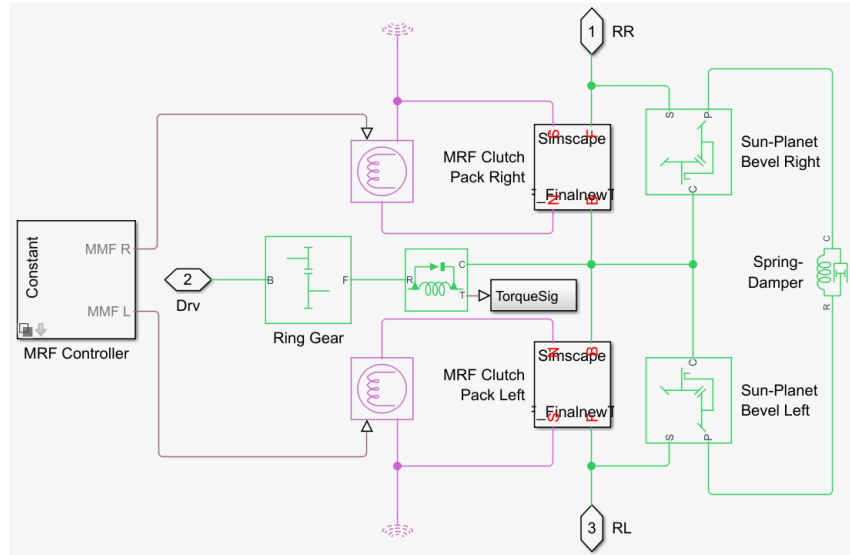
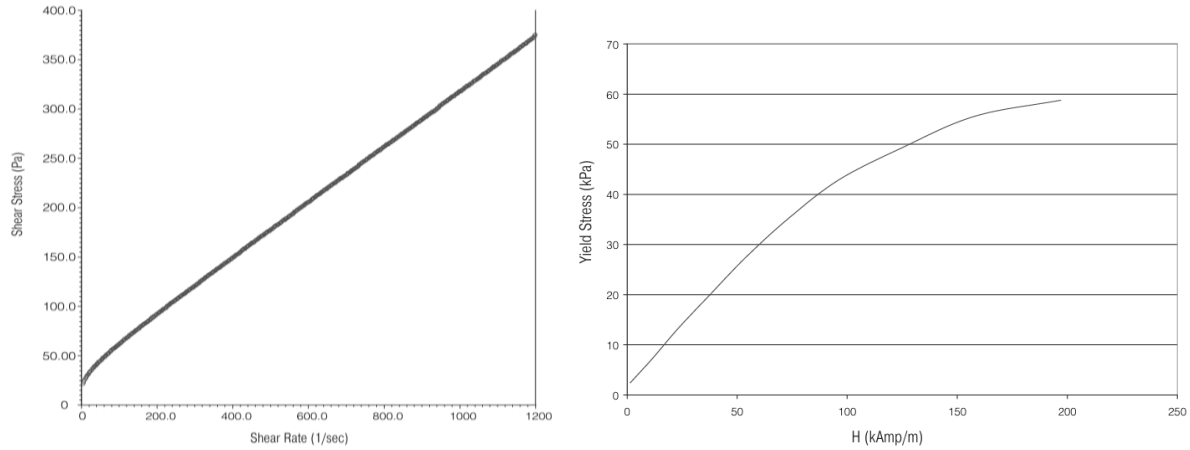


Figure 31: Simscape Driveline Magnetorheological Fluid LSD Model.

The fundamental principles of this differential and Simscape block are based on the fluid dynamics of MRF within the clutch pack. This therefore integrates magnetism and clutch mechanics into the block script and equations. The fluid within this clutch pack is based on the Parker Lord MRF-140CG Magneto-Rheological Fluid for technical data (Parker Lord, 2024). The data in Graph 4 (right) is utilised as a lookup table within the custom Simscape block to represent the magnetic field strength effect on yield stress. Whilst Graph 4 (left) is not perfectly linear, in fluid mechanics the Bingham model (equation 24) is often used to describe similar non-Newtonian fluids (Park, et al., 2022). Testing of the fluid results in a fluid viscosity of 0.336 Pa.s (Parker Lord, 2024), this value can be used as the gradient in the Bingham model demonstrated, equation 25.

$$\tau = \tau_y + \eta\gamma \quad (24)$$

$$\tau = \tau_y + 0.336\gamma \quad (25)$$



Graph 4: MRF-140CG Data Sheet Plots, (Left) Shear Stress as a Function of Shear Rate with no Magnetic Field Applied at 40 Degrees Celsius, (Right) Yield Stress against Magnetic Field Strength (Parker Lord, 2024).

Additional equations utilised in the calculation of torque transfer within the MRF clutch pack include angular velocity difference (equation 26), shear rate formula (equation 27), area of a circle (equation 28), stress equation (equation 29) and torque formula (equation 30).

$$\Delta\omega = \omega_D - \omega_P \quad (26)$$

$$\gamma = \frac{r \times \Delta\omega}{d} \quad (27)$$

$$A = \pi r^2 \quad (28)$$

$$\sigma = \frac{F}{A} \therefore F = \sigma \times A \quad (29)$$

$$T = R \times F \sin(\theta) \quad (30)$$

The magnetics equation relating MMF to magnetic field strength is described in equation 31 and is a crucial aspect of this differentials control mechanism (Karapetoff, 2003). Once the magnetic field strength is calculated from MMF, yield stress of the MRF can be interpolated from a MATLAB lookup table and utilised in the custom Simscape block (Figure 32); lookup table data is based on the Parker Lord product datasheet in Graph 4 – Right.

$$H = \frac{mmf}{l} \quad (31)$$

The force of the fluid can therefore be expressed in terms of the Bingham model and clutch plate area, equation 32 (outer subtract inner radius), additionally expressed by replacing shear rate (equation 33):

$$F = (\tau_y + \eta\gamma) \times (\pi r_o^2 - \pi r_i^2) \quad (32)$$

$$\therefore F = \left(\tau_y + \eta \left(\frac{r \times \Delta\omega}{d} \right) \right) \times (\pi r_o^2 - \pi r_i^2) \quad (33)$$

MRF clutch torque is expressed in equation 34, by combining equation 30 and 33:

$$T = R \times \left(\left(\tau_y + \eta \left(\frac{r \times \Delta\omega}{d} \right) \right) \times (\pi r_o^2 - \pi r_i^2) \right) \quad (34)$$

Due to a clutch pack having multiple friction surfaces, an additional term 'n' is included within the formula to account for this, equation 35:

$$T = n \times \left(R \times \left(\left(\tau_y + \eta \left(\frac{r \times \Delta\omega}{d} \right) \right) \times (\pi r_o^2 - \pi r_i^2) \right) \right) \quad (35)$$

The following assumptions are made within the above calculations: the fluid is assumed to behave in a linear manner with the Bingham plastic model, and that the torque strength is calculated at the singular outer radius of the clutch pack, instead of the torque generated at each point of the clutch surface. Although the above assumptions reduce the true value accuracy of the torque transmitted, the general properties of the clutch pack are adequately captured (Park, et al., 2022). The magnetic effect of the coil is vital to the operation of the MRF LSD, this is implemented into the lookup table aspect of the yield stress using the data from Graph 4 (right). Equation 35 is then incorporated into the Simscape model by means of a custom Simscape block written in the Simscape language (Mathworks [5], 2025), demonstrated Figure 32.

```

component MRF_FinalnewType
% MRF Clutch
% The MRF clutch model simulates a multiplate clutch pack filled with MR
% fluid. The properties of the MRF fluid are based on the Parker Lord
% MRF-140CG MR fluid data sheet, a Bingham plastic model is used to model
% the fluid properties whilst a lookup table based on the data sheet is
% implemented to replicate fluid behaviour.

nodes
    B = foundation.mechanical.rotational.rotational; % B:left
    F = foundation.mechanical.rotational.rotational; % F:right
    N = foundation.magnetic.magnetic; % N:left
    S = foundation.magnetic.magnetic; % S:right
end

parameters
    FVisc = { 0.336, '(N*s)/m^2' }; % Fluid viscosity
    ro = {150e-3, 'm'}; % Clutch plate outer radius
    ri = {130e-3, 'm'}; % Clutch plate inner radius
    nusurf = {4, '1'}; % Number of friction surfaces
    d = { 2e-3, 'm'}; % Distance between plates
    L = { 75e-3, 'm'}; % Length of magnetic path
    Mag_axis = { [0], 'N/m^2' }; % Magnetic field strength lookup table data
    ySint = { [0], 'N/m^2' }; % Yield stress lookup table data
    mu0 = {4*pi*1e-7, 'N/(A^2)'}; % Vacuum permeability
    mu_r = {200, '1'}; % Relative permeability of MR-fluid and material
    Alpha = { 0.6, '1'}; % Kinetic Friction Scalling Factor
    w_tol = {1e-3, 'rad/s'}; % Slip tolerance
    initial_state_locked = sdl.enum.initial_lock.unlocked; % Initial state
end

components(ExternalAccess = observe) % This section implements the fundamental friction clutch
    fundamental_clutch = sdl.clutches.fundamental_components.fundamental_clutch(...
        unidirectional = 0, w_tol = w_tol, initial_state_locked=initial_state_locked,...
        temperature.priority = simscape.priority.none);
end

variables
    t = { 0, 'N*m'}; % Torque variable
    TauY = { 0, 'N/m^2'}; % Yield stress of MRF fluid
    phi = { 0, 'Wb'}; % Magnetic flux
    mmf = { 0, 'kA'}; % Magnetic motive force
    H = { 0, 'kA/m'}; % Magnetic field strength
    Slip = { 0, 'rad/s'}; % Wheel speed difference
    A_eff = { 0, 'm^2'}; % Effective area of clutch plate
    tmax = { 0, 'N*m'}; % Maximum torque transferable by MRF clutch
end

branches
    phi : N.phi -> S.phi;
    t : B.t -> F.t;
end

equations
% Magnetics and yield stress calculations
    mmf == abs(N.mmf - S.mmf); % Calculation of MMF
    H == mmf / L; % Magnetic field strength
    phi == mu0 * mu_r * H * (pi * (ro^2 - ri^2)); % Magnetic flux calculations
    TauY == tablelookup(Mag_axis, ySint, H, interpolation=smooth, extrapolation=nearest); % MRF yield stress lookup table

% Torque and other associated equations
    if mmf == 0 % Prevents inverting torque
        Slip == abs(F.w - B.w); % Wheel slip
    else
        Slip == F.w - B.w;
    end

    A_eff == pi * (ro^2 - ri^2); % Disc effective area
    tmax == TauY * A_eff * ro * nusurf; % Maximum transmittable torque
    t == (nusurf * (ro * (TauY + FVisc * ((ri * (Slip)/ d)) * ((pi * ro^2) - (pi * ri^2))))); % Torque transmitted

% Clutch locking mechanism and assignment to fundamental block
    fundamental_clutch.tK == Alpha * TauY * A_eff * ro * nusurf;
    fundamental_clutch.tP == tmax;
    fundamental_clutch.tM == -tmax;
end

connections
    connect(fundamental_clutch.B,B)
    connect(fundamental_clutch.F,F)
end
end

```

Figure 32: Simscape MRF Clutch Component Written in Simscape Language.

2.1.2 Simscape Driveline Vehicle Model

In addition to the differential models, Simscape driveline permits construction of vehicle models in the longitudinal and vertical displacement axes, Figure 33 demonstrates the landing page of the FWD driveline model. The model is partitioned into subsystems to isolate distinct elements, including road condition inputs, differential vehicle configurations, and the results analysis module.

FWD Differential Model

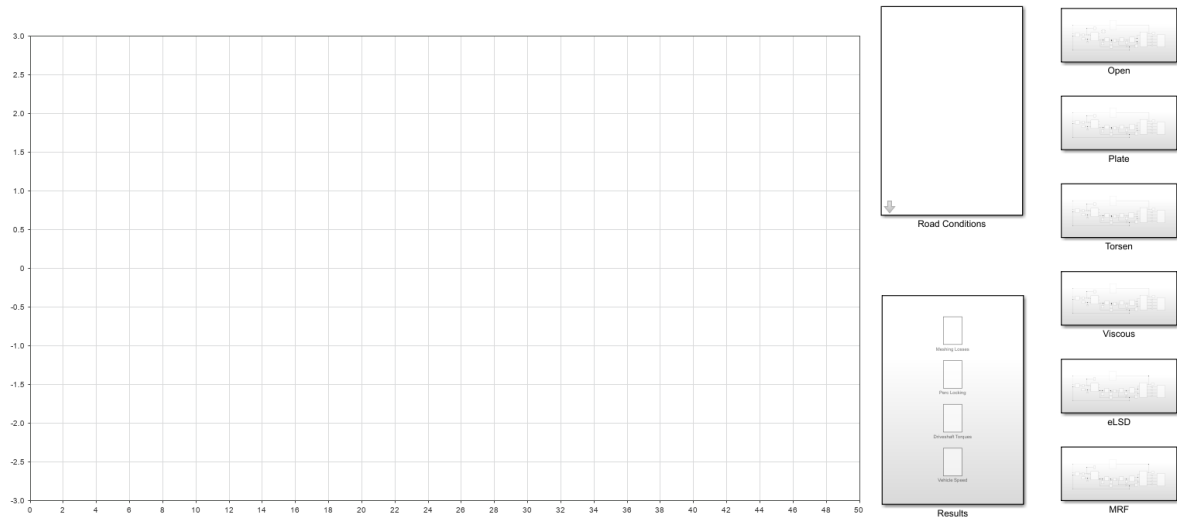


Figure 33: Simscape Driveline FWD Vehicle Model.

The open differential drivetrain utilises the annotated Simscape blocks demonstrated in Figure 34, user generated ‘stateflow chart’ and vehicle body subsystem; this configuration is the same for each differential subsystem in Figure 33. A simple gear with a follower to teeth ratio of 1.33 is used instead of a gearbox to reduce model solve time and stiffness. The torque converter is utilised to transmit engine power to the driveline and is based on a two-mode coast transition model (Mathworks [9], 2025).

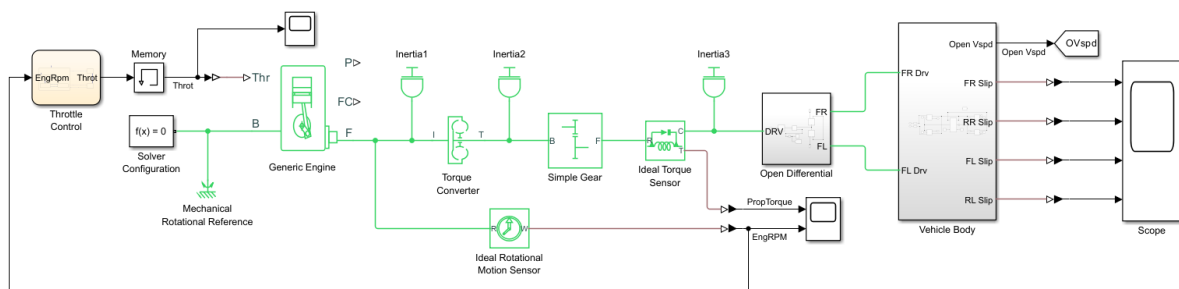
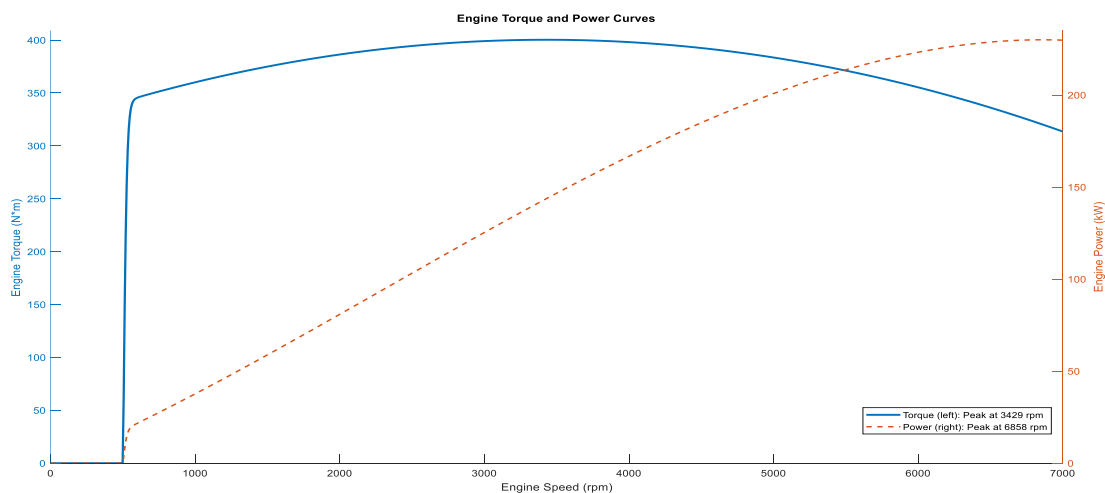


Figure 34: Simscape Driveline Vehicle Driveline Model - Open Differential.

The power and torque curves for the engines utilised in the Simscape driveline model are demonstrated in Graph 5. This engine data is the same for each differential driveline model to ensure consistent control parameters. The stall speed threshold is set at 500rpm, whilst redline is introduced at 5800rpm within the stateflow chart throttle controller, demonstrated in Figure 35. The throttle controller uses engine rpm as an input and generates a throttle output. The stateflow chart has three states (ThrotInc, WOT and Redline) which it transitions between based on specified conditions. The 'ThrotInc' (Throttle Increase) state uses a sub-chart to increase the throttle output in a sine wave (from 0-90 degrees) format that increases in value based on a specified simulation time step. 'WOT' (Wide Open Throttle) is activated when the throttle ('Throt') value equals 1 and the 'RedLine' state is activated if engine rpm equals or exceeds 5800rpm. Upon activation of the redline state, the throttle output value is reduced to 0.2 for a specified time (2.5 seconds as demonstrated in Figure 35).



Graph 5: Simscape Driveline Engine Power and Torque Curves.

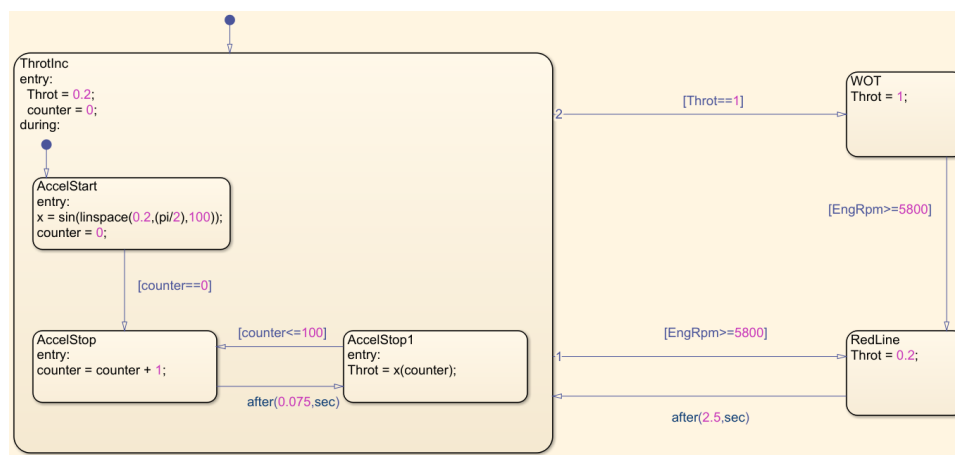


Figure 35: Simscape Driveline Throttle Control Stateflow Chart.

Modelling of the vehicle body and tyres is demonstrated in Figure 36 where connection inputs from the differential are represented as ‘FR Drv’ and ‘FL Drv’. The connection ports are then linked to driveshafts which are modelled using a rotational damper and inertia block, ultimately attaching to the respective wheel. Due to the vehicle being FWD, the rear wheels are connected to a ‘rotational free end’ block to allow free rotation in respect to vehicle movements, whilst maintaining a physical connection to the ground within the model. The tyre blocks are modelled using the MF, as described in the literature review. The road control subsystems (‘R Road’ and ‘L Road’) provide MF coefficient values to the tyre based on preselected road conditions (detailed in Figure 37). Ports ‘NF’ and ‘NR’ correspond to normal force front and rear, which are calculated within the vehicle body and are based on forces, motion and setup data of the vehicle. Connection ports beta and W represent road inclination and wind speed respectively; both are set at a constant zero.

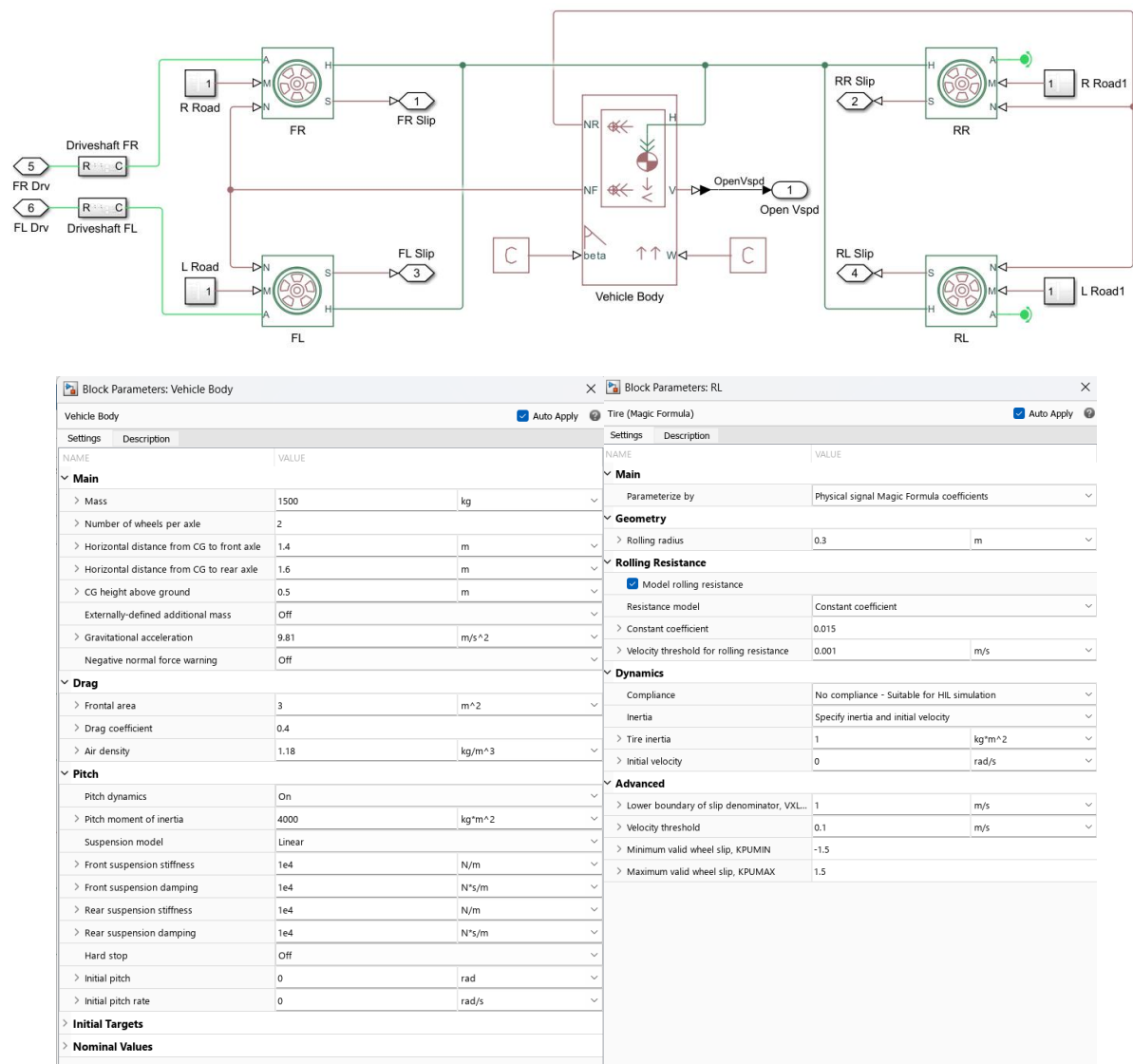


Figure 36: (Top) Simscape Vehicle Model, (Bottom Left) Vehicle Parameters, (Bottom Right) Tyre Parameters.

With the Simscape tyre models configured to utilise an input vector for MF coefficients, the block mask and subsystem demonstrated in Figure 37 (left) allow the model to run a split mu or consistent surface simulation (Mathworks [2], 2025), based on user input. The data in Table 2 demonstrates MF coefficient values for road conditions: dry tarmac, wet tarmac, snow and ice. The subsystem shown in Figure 38 is the contents of blocks ‘R Road’ and ‘L Road’ within Figure 36 and controls the coefficient outputs that are then connected to the vehicle’s tyres.

Table 2: Magic Formula Coefficients for Various Road Conditions (Mathworks [2], 2025).

Surface	B	C	D	E
Dry tarmac	10	1.9	1	0.97
Wet tarmac	12	2.3	0.82	1
Snow	5	2	0.3	1
Ice	4	2	0.1	1

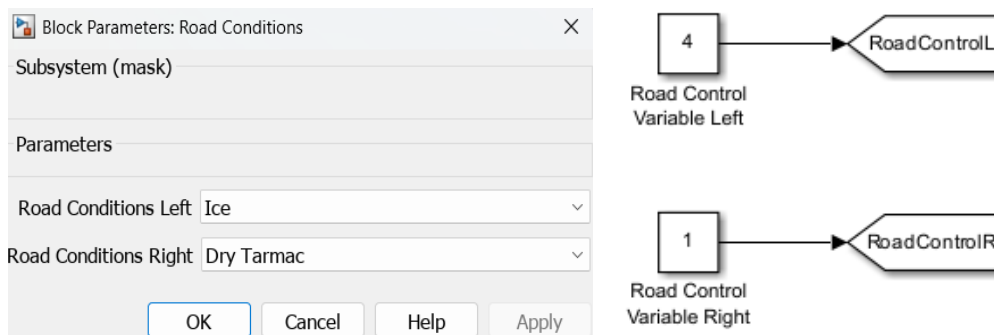


Figure 37: Vehicle Road Condition Control System, (Left) Road Conditions Subsystem Block Mask, (Right) Linked Constant Blocks to Road Conditions Subsystem Mask Parameters.

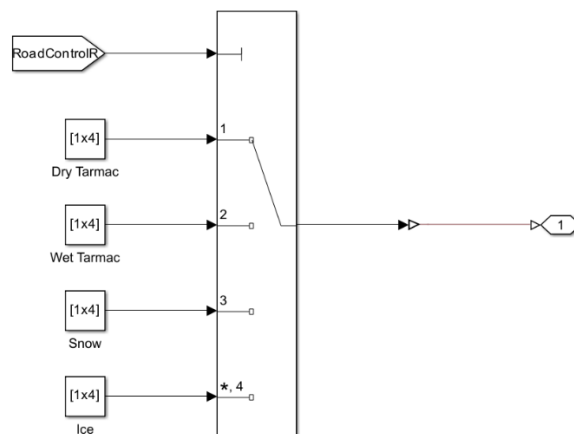


Figure 38: Switch Controller of MF Vector Values.

2.1.3 Simscape Driveline Active Differential Control Systems

The Simscape Driveline active differential models consist of 3 different control systems constructed within a variant subsystem labelled eLSD and MRF Controller respectively. Whilst each differential has an individual control system with unique parameter values, the fundamental control methods remain consistent. Control variant 1 applies a constant user specified value throughout the simulation duration, variant 2 provides a ramped saturated signal, whilst variant 3 utilises a PID controller based on wheel slip. The subsystem contents are demonstrated in Figure 39 with adjacent signal examples, an important note: these signals are examples, the PID controller output is specific to a high drive torque split mu scenario – outputs vary based on setup parameters.

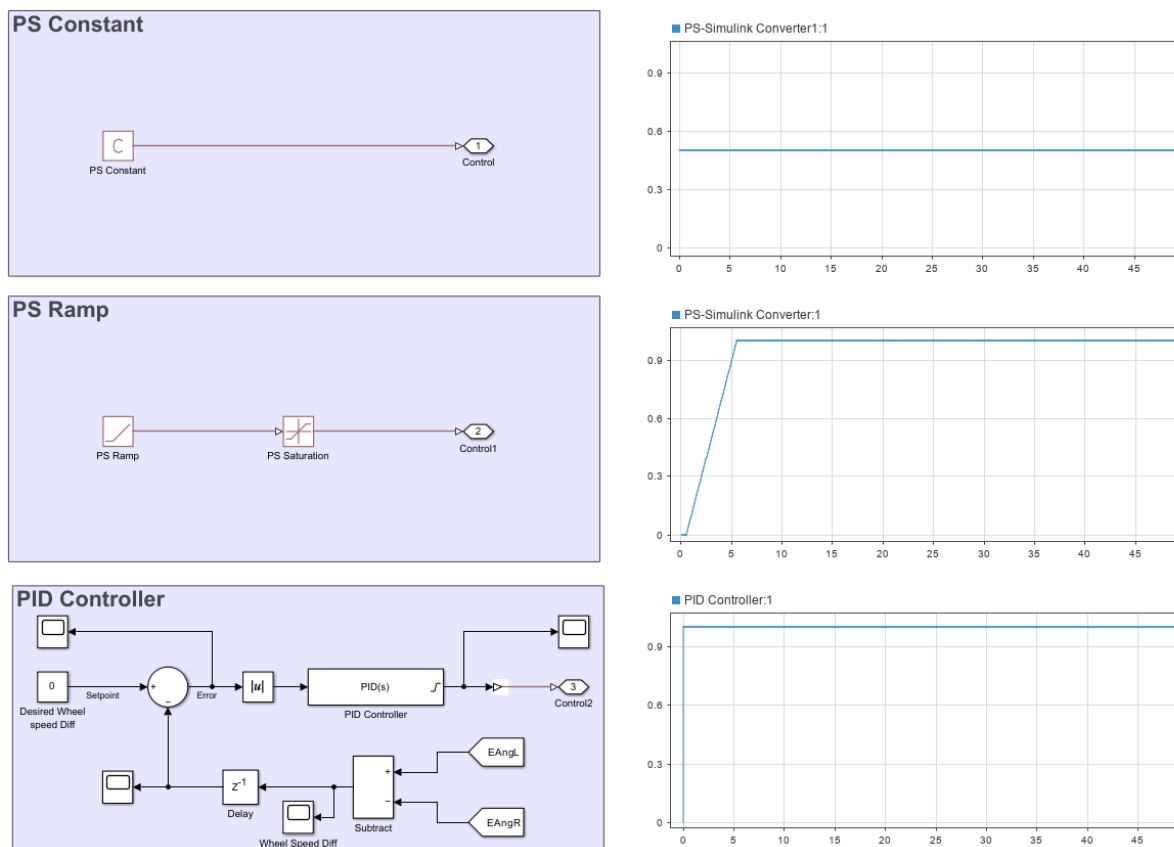
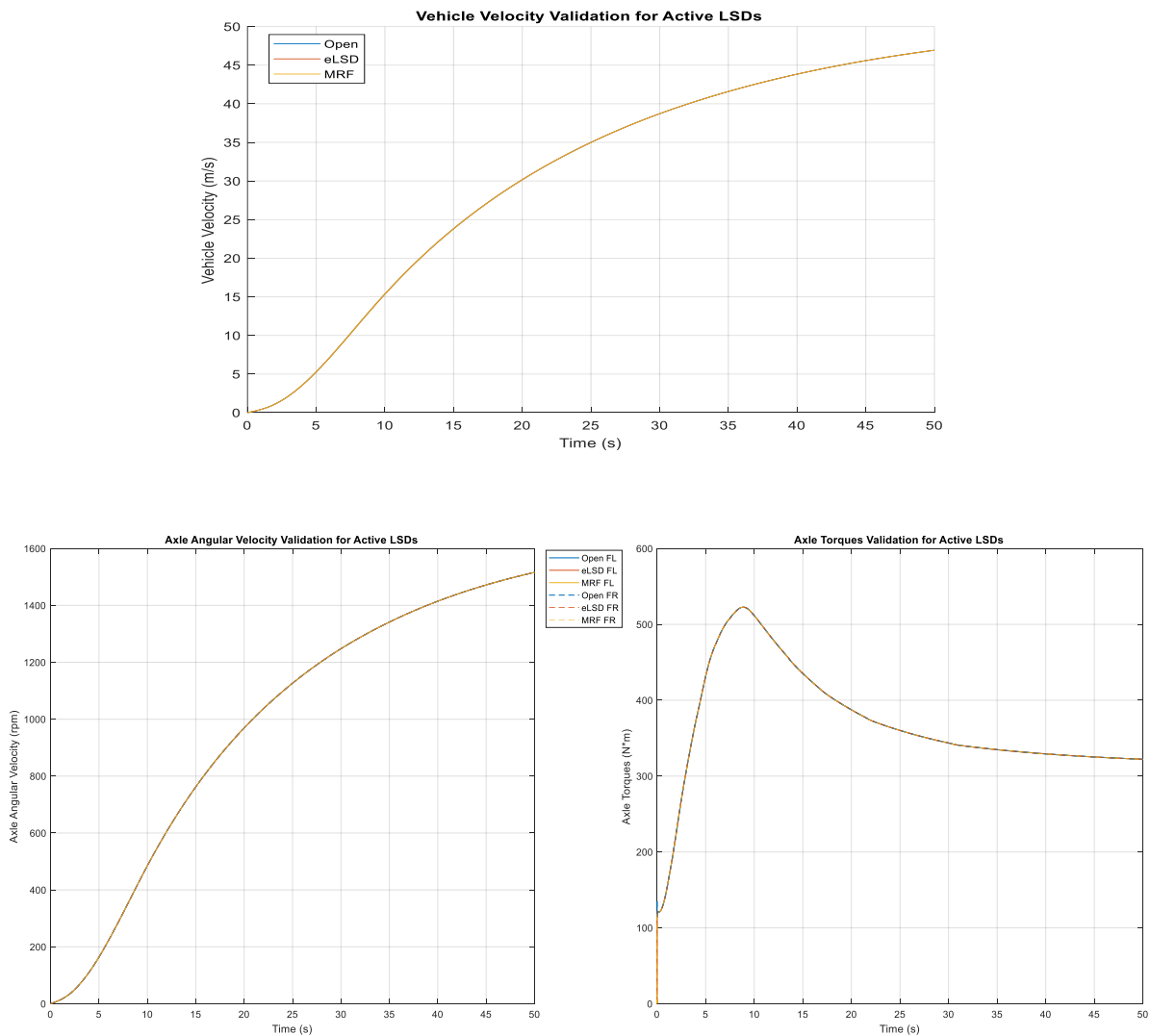


Figure 39: Simscape Driveline eLSD Variant Control Systems and Signal Examples. Graphs: X-Axis is Simulation Time (seconds) and Y-axis Represent Logic Control Value (Unitless).

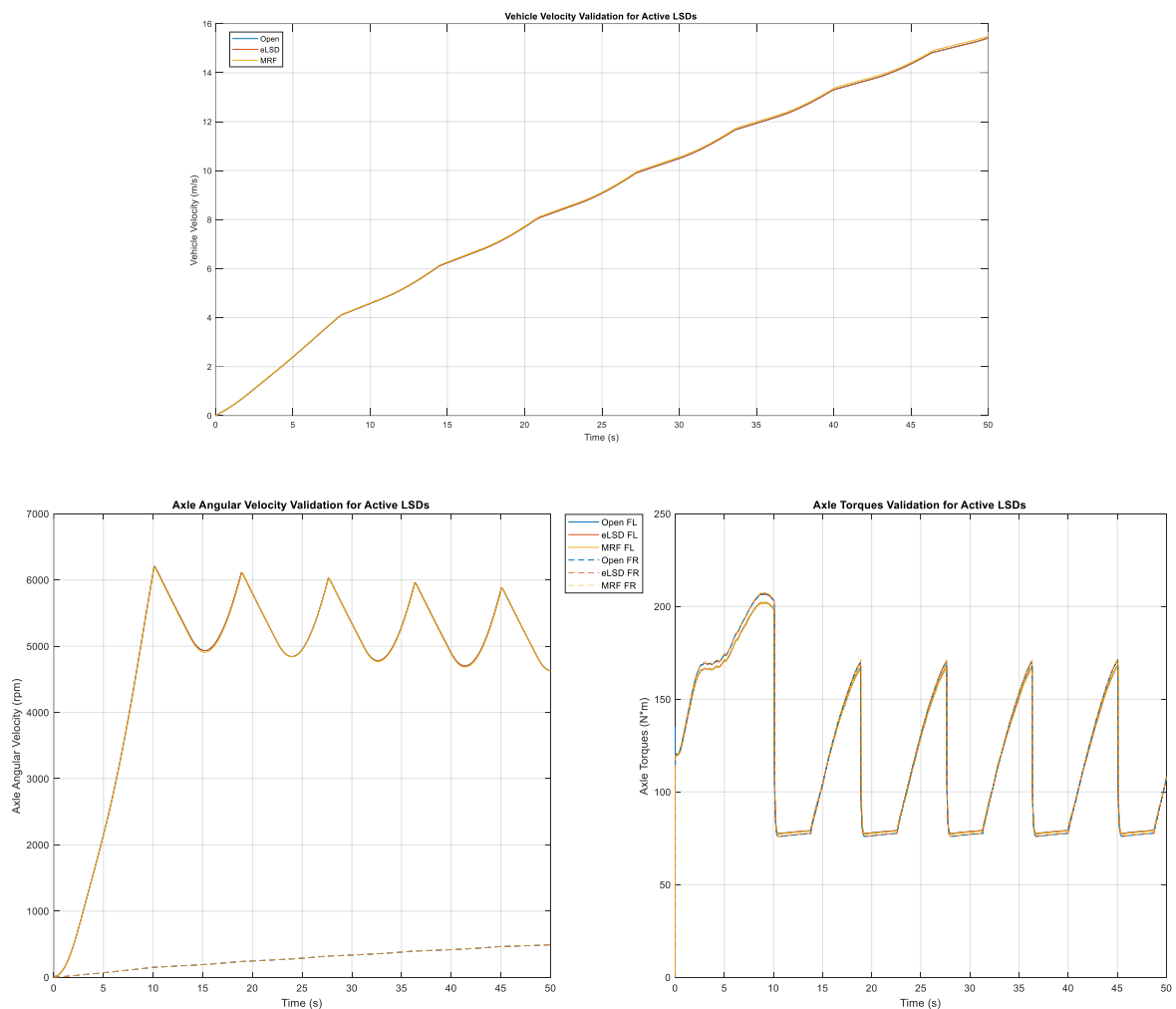
2.1.3.1 Control Variant 1 - Constant

Variant 1 is essential for early testing, ensuring the active LSD equations and block diagrams operate as expected. Initial test runs are completed for the eLSD, MRF LSD and open differential. The open differential is simulated alongside the active LSDs for validation purposes; by comparing the performance of these two devices against the open differential, any result data anomalies and abnormalities can be detected and coding/block diagrams rectified. The first validation run utilised a straight line, single surface friction coefficient (dry tarmac) with control constants for each device set to zero. Subplots in Graph 6 demonstrate simulation results where active devices are seen to perform almost identically to the open differential – as to be expected (Schultz, 1977).



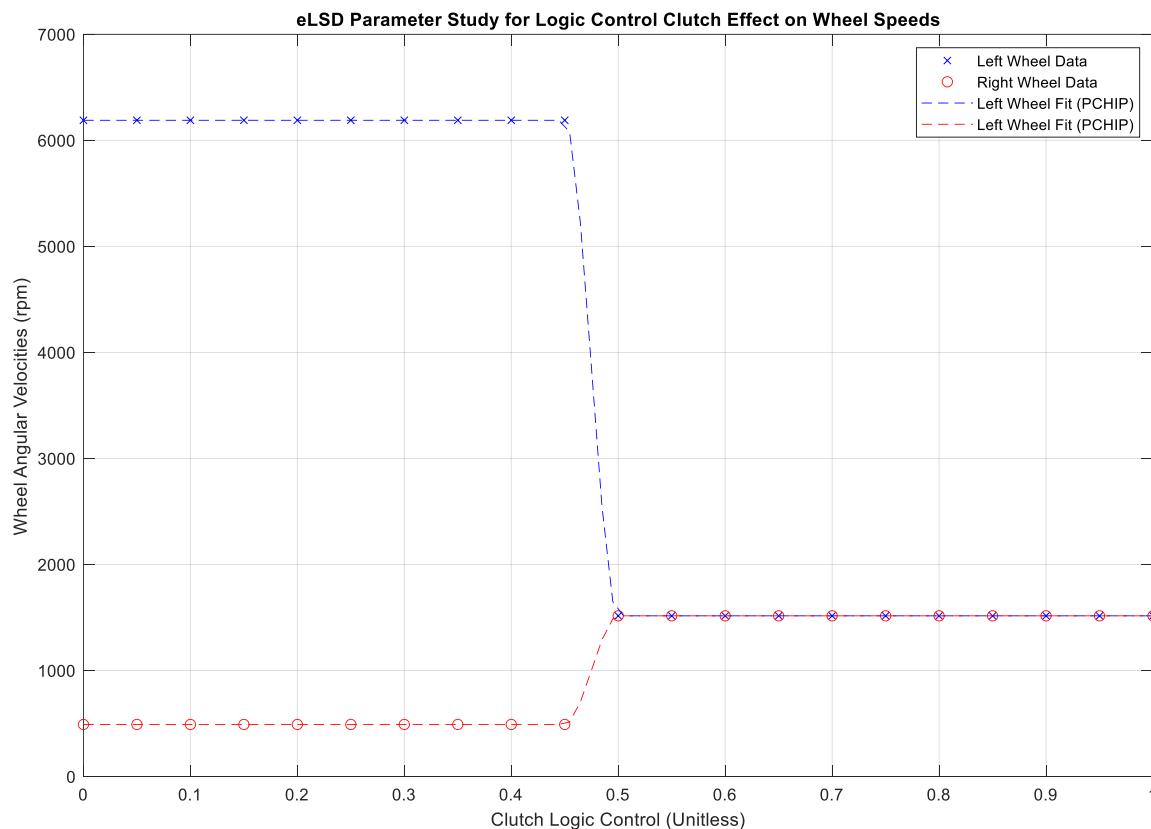
Graph 6: Simscape Driveline Dry Tarmac Simulation Data for Active LSD Validation, (Top) Vehicle Velocity Data, (Bottom Left) Axle Angular Velocity Data, (Bottom Right) Axle Torque Data.

A second simulation is conducted utilising the constant control variant, which again utilises a control constant set to zero. This second simulation implements a split mu scenario with the right tyres in contact with dry tarmac (high mu), whilst the left tyres are in contact with ice (low mu). As the active LSD controllers are ‘off’, results demonstrate that the devices behave in a similar manner to the open differential (Graph 7), as expected (Gadola, et al., 2021). Two important points for observation are the small torque differences between the left and right axles. Whilst open differentials theoretically distribute torque 50-50, frictional losses caused by gear meshing and viscous drag caused by gear oil cause small amounts of torque imbalance (approximately 5 Nm difference within this model), these are accounted for within this model. The final key observation is regarding the MRF LSD vehicle, travelling faster than the other devices by approximately 0.07 m/s. This is attributed to small amounts of torque biasing occurring due to the MRF having a low yield stress present, even with the absence of an MMF.



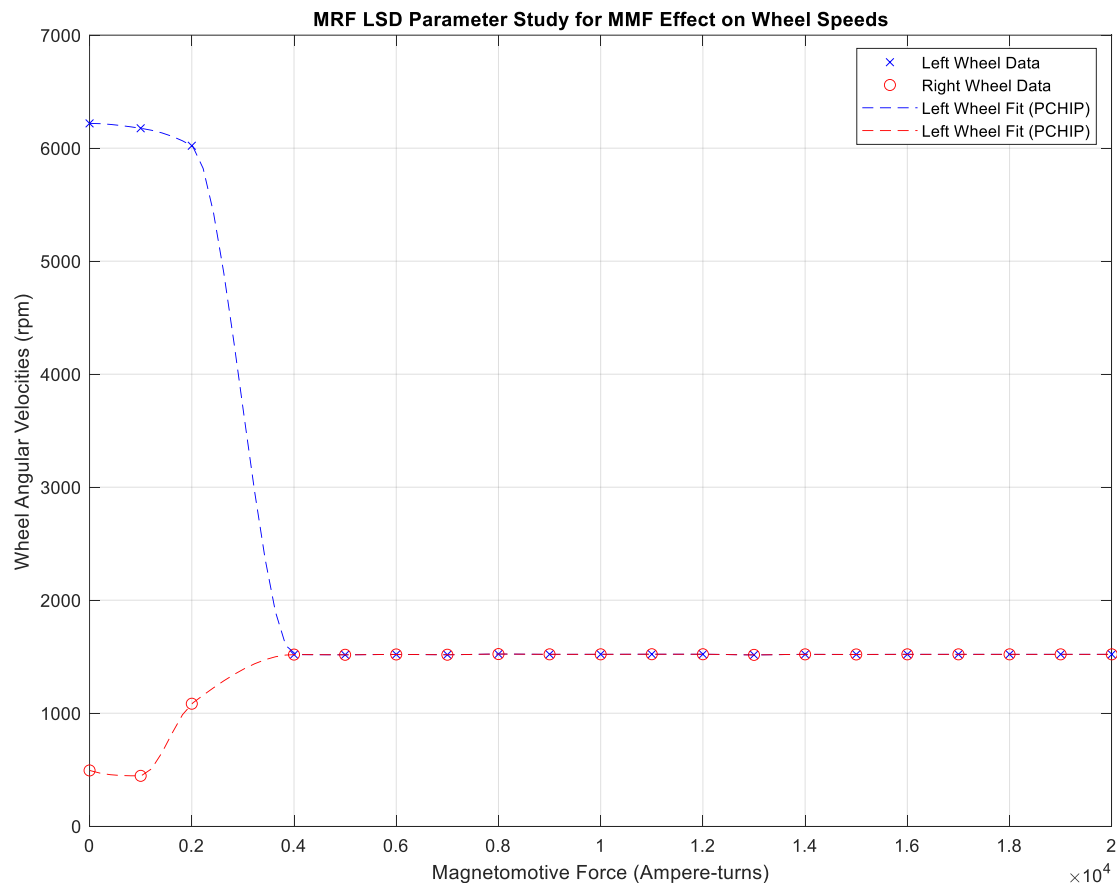
Graph 7: Simscape Driveline Split Mu Simulation Data for Active LSD Validation where Left Tyres Contact Ice and Right Tyres Contact Dry Tarmac, (Top) Vehicle Velocity Data, (Bottom Left) Axle Angular Velocity Data, (Bottom Right) Axle Torque Data.

A parameter study utilising the ‘Simulink Design Optimization Toolbox’ is then conducted to analyse the effect of varying logic control values on the eLSD vehicle wheel speeds. The purpose of this study is to determine the control signal value threshold required to lock the differential. The logic-controlled clutch accepts input signals in the range of 0-1 where the test parameter values are configured to sweep this range in increments of 0.05. The clutch is configured to be fully disengaged when the input logic signal equals 0 and fully engaged when the logic signal equals 1 (Mathworks, 2025). Results from the eLSD control parameter study are demonstrated in Graph 8, when studying the results, it is apparent that a logic control value of 0.5 triggers the engagement and therefore locking of the clutch. To ensure full locking it is still suggested that a value of 1 is utilised during extreme scenarios. If the torque applied overpowers the clamping force of the clutch pack, the clutch will slip. This triggers a new set of equations which utilises a kinetic friction coefficient, lower than the static coefficient (Figure 30); thus, reducing the torque transferring capabilities of the clutch pack.



Graph 8: eLSD Parameter Study of Clutch Logic Control Values Effect on Vehicle Wheels Angular Velocities.

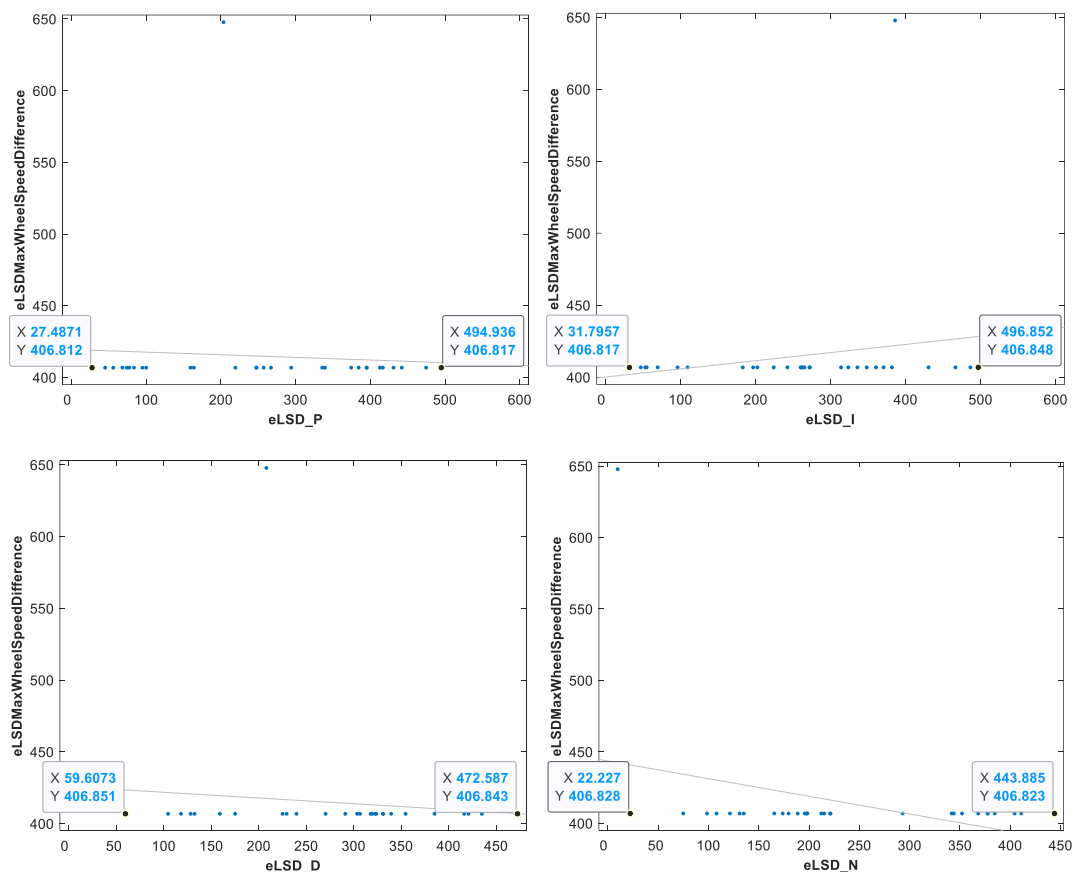
A second parameter study is conducted for the MRF LSD, used to investigate the effects of MMF values on vehicle wheel speeds. The simulation continues to use the previously detailed split mu surface configuration with ice in contact with the left wheels and dry tarmac the right wheels. The MRF LSD responds most effectively between 2000 and 4000 Ampere-turns of MMF for this scenario and vehicle powertrain performance (Graph 9). With the MRF differential parameters implemented into the Simscape block, a magnetic field strength of 66.67 KA/m is generated from a MMF of 5000 Ampere-turns. This ensures sufficient locking of the device modulating wheel slip and maintaining a near zero-wheel speed difference of the vehicle. These parameters align with the Parker Lord MRF-140CG fluid datasheet (Parker Lord, 2024), validating the model is within realistic parameters, given the setup data and model equations. A study using a lower viscosity and faster responding fluid (Parker Lord MRF-132DG) requires higher magnetic field strengths of 150-250 KA/m to suitably lock a MRF LSD effectively (Sciuto, et al., 2023), this data supports the performance evaluation of the LSD simulation testing within this project, given previously mentioned assumptions.



Graph 9: MRF LSD Parameter Study of MMF Effect on Vehicle Wheels Angular Velocities.

2.1.3.2 Control Variant 3 – PID Controller

To optimise PID controller gain parameters for the eLSD and MRF LSD, a Monte Carlo parameter study is configured and simulated within ‘Simulink Design Optimization Toolbox’ (Vagia, 2012). Random values for each gain parameter: proportional (KP), integral (KI), derivative (KD) and filter coefficient (N) are selected from a user specified upper and lower bound for each parameter. Testing for the eLSD utilised 30 random gain parameters for the PID controller where data points and resultant effects on maximum wheel speed difference are demonstrated in Graph 10. Whilst the adjustments in gain parameters appear to have minimal impacts on maximum wheel speed difference, a single simulation alters the data trendlines significantly. Although one data value has significant influence and could be classed as an anomaly, there are trendlines present when studying non-outlier values, this is noticeable when comparing highlighted data points. In summary, the parameter range in this study has very little effect on the PID control system output. After completing additional test simulations, optimal values for gain parameters at a maximum solver step of $1e^{-1}$ are determined to be: $KP = 200$, $KI = 100$, $KD = 1$ and $N = 100$.



Graph 10: eLSD PID Controller Gain Parameters Study using Monte Carlo Simulation Impact on Maximum Wheel Speed Difference, (Top Left) Proportional Gain Parameter, (Top Right) Integral Gain Parameter, (Bottom Left) Derivative Gain Parameter, (Bottom Right) Filter Coefficient Parameter.

This section details PID tuning for the MRF LSD. Graph 11 details a subplot for each parameter data point, where the coefficient values are plotted against maximum wheel speed difference. Although a distinctive trend within the plot data is not clear, a linear line of best fit gives an indication of parameter effects on the dependant variable. From this data and the statistics analysis results in Graph 12, increasing gain parameter KI results in a positive correlation to maximum wheel speed difference. In contrast, KP and KD influence maximum wheel speed difference with a negative correlation, whilst the filter coefficient has negligible to no correlation with the dependant variable. Rise time rate and reduction of steady state error (wheel speed difference) are the key control variables that will affect performance of active differentials the most (Figure 40). According to the ‘Effect of Performance table’ constructed by Hussien, et al., (2015) the gain parameters that reduce steady state error and rise time considerably are integral and proportional values. By combining the analysis from the data plots with information from Table 3 and simulation test runs of varying gain parameters, the optimal PID controller values are found to be: $K_P = 100$ to reduce rise time, $K_I = 10,000$ to eliminate steady state error, $K_D = 5$ to reduce impacts of overshoot and $N = 200$ to effectively filter data. Parameters are configured for a solver maximum time step of $1e^{-1}$.

Table 3: PID Gain Parameters Effect on Control Signal. T_i - Rise Time, T_s - Settling Time, OS - Overshoot and SSE - Steady State Error (Hussien, et al., 2015).

	Effect of Performance			
	T_r	T_s	OS	SSE
P	Decrease	Small Change	Increase	Decrease
I	Decrease	Increase	Increase	Eliminate
D	Small Change	Decrease	Decrease	Small Change

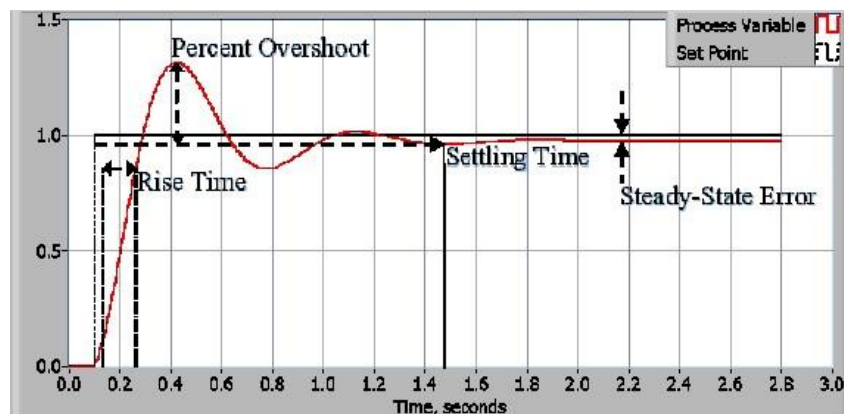
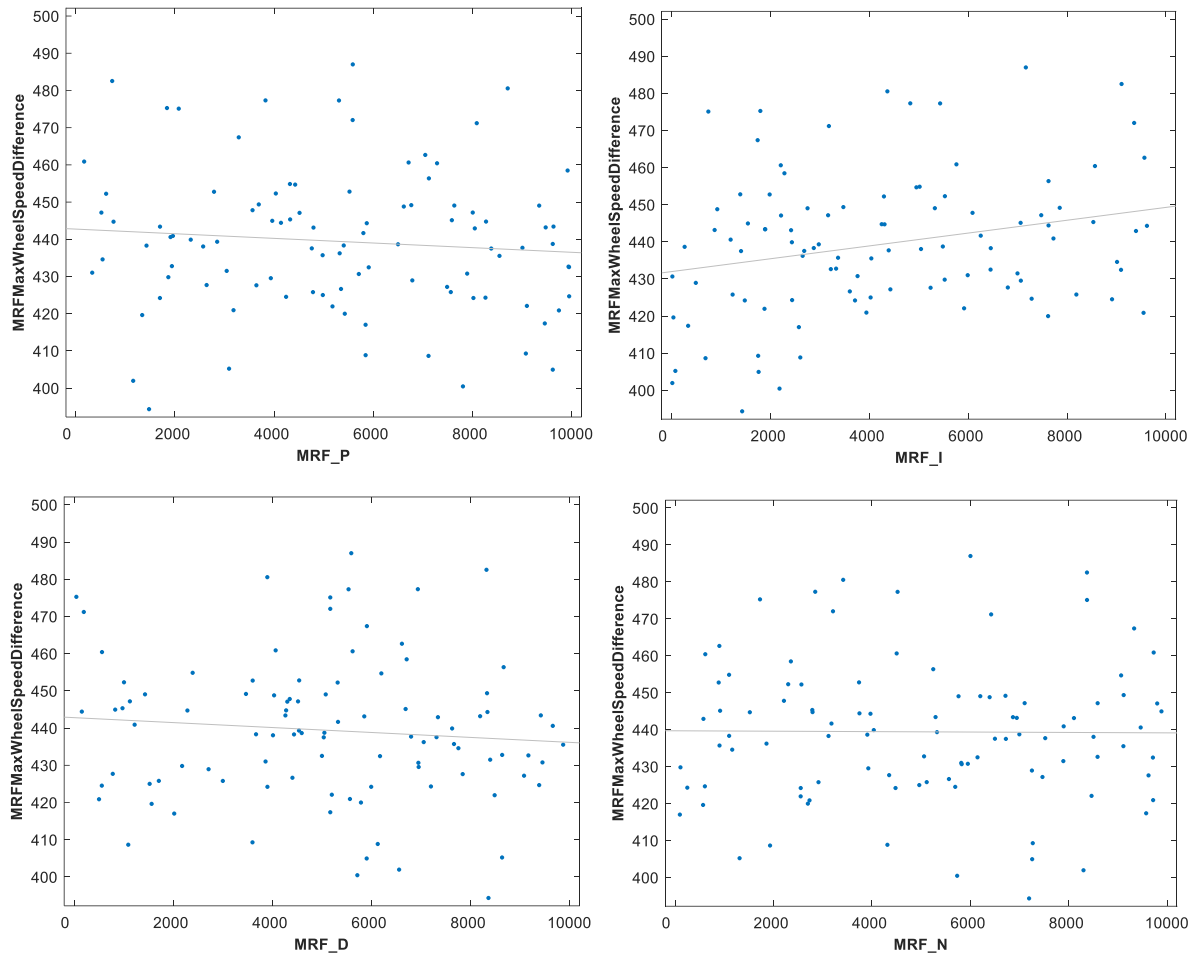
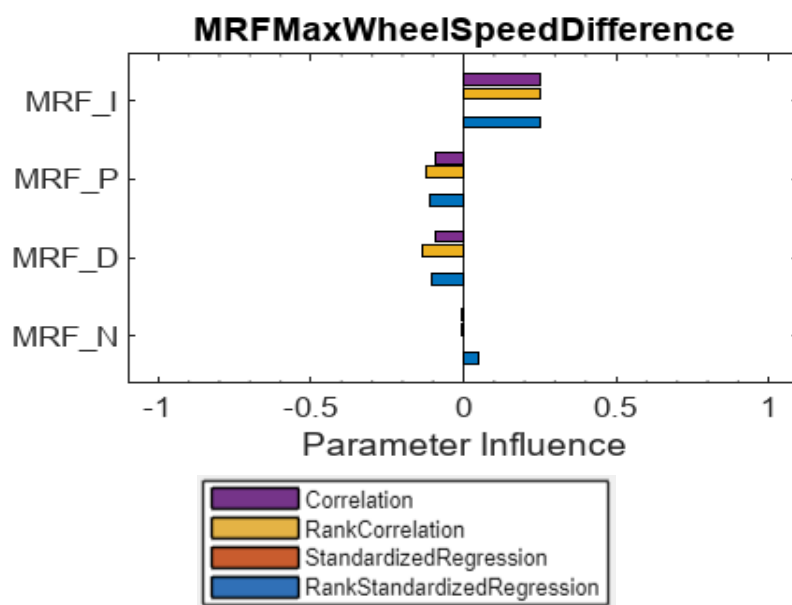


Figure 40: PID Influential Parameters Diagram (NI, 2025).



Graph 11: MRF PID Controller Gain Parameters Study using Monte Carlo Simulation Impact on Maximum Wheel Speed Difference, (Top Left) Proportional Gain Parameter, (Top Right) Integral Gain Parameter, (Bottom Left) Derivative Gain Parameter, (Bottom Right) Filter Coefficient Parameter.



Graph 12: Statistics Analysis of Gain Parameter Influence on Maximum Wheel Speed Difference.

2.2 Simscape Multibody Vehicle Modelling

To model the vehicle dynamic effects of the LSDs, lateral dynamics are an essential aspect of the vehicle model. To capture and simulate this data, a multibody system is utilised due to its ability to model various complex suspension and tyre models, increasing the accuracy of the model in comparison to other methods (Blundell & Harty, 2015). The model used in this project is based on the MATLAB “Full Vehicle on Four Post Testrig” (Mathworks [10], 2025), with adjustments made to the driveline system, tyre model and other aspects. The overview of the Simscape Multibody system is demonstrated in Figure 41, the callback functions to the left are configured to run simulations and plot results when triggered. The ‘signal controls’ subsystem includes data control signals for the braking system, drivetrain, steering, camera configurations and more. The multibody components and connections are configured within the vehicle subsystem whilst the ‘sensing’ block converts units for pitch and roll which are plotted in the connected scope. The control signals for driveline input torque and steering angle are demonstrated in Figure 42, output signals for the driveline operate based on a ramp type signal with the torque quantities demonstrated in Graph 13, the saturation block caps the signals to a specified value, whilst steering signals vary depending on selected manoeuvre (Graph 14).

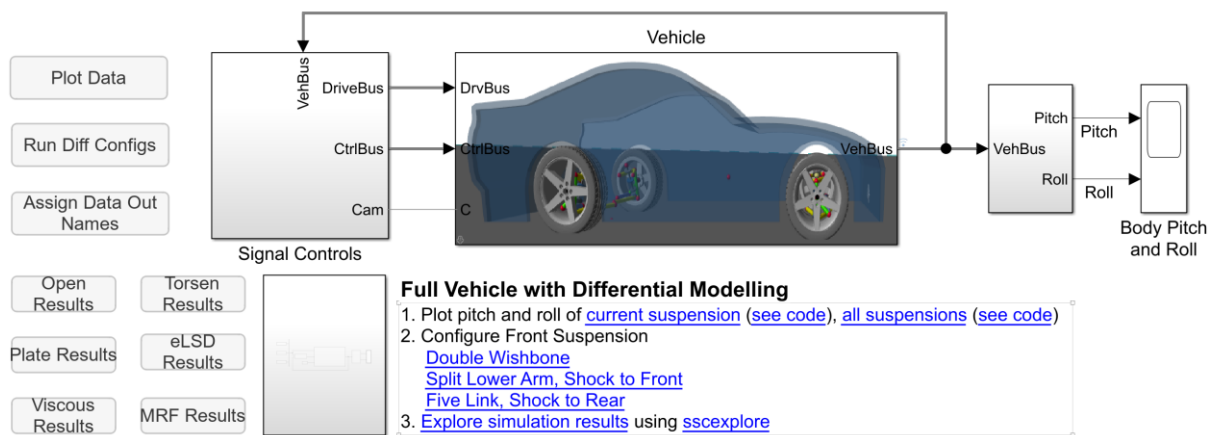


Figure 41: Simscape Multibody Vehicle Model.

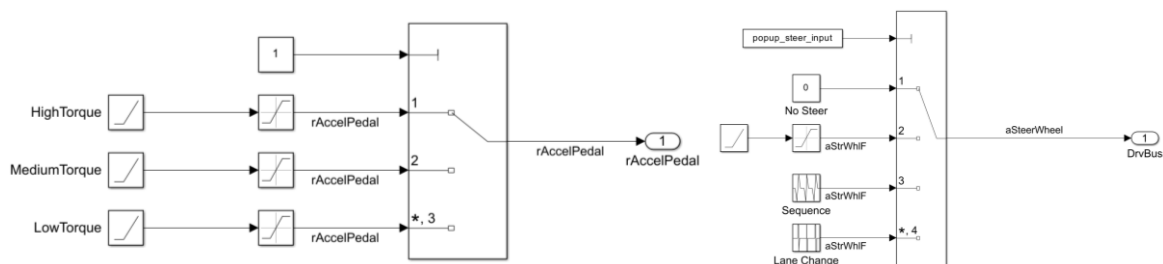
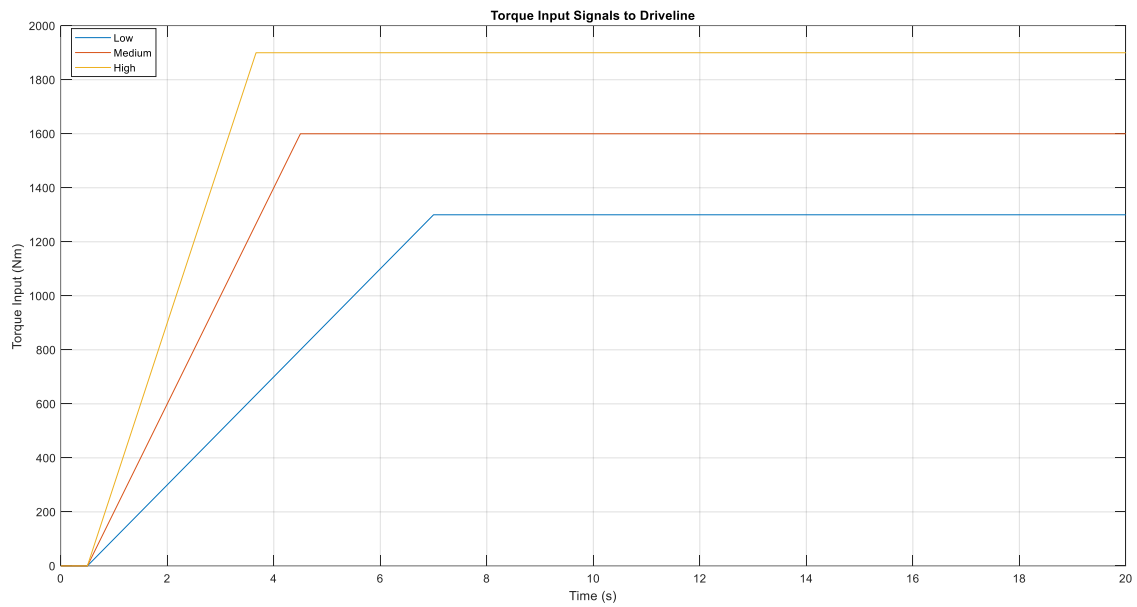
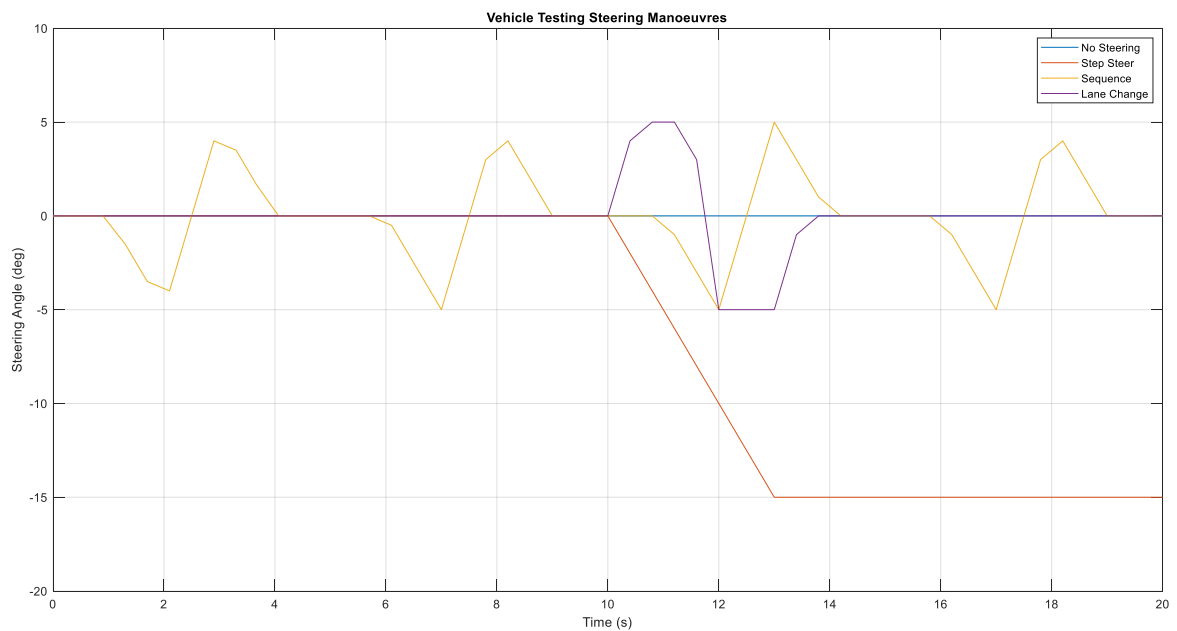


Figure 42: Signal Controls (Left) Driveline Torque, (Right) Steering Angle.



Graph 13: Torque Signal Configurations.



Graph 14: Steering Angles for Vehicle Testing Manoeuvres, a Positive Value Refers to a Right Turn and Negative Left.

The control system signal buses are then sent to the necessary sub-model within the ‘Vehicle’ subsystem (Figure 43). The standard Simulink signal for torque (Graph 13) is converted to a physical signal, which controls the ideal torque source (Figure 44) and Simscape driveline components, finally linking to the Simscape Multibody driveshafts. An ideal torque source is utilised instead of the generic engine block due to improved model stability and control variable purposes, ensuring equal torque quantities are applied to all driveline systems as the differential is the test subject.

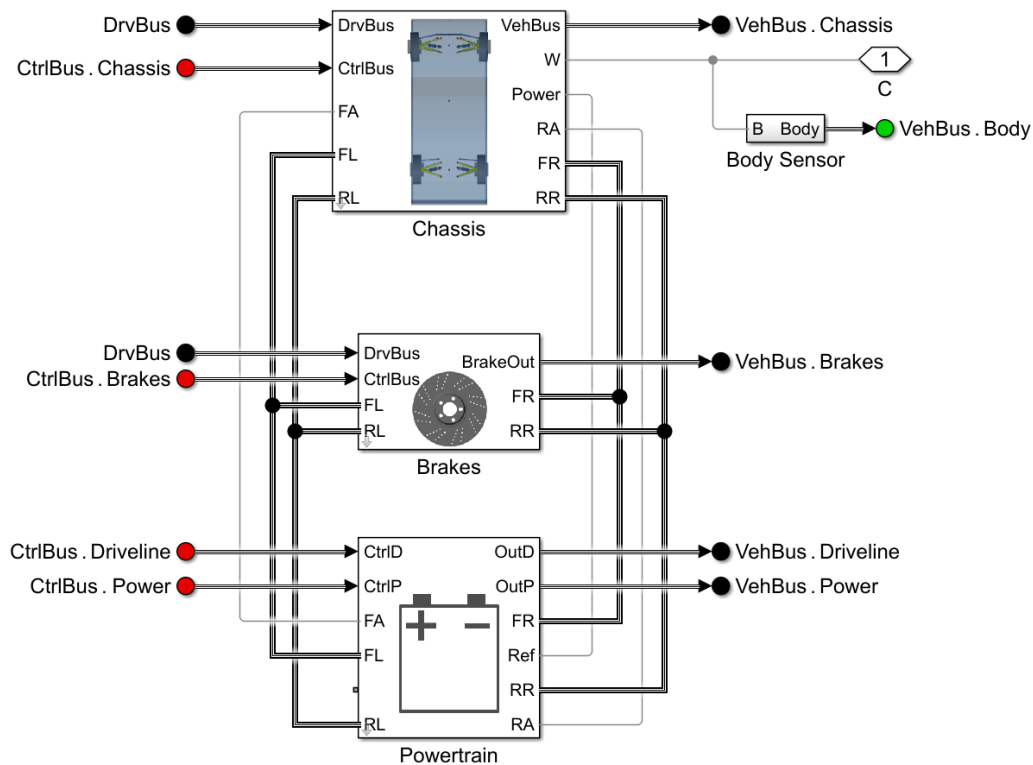


Figure 43: Vehicle Model Subsystem Categories.

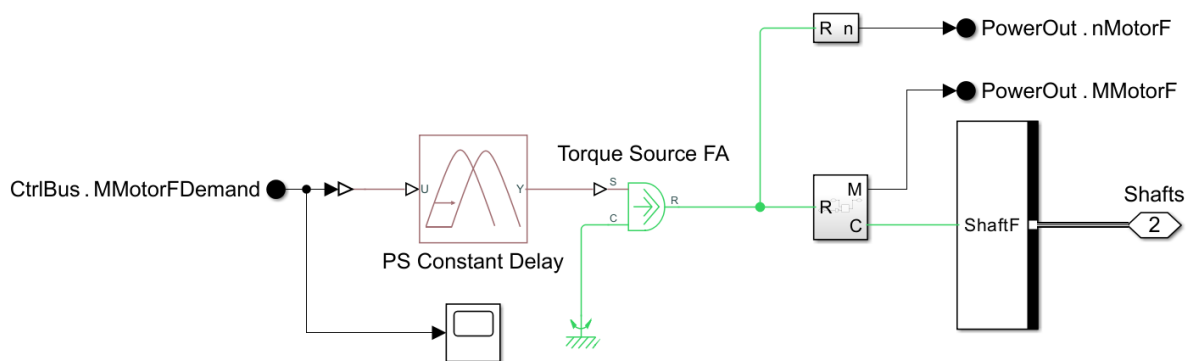


Figure 44: Simscape Driveline Vehicle Model Ideal Torque Source.

2.2.1 Multibody Powertrain

The ideal torque source (Figure 44) is connected to the remaining driveline system (Figure 45) with the ‘Shaft F’ connection port. The variant subsystem labelled ‘Differential’ enables simulation of all 6 differentials previously modelled within the Simscape driveline network. The differentials are modelled to identical specification, with the same technique and blocks mentioned in section 2.1.1. Torque and angular velocity measurements are recorded from each differential output shaft. The differential outputs are connected to the multibody system by a Simscape ‘rotational multibody interface’ (Figure 46) within the ‘Shafts FL and FR’ (Figure 45) subsystems (Mathworks [11], 2025). The rotational multibody interface connects the Simscape driveline to the multibody system by a one rotational degree of freedom revolute joint that uses the rotational multibody interface as an input torque signal.

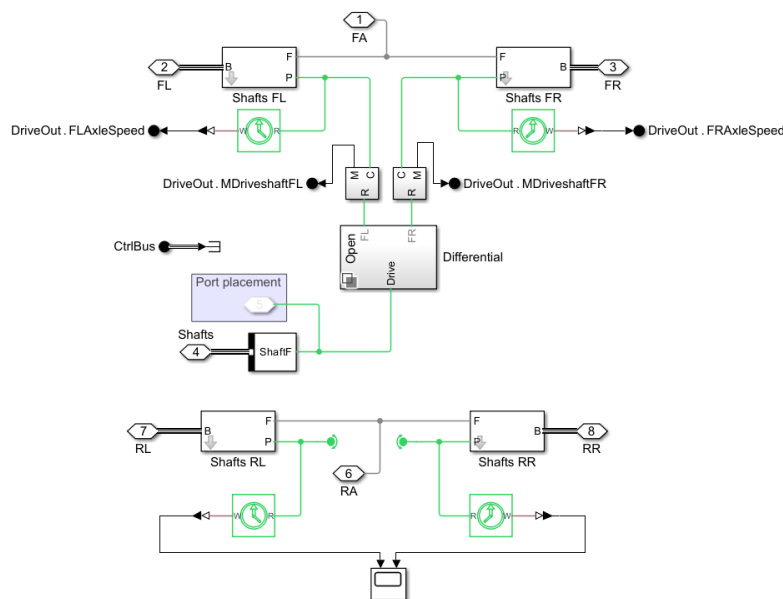


Figure 45: Simscape Driveline Drivetrain Subsystem within Multibody Vehicle Model.

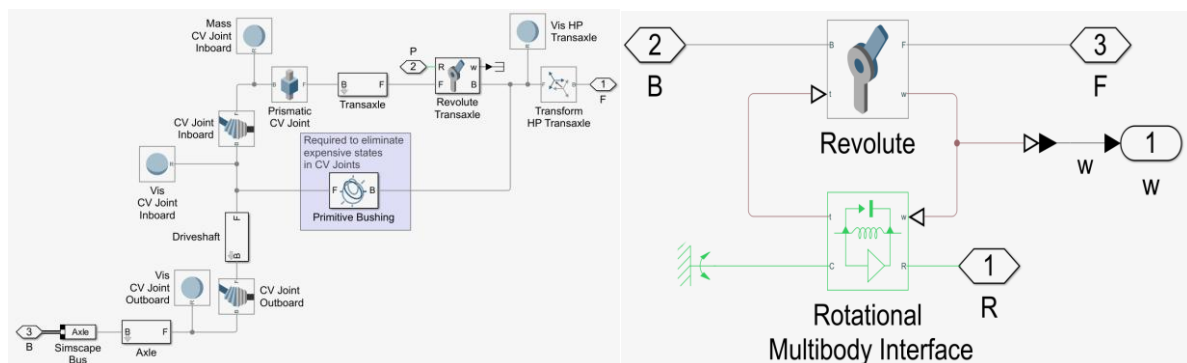


Figure 46: Simscape Multibody Driveshafts and Multibody/Driveline Connection Interface. Subsystem Right is the contents of ‘Revolute Transaxle’.

2.2.2 Multibody Chassis and Suspension

The multibody chassis subsystem content is demonstrated in Figure 47, alternative suspension designs are integrated into the example model as standard by MathWorks (Mathworks [10], 2025). Instead of utilising CAD files for suspension components, this model implements rigid hardpoint objects to optimise the trade-off between simulation time and accuracy. The joints utilised in the system include but are not limited to: ‘spherical joint’, ‘universal joint’, ‘revolute joint’ and more; these joint types are to model the behaviours of those used in real suspension systems, specifically: ball joints, constant velocity joints and general rotation of components such as axles (VanGelder, 2022). A double wishbone suspension configuration is used in this model with a FWD drivetrain; track rods are implemented and connect to either side of the vehicle with a partially implemented steering rack (Figure 48). Movement of the rack is achieved by mathematically translating the ‘viscous rack housing’ reference point, which physically moves the connected steering components within the model.

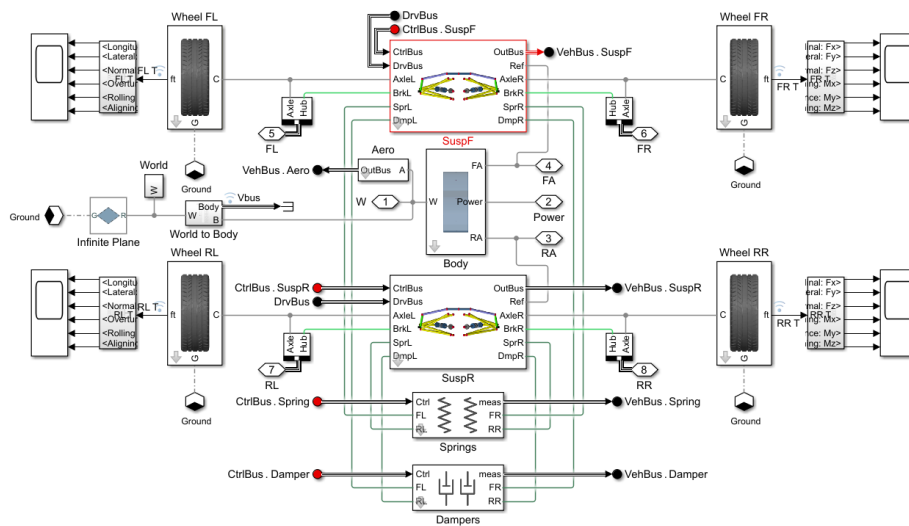


Figure 47: Multibody Vehicle Chassis Subsystem.

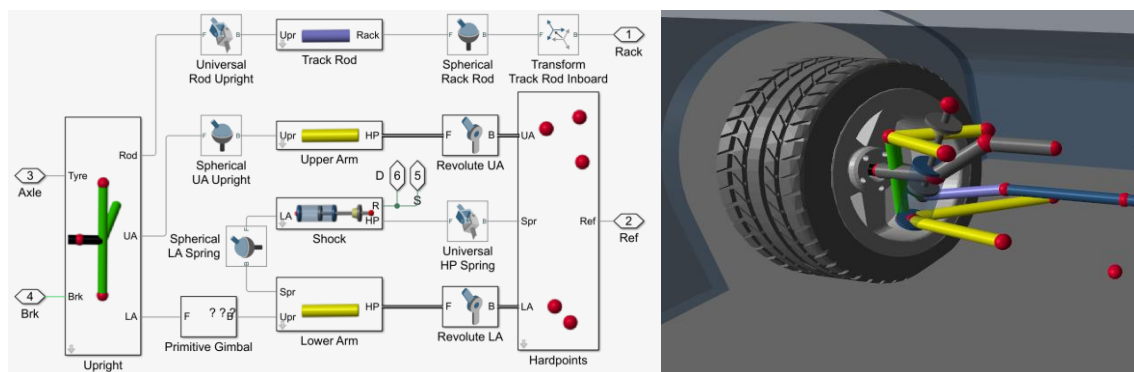


Figure 48: Multibody Front Left Double Wishbone Suspension Model Block Diagram and Virtual Model.

Tyres are integrated into the vehicle module using the ‘Magic Formula Tire Force and Torque’ block. This block uses the fundamental MF equation mentioned in section 1.3 – equation 4 for each slip mode longitudinal and lateral (Pacejka, et al., 2010). Camber angle and other slip effects are factored into the model to improve tyre response accuracy during cornering events and to account for multibody suspension movements. The tyre model is assumed to be a disk during calculations (demonstrated Figure 51) where geometry and inertia properties are applied by connecting additional parameter blocks (Mathworks [13], 2025). To ensure accurate response of the tyre, governing parameters are used from experimental data provided in a ‘.tir’ data file (RPSCOE, n.d.), this data file provides values for tyre geometry, data and MF coefficients. Multibody modelling of this system is demonstrated Figure 52.

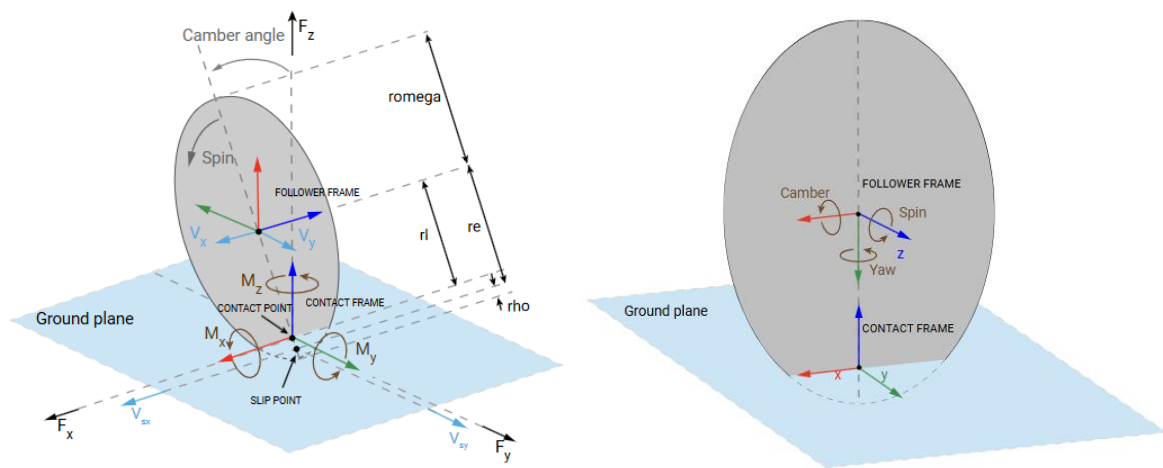


Figure 51: Multibody Tyre Model Longitudinal and Rotational Axis Diagram (Mathworks [13], 2025).

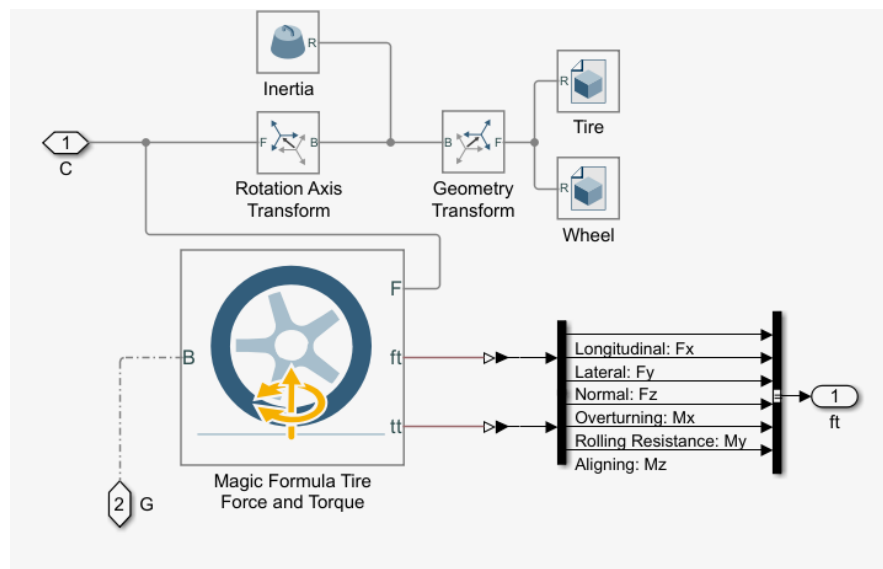


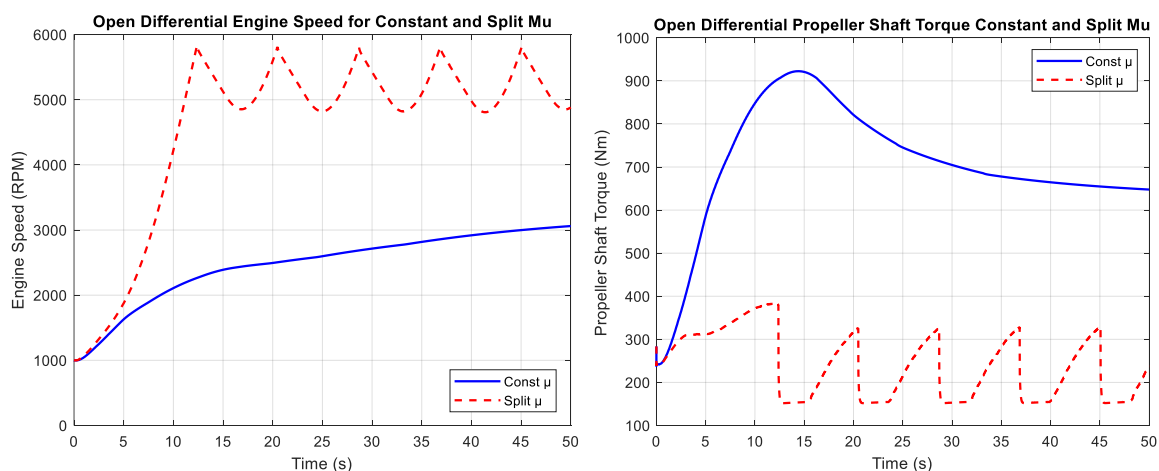
Figure 52: Multibody Vehicle Tyre Model.

3 Results and Analysis

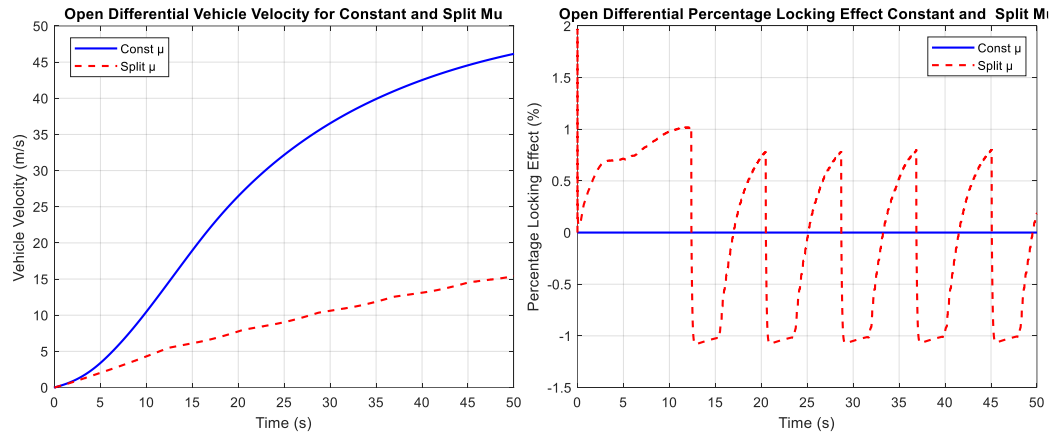
Simulation data and results from the above models are plotted and analysed in the following section. Validation is discussed and completed with the use of existing literature, and alternative testing software (Vi-CarRealTime).

3.1 Open Differential Results

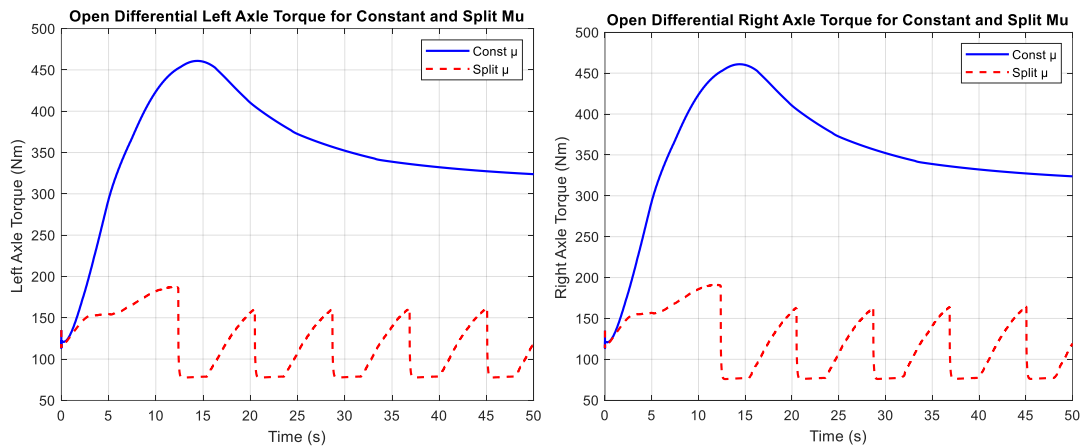
The open differential results from Simscape Driveline constant friction surface (dry tarmac) and split mu friction surface (ice left tyres and dry tarmac right tyres) are presented in Graph 15 - Graph 18. From these results it is inherently obvious that the traction problem significantly reduces the vehicle's ability to accelerate forwards on a split mu surface, demonstrated Graph 16 (Crolla, 2015). The open differentials inability to transfer/bias torque to the wheel with most traction restricts the vehicles' ability to utilise the full amount of engine torque available (Graph 16 and Graph 17). During the split mu event, the vehicles left tyre begins to slip and spin in excess of traction limits (Graph 18). Due to the high amount of slip on the left tyre, the throttle stateflow chart is seen to reduce engine speed before redline is exceeded (Graph 15). The implications of a FWD vehicle squatting under acceleration reduces the vertical load present on the front driven axle, this decreases open differential performance further on a FWD vehicle when compared to RWD. As a result of the low torque put down and near symmetrical drive forces, a reduced vehicle pitch and yaw rate is experienced when compared to LSDs.



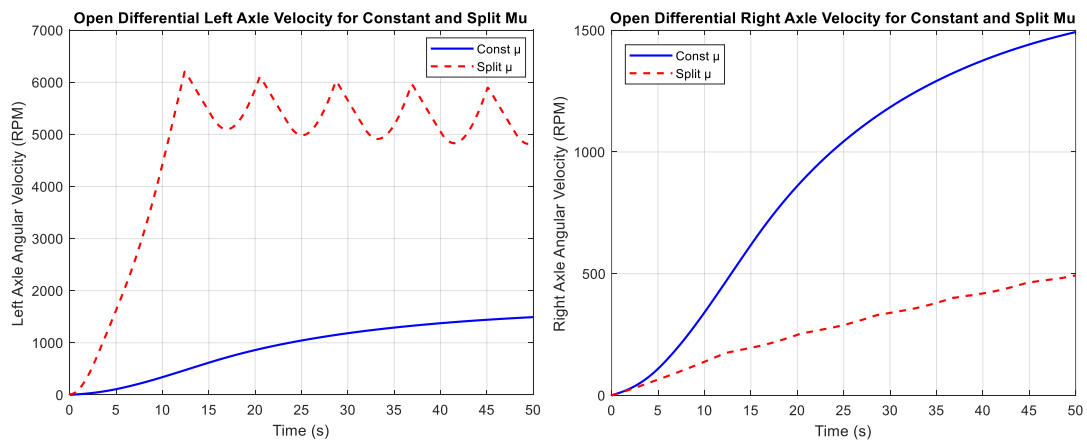
Graph 15: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Engine Speeds, (Right) Propeller Shaft Torque.



Graph 16: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



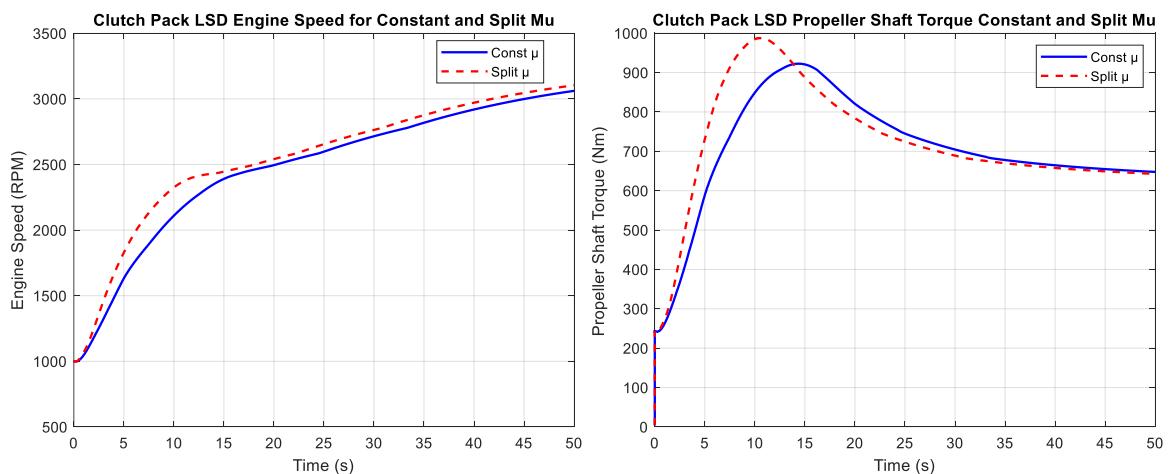
Graph 17: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.



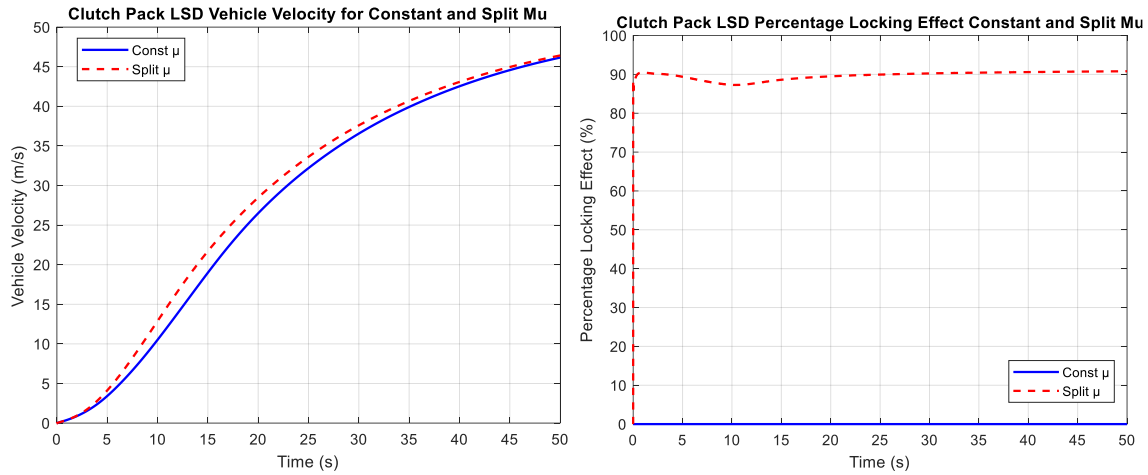
Graph 18: Open Differential Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

3.2 Clutch Pack LSD Results

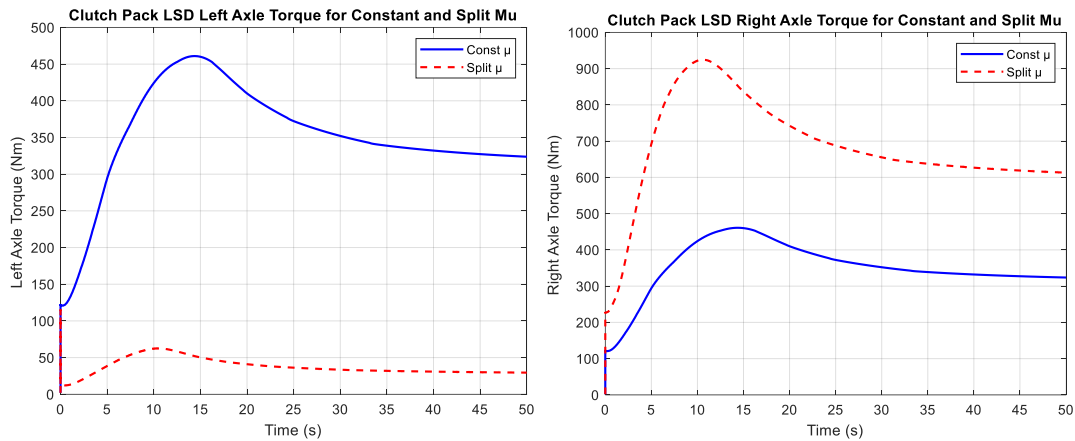
The clutch pack LSD Simscape Driveline results are demonstrated in Graph 19 - Graph 22. Under ideal straight line acceleration conditions this LSD behaves as a standard open differential, splitting torque equally between the two drive wheels and maintaining symmetrical wheel angular velocities (Tremlett, et al., 2014). However, during a straight-line split μ acceleration scenario, the engine speed for the split μ simulation is seen to increase at a higher rate and reach a greater maximum value when compared to the constant μ simulation. As a result of this higher engine speed, the engine and torque converter transmit a greater amount of torque to the differential and remaining driveline (approximately 80-90 Nm more). This can be attributed to the delay in locking response (when compared to the Torsen LSD) permitting small amounts of slip for the left wheel, resulting in less frictional resistance acting on the driveline and engine (Graph 19). The benefits of an LSD are demonstrated in Graph 21 and Graph 22 where torque is transferred to the right axle due to the higher available grip. This model achieves a locking percentage of approximately 90% for the duration of the split μ simulation, this demonstrates the clutch pack LSDs ability to cope well under significant traction differences and respond promptly (within less than half a second) by clamping the clutch packs and limiting wheel slip (DSport, 2022). Whilst the longitudinal results from this simulation seem promising, it is important to consider lateral dynamics have been neglected from this model. When considering lateral dynamics, the large imbalance of drive forces caused by the asymmetric torque split will inevitably result in vehicle yaw moments; the human driver controllability of these yaw moments will depend on the LSD torque splitting capabilities, vehicle rotational inertia, difference in surface friction coefficients and much more.



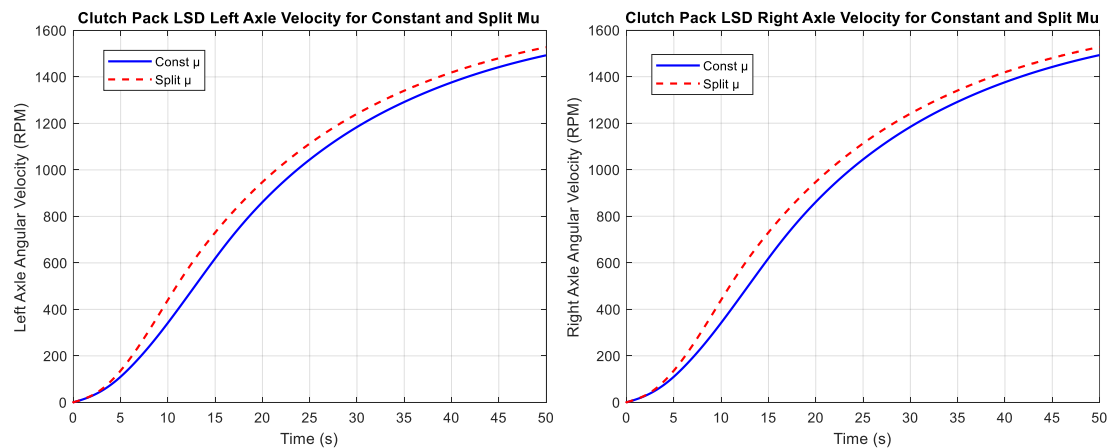
Graph 19: Clutch Pack LSD Simscape Driveline Results for Constant and Split μ Comparison, (Left) Engine Speed, (Right) Propeller Shaft Torque.



Graph 20: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



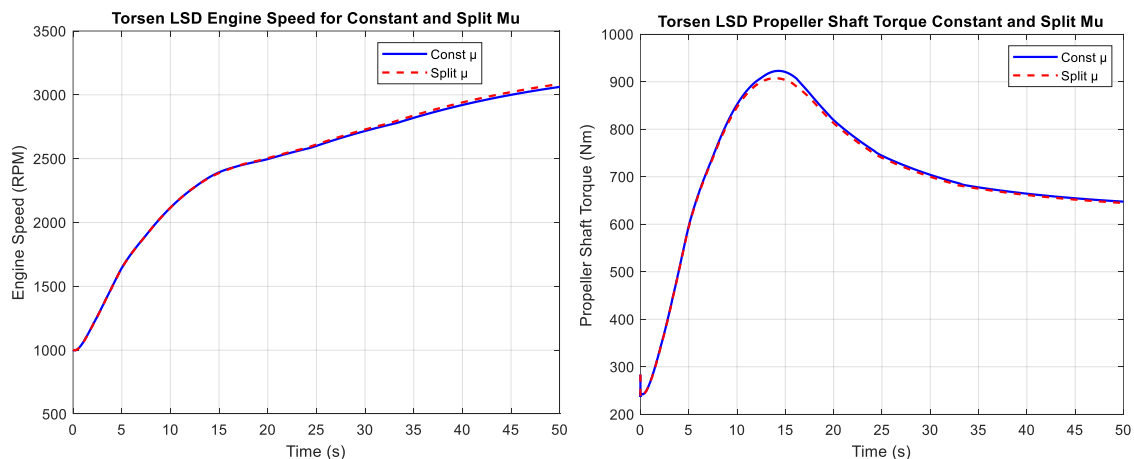
Graph 21: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.



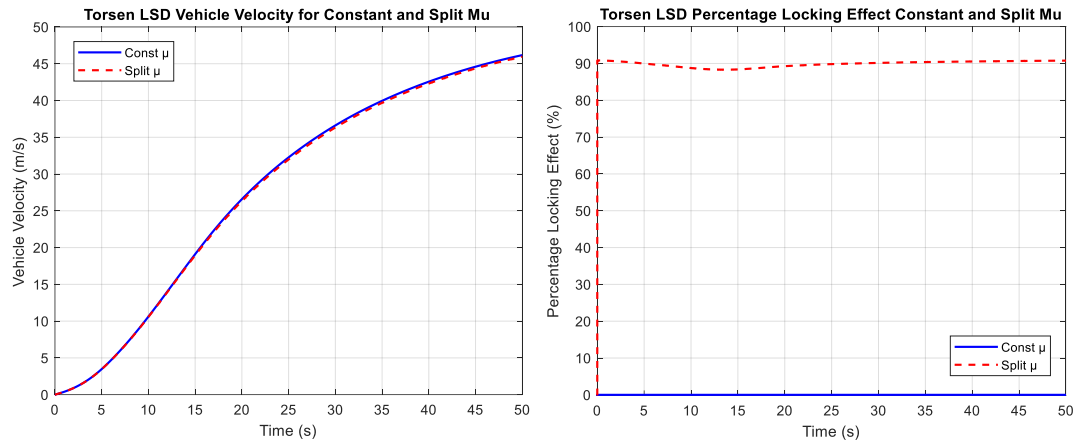
Graph 22: Clutch Pack LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

3.3 Torque Sensing LSD Results

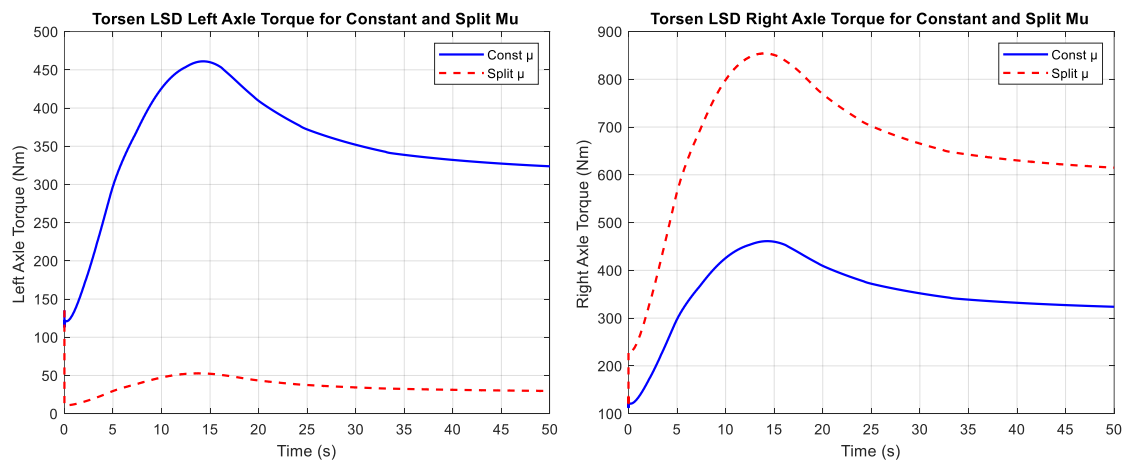
A torque sensing LSD replicates open differential behaviour during constant μ events, where both tyres have equal traction conditions. During this straight-line manoeuvre the differential casing rotates in unison with both driveshafts; an ideal zero traction difference between the two wheels (as modelled in the Simscape Driveline system) results in equal torque split to both driveshafts, and a consistent wheel speed difference of zero (Graph 25 and Graph 26). During a split μ event however, the torque sensing differential stands out as the most responsive LSD. In the event of wheel slip, this device reacts instantaneously by biasing torque to the wheel with most traction (VanGelder, 2022). Due to safety concerns, it is common for FWD vehicles to have a lower torque biasing ratio preconfigured within the torque sensing differential than the counterpart RWD devices. This Simscape Driveline simulation does not limit TBR to that of a typical FWD vehicle as it is crucial to understand how the different LSDs respond during identical testing conditions. In the real-world, the reduced TBR limits the torque biasing capabilities, ultimately decreasing the difference in drive forces (Frömmig, 2023). This reduced variation limits torque steering effects and ultimately yaw moments. The responsive locking characteristics of a torque sensing LSD are demonstrated in Graph 24 where the initial gradient reaches 90% in a near vertical manner, this is faster than all other differentials within this study. This effect is also noticeable in the axle torque graphs shown in Graph 25. The limited slip aspect of the torque sensing LSD is demonstrated in Graph 26 where left and right angular velocities are consistent.



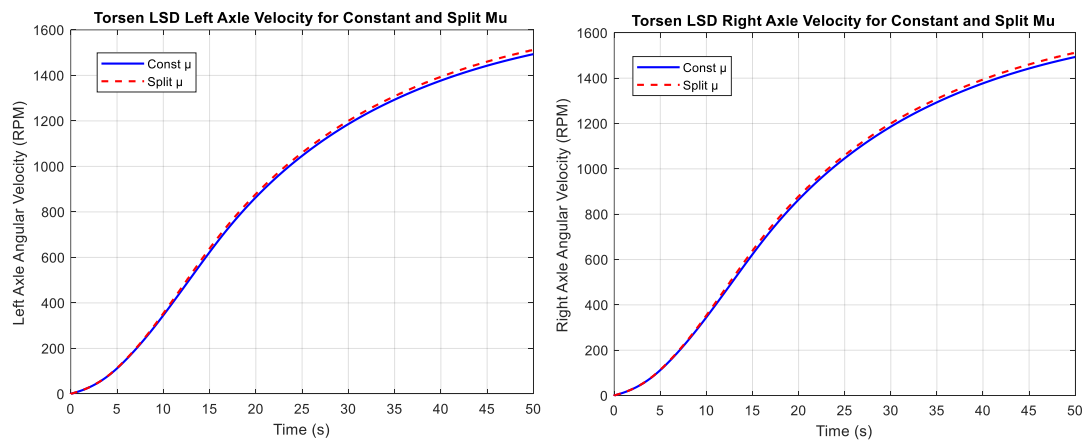
Graph 23: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Torsen Engine Speed, (Right) Propeller Shaft Torque.



Graph 24: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



Graph 25: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.

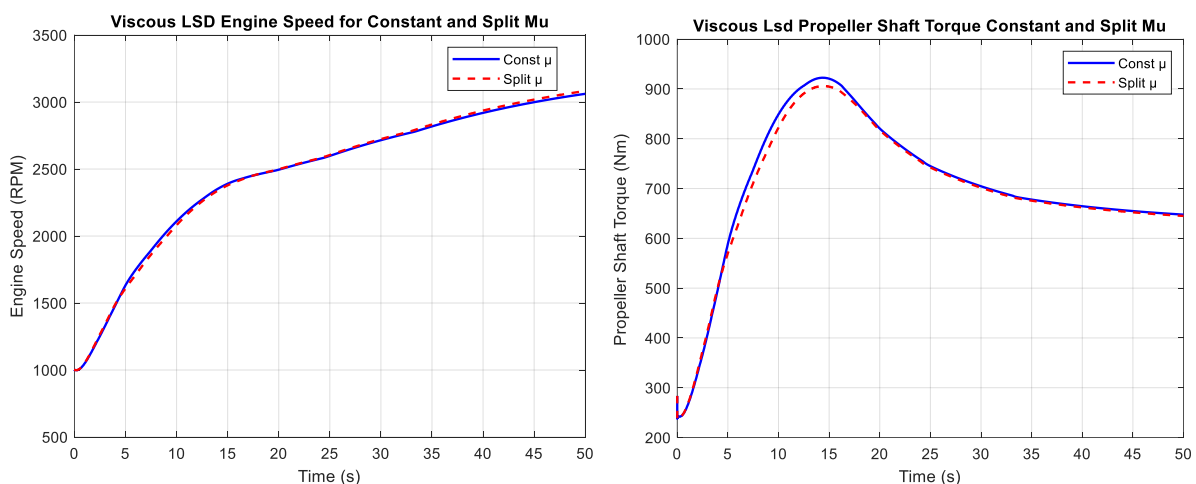


Graph 26: Torsen LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

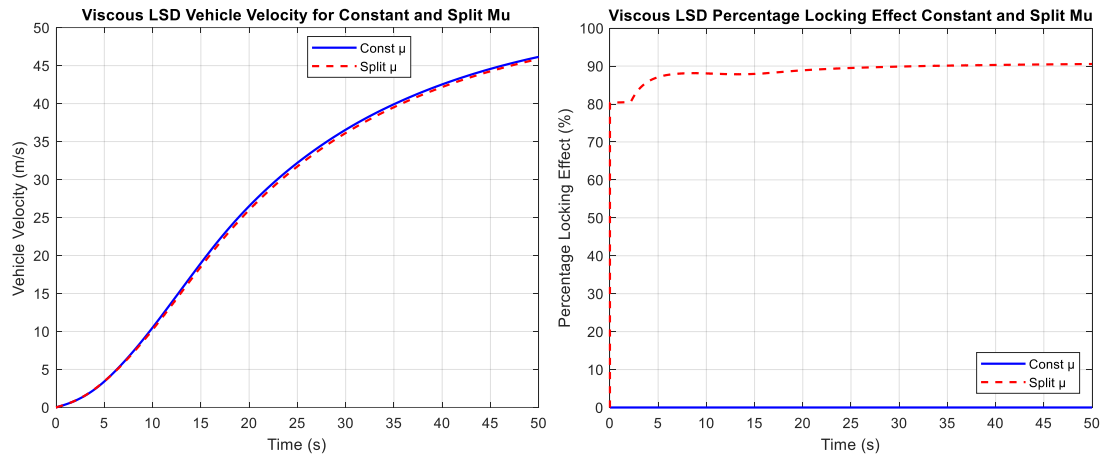
3.4 Viscous LSD Results

The viscous LSD exhibits significant differences in performance when compared to the alternative passive devices investigated within this project (Graph 27 - Graph 30). As this particular device is speed dependent, the fundamental mechanism for limiting slip and transferring torque is based on the shearing of a viscous fluid (commonly silicon), this therefore requires a difference in wheel speed to trigger the slip limiting fluid (Graph 30). Due to this slip requirement, the viscous device exhibits a delayed and reduced percentage locking effect during early slip events (Graph 28) in comparison to the clutch pack and torque sensing LSDs (Palazzolo, 2009). The torque transfer rate is demonstrated to be more gradual and therefore theoretically, increases driver controllability (Graph 29). Due to the gradual locking characteristics, it is anticipated that both yaw and pitch rates are lower than torque dependant and active LSDs.

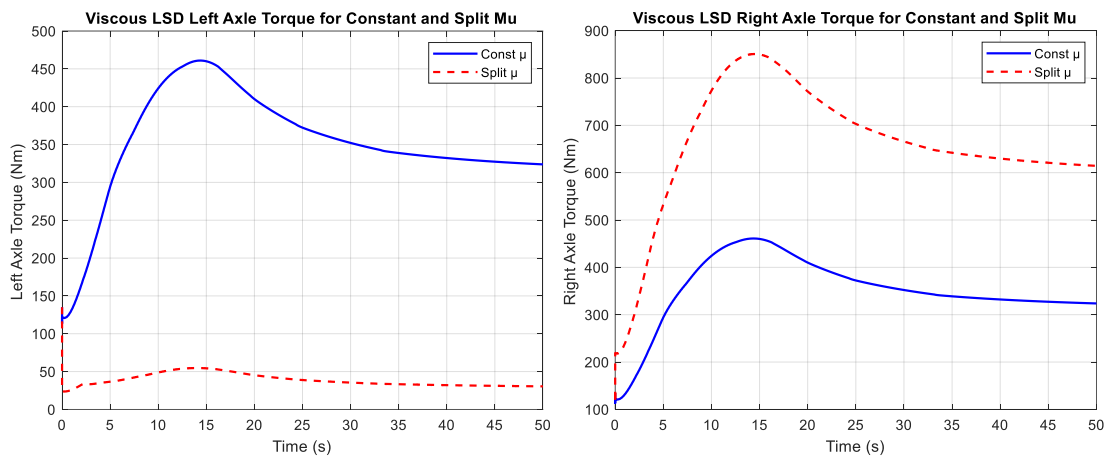
During acceleration, load transfer increases the normal force on the rear tyres, inherently favouring RWD configurations in terms of traction. In a split mu scenario, the FWD vehicle faces compounded limitations: reduced surface friction on the low mu side restricts available traction, while the squatting effect further unloads the front axle (Heisler, 2002). This combination diminishes the low mu tyre's capacity to apply drive force, resulting in earlier and increased wheel slip in FWD vehicles equipped with viscous LSDs.



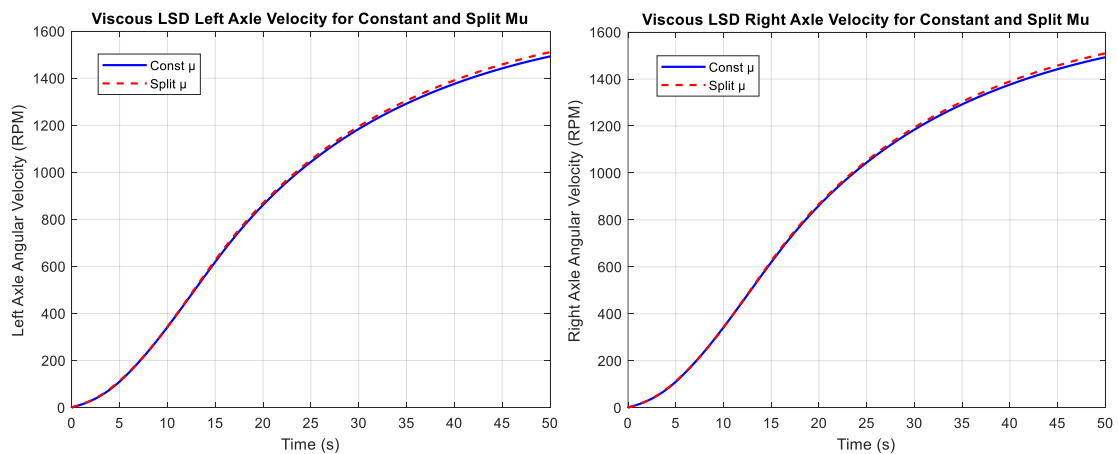
Graph 27: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Engine Speed, (Right) Propeller Shaft Torque.



Graph 28: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



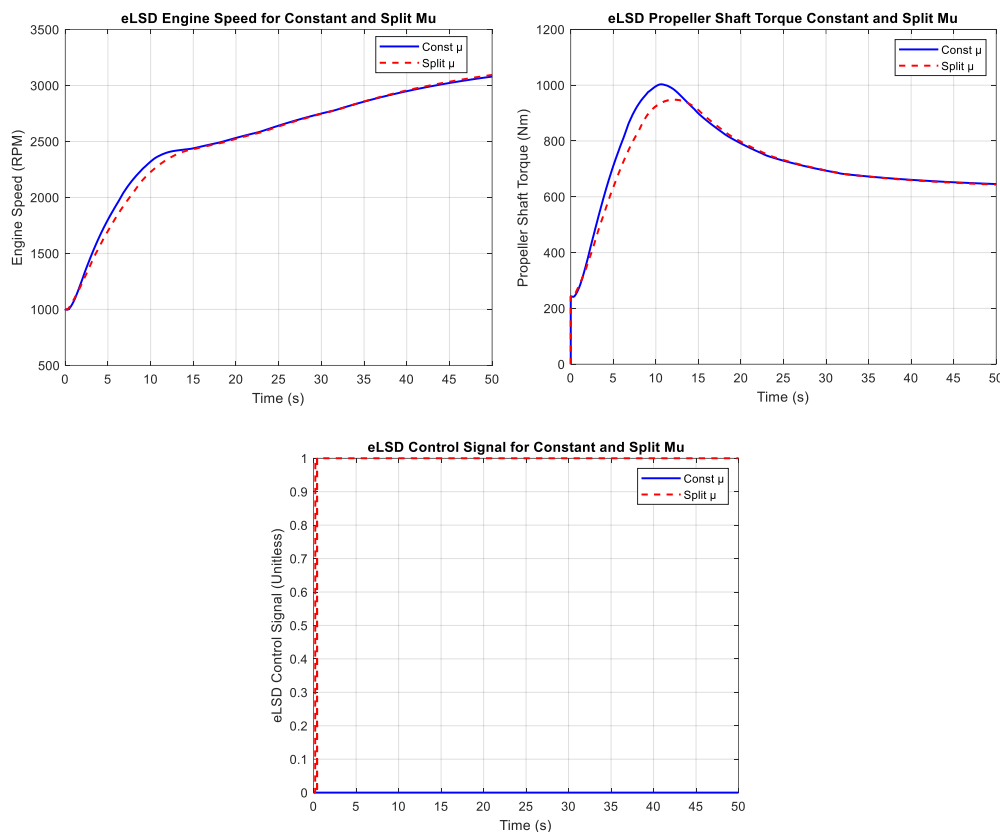
Graph 29: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.



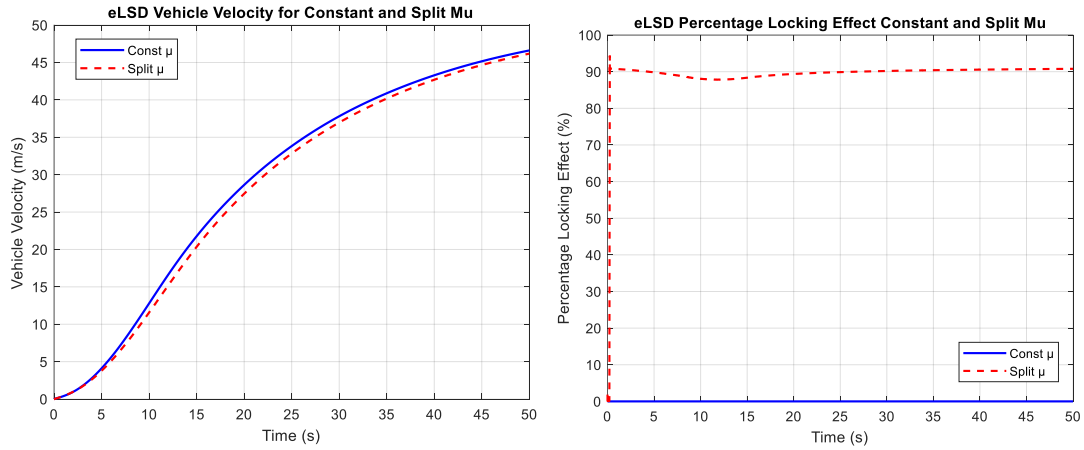
Graph 30: Viscous LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

3.5 eLSD Results

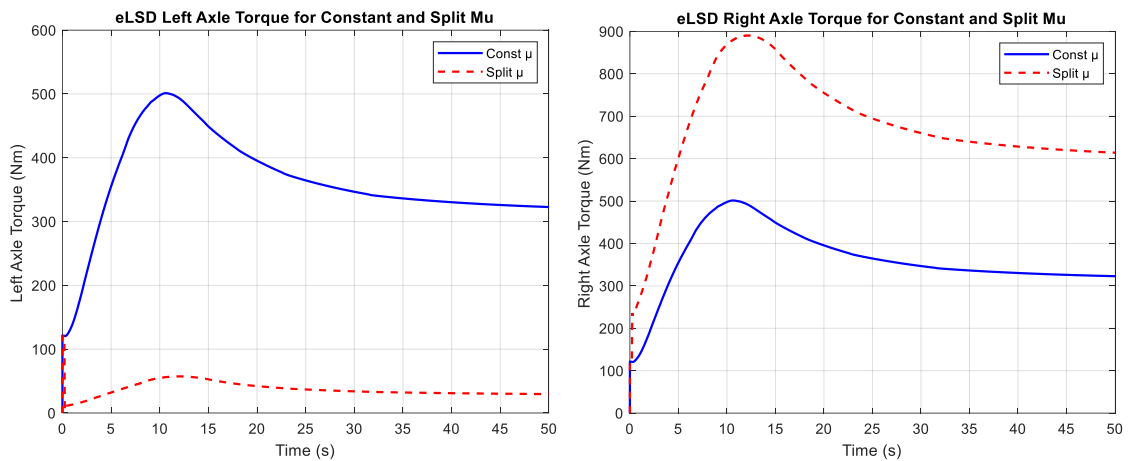
The eLSD exhibits similar locking characteristics to the passive clutch pack LSD due to similarities in design and components, where both rely on dual clutch packs to regulate torque transfer and wheel slip. Whilst the eLSD has the distinct advantage of being activated or deactivated based on control system logic, rather than the fixed mechanical principles of passive devices, the initial response time of the active eLSD can be delayed in situations such as a split mu acceleration event where complex control logic is implemented. This delay period can be attributed to: sensor and communication system delays, control system logic calculations, actuation systems and more. To ensure the device operates in a timely and effective manner (demonstrated Graph 31 - Bottom), control system design should account for suitable sensor bit-rates and sampling time (Happee, et al., 2023). The velocity performance results for the eLSD are noticeably lower for the split mu scenario in comparison to the constant mu surface (Graph 31-Graph 34). Causes of this are a combination of previously detailed control and actuation systems delay. At initial stages of locking (Graph 32), overshoot is caused by the PID controller attempting to overcorrect for large quantities of wheel slip, which increases with prolonged sensor related delays (Patronis, et al., 2013). When steady state error (wheel speed difference) is reduced to acceptable tolerances the device continues to transfer torque and maintain wheel speeds (Graph 33 and Graph 34).



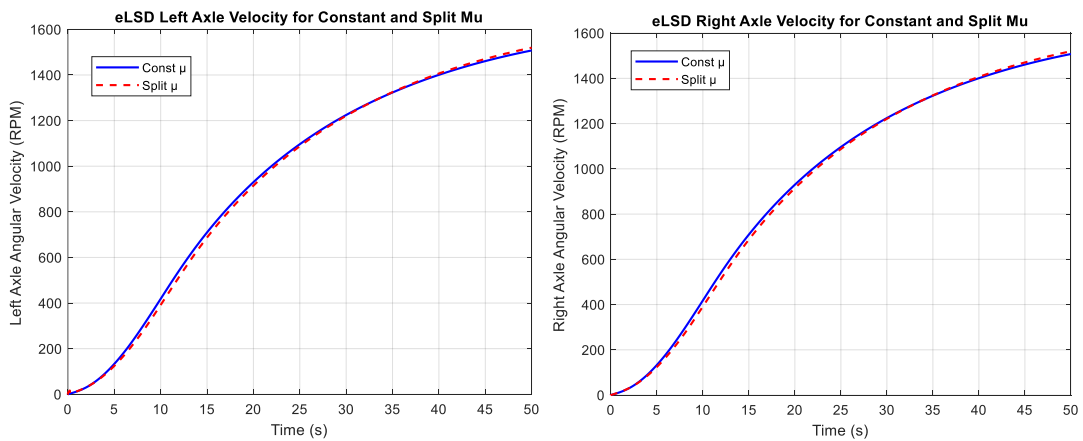
Graph 31: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Top Left) Engine Speed, (Top Right) Propeller Shaft Torque, (Bottom) eLSD Control Signals.



Graph 32: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



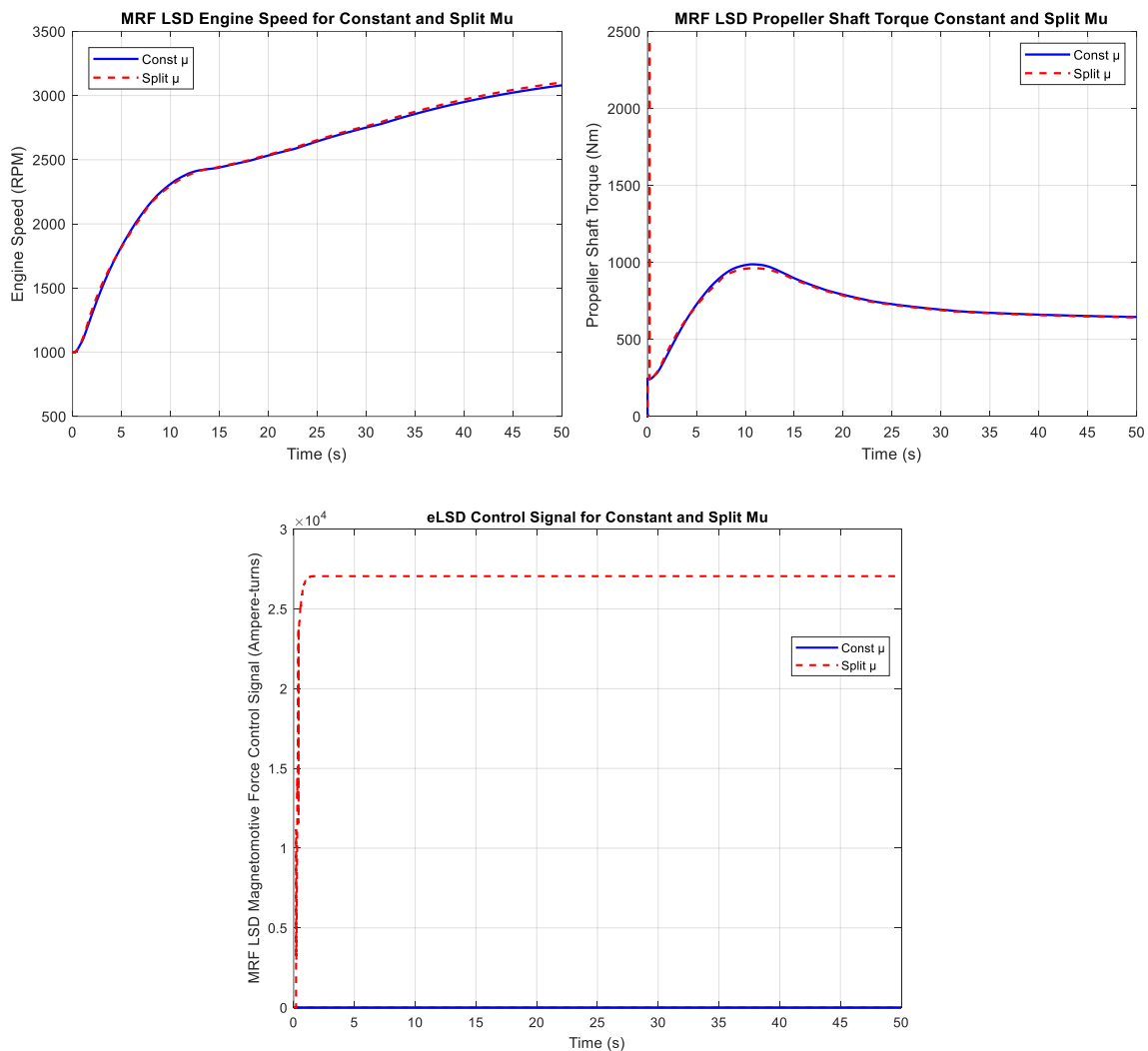
Graph 33: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.



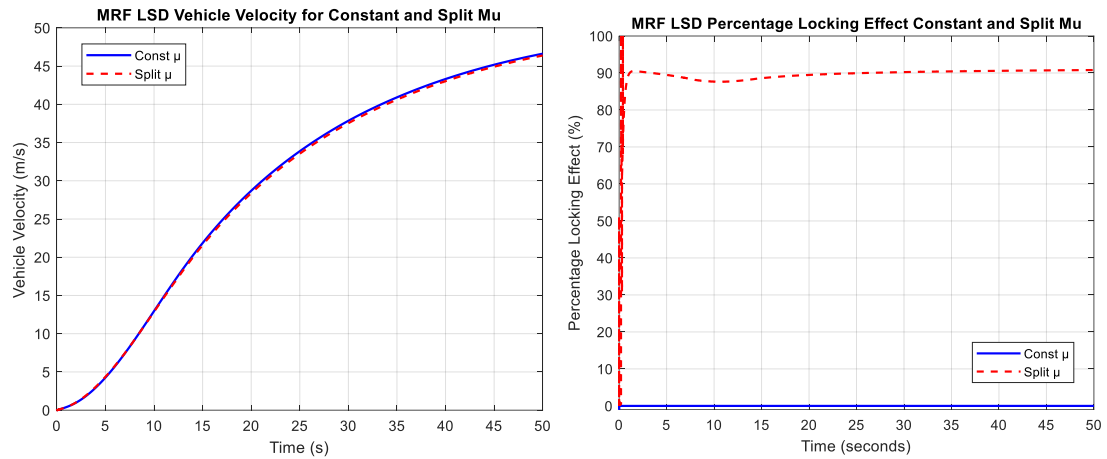
Graph 34: eLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

3.6 MRF Results

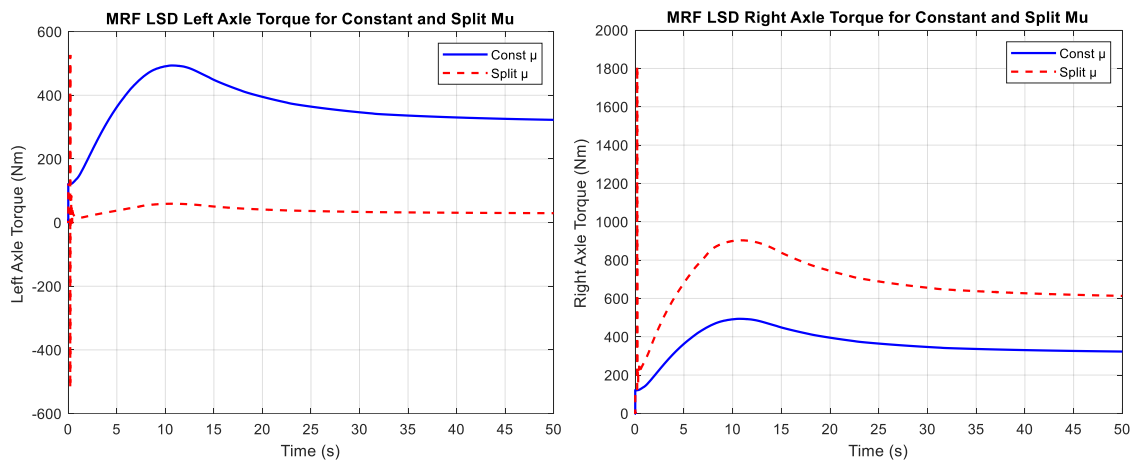
The MRF active LSD maintains similar values across engine speeds and vehicle velocity when performing a constant or split mu simulation. Initialisation of the MRF LSD simulation presents erratic initial results in propeller shaft torque, percentage locking effect, axle angular velocities and axle torques (Graph 35-Graph 38); this is attributed to solver maximum time step configurations and can be eliminated by reducing step sizes (Pelster, 2024). However, decreasing step size increases simulation duration, exacerbating control system delay. Current configurations and outputs of the control system (demonstrated Graph 35 – Bottom) are seen to precisely regulate torque transfer based on wheel speed differences after initial fluctuations, as demonstrated in Graph 37 and Graph 38. After these initial fluctuations, the device settles to a percentage locking effect of approximately 90% (Graph 36) which is consistent with other devices tested.



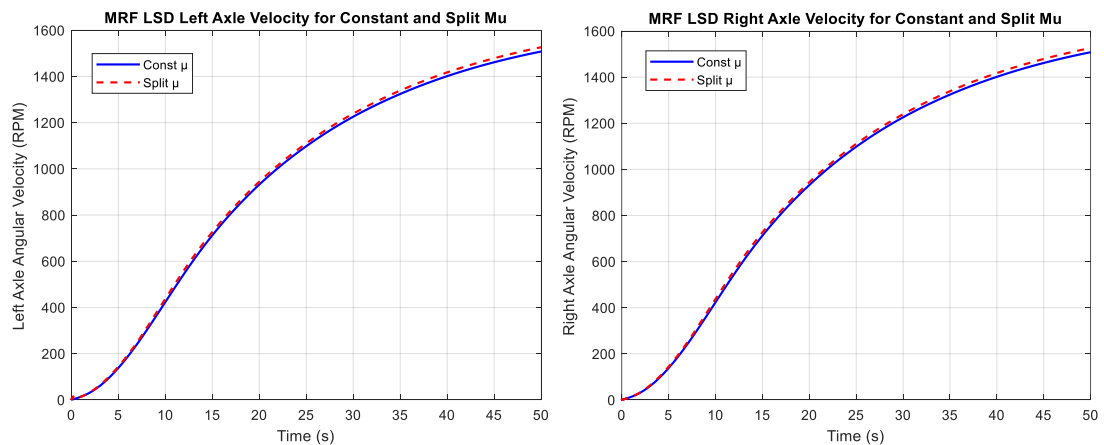
Graph 35: MRFLSD Simscape Driveline Results for Constant and Split Mu Comparison, (Top Left) Engine Speed, (Top Right) Propeller Shaft Torque, (Bottom) Magnetomotive Force Control Signal.



Graph 36: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Vehicle Velocity, (Right) Percentage Locking Effect.



Graph 37: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Torque, (Right) Right Axle Torque.



Graph 38: MRF LSD Simscape Driveline Results for Constant and Split Mu Comparison, (Left) Left Axle Angular Velocity, (Right) Right Axle Angular Velocity.

3.7 Validation of Results: Split Mu

To validate the Simscape Driveline results, a similar test scenario is simulated within Vi-CarRealTime. Prior to simulating the split mu test, a road data file is constructed within Vi-Road to replicate the surface friction data utilised in Simscape Driveline. The Vi-Road data is designed to implement a 0.1μ surface friction coefficient on the left half of the road and a 1μ friction coefficient on the right half (Figure 53), representing ice and dry tarmac respectively (VI-GRADE [3], 2020). To replicate the vehicles stationary start followed by rapid accelerator pedal input, an event control system is constructed using Vi-EventBuilder. The model triggers a throttle ramp input after one second of simulation time is passed. A path file controller is implemented to ensure vehicles maintain close trajectory to the centreline (VI-GRADE [2], 2020); this is to prevent vehicles deviating from the desired trajectory when asymmetric drive forces are introduced.

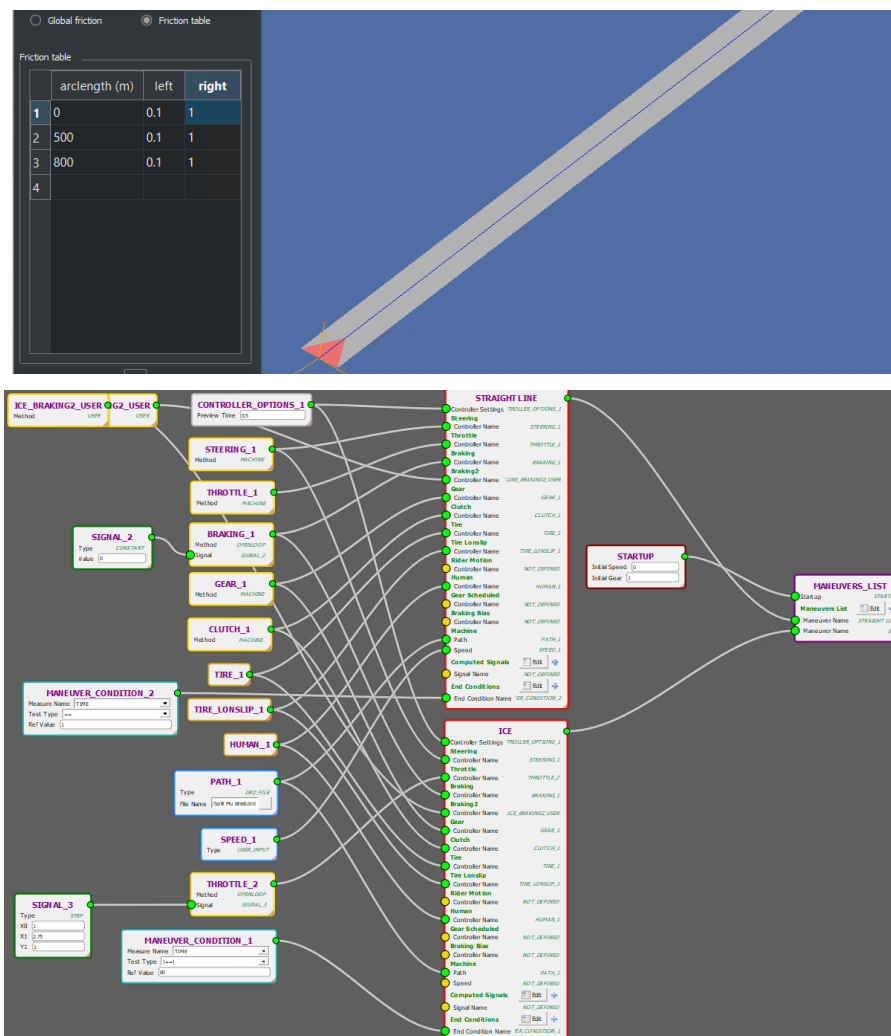
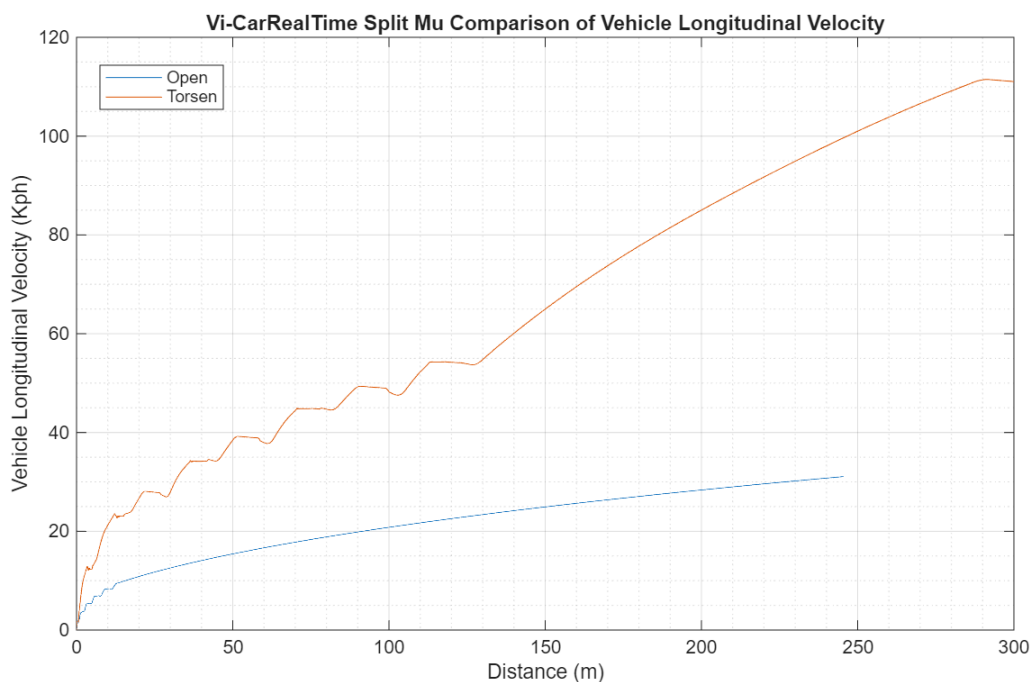
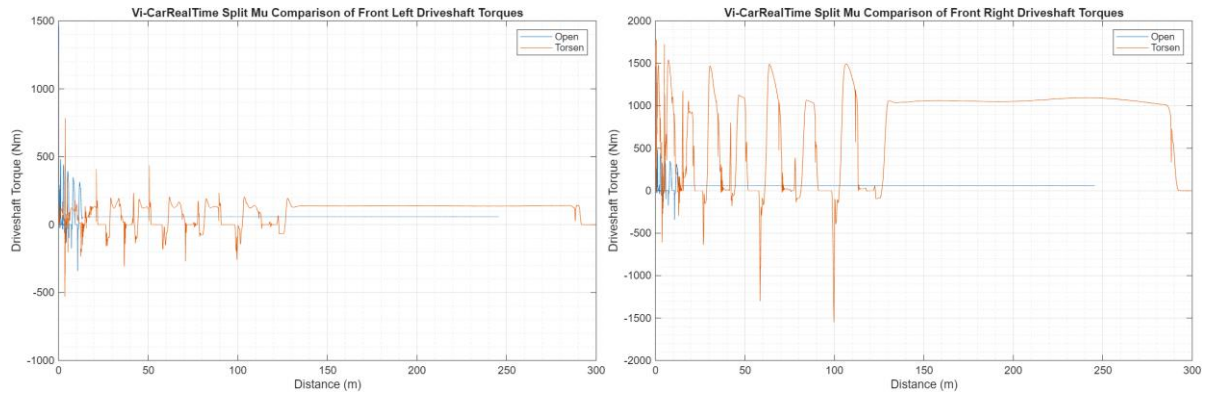


Figure 53: Setup Data for Split Mu Scenario (Top) Vi-Road Surface Friction Data, (Bottom) Vi-EventBuilder for Event Control System.

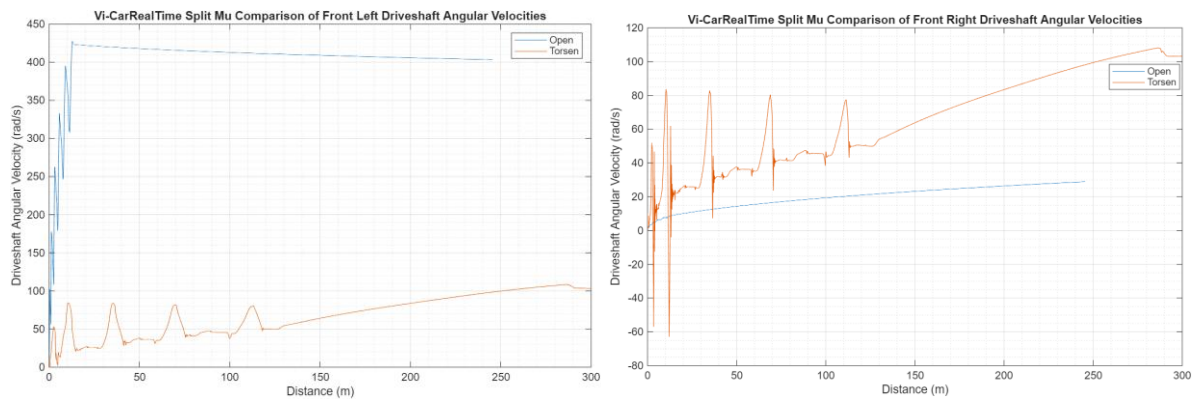
Two differentials are modelled and tested within Vi-CarRealTime to provide reference data for open differential and LSD validation. As previous literature and Simscape Driveline modelling demonstrates, the open differential performs poorly on split mu surface conditions (Graph 39). Soon after initial throttle inputs, drive force applications are limited by the wheel with least traction (Graph 40), the inability to transfer torque to the wheel with most traction causes the low traction wheel to spin up (Graph 41), thus further reducing torque application capabilities. When compared to the torque sensing differential, vehicle longitudinal speed is drastically lower resulting in the vehicle covering significantly shorter distances in the same amount of time; Graph 39 demonstrates that at 240 metres the torque sensing differential is travelling at approximately three and a quarter times faster than the open differential vehicle. This illustrates the significant performance benefits of an LSD in low slip scenarios such as split mu events. Simulation data also revealed significant torque steer reactions occurring when a FWD vehicle is fitted with an LSD (Graph 42), in particular a torque sensing device which reacts instantaneously (Frömmig, 2023). The Vi-CarRealTime simulation utilises a ‘robotic’ driver that can account for and react to drastic torque steer events, maintaining the vehicle on the prespecified path. However, considering a human driver the drastic changes in yaw rates caused by asymmetric drive forces will inevitably lead to loss of vehicle control with such a high TBR device fitted. The trends and performance gains demonstrated in the Vi-CarRealTime results support those from the Simscape Driveline results.



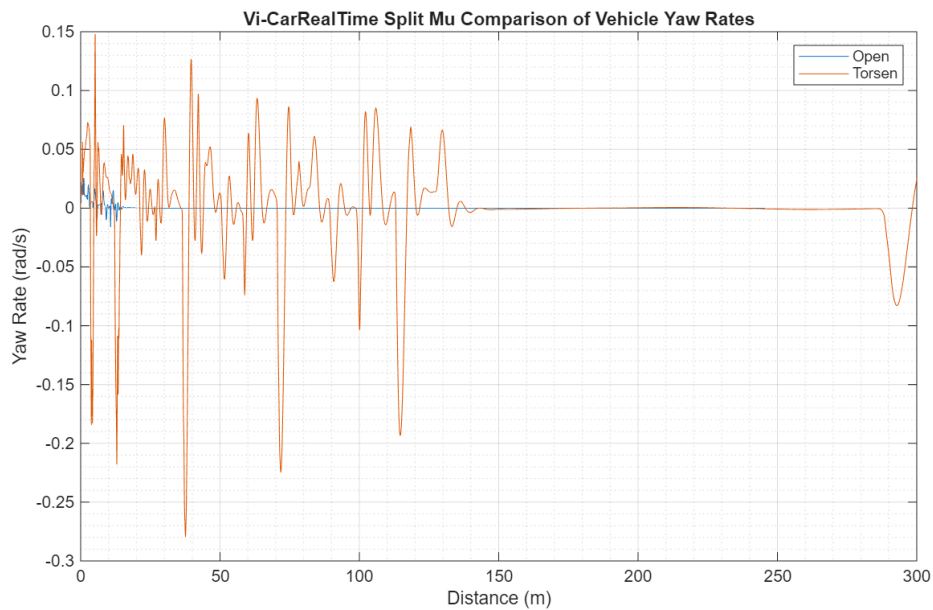
Graph 39: Vi-CarRealTime Vehicle Longitudinal Velocity Results for Split Mu Simulation for Open and Torsen Differentials.



Graph 40: Vi-CarRealTime Driveshaft Torque Results for Split Mu Simulation for Open and Torsen Differentials.



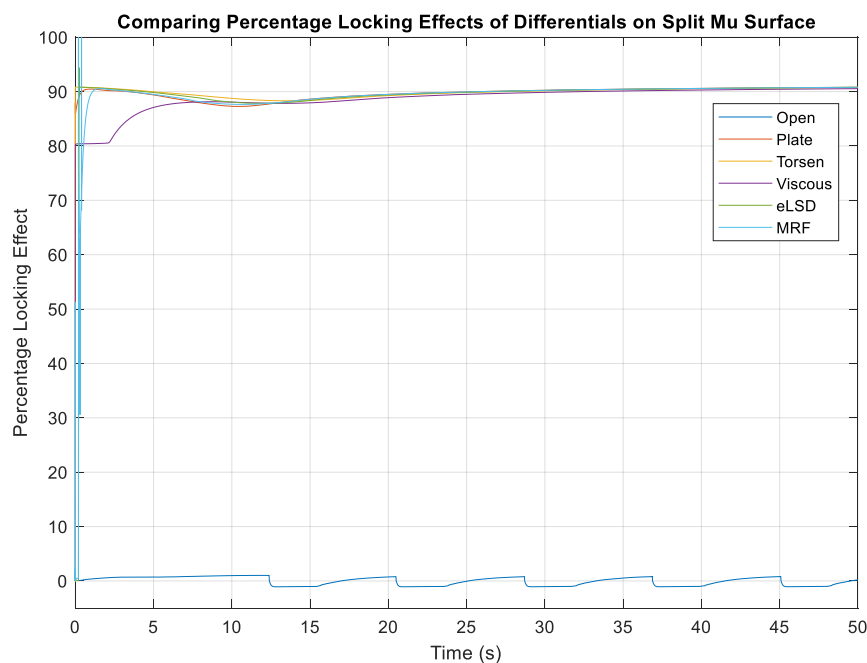
Graph 41: Vi-CarRealTime Driveshaft Angular Velocity Results for Split Mu Simulation for Open and Torsen Differentials.



Graph 42: Vi-CarRealTime Vehicle Yaw Rate Results for Split Mu Simulation for Open and Torsen Differentials.

3.8 Results Comparison and Analysis

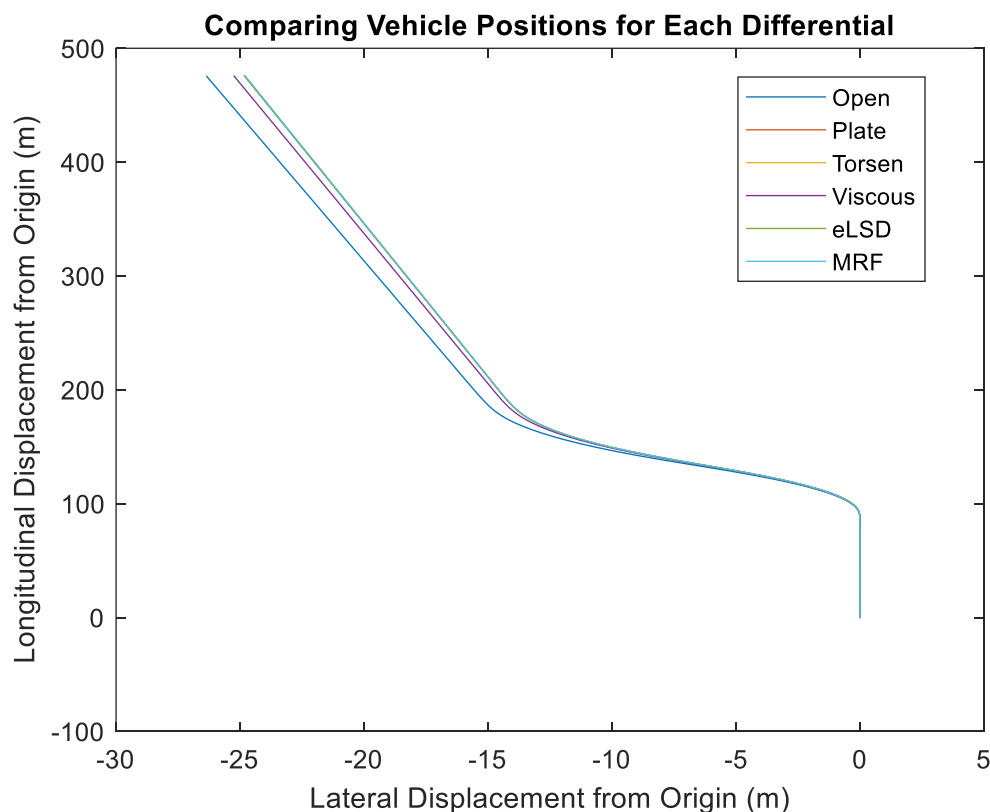
To establish the differences in LSD performances, plots in the following section compare responses of each device directly. A combination of Simscape Driveline and Simscape Multibody simulations are utilised in this section, whilst lateral dynamics are only accounted for within Multibody simulations. The percentage locking effect results from previous individual differential analysis are plotted for comparison in Graph 43. From these results, the torque sensing (Torsen) LSD reacts faster than all other differentials, locking in the shortest amount of time and consistently maintaining the highest locking effect during the first quarter section of the simulation (Bruls, et al., 2011). The eLSD also performs well, closely mirroring the torque sensing LSD with second fastest response time to achieve appropriate required locking, performance is well maintained across the duration of the simulation. Whilst the eLSD maintains similar performance to the torque sensing differential, the passive equivalent clutch pack LSD experiences a slower response time and out of all LSDs experiences the lowest percentage locking effect at 10 seconds, for a noticeable duration of approximately 4-5 seconds. The viscous device response time is slower and more gradual than mechanical alternatives due to the wheel speed difference requirements (Palazzolo, 2009). The MRF LSD demonstrates unpredictable and rapid changes during simulation initialisation and as a result is the last device to reach a stable percentage locking effect, although this is not ideal, further refinement to control algorithms would improve model stability. Demonstrated during final stages before stabilisation (1-3 seconds), the MRF device's locking characteristics demonstrate similar trendlines to PID output control signals. The split mu simulation highlights the poor performance of an open differential during this scenario.



Graph 43: Simscape Driveline Comparing Differential Percentage Locking Effects on split mu surface.

Multibody Lane Change Manoeuvre:

The following results section details a Simscape Multibody Lane change manoeuvre which compares the response of each differential. Graph 13 demonstrates the torque input where test simulations utilise ‘high’ signal, Graph 14 examples the steering signal where ‘lane change’ manoeuvre is utilised. Simulation results for this manoeuvre are demonstrated in Graph 44 - Graph 49, positions of the vehicles dictates that the open differential travels on a wider path from the origin in the lateral direction than all LSD vehicles (Graph 44 and Figure 54). On the contrary, the torque sensing LSD maintains the closest lateral distance to the origin; this is a result of torque transfer occurring within the LSDs (Graph 45). As demonstrated previously in Simscape Driveline results, the torque sensing differential exhibits instantaneous torque biasing (Graph 46) and is the cause for shortest lateral displacement from the origin. Upon examination of subplots in Graph 46, all LSDs transfer torque to the inside wheel during the lane change manoeuvre, the viscous coupling device transfers the least out of all other LSDs which is supported by the position data in Graph 44. Vehicle longitudinal (x-axis) velocities remain consistent for all differentials within this test scenario (Graph 45).



Graph 44: Comparing Vehicle Position Results for Simscape Multibody Lane Change Manoeuvre.

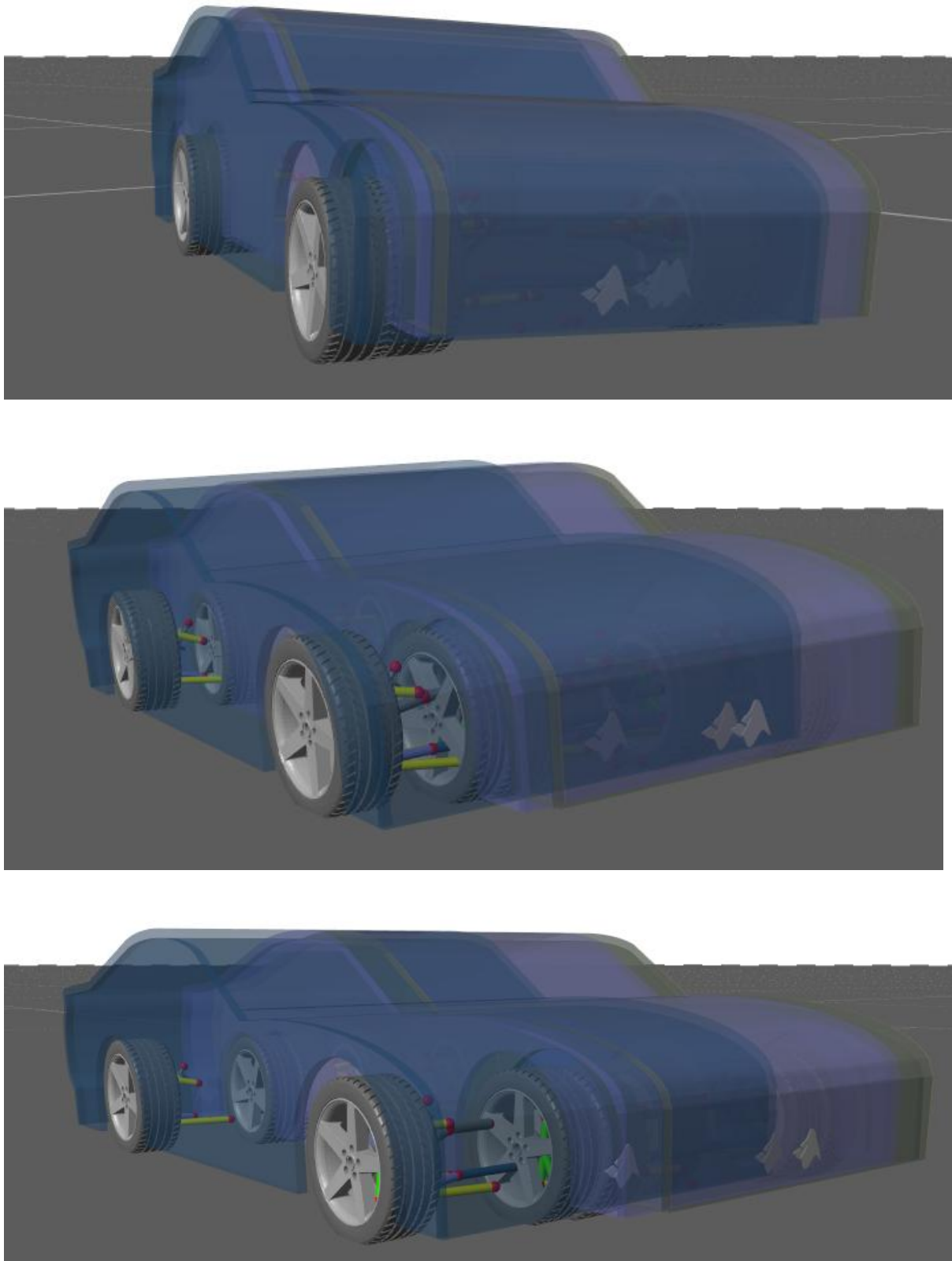
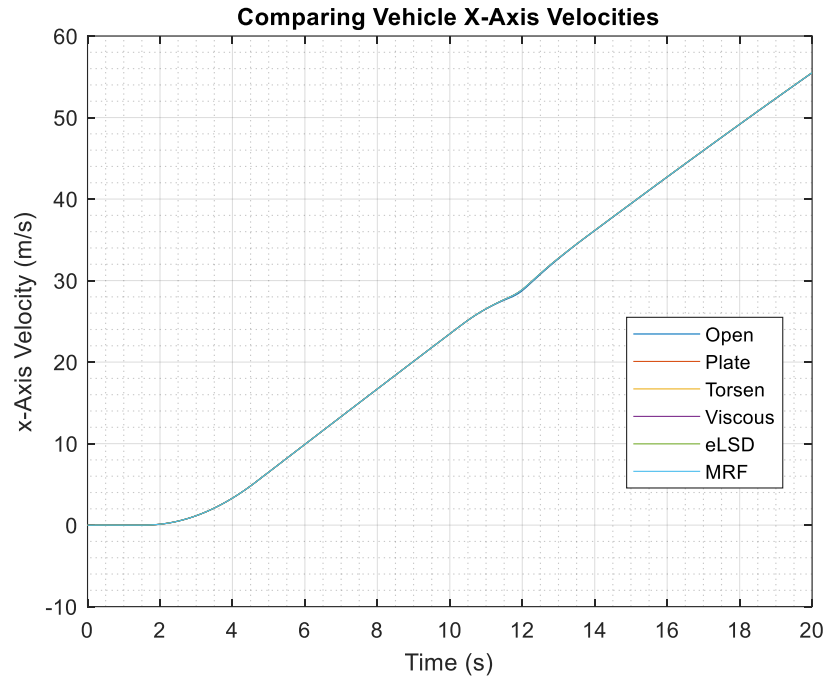
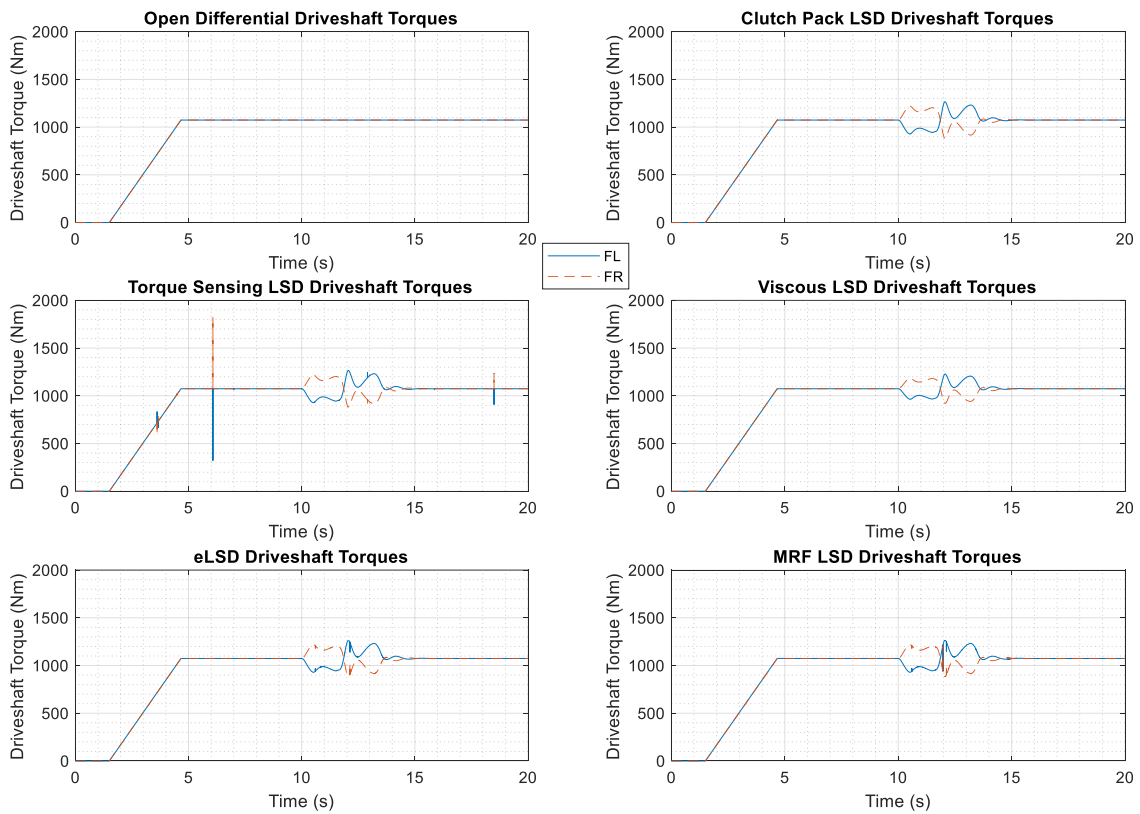


Figure 54: Simscape Multibody Lane Change Manoeuvre Demonstrating Key Time Frames of Right Steering (Top), Left Steering (Middle) and Straight Steering (Bottom) for the Following Differentials: Open (Blue), Torsen (Orange), Viscous (Purple) and MRF (Light Blue).



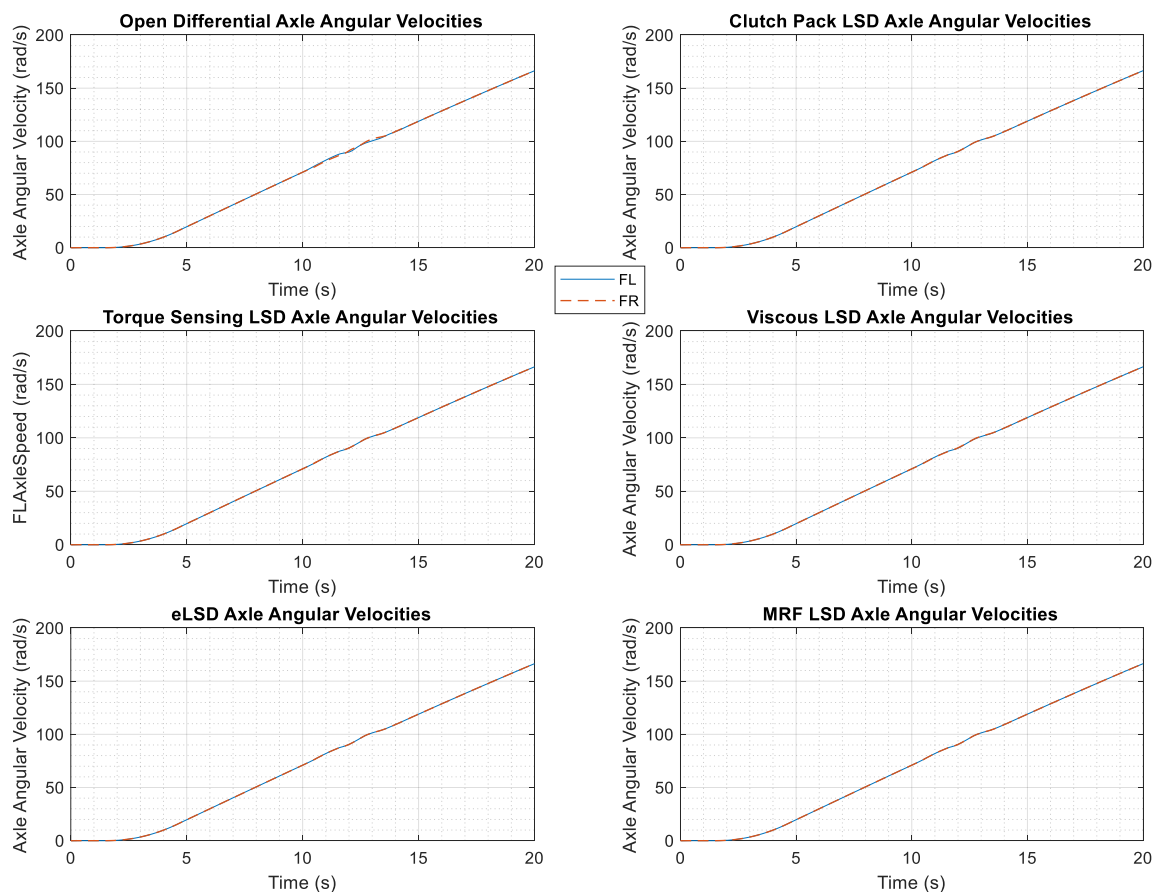
Graph 45: Comparing Vehicle Longitudinal Velocity Results for Simscape Multibody Lane Change Manoeuvre.



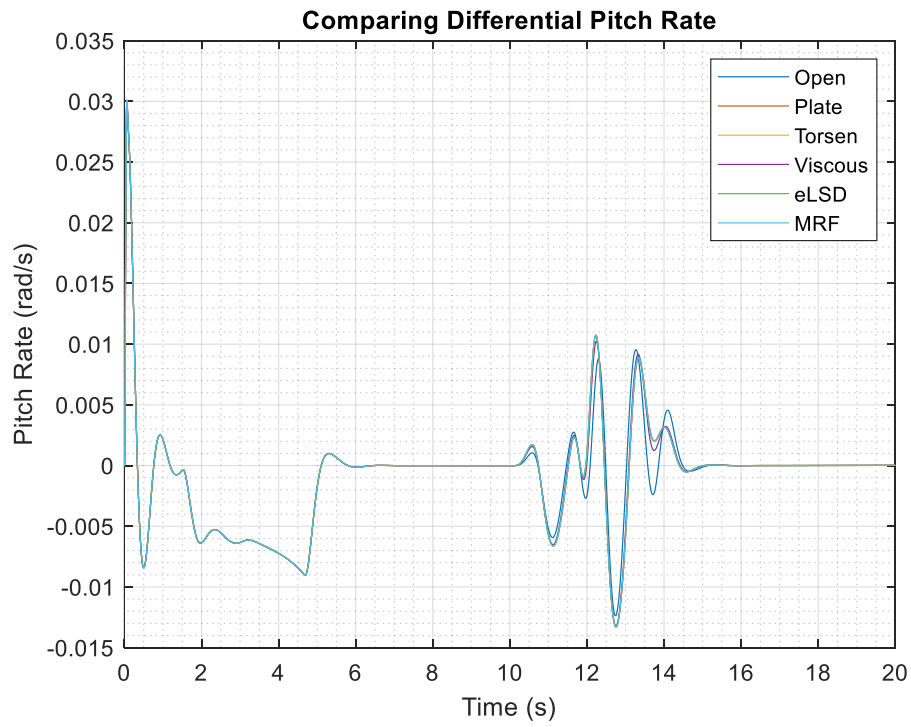
Graph 46: Comparing Vehicle Driveshaft Torque Results for Simscape Multibody Lane Change Manoeuvre.

Data from subplots in Graph 47 demonstrate that all LSDs limit wheel speed differences between the left and right drive axles. However, due to the open differentials design, wheel speed differences are permitted during cornering events whilst torque biasing is prohibited due to mechanical design (Crouse & Anglin, 1983).

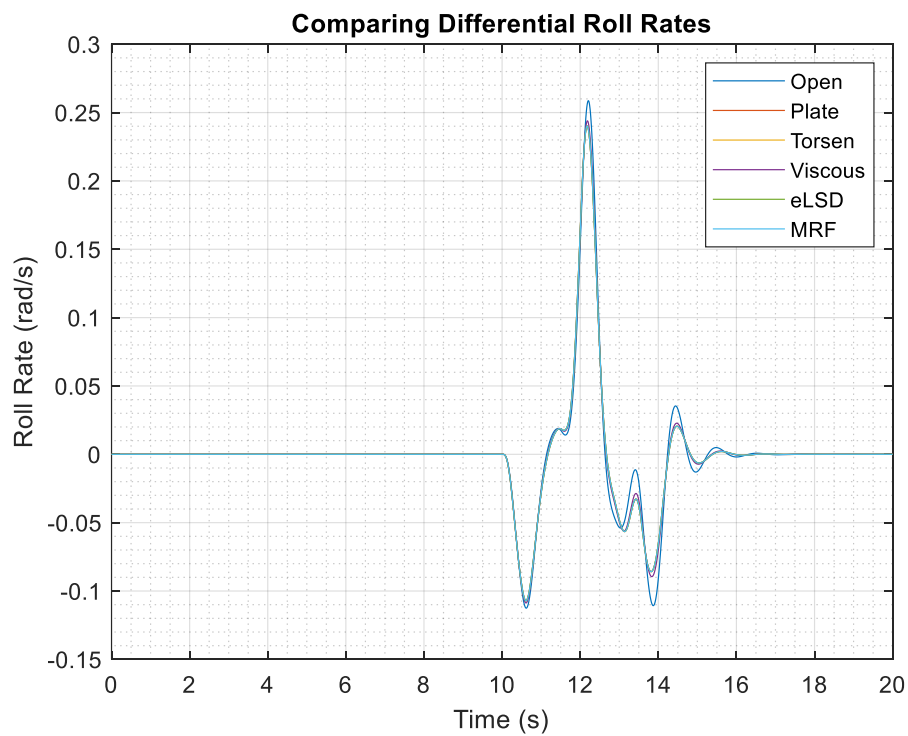
Pitch rate analysis (Graph 48) reveals that vehicles equipped with open differentials exhibit slower pitch dynamics, whereas those fitted with LSDs demonstrate more rapid pitching responses. In contrast, roll behaviour is inverted: open differentials produce higher roll rates, while LSD-equipped configurations show reduced roll motion (Graph 49). Among the LSD variants, the MRF and torque-sensing units yield the lowest roll responses, whereas the viscous coupling device exhibits the highest. Although the variation across the five LSD types is relatively small, it remains perceptible over extended longitudinal travel, particularly as lateral displacement from the origin increases (Graph 44).



Graph 47: Comparing Vehicle Driveshaft Axle Angular Velocity Results for Simscape Multibody Lane Change Manoeuvre.



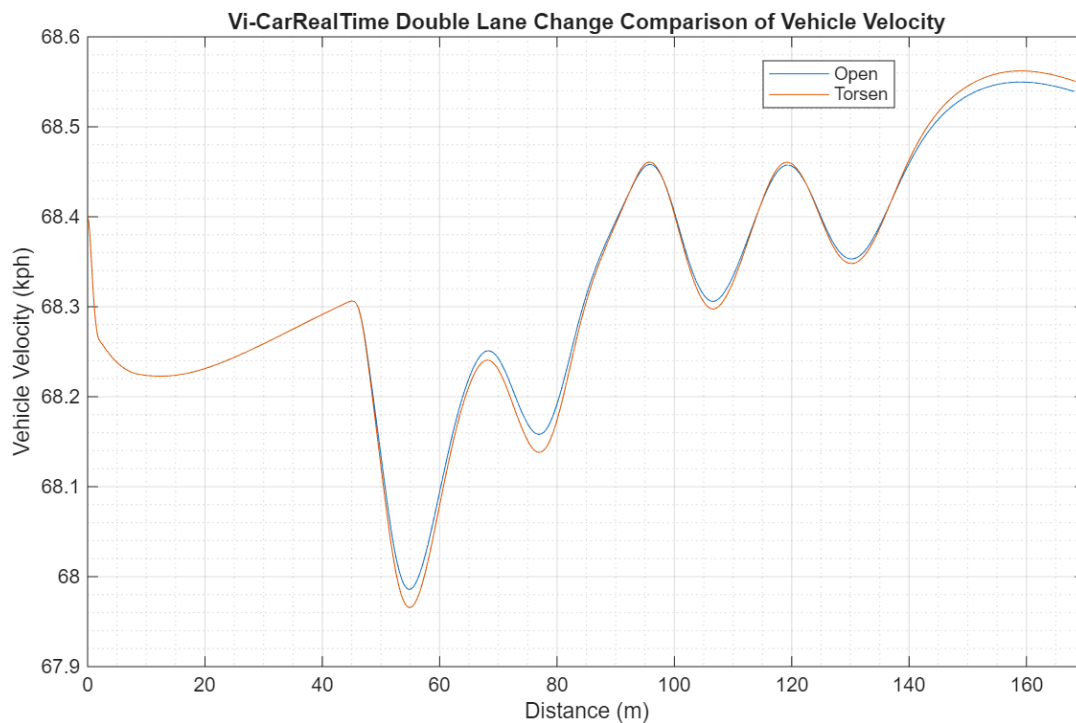
Graph 48: Comparing Vehicle Pitch Rate Results for Simscape Multibody Lane Change Manoeuvre.



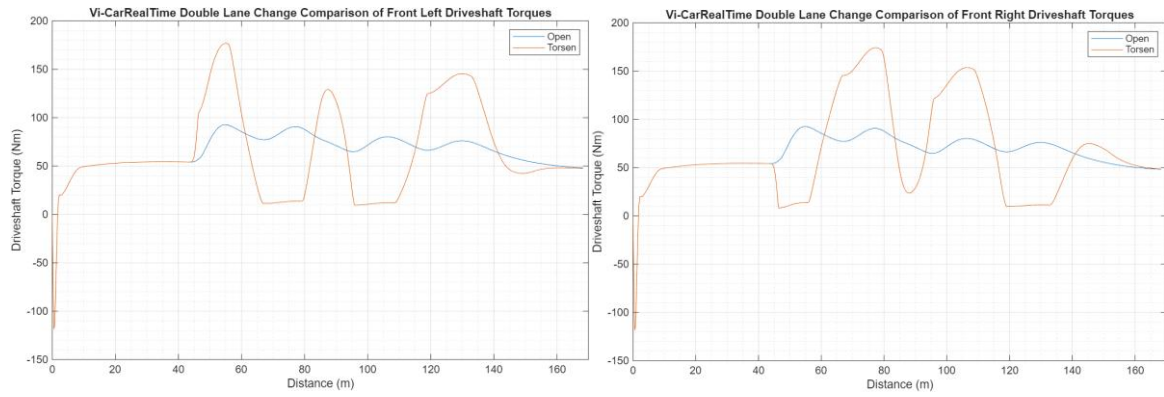
Graph 49: Comparing Vehicle Roll Rate Results for Simscape Multibody Lane Change Manoeuvre.

Lane Change Validation:

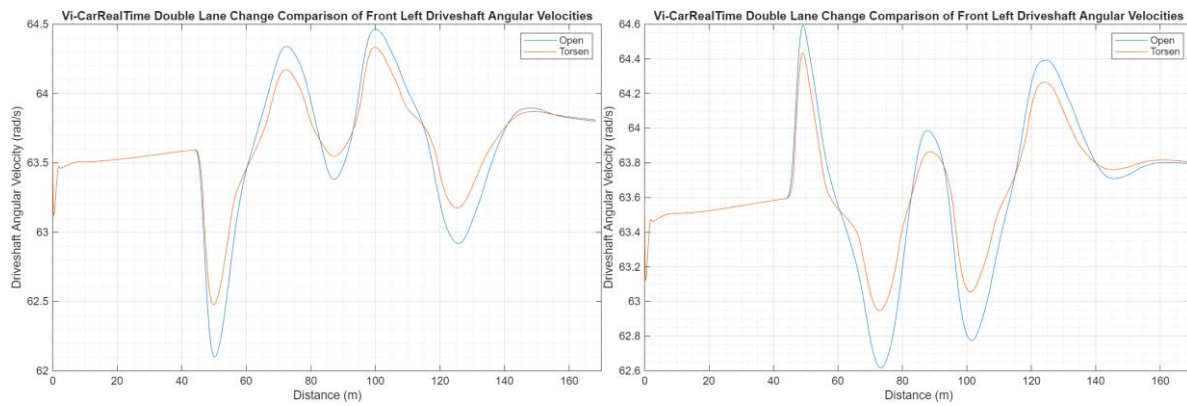
A second Vi-CarRealTime simulation is conducted for a double lane change manoeuvre utilising the open and torque sensing LSD. During the initial lane change, the open differential maintains a slightly higher velocity which later reverses on exit of the final lane change manoeuvre (Graph 50). During this test, torque is biased to the inside wheel during cornering for the LSD, the open differential maintains a 50-50 torque split throughout this event (Graph 51). Torque is biased to the inside wheel during low torque events where the locking torque does not reach required values to bias to the outside wheel. This situation is also demonstrated in the Simscape Multibody results. Differences arise between Vi-CarRealTime and Simscape Multibody results when inspecting wheel speed differences. This can be attributed to the locking methodology utilised within Simscape which behaves as a fully locked device, whilst Vi-CarRealTime permits speed differences during cornering (Graph 52). This assumption does decrease validity of results when considering wheel speed differences. However, all other data outcomes for both simulation techniques follow the same trendlines in results. Due to the torque sensing differential biasing torque to the inside wheel, maximum yaw rates for the LSD are lower than the open differential (Graph 53).



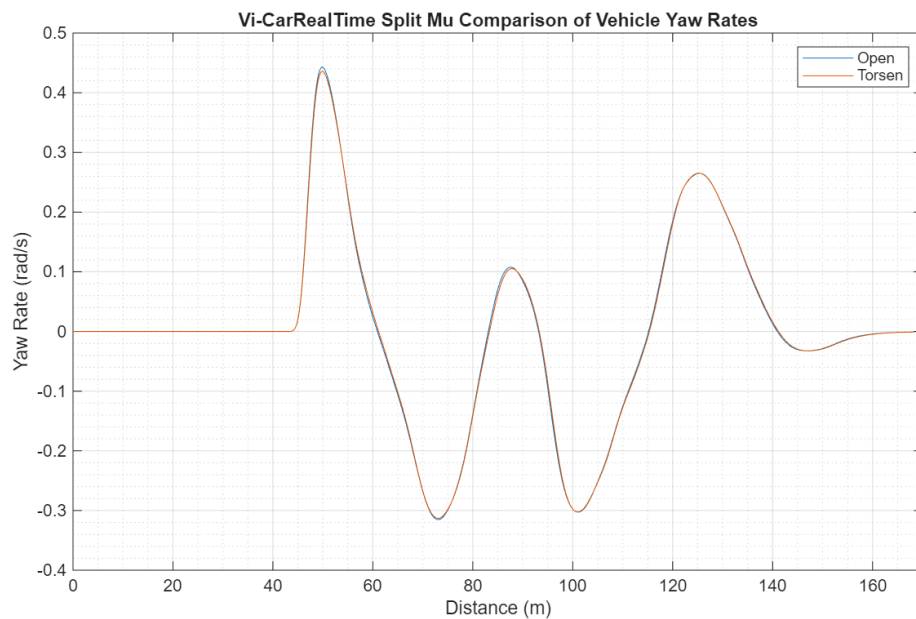
Graph 50: Vi-CarRealTime Vehicle Longitudinal Velocity Results for Double Lane Change Simulation for Open and Torsen Differentials.



Graph 51: Vi-CarRealTime Driveshaft Torque Results for Double Lane Change Simulation for Open and Torsen Differentials.



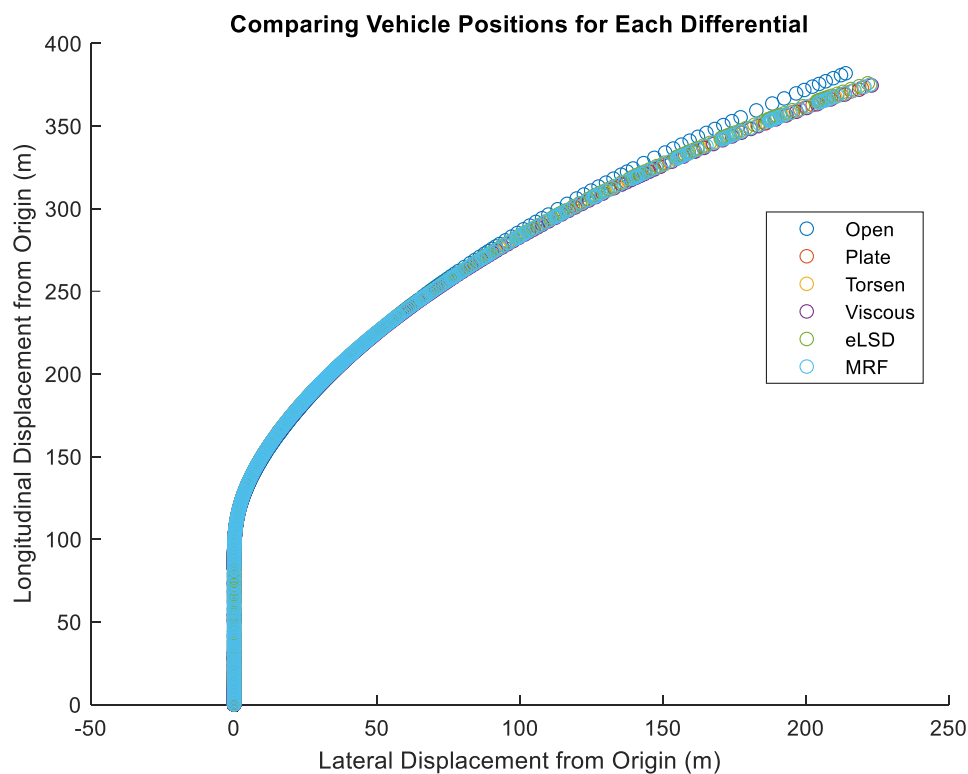
Graph 52: Vi-CarRealTime Driveshaft Axle Angular Velocity Results for Double Lane Change Simulation for Open and Torsen Differentials.



Graph 53: Vi-CarRealTime Vehicle Yaw Rate Results for Double Lane Change Simulation for Open and Torsen Differentials.

Multibody Ramp Steer Manoeuvre

A second Multibody simulation is conducted which investigates vehicle dynamic response during a ramp steer input, again torque input is ‘high’ signal (Graph 13) and ramp steer signal (Graph 14). Result data is demonstrated in Graph 54 - Graph 59, where the viscous device carries out the steer signal input in the tightest radius turn. As anticipated, the open differentials inability to transfer torque reduces the yaw moment acting on the vehicle due to greater limitations of drive force application. The significant asymmetric drive forces present on a vehicle equipped with an LSD increase the yaw moment acting on the vehicle, assisting in rotation and cornering (Frömmig, 2023). During initial vehicle turn in, LSDs transfer torque to the inner wheel which hinders vehicle turn in capabilities (Graph 54 and Figure 55), after specific dynamic loading criteria is met, torque is then transferred to the outer wheel which increases vehicle cornering abilities. The reduced torque transfer to the inner wheel of the viscous LSD vehicle during initial torque transfer stages assists in helping the vehicle achieve the tightest cornering radius (Graph 55). This analysis is supported by the x-axis velocity decreasing as the vehicle begins to travel further and faster in the y-axis coordinate frame. As the viscous LSD velocity in ‘x’ is lowest, ‘y’ velocity is therefore highest. Angular velocity of axle shafts (Graph 56) demonstrates that the open differential experiences wheel spin on the inside front wheel in addition to the eLSD. Thus, indicating the control system requires refinement to prevent wheel slip (Happee, et al., 2023).



Graph 54: Comparing Vehicle Position Results for Simscape Multibody Ramp Steer Manoeuvre.

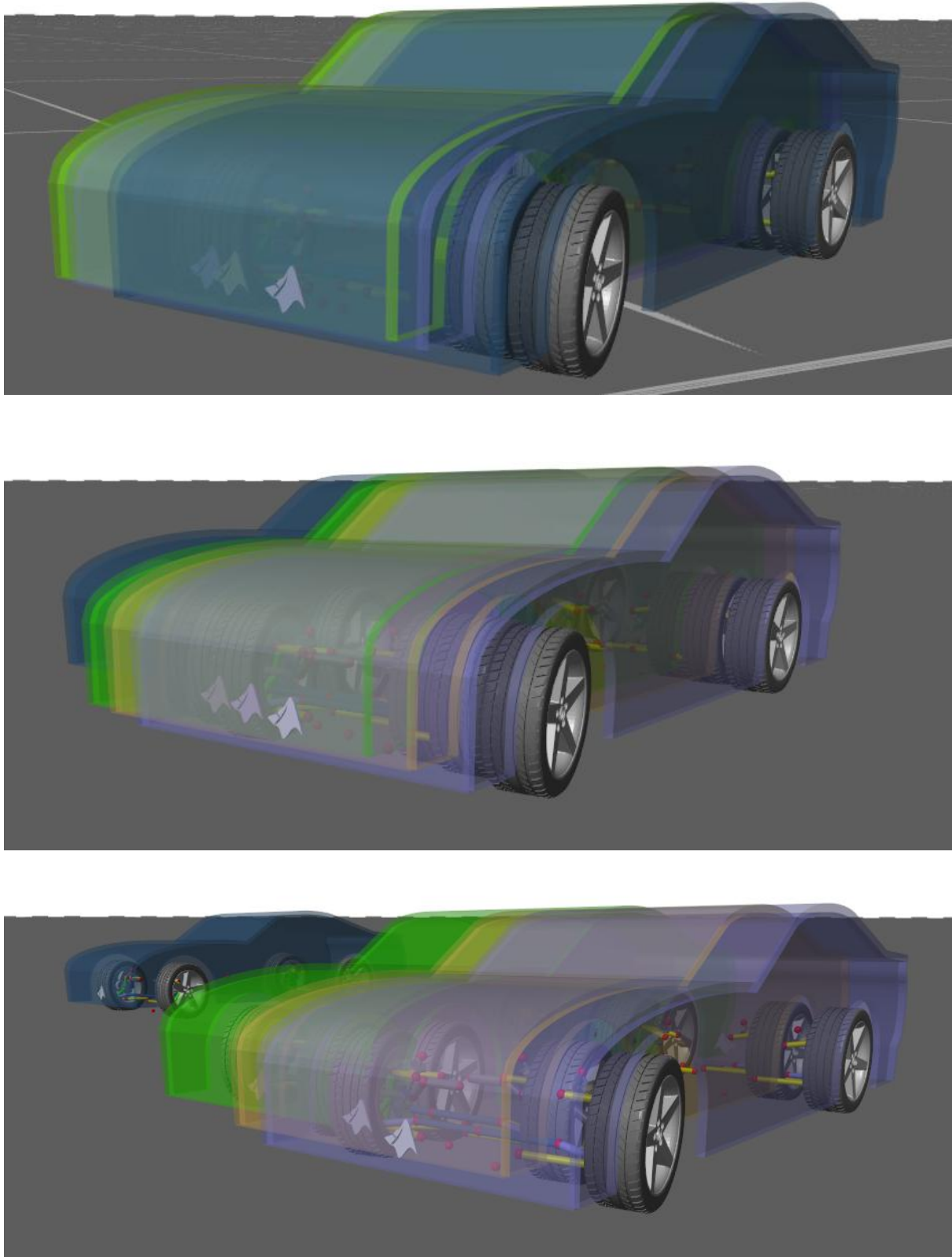
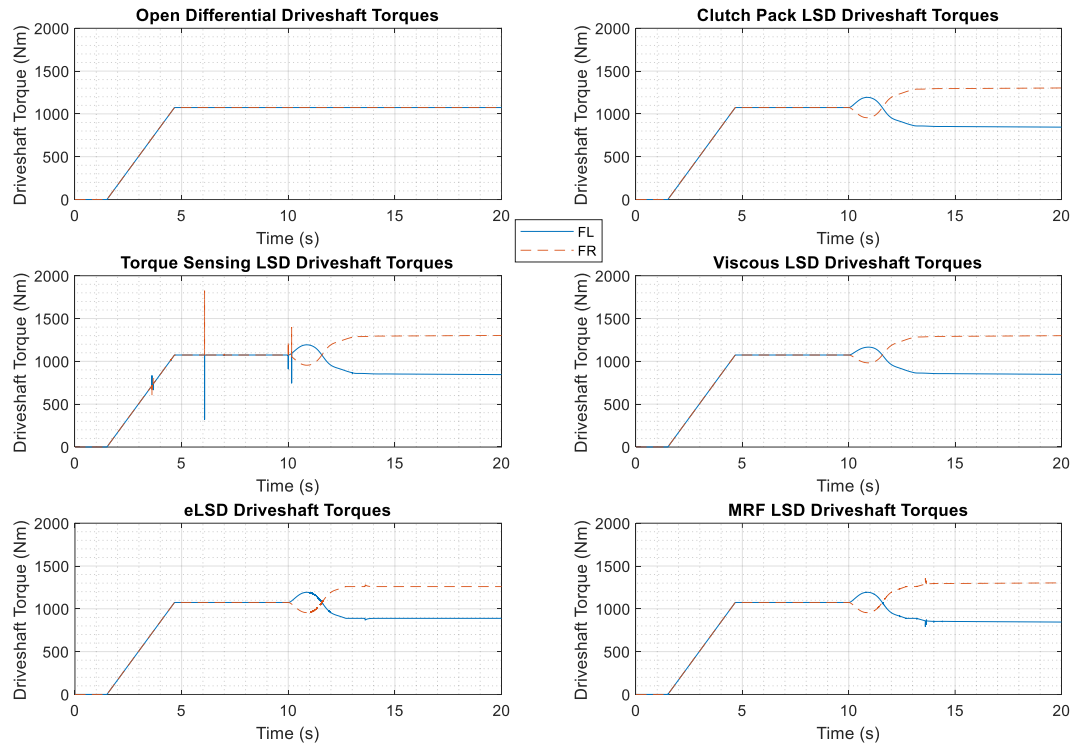
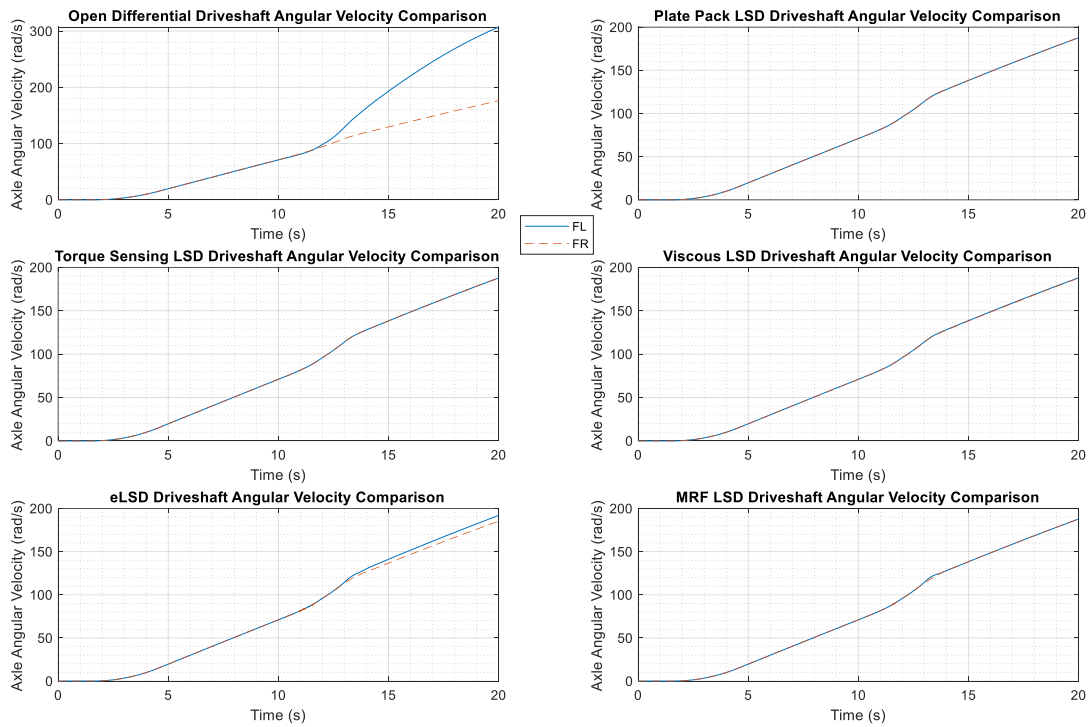


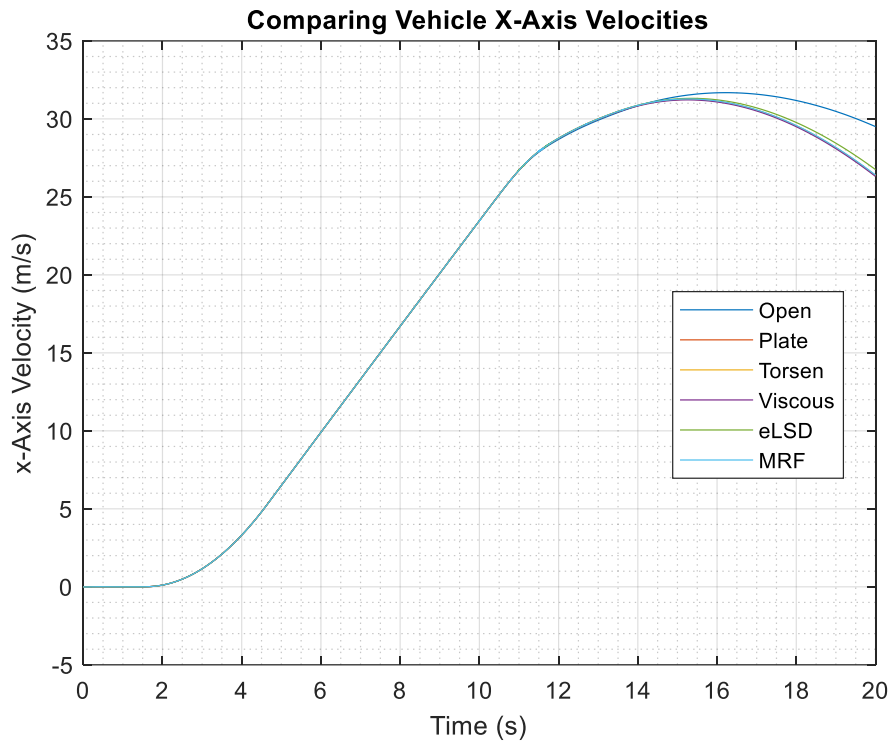
Figure 55: Simscape Multibody Ramp Steer Manoeuvre Demonstrating Key Time Frames of Initial Left Turn-in (Top), Favourable Torque Transfer (Middle) and Final Effects (Bottom) for the Following Differentials: Open (Blue), Torsen (Orange), Viscous (Purple) and eLSD (Green).



Graph 55: Comparing Vehicle Driveshaft Torque Results for Simscape Multibody Ramp Steer Manoeuvre.

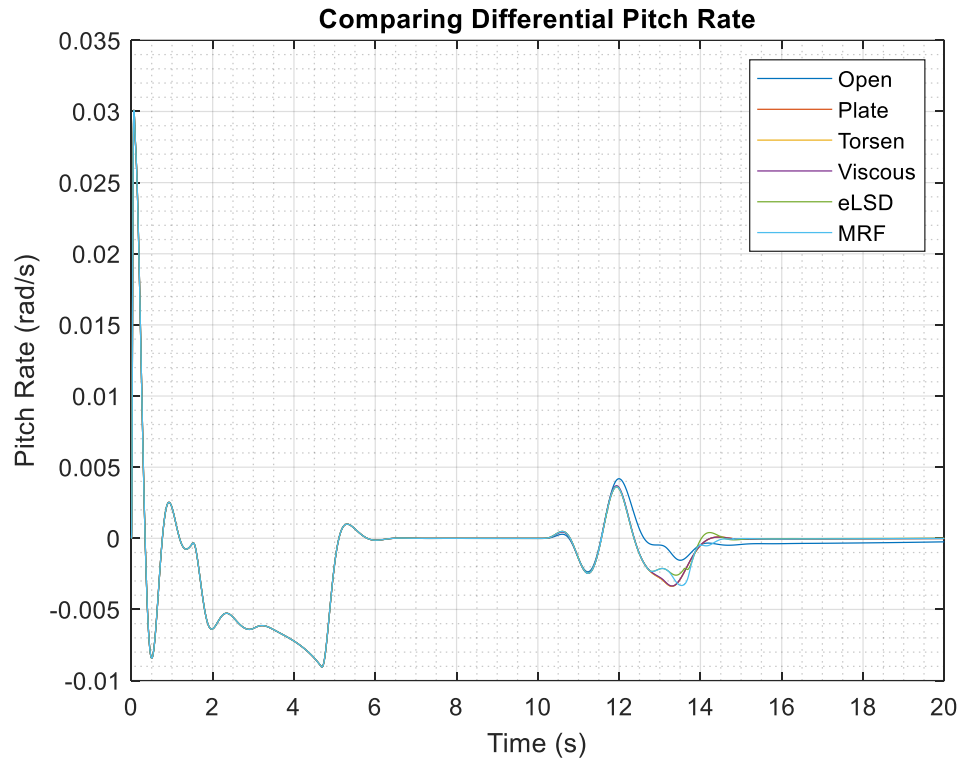


Graph 56: Comparing Vehicle Driveshaft Axle Angular Velocity Results for Simscape Multibody Ramp Steer Manoeuvre.

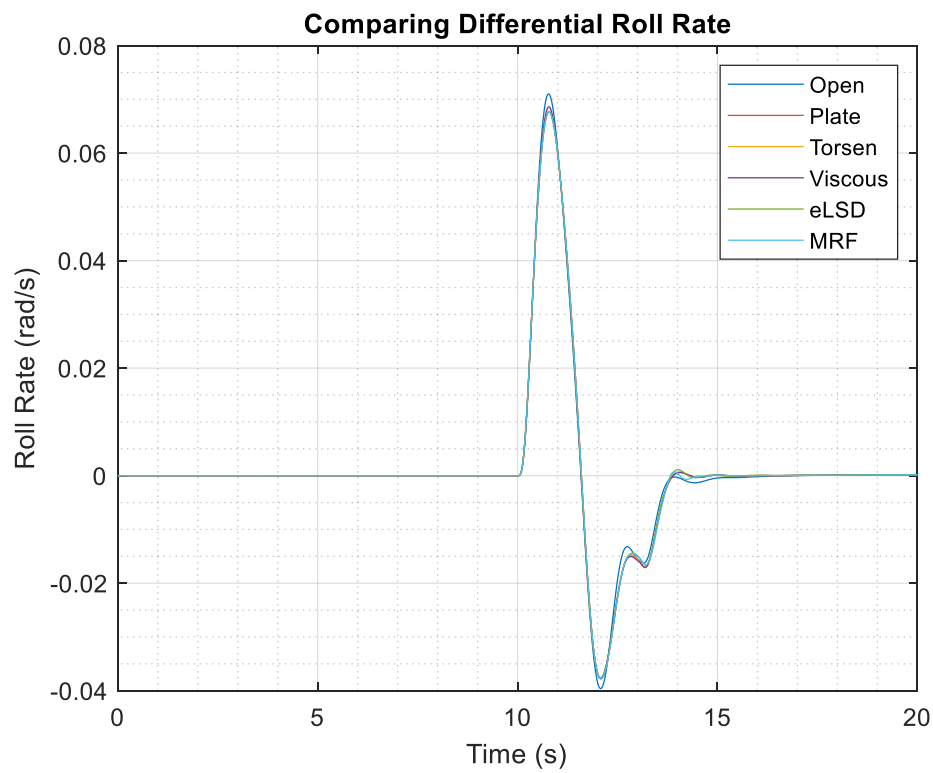


Graph 57: Comparing Vehicle Longitudinal Velocity Results for Simscape Multibody Ramp Steer Manoeuvre.

Pitch and roll data in Graph 58 and Graph 59 respectively demonstrate that significant differences between LSD and open differential responses occur between 11 and 14 seconds. Pitch rates increase considerably more for LSDs where the clutch pack type exceeds values greater than all others. When inspecting roll rates, initial turn in conditions demonstrate the open differential corners tighter than LSDs which attempt to limit wheel speed differences. However, once torque is transferred to outer wheels, pitch rates increase again for a short duration at a greater rate for all LSDs (between 12.5-13.5 seconds - Graph 59); most noticeably the clutch pack device. The performance differences between most passive LSDs are less drastic when compared to that of active devices, a wider cornering radius illustrates the downside of a basic wheel speed difference PID control system. To further improve the performance of these devices, implementation of a model predictive controller consisting of a vehicle dynamics bicycle model would enable specific actuation of control mechanisms to better respond to the drivers desired trajectory. Capturing the additional data for this developed control system would require additional sensor signal data such as: handwheel angle, yaw rate, accelerator pedal position, brake pedal position and more (Piyabongkarn, et al., 2006).



Graph 58: Comparing Vehicle Pitch Rate Results for Simscape Multibody Ramp Steer Manoeuvre.



Graph 59: Comparing Vehicle Roll Rate Results for Simscape Multibody Ramp Steer Manoeuvre.

4 Further Development

The findings from this project demonstrate a good insight into the performance of the 6 differentials investigated. The lack of real-world data to validate these findings does raise questions regarding the physical responses of these devices when installed on actual FWD vehicles. To combat this, 3 different methods were implemented to compare results for validation, these being: Simscape Driveline, Simscape Multibody and Vi-CarRealTime. Whilst consistent trendlines were seen across the three modelling methods, equation-based solvers introduce discontinuities and numerical noise during simulations to satisfy governing equations, reducing accuracy of results. To improve the projects accuracy of results, the further development suggestions mentioned below should be considered:

Simscape Driveline Model Development:

- Incorporate thermal dynamics in driveline modelling of differentials for increased accuracy of results during high intensity applications such as motorsport. LSDs particularly susceptible to thermal effects are the viscous coupling device and MR-Fluid (Palazzolo, 2009).
- Investigate alterations to differential parameters, some examples include: TBR for torque sensing LSD, preload, number of friction surfaces (clutch pack devices), alternative fluids with varying properties such as viscosity and yield stress (viscous and MRF LSDs).
- Consider and compare performance of alternative driveline configurations such as RWD, AWD and 4WD (Note: RWD investigations were conducted as a separate project previously).
- Investigate other LSDs such as torque vectoring systems, Salisbury and more (Jalali, et al., 2013).
- Consider LSD performance when combined with vehicle control systems such as ABS, YSC, traction control and more (Annamalai, et al., 2013).

Simscape Multibody Model Development:

- Construct multibody models of differentials using CAD models of gears and driveshafts for increased accuracy, thus replacing the Driveline differential models within Multibody systems (Figure 56).
- Increase suspension system accuracy by integrating: kinematic models of suspension joints and chassis components, non-linear springs and dampers, CAD modelling of real-world suspension components with flexible models instead of assumed rigid (Archut & Corves [2], 2024).
- Path following control logic for simulation of scenarios such as racing circuits, ISO approved manoeuvres and more (VI-GRADE, 2020).

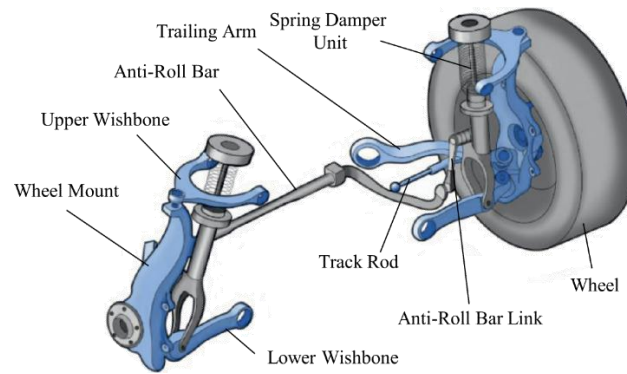


Figure 56: Multibody Suspension System Example (Archut & Burkhard, 2025).

General Further Development:

- Driver in the loop testing for human controllability aspect.
- Implementing the following improvements to MRF LSD model: completing magnetic studies (Figure 57), increased accuracy fluid model, conduct fluid dynamics testing (Park, et al., 2022).
- Implementation of improved/more advanced controller systems for active differentials utilising a bicycle model for anticipated vehicle response (Bhatt, et al., 2019).
- Conduct investigations and experimentation into model predict control systems (Li, et al., 2020).
- Complete real-world testing with physical devices to validate simulation data.
- Implement remaining LSDs into Vi-CarRealTime for additional test data validation.
- Modelling of an accurate braking system.

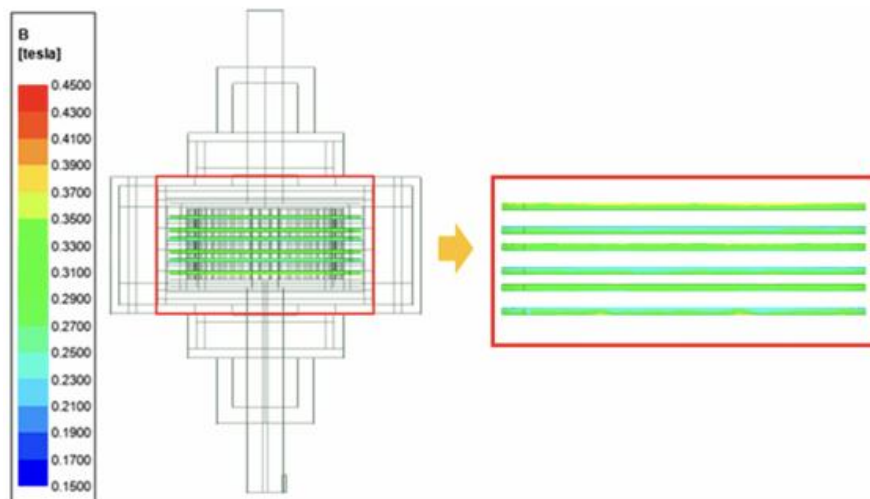


Figure 57: Electromagnetic Field Analysis Results Example from (Park, et al., 2022).

5 Conclusion

In conclusion, this project met the aims and objectives outlined at the start of the project. The Multibody simulation approach chosen to investigate vehicle dynamic effects proved invaluable to gaining insight into each device's vehicle dynamic effects and performance. The anticipated torque steering effects on FWD vehicles are well presented using multibody modelling and reinforce the sudden impacts these devices have on vehicle steering characteristics during extreme manoeuvres and high-performance scenarios. The split μ event demonstrates the rapid changes in drive forces and torques of the driven wheels, these sudden and near instantaneous changes (in the case of torque sensing and clutch type LSDs) resulted in approximately 6 times greater yaw rates and 3 times faster vehicle velocity. This illustrates just how uncontrollable these devices can be, even in the hands of experienced drivers. The rapid change in drive torques lead to increased yaw moments acting on the vehicle, exaggerated by FWD torque steer effects. The active differentials performed well in longitudinal testing scenarios throughout this project. However, when additional lateral degrees of freedom are modelled, the basic wheel speed difference PID controller struggles to predict driver intentions and does not reach the devices full potential. Earlier sections detailing further development provide ideas for optimising this control algorithm to better replicate systems utilised in modern vehicles. The results from this test assist in determining the locking characteristics of each LSD where the ranking of fastest to slowest reacting is as follows: torque sensing ('Torsen'), eLSD, clutch pack, MRF and finally viscous; as the open differential is unable to transfer/bias torque, it cannot be included in this ranking.

During dynamic test manoeuvres such as lane change and ramp steer events, the comparative performance for LSDs are similar. However, the torque sensing device is susceptible to sudden and small changes where momentary torque spiking occurs within data results, the viscous LSD demonstrates delayed response periods and, in some cases, reduced percentage locking effect, the clutch pack device exhibits similar behaviours to the torque sensing device but with a less abrupt and harsh response. Considering the variation in: response time, torque transferring/biasing capabilities, slip limiting proficiencies and driver controllability, there is no definitive solution in regards to which is the best LSD. The answer to this depends on too many variables: driver proficiency, surface type/conditions, racing regulations, tyre performance/quality and much more. However, the following recommendations and conclusions can be drawn: for competent racing drivers, a clutch pack or torque sensing differential will benefit high performance vehicles during on track racing where regulations prohibit active LSDs, for automotive applications a suitable passive device would be a viscous coupling unit, giving drivers the benefits of an LSD, but in a more controllable and safer form. Alternatively, active devices offer added benefits to vehicle safety systems with the addition of improved handling, this approach is more expensive.

References

- Abd elhafiz, M. & Metered, H., 2018. *Performance Evaluation of Magnetorheological Limited Slip Differential for Automotive Applications*, Warrendale: SAE Technical Paper.
- Alferink, T., 2019. *KMP Drivetrain Solutions: Plated Limited Slip Differential Explained*. [Online] Available at: <https://www.kmpdrivetrain.com/differentials/plated-limited-slip-differential-explained/> [Accessed 3 April 2024].
- Allen, J., 2009. *Four-Wheeler's Bible*. United States: MBI Pub. Company.
- Annamalai, R. et al., 2013. *Development of Vehicle Yaw Stability Controller*, India: SAE Technical Paper 2013-26-0086.
- ANSYS, 2023. *Ansys Blog: Multibody Dynamics: All Together Now*. [Online] Available at: <https://www.ansys.com/blog/what-is-multibody-dynamics> [Accessed 27 July 2025].
- Ansys, 2024. *What is an EV Powertrain?*. [Online] Available at: <https://www.ansys.com/en-gb/simulation-topics/what-is-an-ev-powertrain> [Accessed 17 February 2025].
- Archut, J.-L. & Burkhard, C., 2025. Real-time multibody simulation of vehicle wheel suspensions of different topologies with elastokinematic properties. *Multibody System Dynamics*, Volume 63, pp. 255-271.
- Archut, J. & Corves [2], B., 2024. Real-Time Flexible Multibody Simulation of a Vehicle Wheel Suspension with Elastokinematic Properties Based on Inertia Relief Modes. *New Trends in Mechanism and Machine Science*, Volume 165.
- AuburnGear, n.d.. *New Grip-N-Loc Limited Slip Differential: Built to Exceed your Expectations..* [Online] Available at: <https://auburngeardiffs.com/grip-n-loc/> [Accessed 19 February 2025].
- Autodata Training, 2019. *Youtube: Limited Slip Differentials Training Module Trailer*. [Online] Available at: <https://www.youtube.com/watch?v=jp5KR-tf0Ic> [Accessed 21 February 2025].
- AutoPivot, 2023. *Youtube: Drive Configurations Explained AWD, 4WD, RWD, FWD which do you Prefer?*. [Online]

Available at: <https://www.youtube.com/watch?v=ILFYBH4ciqI>

[Accessed 17 February 2025].

Bhatt, G., Manoharan, K., Chauhan, P. & Bhattacharya, S., 2019. MEMS Sensors for Automotive Applications: A Review. In: *Sensors for Automotive and Aerospace Applications*. Germany: Springer Nature Singapore, pp. 223-239.

Blundell, M. & Harty, D., 2015. *The Multibody Systems Approach to Vehicle Dynamics*. 2nd ed. Coventry: Elsevier Science & Technology.

Bruls, O., Duysinx, P., Poulet, N. & Virlez, G., 2011. *Simulation of Differentials in Four-Wheel Drive Vehicles Using Multibody Dynamics*, Washington: Department of Aerospace and Mechanical Engineering.

Chocholek, S., 1988. *The Development of a Differential for the Improvement of Traction Control*, New York: IMechE.

Crolla, D., 2015. *Encyclopedia of Automotive Engineering*. United Kingdom: Wiley.

Crolla, D. & Mashadi, B., 2011. *Vehicle Powertrain Systems*. Germany: Wiley.

Crouse, W. & Anglin, D., 1983. *Automotive Manual Transmission and Power Trains*. 6th ed. United Kingdom: McGraw-Hill.

Doyle, S., 2025. *Research Proposal Report*, Swansea: n.p.

DSport, 2022. *DSport Performance and Tech Magazine: Everything You Need To Know About Limited Slip Differentials*. [Online]

Available at: <https://dsportmag.com/the-tech/speed-shop/everything-you-need-to-know-about-limited-slip-differentials/2/>

[Accessed 3 April 2024].

Eaton, 2016. *Youtube: Eaton IntelliTrac electronic limited slip differential rear wheel drive features*. [Online]

Available at: <https://www.youtube.com/watch?v=GYUdFWzwgeM>

[Accessed 24 February 2025].

Forstinger, M., Bauer, R. & Hofer, A., 2015. Modelling and Simulation of Passive Limited-slip Differentials. *IFAC-PapersOnLine*, 48(1), pp. 502-507.

Frömmig, L., 2023. *Basic Course in Race Car Technology: Introduction to the Interaction of Tires, Chassis, Aerodynamics, Differential Locks and Frame*. Germany: Springer Fachmedien Wiesbaden.

- Gadola, M., Chindamo, D. & Lenzo, B., 2021. Revisiting the Mechanical Limited-Slip Differential for High-Performance and Race Car Applications. *Engineering Letters*, 29(3), pp. 824-839.
- Gillespie, T., 2021. *Fundamentals of Vehicle Dynamics*. United States: SAE International.
- Guiggiani, M., 2018. *The Science of Vehicle Dynamics Handling, Braking, and Ride of Road and Race Cars*. Germany: Springer International Publishing.
- Happee, R., Irmak, T., Winkel, K. & Shyrokau, B., 2023. Standards for Passenger Comfort in Automated Vehicles: Acceleration and Jerk. *Applied Ergonomics*, Volume 106.
- Heisler, H., 2002. *Advanced Vehicle Technology*. United Kingdom: Elsevier Science.
- Hussien, S., Jaafar, H., Ghazali, R. & Razif, N., 2015. The Effects of Auto-Tuned Method in PID and PD Control Scheme for Gantry Crane System. *International Journal of Soft Computing and Engineering (IJSCE)*, 4(6), pp. 121-125.
- ISO, 2011. *ISO 8855:2011 Road Vehicles Vehicle Dynamics and Road-Holding Ability Vocabulary*, Geneva: International Organization for Standardization.
- Jalali, K., Uchida, T., Lambert, S. & McPhee, J., 2013. Development of an Advanced Torque Vectoring Control System for an Electric Vehicle with In-Wheel Motors using Soft Computing Techniques. *SAE International Journal of Alternative Powertrains*, 2(2), pp. 261-278.
- Jin, L. et al., 2021. Calculation and Verification of the Real-Time Working Characteristics of a Viscous Coupling. *Applied Science*, 11(3).
- Karapetoff, V., 2003. *The Magnetic Circuit - Electromagnetic Engineering*. n.p: Wexford College Press.
- Li, s. et al., 2020. Vehicle Yaw Stability Control at the Handling Limits Based on Model Predictive Control. *International Journal of Automotive Technology*, Volume 21, pp. 361-370.
- Mathworks [1], 2025. *MATLAB Help Centre: Basic Principles of Modeling Physical Networks*. [Online]
Available at: <https://uk.mathworks.com/help/simscape/ug/basic-principles-of-modeling-physical-networks.html#seealso>
[Accessed 27 July 2025].
- Mathworks [10], 2025. *MATLAB Help Centre: Full Vehicle on Four Post Testrig*. [Online]
Available at: <https://uk.mathworks.com/help/sm/ug/sfull-vehicle-on-four-post-testrig.html>
[Accessed 6 August 2025].

Mathworks [11], 2025. *MATLAB Help Centre: Rotational Multibody Interface*. [Online]
Available at: <https://uk.mathworks.com/help/simscape/ref/rotationalmultibodyinterface.html>
[Accessed 8 August 2025].

Mathworks [12], 2025. *MATLAB Help Centre: Translational Hard Stop*. [Online]
Available at: <https://uk.mathworks.com/help/simscape/ref/translationalhardstop.html>
[Accessed 8 August 2025].

Mathworks [13], 2025. *MATLAB Help Centre: Magic Formula Tire Force and Torque*. [Online]
Available at: <https://uk.mathworks.com/help/sm/ref/magicformulatireforceandtorque.html>
[Accessed 11 August 2025].

Mathworks [2], 2025. *MATLAB Help Centre: Tire-Road Interaction (Magic Formula)*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ref/tireroadinteractionmagicformula.html>
[Accessed 28 July 2025].

Mathworks [3], 2025. *MATLAB Help Centre: Custom Tire and Combined Slip Interface - Car with Heave and Roll*. [Online]
Available at: <https://uk.mathworks.com/help/sm/ug/custom-tire-and-combined-slip-interface.html>
[Accessed 28 July 2025].

Mathworks [4], 2025. *MATLAB Help Centre: Open Differential*. [Online]
Available at: <https://uk.mathworks.com/help/autoblks/ref/opendifferential.html>
[Accessed 29 July 2025].

Mathworks [5], 2025. *MATLAB Help Centre: Simscape Component*. [Online]
Available at: <https://uk.mathworks.com/help/simscape/ref/simscapecomponent.html>
[Accessed 1 August 2025].

Mathworks [6], 2025. *Matlab Help Centre: Differential*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ref/differential.html>
[Accessed 1 August 2025].

Mathworks [7], 2025. *MATLAB Help Centre: Limited Slip Differential with Clutches*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ug/limited-slip-differential-with-clutches.html>
[Accessed 1 August 2025].

Mathworks [8], 2025. *MATLAB Help Centre: Torsen Differential*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ug/torsen-differential.html>
[Accessed 1 August 2025].

Mathworks [9], 2025. *MATLAB Help Centre: Torque Converter*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ref/torqueconverter.html>
[Accessed 4 August 2025].

Mathworks, 2025. *MATLAB Help Centre: Driveline Modeling*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/driveline-modeling.html>
[Accessed 7 July 2025].

Mathworks, 2025. *MATLAB Help Centre: Logic-Controlled Clutch*. [Online]
Available at: <https://uk.mathworks.com/help/sdl/ref/logiccontrolledclutch.html>
[Accessed 21 August 2025].

NI, 2025. *The PID Controller & Theory Explained*. [Online]
Available at: <https://www.ni.com/en/shop/labview/pid-theory-explained.html>
[Accessed 21 August 2025].

Pacejka, H. & Besselink, I., 2012. *Tire and Vehicle Dynamics*. 3rd ed. Amsterdam : Elsevier/BH.

Pacejka, H., Besselink, I. & Schmeitz, A., 2010. An Improved Magic Formula/Swift Tyre Model that can Handle Inflation Pressure Changes. *Vehicle System Dynamics*, 48(1), p. 337–352.

Palazzolo, J., 2009. *High-Performance Differentials, Axles & Drivelines*. United Kingdom: CarTech.

Parker Lord, 2024. *MRF-140CG Magneto-Rheological Fluid Technical Data Sheet*, Cary: Parker Lord.

Park, J.-Y., Oh, J.-S. & Kim, Y.-C., 2022. Design and Control of Multi-Plate MR Clutch Featuring Friction and Magnetic Field Control Modes. *Sensors*, 22(5).

Patronis, E., Davis, D. & Brown, P., 2013. *Sound System Engineering 4e*. United Kingdom: Taylor & Francis.

Pelster, E., 2024. *Youtube: Using Solver Profiler for Analyzing Variable Step Solver Performance | Simscape Electrical Modeling*. [Online]
Available at: https://www.youtube.com/watch?v=_lZ3VGbrMdE
[Accessed 12 August 2025].

Pena, P., Garcia, M. & Tekes, A., 2020. Modeling of Compliant Mechanisms in MATLAB Simscape. *Proceedings of the ASME 2020 International Mechanical Engineering Congress and Exposition. Volume 7B: Dynamics, Vibration, and Control.*, Volume 7B.

Piyabongkarn, D., Lew, J., Grogg, J. & Kyle, R., 2006. *Stability-Enhanced Traction and Yaw Control using Electronic Limited Slip Differential*, Detroit: SAE Technical Paper 2006-01-1016.

Polyphony Digital Inc, 2025. *Beyond the Apex* The Gran Turismo Magazine. [Online]

Available at: <https://www.gran-turismo.com/tr/gt7/apex/mechanics/07>

[Accessed 20 February 2025].

Radzevich, S., 2021. *Recent Advances in Gearing Scientific Theory and Applications*. Germany: Springer International Publishing.

Rahnejat, H., Mendeny, M., Farshidianfar, A. & Ebrahimi, M., 2002. Optimization of the High-Frequency Torsional Vibration of Vehicle Driveline Systems using Genetic Algorithms. *Proceedings of the Institution of Mechanical Engineers Part K Journal of Multi-Body Dynamics*, 216(3), pp. 249-262.

RPSCOE, n.d.. *Raghupati Singhania Centre of Excellence for Tyre and Vehicle Mechanics (RPSCOE): Virtual Proving Ground & Simulation Lab*. [Online]

Available at: <https://prof-rkkumar.wixsite.com/iitm-vpg-lab>

[Accessed 11 August 2025].

Rubin, D. & Arogeti, S., 2015. Vehicle Yaw Stability Control using Active Limited-Slip Differential via Model Predictive Control Methods. *International Journal of Vehicle Mechanics and Mobility*, 53(9), pp. 1315-1330.

Russo, R., Terzo, M. & Strano, S., 2016. Enhancement of vehicle dynamics via an innovative magnetorheological fluid limited slip differential. *Mechanical Systems and Signals Processing*, Volume 70-71, pp. 1193-1208.

SAE, 2022. *Vehicle Dynamics Terminology J670_202206*, n.p.: Society of Automotive Engineers.

Schultz, M., 1977. Viva la Differential!. *Popular Mechanics*, 147(1), pp. 86-88.

Sciuto, G., Kowol, P. & Capizzi, G., 2023. Modeling and Experimental Characterization of a Clutch Control Strategy Using a Magnetorheological Fluid. *Fluids*, 8(5).

Sharma, C. & Purohit, K., 2004. *Design of Machine Elements*. India: PHI Learning.

Shih, S. & Bowerman, W., 2002. *An Evaluation of Torque Bias and Efficiency of Torsen Differential*, s.l.: SAE Technical Paper.

Smith, J., 2013. *Smith's Fundamentals of Motorsport Engineering*. United Kingdom: Oxford Nelson Thornes Ltd.

Stone, R. & Ball, J., 2004. *Automotive Engineering Fundamentals*. United Kingdom: SAE International.

Team O'Neil, 2020. *Youtube: Limited Slip Differentials: LSD Selection, Setup, and Tuning*. [Online] Available at: <https://www.youtube.com/watch?v=ceT61lgERmA&t=302s> [Accessed 26 July 2025].

Torsen Traction, n.d.. *Ask Torsen: Torque Bias Ratio Functional Questions*. [Online] Available at: <https://torsen.com/ask-torsen-torque-bias-ratio-functional-questions/> [Accessed 6 September 2025].

Tremlett, A. et al., 2014. Quasi-Steady-State Linearisation of the Racing Vehicle Acceleration Envelope: a Limited Slip Differential Example. *Vehicle System Dynamics*, 52(11), p. 1416–1442.

Turner Motorsport, n.d. *Differential Upgrade Guide*. [Online] Available at: https://www.turnermotorsport.com/t-Differential_Upgrade_Guide [Accessed 31 Julh 2025].

Vagia, M., 2012. *PID Controller Design Approaches: Theory, Tuning and Application to Frontier Areas*. Croatia: IntechOpen.

VanGelder, K., 2022. *Fundamentals of Automotive Technology*. United States: Jones & Bartlett Learning.

VI-GRADE [2], 2020. *VI-EventBuilder 20.0 Documentation*, Germany: VI-GRADE GmbH.

VI-GRADE [3], 2020. *VI-Road 20.0 Documentation*, Germany: VI-grade GmbH.

VI-GRADE, 2020. *VI-CarRealTime 20.1 Documentation*, Germany: VI-grade GmbH.

Vogel, J., 2021. Tech Explained: Formula 1 Tyre Model Development. *Racecar Engineering*, Volume <https://www.racecar-engineering.com/articles/tech-explained-formula-1-tyre-model-development/>.

Wenbourne, A., 2007. *A Clutch of Differentials*. [Online] Available at: <https://selmec.org.uk/articles/38-a-clutch-of-differentials> [Accessed 4 April 2024].

Z1 Motorsports, 2018. *Why VLSD Differentials Suck | Why You Should Upgrade*. [Online] Available at: <https://www.youtube.com/watch?v=DscnU5bN9-8> [Accessed 3 April 2024].

Zhou, W. et al., 2023. Cost, Range Anxiety and Future Electricity Supply: A Review of how Today's Technology Trends may Influence the Future Uptake of BEV's. *Renewable and Sustainable Energy Reviews*, 173(3).