Simulation Model Development of Vehicle Dynamics-Brakes

KARTHIKEYAN SHANMUGAM
Abstract

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The advancement in Vehicle technologies have given opportunity for various companies to innovate in development of Vehicle-Sub systems and Active Safety systems. Although they come with different specifications, their core functionality remains the same. For example, the Brake-system could have a unique brake circuit design which enhances braking efficiency. However, its core functionality remains the same i.e. to assist in decelerating the vehicle. One can imagine it could be time consuming when it comes to test a vehicle sub system manufactured by different vendors. Having a Simulation model could greatly help in performance validation much before the hardware is acquired and tested in a given vehicle. There are a number of powerful vehicle simulation environments where one can plug in such models to analyze the performance. Aim of this thesis is to develop a parameterized plant model which could be used to test brake system and ABS manufactured by various vendors. The model parameters could be initialized with the data specification from vendors and validate its performance in the chosen simulation environment.
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1. Introduction

1.1 Brake System
Brake system is vital equipment which helps in deceleration of vehicle. Modern cars have brake on all four wheels operated by hydraulic brake system. They may be disc type or drum type. Front brakes are more powerful than the rear ones because during deceleration the load of vehicle tends to shift more on front wheel as compared to rear wheel. A hydraulic brake system consist of a master cylinder and four wheel cylinders that are connected by pipes. These pipes form the skeleton of the brake system called the brake circuit. All the above mentioned components are filled with brake fluid. This brake fluid is forced out of master cylinder when brake pedal pushes the master-cylinder piston. It travels in pre-determined proportion to each of the wheel cylinders forcing respective wheel cylinder piston outward. Combined surface 'pushing' area of all the wheel cylinder pistons is much greater than that of the piston in master cylinder. The master piston travels several inches to move the wheel cylinder pistons by fraction of an inch there by applying brakes. This arrangement allows great force to be exerted by the brakes. Hydraulic brake systems can differ based on how their brake circuits are designed. Sometimes there is a separate circuit for front and rear, or one circuit for each of the front brakes and one for both rear brakes; or one circuit for all four brakes and the other is only for front brakes. Under heavy braking, so much weight may come off the rear wheels that they lock, possibly causing a dangerous skid.

1.2 Anti-lock Braking System (ABS)
Under harsh braking conditions, the driver needs to maintain some steering ability and avoid skidding. ABS helps in achieving the above goal. ABS is an automatic safety system that helps the wheel on a vehicle to maintain a desired level of traction on road and prevents wheel lock. It works on the principle of threshold braking or cascade braking [1]. It helps not only in better vehicle control while braking but also reduces the stopping distance which can be vital under extreme conditions.
1.3 Motivation
Simulation plays a vital role in today’s development process. This saves a lot of time and resources which otherwise is consumed in plenty to develop a new product and especially in the automotive industry, where there are many regulations which has to be satisfied by the vehicle. Modelica tool gives an opportunity to model complex physical systems using equation based language, which automatically makes the model comparable to the real life systems. This powerful tool is already in use for many applications in the automotive industry.

Another important part of a product development cycle is testing. As far as it is concerned with the brake system of a vehicle, real vehicle is needed to test a newly developed function and to notice the behavior of each of the components. IPG Carmaker has the virtual testing environment, where the functionality and reliability of the system can be tested.

The motivation of this thesis work is to merge these two processes for quick and effective development of a product, with the main focus on the development of brake system for a two-axle vehicle. Along with an ABS controller an attempt is made to create a Modelica library exclusively for brake system modelling with a robust structure that could be used to develop brake system model of given specification. The brake system model can be used both in active safety domain and in vehicle dynamics domain to perform desired analysis.

1.4 Modelica language & Tools
In this thesis work, the brake system model is built in Modelica language. Modelica is a non-proprietary, object-oriented, equation based language to conveniently model complex physical systems containing, e.g. mechanical, electrical, electronic, hydraulic, thermal, control, electric power or process-oriented subcomponents. Modelica Libraries with a large set of models are available. The open source Modelica Standard Library contains about 1280 model components and 910 functions from many domains [2]. Most of the components used in the Brake system model are from Modelica Standard Library.

Modelica simulation environments are available both commercially and free of charge, both OpenModelica (open source) and Dymola (commercial) are used in this thesis work for
modelling the physical components. Besides, IPG Carmaker’s virtual vehicle environment brings in an opportunity to test the brake model along with different subsystems of the vehicle and also for different maneuver. CarMaker for Simulink is used to create the simulator. Matlab/Simulink is used to model the ABS controller and for post processing.

1.5 Thesis Method
The brake system and ABS models are built in two stages. They are:

- The first step is to develop a simple model of brake system and ABS in Dymola.
- The second step is to develop a more advanced model of brake system in Dymola and ABS in Simulink-StateFlow.

The overall model development cycle can be seen in the Figure 1.1 below.

![Figure 1.1: Thesis method](image-url)
1.6 Thesis Outline

This master thesis report presents the modelling of the brake system for two-axle vehicles using the Modelica tools (Open Modelica and Dymola) and validating the models using Virtual Validation Environment (VVE).

Chapter 3 presents simple model, which includes mathematical models of brake system and ABS controller. This model focuses on system level behavior where brake system model consist of look-up tables and mathematical blocks and ABS controller comprises of mathematical blocks. The ABS controller calculates appropriate brake pressure and signals them to look-up tables in brake system model. Furthermore, this model is co-simulated in IPG Carmaker with the entire vehicle and tested in VVE. The result shows a good similarity between the stopping distance of the real car and the virtual car.

Chapter 4 presents an advanced model, which includes a more detailed brake system model and an ABS controller. This model focuses on component level behavior where brake system model comprises of brake component models like master and wheel cylinders, valves, accumulator, pipes etc. The ABS controller gives signals for increasing or decreasing or holding pressure in the four wheel cylinders of brake system model. Furthermore, this model is co-simulated in IPG Carmaker with the entire vehicle and tested in VVE. The results shows a good similarity between the advanced model and the real life ABS enabled brake system.

Chapter 5 presents the Virtual Validation Environment using IPG Carmaker. The physical plant is FMU exported with co-simulation capabilities. This FMU is then plugged in the IPG vehicle to have a complete virtual vehicle. Chassis, road, maneuver and environment are defined in IPG Carmaker. Carmaker for Simulink is used for manually driving the vehicle with the help of a joystick and thus creating a simulator.

Chapter 6 presents the conclusion of this thesis work and the possibilities for future development.
2. Background

In this chapter, hydraulic brake system is introduced in detail, including both mechanical and hydraulic components and their working principles. Then the functionality of the Anti-lock braking system is explained in detail.

2.1 Brake System

A typical brake system is shown in the figure below. As illustrated in the figure, driver actuates the brake pedal to get braking torque at the wheels and therefore decelerating the vehicle. Each of the components is explained in detail in the following section.

![Figure 2.1: Brake System components [3]](image)
2.2 Brake Pedal
Brake pedal is the interface for the driver to decelerate the vehicle. It multiplies the force exerted by the driver’s foot [4].

\[ F_{bp} = F_d \cdot \frac{L_2}{L_1} \]  \hspace{1cm} (2.1)

where,

- \( F_{bp} \) is the force output from the brake pedal, N
- \( F_d \) is the force applied to the pedal by the driver, N
- \( L_1 \) is the distance from the brake pedal arm pivot to the output rod, m
- \( L_2 \) is the distance from the brake pedal arm pivot to the driver foot, m.

2.3 Brake Booster
For given dimensions of break pedal input force from driver's foot can be amplified to a certain magnitude only. This can be deduced using the equation (2.1). However, the force needs to be much larger for effective braking. Hence, a booster is used to amplify force output from brake pedal \( F_{bp} \). When this amplified force equals pressure in the master cylinder as shown in equation (2.3) the amplification factor becomes one [5]

\[ F_{BooOut} = x \cdot F_{bp} \]  \hspace{1cm} (2.2)

where,

- \( F_{BooOut} \) is the force output from the booster, N
- \( x \) is the amplification factor.

2.4 Master Cylinder
Booster force \( F_{BooOut} \) is transformed into brake pressure in master cylinder. \( F_{BooOut} \) when applied on to the piston inside master cylinder creates a high pressure in master cylinder. Resultantly, brake fluid in master cylinder flows to rest of the brake system via brake circuit. Brake fluid flows until the pressure in the whole system reaches an equilibrium. Pressure developed in master cylinder is shown below [5]
\[ P_{MC} = \frac{F_{BooOut} - F_{MC,0} - c_{MC} \cdot x_{MC}}{A_{MC}} + P_{Amb} \]  

(2.3)

where,

\( P_{MC} \) is the master cylinder pressure, Pa

\( F_{MC,0} \) is the pre-charged force of the return spring, N

\( c_{MC} \) is the spring constant of the return spring, N/m

\( x_{MC} \) is the piston travel, m

\( A_{MC} \) is the area of the master cylinder, m²

\( P_{Amb} \) is the ambient pressure, Pa.

### 2.5 Wheel Cylinder

Pressurized brake fluid in the brake circuit is fed to slave cylinders at each wheel. As volume of brake fluid increase the piston inside slave cylinder exerts a force on the caliper pad. This force of the piston is shown below

\[ F_{SC} = (P_{SC} - P_{Amb}) \cdot A_{SC} \]  

(2.4)

where,

\( F_{SC} \) is the piston force of the wheel cylinder, N

\( P_{SC} \) is the pressure in the wheel cylinder, Pa

\( A_{SC} \) is the area of the wheel cylinder, m².

### 2.6 Pads and Disc

Slave cylinder piston pushes the caliper pads against the disc. Due to the frictional force between the pads and the disc, brake torque is generated. The brake torque is given below

\[ T_B = F_f \cdot R = F_{SC} \cdot \mu \cdot R \]  

(2.5)
where,

\[ T_B \] is the brake torque, Nm

\[ F_f \] is the frictional force, N

\[ R \] is the effective radius, m

\[ \mu_p \] is the frictional co-efficient between the pads and the disc.

2.7 Proportioning Valves

Due to dynamic effects during a braking maneuver, center of gravity of a vehicle shifts towards its front axle. Resultantly, as brake force increases normal force increases on the front axle and decreases on the rear axle respectively. Because of this phenomenon, rear wheels lock prior to front wheels, which causes the vehicle to be unstable. With the help of a proportioning valve, brake fluid flowing to wheel cylinders at rear axle is limited thereby limiting the pressure buildup thus lowering brake force and avoiding wheel lock.

2.8 Solenoid Valves

A solenoid valve is an electro-mechanical device that is operated by ABS controller to regulate pressure in wheel cylinders. It consist of two ports, an inlet port and an outlet port. When the valve is open, the two ports are connected and brake fluid flows according to the pressure difference. The two ports are isolated when the valve is closed.

There are two such valves present in the brake system with ABS. One is the inlet valve that is connected between the master cylinder and a wheel cylinder. Another valve is the outlet valve that connects the wheel cylinder and a low pressure accumulator. Both these valves have a check valve, which does not allow reverse flow of brake fluid. For the inlet valve, the flow is from the inlet side to the wheel cylinder and for the outlet valve, the flow is from the wheel cylinder to the low pressure accumulator. [5]

2.9 Low pressure accumulator

It accumulates brake fluid coming out of the outlet valve before the fluid is pumped back into the brake circuit. A low pressure accumulator usually consists of a cylinder and a
piston (loaded by a spring) arrangement. When the outlet valve is open, brake fluid from wheel cylinders flow into the accumulator which in turn compresses the spring.

2.10 Hydraulic pump
Brake fluid flows from high pressure region to low pressure region without the need of external work. But when brake fluid is required to flow from low pressure to high pressure region, an external work has to be done on it. This is achieved with the help of hydraulic pumps. Flow of brake fluid is proportional to the rotational velocity of hydraulic pump. Low pressure side of the pump is connected to accumulator and high pressure side is connected to brake circuit. Brake fluid from low pressure accumulator is pumped back to brake circuit during ABS event.

2.11 Anti-lock Brake System controller
Friction between tire and road is also important during deceleration. Magnitude of this friction is determined by $\mu$, the coefficient of friction. During emergency braking condition a very high brake pressure gets developed in the wheel cylinder of each wheel that makes them decelerate faster than the whole vehicle, ultimately resulting in wheel lock and loss traction with the road. This loss of traction is termed as slip $\lambda$. $\lambda$ is defined mathematically as the ratio of the relative velocity between the wheel and the vehicle to the maximum of vehicle or wheel velocity [8]

$$\lambda = \frac{\omega \cdot r_{eff} - v_{vehicle}}{\text{max}(v_{vehicle}, \omega \cdot r_{eff})} \quad (2.6)$$

where,

$\lambda$ is Longitudinal slip

$\omega$ is the wheel rotational velocity, rad/s

$r_{eff}$ is the effective radius of the wheel, m

$v_{vehicle}$ velocity of the vehicle, m/s.

It can be verified from the equation (2.6) that the slip in longitudinal direction varies from zero when wheel speed is same as the $v_{vehicle}$, to one when wheel locks. Loss of traction leads to wheel lock and the vehicle goes out of control and it becomes difficult to steer.
One way to maintain maximum traction is to have high friction. This could be achieved by regulating fluid pressure in the wheel cylinders such that $\lambda$ of each wheel remains within a range that will result in maximum $\mu$. Empirical data highlights that maximum $\mu$ is achieved when the $\lambda$ is around 20%. It can be seen from Figure 2.2, that the $\mu$ is maximum between 10% - 30% $\lambda$ [15], [16]. ABS controller is responsible for sending signals to inlet and outlet valves in brake circuit that regulate fluid pressure in the wheel cylinders. This will ultimately maintain a good traction between the wheels and the road and avoid wheel lock.

![Figure 2.2: Coefficient of friction $\mu$ vs tire slip $\lambda$][6]

<table>
<thead>
<tr>
<th>Brake Pressure</th>
<th>Inlet Valve</th>
<th>Outlet Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase</td>
<td>OPEN</td>
<td>CLOSED</td>
</tr>
<tr>
<td>Hold</td>
<td>CLOSED</td>
<td>CLOSED</td>
</tr>
<tr>
<td>Decrease</td>
<td>CLOSED</td>
<td>OPEN</td>
</tr>
</tbody>
</table>

*Table 2.1: Shows different configurations of an ABS*

There are wheel speed sensors for each wheel that send wheel speed data to ABS controller, where $\lambda$ is being calculated with the help of reference velocity which is also acquired by sensors that calculate vehicle velocity. The ABS then decides whether brake...
fluid pressure in wheel cylinders has to be increased, decreased or to hold the pressure to get the desired slip valve [18]. ABS controller regulates brake fluid pressure in wheel cylinders by sending signals to the inlet and outlet valves in the brake circuit.

![Hydraulic Brake Circuit]

1. Master Cylinder 2. Inlet Valve
3. Outlet Valve 4. Wheel Cylinder
5. Low Pressure Accumulator 6. Hydraulic Pump

*Figure 2.3: Hydraulic Brake Circuit shown for two wheels*

During pressure increase, inlet valve is open and outlet valve is closed. Brake fluid flows from master cylinder to wheel cylinder. In situations when master cylinder is fully depressed, which means that there is no flow of fluid from the master cylinder, ABS gives signal to run a motor that drives an hydraulic-pump to pump back brake fluid from accumulator into the brake circuit.

During pressure hold, both the inlet and outlet valves are closed, thus cutting off brake fluid flow in and out of the wheel cylinder. Ideally the pressure remains same in the wheel cylinder when both the valves are closed.
During pressure decrease, inlet valve is closed cutting off brake fluid flow into the wheel cylinder, but outlet valve is opened thus allowing the fluid to flow to the low pressure accumulator from the wheel cylinder, which in turn decreases brake pressure.
3. Simple Model

This section explains the simple model consisting of brake system model, ABS controller, co-simulation interface and the simulation results.

3.1 Brake System Model

Figure 3.1 shows the brake system modelled in Dymola and various components marked with numbers are explained as follows:

1. Pedal and Boost:

These are taken as inputs for the brake system. The driver’s input from the IPG Carmaker ranges from 0 to 1, where 0 being no brake and 1 being full brake. The pedal input is multiplied by boost, which is also taken as a constant input from CarMaker. This gives an opportunity to use the brake system model to produce different peak brake torque instead of changing the parameters of each of the components every time. The boost value includes both the pedal ratio and the vacuum booster.
2. **Master Cylinder:**

After the pedal input is amplified, it is then converted into a pressure value, which is the ratio of input to master cylinder area.

3. **Proportional Valve:**

A gain is used to proportionate the pressure value to the front and the rear brake circuit.

4. **Wheel Cylinder:**

The wheel cylinders for each of the four wheels are represented by look up tables. Brake torque is interpolated according to the pressure input.

<table>
<thead>
<tr>
<th>Master Cylinder Area = 3.871 x 10^-4 m²</th>
<th>Brake Pressure Proportion Front = 57%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost = 2000</td>
<td>Wheel Cylinder Area = 0.0032 m²</td>
</tr>
<tr>
<td>(µ . R) = 0.27</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.1: Parameters used in simple model simulation*

Below figures shows the performance of each of the brake components.

![Pedal Actuation](image)

*Figure 3.2: Pedal actuation*
3.2 Anti-Lock Brake System Controller

A four-channel four-sensor ABS model is developed i.e. each wheel has a controller to control its $\lambda$ (equation 2.6). Literature study on ABS highlights that $\lambda$ should be maintained
within a desired range to attain maximum friction between wheel and road surface. This is the driving logic for the ABS model. From Figure 2.2 it can be deduced that $\mu$ is high when $\lambda$ between the range 10% and 30%.

Following are the inputs to ABS:

- Pressure from Master cylinder at each wheel brake circuit.
- Velocity of vehicle to calculate reference wheel speed.
- Wheel speed of each wheel.

The ABS controller block is divided into three reusable components:

- Slip Calculator.
- Slip Detector.
- Hydraulic Control Unit.

![Figure 3.5: Structure of ABS controller](image)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slip Calculator</td>
</tr>
<tr>
<td>2</td>
<td>Hydraulic Control Unit</td>
</tr>
<tr>
<td>3</td>
<td>Slip Detector</td>
</tr>
<tr>
<td>4</td>
<td>Wheel Speed</td>
</tr>
<tr>
<td>5</td>
<td>Vehicle Velocity</td>
</tr>
<tr>
<td>6</td>
<td>Pressure from Pr sensor</td>
</tr>
<tr>
<td>7</td>
<td>Actual Slip</td>
</tr>
<tr>
<td>8</td>
<td>Slip Difference</td>
</tr>
<tr>
<td>9</td>
<td>Pressure in wheel cylinder</td>
</tr>
</tbody>
</table>
ABS components listed in Figure 3.5 are discussed in detail below:

1. **Slip Calculator**

   This component is responsible for calculation of $\lambda$ of wheel based on current vehicle speed and wheel speed. $\lambda$ is calculated according to the equation (2.6). It also calculates reference wheel speed from current vehicle speed

   $$\omega_{ref} = \frac{v_{vehicle}}{r_{eff}} \quad (3.1)$$

   where, $\omega_{ref}$ is the wheel rotational velocity, rad/s

   $r_{eff}$ is the effective radius of the wheel, m

   $v_{vehicle}$ velocity of the vehicle, m/s.

2. **Slip Detector**

   This component determines $\sigma$, the deviation of $\lambda$ from desired range. If $\lambda$ is within range the $\sigma$ is zero. It also generates a signal to activate/ deactivate ABS.

3. **Hydraulic Control Unit**

   This component consist of a PI controller block and a memory block. A memory block retains $P_{SC}$ (equation 2.4) value calculated in the previous time step. Hydraulic Control Unit converst $\sigma$ into an appropriate pressure value using a PI controller that is either subtracted or added to $P_{SC}$ stored in the memory block. It performs the above mentioned computation as long as Slip-Detector sends an Active signal.

4. **Algorithm**

   ABS is activated when $\lambda$ crosses 90% that represents wheel lock condition. After activation, ABS remains active as long as $F_{bp}$ (equation 2.1) is not zero and calculates the desired $P_{SC}$ (equation 2.4) for current $\sigma$. $P_{SC}$ is always less than or equal to $P_{MC}$ (equation 2.3).
3.3 Simulation Results

All the simulations are performed for hard braking maneuver on dry asphalt road with initial velocity of 80 kmph till complete stop. Both simple models of Brake system and ABS are exported as one FMU. Interfaces between the FMU and IPG CarMaker can be seen in Table 5.1.

First simulation of simple model is performed without ABS assist by plugging in the corresponding FMU. Interface remains same as mentioned in Table 5.1. When brakes are applied a constant high magnitude Brake torque is generated in each wheel cylinder. Resultantly, the wheels lock as shown in Figure 3.7 & Figure 3.8.

Second simulation is performed by adding ABS controller in the brake system model. Figure 3.9 & Figure 3.10 show that as the \(\lambda\) goes below certain minimum value \(P_{Sc}\)
(equation 2.4) is decreased thereby decreasing brake torque. Similarly if the $\lambda$ goes above certain maximum value $P_{SC}$ is increased thereby increasing brake torque. Thus, ABS is able to prevent wheel lock condition.

Figure 3.7: Wheel speed of front left wheel, without ABS

Figure 3.8: Pressure in Master Cylinder and front left Wheel Cylinder, without ABS

Figure 3.9: Longitudinal slip $\lambda$ of front left wheel

Figure 3.10: Pressure in Master Cylinder and front left Wheel Cylinder
Figure 3.11 shows that there is no lock in any of the four wheels. Hence, asserting the behavior of ABS controller is as expected.

**Figure 3.11: Wheel speed and reference velocity**
3.4 Conclusion

Brake system model consists of predefined values for each of the components, making it easier to tune. Since the complexity of the model is minimal, the co-simulation takes lesser processing time, making it possible to have real time simulation.

ABS controller has some shortcomings. They are:

- It relies on a memory block to remember $P_{SC}$ calculated in previous time step which can be a heavy operation given memory constraint of ABS ECU in real scenario.
- It calculates the $\lambda$ and its deviation $\sigma$ from desired range to calculate optimum $P_{SC}$. However, in real scenario $P_{SC}$ is controlled directly which results in optimum $\lambda$.

In simple model the brake system model contains only lookup tables mathematical blocks that emulate actual brake components. Hence, simple model cannot be used to determine the factors which will affect the brake performance in real scenario. However, it is useful when brake functionality is needed in a simulation but the focus is more on verifying other active safety features.
4. Advanced Model

This section explains the advanced model consisting of improved brake system model and ABS controller, co-simulation interface and the simulation results.

4.1 Brake System Model

Figure below shows the advanced brake system modelled in Dymola. Brake component models marked by number are explained in detail as follows:

Figure 4.1: Advanced Brake System model
1. **Pedal and Boost:**

The Pedal and Boost are modelled in the same way as shown in Figure 3.1.

2. **Master Cylinder Piston:**

   ![Figure 4.2: Master Cylinder Piston](image)

   Product of pedal input and boost is defined as translational force that is applied onto the master cylinder piston. Master cylinder piston is modelled using the `MassWithStopAndFriction` model block from the Modelica library [25]. This block simulates sliding of piston along the master cylinder axis considering frictional effect involved between piston and cylinder wall. A function to limit the piston travel is also included, so that the piston does not slide more than a specified length, thus limiting the capacity of master cylinder.

3. **Master Cylinder:**

   ![Figure 4.3: Master Cylinder](image)

   Master cylinder [21] is modelled using equation (2.3). It consists of a hollow cylinder, a spring as shown in Figure 4.3, a flang that moves laterally in the cylinder at one end and a port on the other. Piston movement pushes the flang inward there by pushing brake fluid out from the port. Master cylinder also inherits from a fluid machine model called Swept Volume that is present in Modelica Fluid library. This inheritance enables to plug a model of desired brake fluid type and simulate its flow i.e. as the flang moves inward $P_{MC}$ increases causing brake fluid to be pushed out into the brake circuit. This flow can be measured in terms of the fluid property mass flow rate. Brake fluid flow takes places until pressure across the brake system model reaches equilibrium or when the piston has travelled to a maximum limit. The spring pushes back the flang when brake pedal is not pressed. Due to the spring $P_{MC}$ increases only after the force on flange overcomes the spring force. This can be seen in Figure 4.4 indicated by the red circle. The pedal input is shown in Figure 3.2.
4. **Brake Circuit:**

Brake circuit [19] is divided into two parts, one for the front axle and the other for the rear axle. ABS controller sends signals to open and close the solenoid valves in the two brake circuits there by regulating brake fluid mass in each wheel cylinder. Figure 4.5 shows the model of a brake circuit. Pipes are also included between the ports and the valves. T-joints are used to branch the fluid flow from the source to all the wheels. In the figure below the pipes between master cylinder and inlet valves are called the Inlet pipes and the pipes between outlet valve and the low-pressure-accumulator are called Outlet pipes.

![Master Cylinder Pressure Graph](image)

*Figure 4.4: Master Cylinder performance in advanced brake system model*

![Brake Circuit Diagram](image)

*Figure 4.5: Brake circuit*
During pressure increase state, brake fluid from master cylinder flows to the wheel cylinder through Port MC, Inlet valve and Port SC_L (Port SC_R for right wheel).

During pressure hold state, wheel cylinder is isolated from rest of the circuit as both inlet and outlet valves are closed. Resultantly brake fluid remains in the wheel cylinder.

During pressure decrease state, inlet valve is closed and outlet valve is open. Brake fluid flows from wheel cylinder to low pressure accumulator through Port SC_L (Port SC_R for right wheel), Outlet valve and Port Acc_L (Port Acc_R for right wheel).

5. **Wheel Cylinder:**

Working principle of a wheel cylinder is similar to that of a master cylinder. Here brake fluid flows into the wheel cylinder from the brake circuit. Due to increase in mass of the fluid in wheel cylinder, the flange moves outward. $P_{SC}$ is calculated using the equation (2.4).

![Graph of Flange force vs Pressure](image1)

*Figure 4.6: Wheel Cylinder performance in advanced brake system model*

6. **Pads and Disc:**

Pads and Disc [24] are modelled as one model block. In Modelica, the displacement of wheel cylinder flange will not be present unless there is transfer of energy. Hence the pads are modelled as a very stiff translational spring. When wheel cylinder flange is displaced, the

![Diagram of Brake Pads & Disc](image2)

*Figure 4.7: Brake Pads & Disc*
translational spring is compressed and a corresponding translational force $F_{SC}$ is generated. $F_{SC}$ is then converted to the brake torque $T_B$ as shown in equation (2.5). Figure 4.7 shows brake pads & disc modelled in Dymola. Effective radius at which the force is being applied on disc and co-efficient of friction between the pad-disc are the parameters considered for brake disc modelling. Figure 4.8 shows the performance of the modelled brake disc.

![Brake Disc](image)

*Figure 4.8: Brake torque versus Wheel Cylinder force in brake system model*

7. **Hydraulic Pump:**

Hydraulic-Pump [21] is needed in advance brake system model because of the limited displacement of flange in master cylinder. It pumps back brake fluid into brake circuit thereby helping maintaining brake fluid pressure in entire brake system. A default prescribed pump available from the standard Modelica fluids library is used, with speed of pump taken as input to attain the desired pressure and fluid flow. Speed of the pump is controlled by the ABS-controller and is explained in detail in Section 4.2.
8. **Low Pressure Accumulator:**

Fixed boundary available from the Modelica standard library [21] is being used as the low pressure accumulator. This acts as both source (from which the pump draws brake fluid) and sink (for high pressure brake fluid from wheel cylinders to flow into it). Low pressure accumulator is specified to be at ambient pressure throughout the simulation.

![Fixed Boundary acting as accumulator](image)

*Figure 4.10: Fixed Boundary acting as accumulator*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Cylinder Area</td>
<td>$3.871 \times 10^{-4}$ m$^2$</td>
<td>Mass of piston</td>
<td>0.1 kg</td>
</tr>
<tr>
<td>Boost</td>
<td>2500</td>
<td>Front Wheel Cylinder Area</td>
<td>0.0015 m$^2$</td>
</tr>
<tr>
<td>MC spring constant</td>
<td>1000 N/m</td>
<td>Precharge of MC spring</td>
<td>80 N</td>
</tr>
<tr>
<td>WC spring constant</td>
<td>100 N/m</td>
<td>($\mu \cdot R$) for front axle</td>
<td>0.3</td>
</tr>
<tr>
<td>Length of master cylinder</td>
<td>0.1 m</td>
<td>($\mu \cdot R$) for rear axle</td>
<td>0.12</td>
</tr>
<tr>
<td>Ambient Pressure</td>
<td>101325 Pa</td>
<td>Ambient Temperature</td>
<td>$20^\circ$C</td>
</tr>
<tr>
<td>Acceleration due to gravity</td>
<td>$9.81$ m/s$^2$</td>
<td>Brake Fluid</td>
<td>Glycol47 (Modelica standard library)</td>
</tr>
</tbody>
</table>

*Table 4.1: Parameters used in advance model simulation*

4.2 **Anti-Lock Brake System Controller**

ABS introduces brake circuit as explained in section 4.1. This helps in implementing Three State Pressure control. Brake-pressure is increased, decreased or held to maintain $\lambda$ within desired range. In real driving condition calculating the value of $\lambda$ very complex. Hence, wheel speed and wheel acceleration are measured instead. The algorithm then tries to maintain wheel speed and wheel acceleration within a desired range thereby resulting in optimal $\lambda$. 
4.2.1 ABS Algorithm:
The operation of ABS is divided into three phases.

**Increase State:** Here input valve is open and output valve is closed allowing brake fluid enter wheel cylinder and increase the pressure. This state is active as long as the wheel speed or wheel acceleration is greater than its respective maximum threshold value.

**Hold State:** Input and Output valves are closed. Resultantly, volume of brake fluid remains constant thereby maintaining brake pressure. This state is active when either wheel speed or the wheel acceleration is within its respective threshold value.

**Decrease State:** Output valve is open and input valve is closed thereby allowing some brake fluid to exit from the wheel cylinder that decreases brake pressure. This state is active when either the wheel speed or wheel acceleration is below its respective minimum threshold value. Figure 4.11 show when the ABS states change. [7]

![Figure 4.11: State space model of ABS](image)

4.2.2 Algorithm Tuning:
For this algorithm to work, four parameters are considered. They are $\omega_{\text{max}}$, $\omega_{\text{min}}$, $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ [8]. $\omega$ is considered as the wheel speed measured from the wheel speed sensor and $\alpha$ and the wheel acceleration.
From Figure 2.2 it can inferred that frictional coefficient $\mu$ is maximum when $\lambda$ is within the range 0.1 and 0.3. Using this information the maximum and minimum wheel speeds are calculated in following manner

\[
\omega_{\text{max}} = \omega_{\text{ref}} (1 - \lambda_{\text{min}}) \quad \text{(4.1)}
\]

\[
\omega_{\text{min}} = \omega_{\text{ref}} (1 - \lambda_{\text{max}}) \quad \text{(4.2)}
\]

where,

$\omega_{\text{max}}$ is maximum threshold wheel speed, rad/s

$\omega_{\text{min}}$ is minimum threshold wheel speed, rad/s

$\omega_{\text{ref}}$ is desired wheel speed, rad/s

$\lambda_{\text{min}} = 0.1$, is minimum desired slip

$\lambda_{\text{max}} = 0.3$, is maximum desired slip.

Setting wheel acceleration range in the ABS controller greatly affects performance of the brake system model described in section 4.1. Following tests illustrate this effect for three different $\alpha$ ranges.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_{\text{max}}$ (rad/s$^2$)</th>
<th>$\alpha_{\text{min}}$ (rad/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>300</td>
<td>-300</td>
</tr>
<tr>
<td>Test 2</td>
<td>100</td>
<td>-100</td>
</tr>
<tr>
<td>Test 3</td>
<td>20</td>
<td>-50</td>
</tr>
</tbody>
</table>

*Table 4.2: Desired wheel acceleration range*

Note: Throughout the experiment wheel speed range is kept the same as discussed above.

In Test 1 acceleration range is very large i.e. $-300$ rad/s$^2 < \alpha < 300$ rad/s$^2$. Throught the simulation $\alpha$ remains between $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ that can be seen in the figure 4.12. Thus ABS controller signals hold state and maintains this state till the vehicle stops. This results in a constant $P_{SC}$ inside the wheel cylinder and $\lambda$ is within desired range ($\lambda_{\text{max}}, \lambda_{\text{min}}$) for some time. However, due to high constant $P_{SC}$ slip $\lambda$ eventually reaches one indicating wheel lock condition. Appendix B.1 shows similar comparisons for remaining three wheels.
Figure 4.12: Results of front left wheel for $-300 < \alpha (rad/s^2) < 300$
In Test 2 wheel acceleration range is between $100 \text{ rad/s}^2$ and $-100 \text{ rad/s}^2$. $\alpha$ goes more out of the range $(\alpha_{\text{max}}, \alpha_{\text{min}})$. Hence, ABS state gets changed more frequently. From the below Figure 4.13 it can be seen that after 1.5 seconds $P_{SC}$ is not enough to cause substantial deceleration. $\alpha$ falls within desired acceleration range. Resultantly, ABS controller maintains hold state throughout. Due to constant $P_{SC}$, $\alpha$ soon reaches near zero value and $\omega$ decreases constantly outside range $(\omega_{\text{max}}, \omega_{\text{min}})$. Hence, the slip is always less than optimal slip range resulting in less friction force. Appendix B.2 shows similar comparisons for remaining three wheels.
(d) Slip $\lambda$

**Figure 4.13: Results of front left wheel for $-100 < \alpha < 100$**

In Test 3 wheel acceleration rage is between 20 rad/s$^2$ & -50 rad/s$^2$. The short range helps in varying $P_{SC}$ very quickly so that $\omega$ is maintained within desired range. Resultantly $\lambda$ is optimal throughout the braking maneuver. Since $\lambda$ is within range no wheel locking is experienced while braking. This can be seen in the Figure 4.14. It can be observed that as the $\lambda$ goes beyond $\lambda_{max}$ ABS increase state is signaled resulting in increased $P_{SC}$ and for $\lambda$ below $\lambda_{min}$ ABS decrease state is signaled thereby reducing the pressure. Hence, a controlled pressure variation results in optimal slip $\lambda$. Appendix B.3 show similar comparisons for remaining three wheels.
4.3 Pump Control:

It runs the pump at a predetermined RPM. Start signal is sent to pump when at least one wheel circuit is in ABS decrease state. The pump is then kept active till the brake-pedal is pressed or vehicle has not stopped. In Figure 4.12, Figure 4.13 and Figure 4.14 a slight increase in master cylinder pressure $P_{MC}$ is seen at around 0.5 second of simulation time. This is due to pump control activating the pump.
4.4 Conclusion

4.4.1 ABS

For a given dimensions of brake system model mentioned in Table 4.1, stopping distance was recorded for tests mentioned in Table 4.2. Stopping distance varies as the acceleration range is changed in ABS controller. From Table 4.3 it can be inferred that -50 < \( \alpha \) < 20 range gives the best result. Thus emphasizing that ABS controller in advance model can be tuned easily.

<table>
<thead>
<tr>
<th>#</th>
<th>Acceleration Range</th>
<th>Stopping Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>-300 &lt; ( \alpha ) &lt;300</td>
<td>35.85</td>
</tr>
<tr>
<td>Test 2</td>
<td>-100 &lt; ( \alpha ) &lt; 100</td>
<td>36.34</td>
</tr>
<tr>
<td>Test 3</td>
<td>-50 &lt; ( \alpha ) &lt; 20</td>
<td>35.79</td>
</tr>
</tbody>
</table>

*Table 4.3: Stopping distance vs Acceleration range*

4.4.2 Brake System

Section 4.1 introduces brake system model with modeling of its individual components. The dimensions of these components have acute effect on brake pressure in wheel cylinder. Varing the dimensions of these component models result in varying brake efficiency. This is illustrated with following examples. A smaller area of crossection of pipe in brake circuit will cause \( P_{SC} \) to rise and fall slowly in a wheel cylinder and faster if it is large. For a fixed master cylinder volume, a smaller wheel cylinder area produces less brake torque and larger wheel cylinder draws more fluid from master cylinder thus not producing high pressure in the brake circuit.

Following tables show the stopping distance for different pipe dimensions and wheel cylinder dimension respectively; that supports the above mentioned conclusion.

<table>
<thead>
<tr>
<th>#</th>
<th>Inlet Pipe diameter [m]</th>
<th>Outlet Pipe diameter [m]</th>
<th>Stopping Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.003</td>
<td>0.008</td>
<td>36.88</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.01</td>
<td>36.36</td>
</tr>
<tr>
<td>3</td>
<td>0.004</td>
<td>0.003</td>
<td>35.86</td>
</tr>
<tr>
<td>4</td>
<td>Without pipe</td>
<td></td>
<td>36.92</td>
</tr>
</tbody>
</table>

*Table 4.4: Stopping distance vs Pipe area*
<table>
<thead>
<tr>
<th>#</th>
<th>Wheel Cylinder Area [m²]</th>
<th>Stopping Distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.003</td>
<td>59.89</td>
</tr>
<tr>
<td>2</td>
<td>0.0008</td>
<td>43.01</td>
</tr>
<tr>
<td>3</td>
<td>0.0015</td>
<td>35.86</td>
</tr>
</tbody>
</table>

Table 4.5: Stopping Distance vs Wheel Cylinder Area

4.4.3 Brake System and ABS

Section 2.11, talks about how ABS helps in avoiding wheel lock and at the same time allows the driver to steer thereby maintaining vehicle stability. A typical test to verify above behavior is Obstacle-Avoidance-Maneuver while braking. Figure 4.15 & Figure 4.16 show two graphs comparing vehicle maneuver for brake system model (discussed in section 4.1) with and without ABS controller (discussed in section 4.2) assistance respectively. From simulation output shown in Figure 4.15 it can be seen that IPG driver model is not able to steer under braking condition due to wheel lock as compared to vehicle trajectory shown in Figure 4.16. Hence, this result validates that the advanced brake system model behaves similar to real systems. Appendix B.4 show speeds of remaining three wheels.
Figure 4.15: Obstacle avoidance maneuver without ABS

Figure 4.16: Obstacle avoidance maneuver with ABS
5. Co-Simulation Environment

The simple and advanced models have been developed and some simple simulations of these models have been done in Dymola to study the performance of individual components. But the limitation of running the models in Dymola is that the dynamics of the entire vehicle are not considered. To test the models considering detailed dynamics of vehicle and also for various test scenarios, a more complete vehicle dynamics tool ‘IPG CarMaker’ had to be used, thus creating co-simulation environment.

The implementation is realized by exporting the brake system models as FMI (Functional Mock-up Interface) in Dymola and reformulating it in IPG CarMaker. FMI technology for co-simulation purpose will be introduced in detail later on. The co-simulation environment is developed accordingly to the ESOW from CEVT [9].

Figure 5.1 shows the co-simulation environment among Dymola, CarMaker and Simulink. The operational principle of the closed loop system in Figure 5.1 can be described as following:

- CarMaker for Simulink collects and processes the signals from the driving simulator or from IPG driver model, e.g. steering wheel angle, gas pedal, brake pedal, clutch pedal and gear position.
- The collected brake signal is sent to the brake subsystem exported from Dymola as FMI.
- Other signals as gas pedal, steer angle, clutch pedal and gear position are sent to the respective IPG CarMaker subsystems.
- ABS controller in CarMaker for Simulink sends valve opening/ closing signals to control presssure in each wheel cylinder.
5.1 IPG CarMaker

IPG CarMaker is used as the master tool of co-simulation environment in this thesis work. Some important aspects of IPG CarMaker regarding this thesis work will be introduced. The following sections in the user interface have been specified in order to run a simulation in CarMaker.

1. **Car**:

In the data set section of car, vehicle subsystem can be modified by changing certain parameters or changing different subsystems. Under Brake tab in the Vehicle data set, several brake models are available, e.g. Hydraulic brake model, Hydraulic Basic Controller, Pressure Distribution model and models from FMI plugins that are built in Dymola in this thesis work.
2. **Road & Manoeuver:**

In road section, the road in simulation can be defined by creating different segments defined by the length, track width and friction coefficient. In manoeuver section, the manoeuver can be defined by modifying driver inputs. In this thesis work, a manoeuver of 80kmph to stand still and where the driver brake input starts at 0.2s and time duration from no pedal to full pedal being 0.2s.

5.2 **Driving Simulator**

In this thesis work, the Logitech G25 racing simulator is used during simulating brake models along with steer and propulsion models developed by other thesis students. Since the requirement for this purpose is to have real time simulation so that humans can drive the vehicle in virtual environment, simple brake models are used. This unit provides all the driving variables and can be seen in Figure 5.2. It features a steering wheel with dual-motor force feedback mechanism, a six-speed shifter as well as pedals for gas, brake and clutch.

![Logitech G25 racing simulator](image_url)

*Figure 5.2 Logitech G25 racing simulator*

All the signals from the simulator can be collected via a block named Joystick Input in Simulink. Then signals from driving simulator are sent to DriverMan block to replace the signals from the IPG driver.

5.3 **Functional Mock-up Interface**

Functional Mock-up Interface is a tool to support both model exchange and co-simulation using a combination of xml-files and compiled C-code. It was initiated by Daimler AG with the goal to improve the exchange of simulation models between suppliers and OEMs (the original equipment manufacturers). Firstly published in 2010, FMI is currently supported by
86 tools and is popularly used by automotive and non-automotive organizations throughout Europe, Asia and North America [10]. Co-simulation therefore is able to run among different simulation environments using FMI.

The co-simulation used in this thesis work is the co-simulation with single tool. It is the simplest case for co-simulation where only one simulation environment works. As Figure 5.3 shows, subsystem 1 is originally built in Simulation tool 1 and subsystem 2 is imported as FMI from other modelling tools. Both of the subsystems have their own solvers. [11]

![Figure 5.3 Co-simulation with single tool](image)

IPG CarMaker plays as the master simulation tool and the brake system together with its solver from Dymola acts as the slave. An example of exporting models as FMI in Dymola is introduced in the following.

Figure 3.1 shows the simple brake system model in Dymola with several inputs and outputs. It can be considered as a black box with inputs and outputs, when it is exported into FMI. Table 5.1 shows the interface of the simple brake system model and its connection to the signals in CarMaker.

<table>
<thead>
<tr>
<th>Model Class: Brake</th>
<th>Link type</th>
<th>Signal source/destination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FMU Inputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedal</td>
<td>IF Var</td>
<td>Pedal</td>
</tr>
<tr>
<td>V</td>
<td>DDict</td>
<td>Car.v</td>
</tr>
<tr>
<td>Vacuum_Boost</td>
<td>const</td>
<td>2000</td>
</tr>
<tr>
<td>w_fl</td>
<td>DDict</td>
<td>Car.WheelSpd_FL</td>
</tr>
<tr>
<td>Signal Name</td>
<td>Link type</td>
<td>Signal source/destination</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>w_fr</td>
<td>DDict</td>
<td>Car.WheelSpd_FR</td>
</tr>
<tr>
<td>w_rl</td>
<td>DDict</td>
<td>Car.WheelSpd_RL</td>
</tr>
<tr>
<td>w_rr</td>
<td>DDict</td>
<td>Car.WheelSpd_RR</td>
</tr>
</tbody>
</table>

**FMU Outputs**

<table>
<thead>
<tr>
<th>Signal Name</th>
<th>Link type</th>
<th>Signal source/destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB_FL</td>
<td>IF Var</td>
<td>Trq_WB.FL</td>
</tr>
<tr>
<td>TB_FR</td>
<td>IF Var</td>
<td>Trq_WB.FR</td>
</tr>
<tr>
<td>TB_RL</td>
<td>IF Var</td>
<td>Trq_WB.RL</td>
</tr>
<tr>
<td>TB_RR</td>
<td>IF Var</td>
<td>Trq_WB.RR</td>
</tr>
<tr>
<td>pWB_FL</td>
<td>DDict</td>
<td>Brake.Hyd.Sys.pWB_FL</td>
</tr>
</tbody>
</table>

*Table 5.1: FMI interface for simple brake system model*

Figure 4.1 shows the advance brake system model. The interface of the advance brake system model and the its connection to the signals in CarMaker are shown below.

**Model Class: Brake System (Hydraulic)**

<table>
<thead>
<tr>
<th>Signal Name</th>
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<th>Signal source/destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost</td>
<td>const</td>
<td>3000</td>
</tr>
<tr>
<td>Pedal</td>
<td>IF Var</td>
<td>Pedal</td>
</tr>
<tr>
<td>PumpCtrl</td>
<td>IF Var</td>
<td>PumpCtrl</td>
</tr>
<tr>
<td>Valve_FL_In</td>
<td>IF Var</td>
<td>Valve.FL_Inlet</td>
</tr>
<tr>
<td>Valve_FL_Out</td>
<td>IF Var</td>
<td>Valve.FL_Outlet</td>
</tr>
<tr>
<td>Valve_FR_In</td>
<td>IF Var</td>
<td>Valve.FR_Inlet</td>
</tr>
<tr>
<td>Valve_FR_Out</td>
<td>IF Var</td>
<td>Valve.FR_Outlet</td>
</tr>
<tr>
<td>Valve_RL_In</td>
<td>IF Var</td>
<td>Valve.RL_Inlet</td>
</tr>
<tr>
<td>Valve_RL_Out</td>
<td>IF Var</td>
<td>Valve.RL_Outlet</td>
</tr>
<tr>
<td>Valve_RR_In</td>
<td>IF Var</td>
<td>Valve.RR_Inlet</td>
</tr>
</tbody>
</table>
Table 5.2: FMI interface for advance brake system Model

<table>
<thead>
<tr>
<th>Valve_RR_Out</th>
<th>IF Var</th>
<th>Valve.RR_Outlet</th>
</tr>
</thead>
<tbody>
<tr>
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<td>IF Var</td>
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</tr>
<tr>
<td>Trq_WB_FL</td>
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</tr>
<tr>
<td>pWB_RL</td>
<td>IF Var</td>
<td>pWB.RL</td>
</tr>
<tr>
<td>pWB_RR</td>
<td>IF Var</td>
<td>pWB.RR</td>
</tr>
</tbody>
</table>

5.4 Simulink Interface

Besides running a simulation in CarMaker interface itself, a full vehicle simulation is also available in CarMaker for Simulink, which is a complete integration of CarMaker and MATLAB/Simulink.

The CarMaker S-functions are connected the same way as other Simulink blocks are connected, which means that using CarMaker for Simulink is the same as using standard S-Function blocks. By adding Simulink blocks, the functionality and features of CarMaker can be extended further.

The ABS controller for advance model is also developed in Simulink using the state flow feature of Simulink. Velocity of vehicle and wheel speed signals are fed to the controller using the Read-CM blocks and brake pedal input is taken from the drivers input signal. The output of ABS controller is fed to a S-Function block which sends these signals to the brake model plugged in as FMI. Figure 5.4 shows the complete ABS controller implementation in Simulink. The inlet and outlet valve signals and Pump control signals are defined respectively, which forms the connection between the controller and the brake model.
Figure 5.4: ABS controller modelled in CarMaker for Simulink
6. Conclusion & Future Work

6.1 Thesis Work Summary
A Virtual Validation environment was developed by integrating Modelica, Matlab/Simulink and IPG CarMaker together with FMI Methods. Modelica being an equation based language is convenient and efficient for developing physical models in detail as described in Chapter 4. ABS controller in advanced model developed using Simulink/State Flow was easy to tune and connect with IPG CarMaker Simulink version.

Simple model development helped in categorizing the system into three main parts namely Master and wheel cylinders, Brake Circuit and Low-pressure accumulator with pump. In the next step detailed models of these parts were combined together to form a more realistic brake system model with Fluid simulation. During the entire process Brake System was studied in depth. ABS controller algorithm was developed to control fluid flow in brake circuit as compared to manipulation of brake pressure values by ABS controller in simple model.

As compared to simple model, the advanced model is parametric in a sense that the components can be given different dimensions and corresponding results could be compared for braking efficiency. This claim is supported by the conclusions drawn from Chapter 4. Hence, it is possible that the specification given by brake part suppliers can be plugged in brake components and performance can be tested for a desired behavior in the Virtual Validation Environment.

6.2 Future Work
A good starting point for extending the thesis work is to consider some of the assumptions. Models can be built for simulating heat dynamics and pressure losses during brake operation. Like in real scenario advanced brake model simulation can be experimented with compressible fluid.

More detailed version of solenoid Valves and its energizing electrical circuit could be developed. The Pump control logic can be improved to pump required amount of brake fluid as compared to running it at fixed RPM. Low-Pressure Accumulator can be developed in detail so that a definite volume of fluid is used for the braking operation. Lateral
dynamics can be taken into consideration while braking. The ABS logic can be improved to have 5 state pressure control instead of three as developed in the corresponding advanced model. These above improvements can help in making more realistic validations using the Virtual Validation Environment.
7. References


[18] Che-Pin Chen, Mao-Hsiung Chiang, " Mathematical Simulations and Analyses of Proportional Electro-Hydraulic Brakes and Anti-Lock Braking Systems in Motorcycles", National Taiwan University, June 2018


### A. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>FL</td>
<td>Front Left</td>
</tr>
<tr>
<td>FR</td>
<td>Front Right</td>
</tr>
<tr>
<td>RL</td>
<td>Rear Left</td>
</tr>
<tr>
<td>RR</td>
<td>Rear Right</td>
</tr>
<tr>
<td>ABS</td>
<td>Anti-Lock Brake System</td>
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<tr>
<td>FMI</td>
<td>Functional Mock-Up Interface</td>
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<tr>
<td>Trq</td>
<td>Torque</td>
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<tr>
<td>WB</td>
<td>Wheel Brake</td>
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*Table A.1: Abbreviations*
B. Advanced Brake Model Results

B.1 Test 1

(a) Wheel speed $\omega$

(b) $-300 < \alpha (\text{rad/s}^2) < 300$

(c) $P_{SC}$ in wheel Cylinder

(d) Slip $\lambda$

Figure B.1: Front right wheel, $-300 < \alpha < 300$
Figure B.2: Rear left wheel, $-300 < \alpha < 300$
Figure B.3: Rear right wheel, \(-300 < \alpha < 300\)
B.2 Test 2

(a) Wheel speed $\omega$

(b) $-100 < \alpha (\text{rad/s}^2) < 100$

(c) $P_{SC}$ in wheel cylinder

(d) Slip $\lambda$

Figure B.4: Front right wheel, $-100 < \alpha < 100$
Figure B.5: Rear left wheel, -100 < α < 100
Figure B.6: Rear right wheel, $-100 < \alpha < 100$
B.3 Test 3

(a) Wheel speed $\omega$

(b) $-50 < \alpha (\text{rad/s}^2) < 20$

(c) $p_{SC}$ in wheel cylinder

(d) Slip $\lambda$

*Figure B.7: Front right wheel, $-50 < \alpha < 20$*
Figure B.8: Rear left wheel, \(-50 < \alpha < 20\)
Figure B.9: Rear right wheel, $-50 < \alpha < 20$
B.4 Obstacle Avoidance Maneuver

(a) Wheel speed $\omega$

(b) $P_{SC}$ in wheel cylinder

Figure B.10: Front right wheel, Obstacle avoidance maneuver
Figure B.11: Rear left wheel, Obstacle avoidance maneuver

(a) Wheel speed $\omega$

(b) $P_{SC}$ in wheel cylinder
Figure B.12: Rear right wheel, Obstacle avoidance maneuver

(a) Wheel speed $\omega$

(b) $P_{SC}$ in wheel cylinder