Department of Computer Science

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Construction of Automotive Control Software (ABS)

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Executive summary

This paper begins by discussing the benefit to the academic community of an anti-lock braking system that accurately models commercial ABS variants in wide use today by the general public. However, the difficulties pertaining to such a task, owing to the highly sensitive nature of source code belonging to automotive manufacturers is also described.

We continue by providing a review of past work in the area of vehicle dynamics and control research. For this purpose, [2] serves as a primary reference. It is noted that the friction active at any given car wheel is maximised for certain values of wheel slip. This relationship is exploited by systems such as ABS and TCS to provide each of a vehicle's tires with maximum traction under heavy braking/acceleration. Basic operation principles of the hydraulic modulator, a vehicular component key in implementing ABS in real hydraulic braking systems, are also discussed as to provide a intuitive understanding of the basic functionality provided by ABS. Popular methodologies for testing such vehicle control systems are also outlined to motivate the simulation techniques applied later to evaluate ABS performance.

A description of the ABS control cycle provided by [21] is then given, which is well thought to at least somewhat model commercial anti-lock braking systems. However, [21] does not completely describe the necessary implementation details of such a system and thus a decision is made to incorporate an extended Kalman filter for necessary estimation of vehicle velocity under extreme braking. This implementation is outlined as a simplification of those provided by [11] and [16].

Evaluation of this system is then provided through simulations, via Speed Dreams 2, an open source race car simulator [3]. Straight line braking test results clearly show reasonable regulation of slip levels and it is also shown that the EKF provides good vehicle velocity estimations, however, not as promising as those shown in [11] and [16].

In concluding, ideas for future work are suggested, such as further evaluation of the system presented here in varying driving environments. Among suggested improvements, particularly to the vehicle velocity estimation methodology, further work in performing timing analysis on this system is motivated.

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1 Introduction

1.1 Background & Motivation

Whereas the vehicles produced by the dawning automotive industry of the early 1900s were completely mechanical, the 1970s saw the beginning of embedded software systems being used to regulate complex vehicle systems such as fuel injection control [1] and ignition timing. Such software allowed for greater engine power output and fuel efficiency, as well as reduced vehicle emissions. With these benefits, and new legislation requiring reduction of vehicular emissions, the electrical engine control unit became so successful that its mechanical equivalent (the carburetor) is virtually unused today. From then on, the use of embedded software has grown to encompass almost every aspect of the modern motor car. Particularly, todays automotives benefit from a myriad of software control systems enhancing safety, including: anti-lock braking systems (ABS), traction control systems (TCS), electronic stability programs (ESP), active steering, adaptive cruise control (ACC) and countless more. Given the almost universal adoption of these systems, many of which are mandated by law, it is crucial for research into automobiles to incorporate accurate models of them and their effects on vehicular operation. However, implementations of such systems can vary with each manufacturer and source code is highly protected. Thus, it is difficult for researchers to accurately model the commercial safety systems in widespread use today.

This paper will introduce an independently developed Anti-lock Braking System, which attempts to mimic the behaviour of the ABS presented by Bosch in [2, p. 74], for the purpose of providing the academic community with an ABS implementation that accurately models those used in commercial applications. This will allow for further work constructing valuable benchmarks and provide an ABS for use in non-safety critical automotive projects (such as small scale electric vehicles or virtual vehicle simulations).

1.2 Statement of Ethics

The work presented here has no direct ethical implications, although it could be argued that there are ethical considerations inherent in trying to recreate patented code belonging to the giants of the automotive industry. However, as this software is not intended for commercial use, nor is it likely to match the quality of any commercial system in its present form, this issue is trivial. Of course, constructing software responsible for the safety of automotive passengers raises some ethical concerns. However, it should be stated, that the code discussed here is in no way meant to be deployed in any safety-critical situations.

It is also worth mentioning that various third-party tools were used throughout the development and simulation of the work provided here. All such tools are listed here along with their respective licensing agreements. All of which grant the necessary permissions for the modification and redistribution implicit in this research:

Speed Dreams 2, is licensed under the GPL V2 license [3, 4]. This open source racing car simulator is used to simulate deployment of the ABS presented in this paper.

TinyEKF, is licensed under the MIT license [5, 6]. This open source library is used to implement a generic Extended Kalman Filter (EKF) which is then used for velocity estimation of a vehicle under extreme braking conditions.

Eigen, is licensed under the MPL2 license [7, 8]. This open source library is used to manipulate vector and matrix objects in c++.

Autodiff, is licensed under the MIT license [9, 6]. This open source library provides automatic differentiation of C++ code (which is used to automatically determine Jacobian matrices for use with the previously mentioned EKF).

2 Literature Review

In this section, I will give a brief overview of the necessary physics and vehicle components required to fully understand the rest of this paper, although a basic familiarity with physics and automotive vehicles is assumed. The ABS presented in this paper assumes to be run in the context of a gasoline fueled, rear-wheel driven vehicle. As such, only the physics sufficient to describe such a system will be discussed. I will also describe relevant past work in the area of vehicle modelling and ABS Design.

The book “Brakes, Brake control and driver Assistance Systems: Function, Regulation and Components” [2] served as a primary reference for the completion of this project, it’s section entitled “Basic principles of vehicle dynamics” [2, p. 12] is heavily borrowed from in the following chapter. For further information, I recommend reading this book.

2.1 Tyre Dynamics

2.1.1 Tyre Forces

A high level of friction between the road and each of a vehicle's wheels is desirable at any time, not only during braking. This is because the tyres of a car act as the only connecting link between the vehicle and the road and thus ultimately decide the handling of the vehicle. Accurately modelling forces acting at the wheels is a complex problem due to the multitude of factors that need to be accounted for. Many different tyre models are used throughout the academic literature that account for effects that influence tyre forces such as vehicle suspension systems, tyre deformation, road camber, driving torque (driven wheels behave entirely different from undriven wheels during braking and acceleration), inertia, and so on. One of the more popular models is presented by Pacjeka [10], the so called "Magic Formula" model. Other prominent models include the bicycle model (as used in [11], as well as the EKF system presented in this paper) and the quarter car model. This problem is made even more difficult when the constraint of real-time calculation, as required by embedded systems like ABS and TCS, is considered.

However, to motivate the basic concept of an anti-lock braking system, consider the simple model for friction as presented in equation (1). The friction force F_R acting on each of a vehicle's tyres is directly proportional to the normal force F_N according to:

$$F_R = \mu_{HF} \cdot F_N \tag{1}$$

Where μ_{HF} is the coefficient of friction, which is determined by the pairing of tyre and road materials, as well as weather conditions and vehicle speed etc. [2, p. 18]. Thus, a low coefficient of friction results in less friction and hence an uncontrollable vehicle. Maximising the friction between each wheel and the road during braking is the focus of the anti-lock braking system. In so doing this, braking distances can be reduced and, more importantly, control of the vehicle under extreme braking can be maintained. ABS attempts to optimise friction levels for each tyre by maximising the coefficient of friction for each of the wheels. This is turn, is done by taking advantage of the relation between the coefficient of friction and tyre slip, as described in further sections (hence why both ABS and TCS systems are otherwise known as "slip control systems").

2.1.2 Tyre Slip

Slip is the phenomenon of a tyre's circumferential velocity differing from its reference velocity (longitudinal or lateral). For instance, if a tyre has an angular velocity of ω (radians/second, the rate of one complete revolution), then it should have a circumferential velocity v_{ux} (velocity in the longitudinal dimension) according to:

$$v_{ux} = R \cdot \omega \tag{2}$$

$$v_{ux} \approx v_{fx} \quad \text{*Assuming low wheel slip values} \tag{3}$$

Where R is the tyres' radius and v_{fx} is vehicle reference velocity in the longitudinal dimension. However, this is rarely the case due to factors such as tyre deformation (forces such as heat and pressure altering the effective radius of the tyre during operation), lack of traction and vehicle inertia. For example, if a car engages its brakes very abruptly and heavily, its wheels may completely stop rotating (given a large enough restrictive force placed on them by the brake pads). Despite this, the car's velocity will not instantaneously become 0, due to inertia acting on the car, and a loss of traction between the cars' tyres and the road. In this case, the tyres are said to have "locked", I.e: completely stopped revolving. The "normalized slip" of a tyre, represented by λ, can be calculated as follows:

$$\lambda = (v_f - v_u)/v_f \tag{4}$$

Where λ is normalized tyre slip (with 0 being no slip and 1 being complete tyre lock), v_f is vehicle velocity (reference velocity) and v_u is tyre circumferential velocity. A distinction is made between v_u and the previously defined v_{ux} because a tyre can suffer from slip in both the longitudinal λ_x and lateral λ_y dimensions. In the case of lateral slip, side-forces acting on the tyre, such as inertia during a tight bend in the road or strong side-winds, result in a lateral velocity (v_{fy}), that alters the path of the car from its longitudinal travel. The angle between the direction of the longitudinal (v_{fx}) and resultant (v_{fa}) velocities is known as the "lateral slip angle", α.

Tyre slip is particularly prone to occuring during heavy braking, but can also occur during vehicle acceleration. In the case of initial acceleration from a stationary position, the vehicle's tyres spin whilst the car remains still due to lack of traction between the tyres and the road. Limiting such spin to optimum slip values is the purpose of a traction control system, whereas the anti-lock braking system limits such slip values during braking.

2.1.3 Slip Curves and Optimum Slip

As previously mentioned, the motivating aspect of the slip control algorithms is regulation of slip levels to maximize road-tyre friction during braking/acceleration. Figure 1 (below) shows a typical "slip curve", describing the relation between μ_{HF} and brake slip (wheel slip due to braking) for a tyre on dry tarmac.

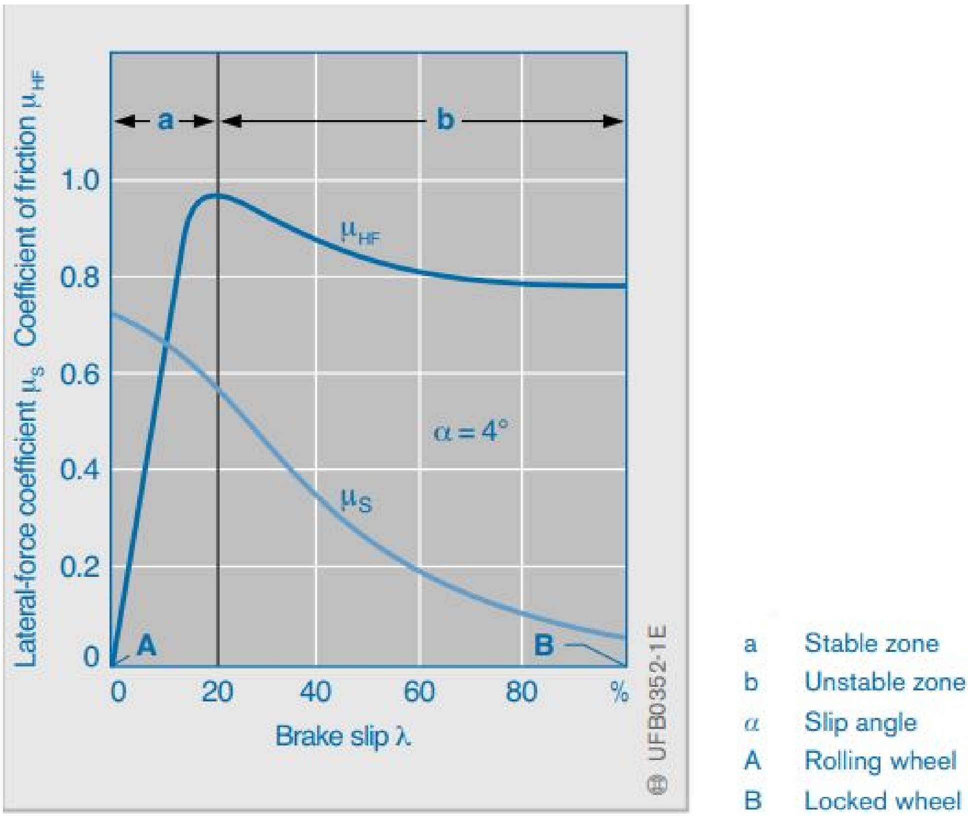

Figure 1: *Example of a "slip curve", showing the relation between brake slip and the friction coefficient in both the longitudinal and lateral dimensions [2, pp. 19].*

Firstly, notice the region of brake slip values between 0.0-0.2, where μ_{HF} increases linearly. This characteristic can be conveniently modelled and safely operated within for real-time control systems and, ideally, the vehicle should always operate within this range. This is known as the “stable zone”, as opposed to the “unstable zone” (0.2-1.0). Clearly, in the above scenario, the brake slip value for optimal friction is 0.2. However, such curves vary drastically for different vehicles and driving conditions. Since these curves cannot be directly measured, the problem of finding optimal slip values makes apparent the need for accurate modelling of tyre forces, motivating some of the models mentioned in section 2.1.1. Another problem encountered when trying to limit brake slip to optimal ranges is presented in the work of Van Zanten, et al. [12], suggesting that manipulation of tyre forces does not result in smooth linear progression along the slip curves, but rather “jumps”. This motivates the need for appropriate real time controllers that can accurately control such non-linear behaviour. For this purpose, a multitude of controllers have been proposed and experimentally used such as PID, fuzzy-logic and sliding mode [13, 14, 15].

2.2 Anti-Lock Braking System

2.2.1 Hydraulic Braking Systems

The components typical of a basic “dual-circuit” hydraulic braking system are outlined below in figure 2. This is a good starting place to discuss vehicle braking systems, although it is worth noting that this design is not very common in practice. As you can see, this basic braking system simply applies a uniform braking pressure to each wheel (via hydraulic circuits connected to disk brakes) as specified by the “master cylinder” which is directly proportional to the amount of force applied to the brake pedal via the driver.

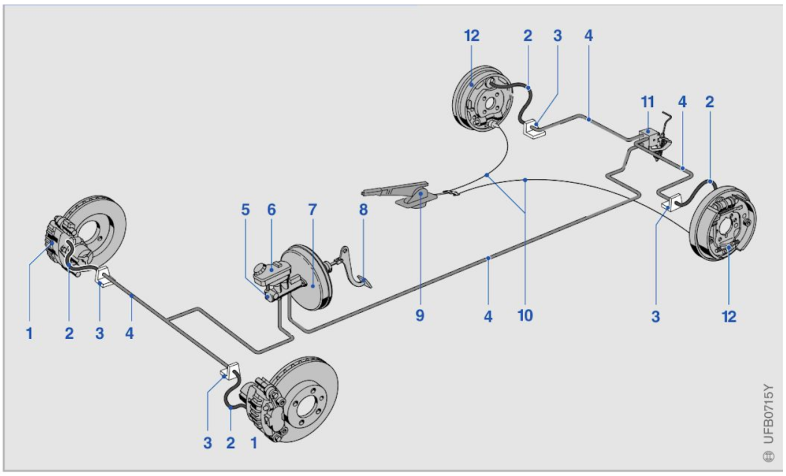

Figure 2: *A diagram highlighting the components of a hydraulic "dual-circuit" car braking system [2, pp. 40].*

Although effective in halting the vehicle, there are a few drawbacks to this design. Firstly, it is difficult to assure that each disk brake applies exactly the same amount of braking pressure to each wheel, and thus unwanted forces can affect the vehicle, due to non-uniform braking. Secondly, in this system, the brake pressure at each tyre is completely specified by the driver. This becomes a drawback under emergency braking conditions. In such a situation, inexperienced drivers are inclined to apply full braking continuously until the vehicle stops. This is likely to incur, almost instantaneously, wheel lock at all wheels. During this time, the driver has virtually no control over the path of the vehicle. Furthermore, it is not possible to control the brake pressure at each individual wheel (necessary for situations when some wheels are in contact with different road surfaces, or an individual brake fails in some way).

To prepare such a vehicle for implementation of ABS, two main functionalities must be added. Firstly, the capability of applying different braking pressures to each wheel must be possible. Secondly, the reduction/maintenance of braking pressure at each wheel must be possible without driver intervention. These features are realised with the addition of the hydraulic modulator.

2.2.2 Hydraulic Modulator

The hydraulic modulator is the vehicular component that provides the anti-lock braking system with the necessary control of brake pressure application. An extended braking system, showing the addition of a hydraulic modulator and ABS control unit, is shown in figure 3 (below). The hydraulic modulator essentially consists of a layout of “solenoid valves” (shown in figure 4, below). These valves allow brake pressure to be maintained and released, at each individual wheel, at the command of electrical signals, provided by the ABS control module. Note that this layout does not allow for the ABS control module to actively build up pressure independently of the driver, as would be required for a traction control system. As such, the anti-lock braking system does not brake without the drivers command, but simply improves the effectiveness of the braking commands issued by the driver (via the brake pedal), by reducing/maintaining the driver specified brake pressure to result in brake slip values for optimum friction.

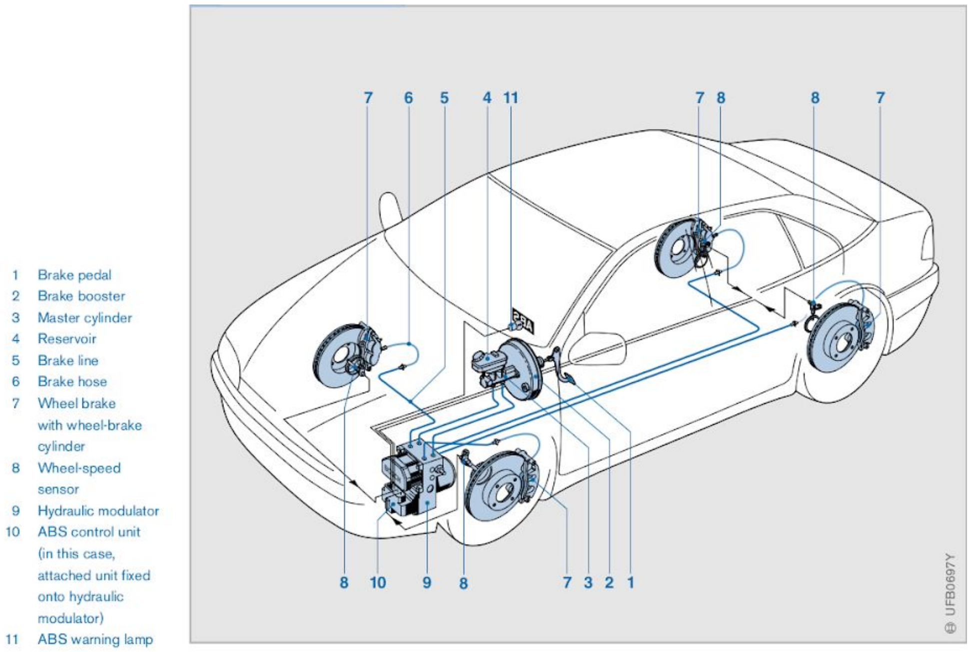

Figure 3: *A diagram highlighting the components of an extended hydraulic car braking system with addition of hydraulic modulator and ABS module [2, pp. 74].*

The hydraulic modulator provides 3 basic settings, which can be applied to each wheel independently by the ABS module. Under normal conditions, the hydraulic modulator is set to the “Pressure application” setting. Here the inlet valve is opened and the outlet valve is closed. Thus pressure from the master cylinder is transferred directly to the brakes. As brake slip increases, and the risk of locking up increases too. As such, the “Maintain pressure” setting may be applied by ABS. For this setting, both the inlet and outlet valves are closed, meaning that pressure cannot be increased or decreased. If the degree of brake slip still increases, then the “Pressure release” setting is applied. Here the inlet valve is left closed and the outlet valve is opened. Slowly reducing the amount of pressure applied to the brake pad [2, pp. 138].

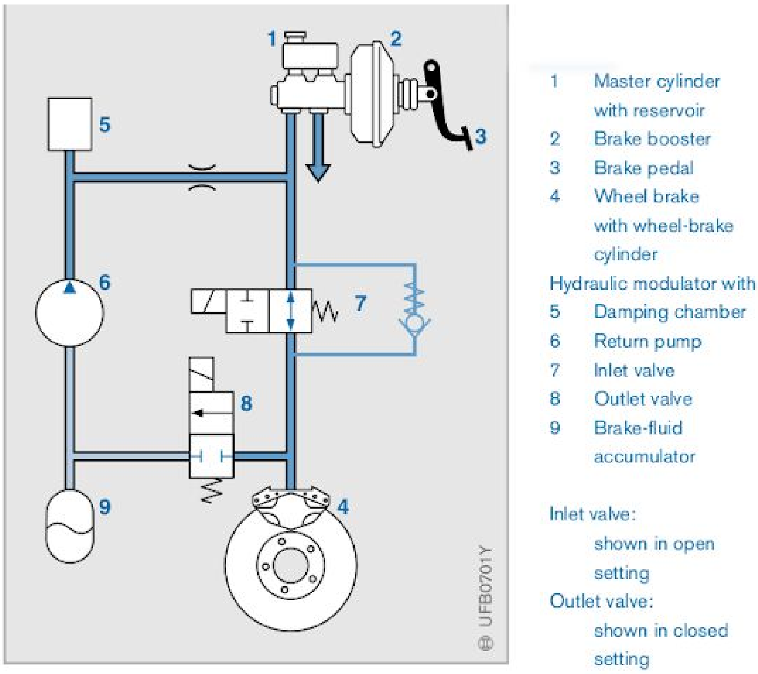

Figure 4: *A diagram highlighting the inner components of a solenoid valve, which provides the hydraulic modulator with the functionality to maintain and release pressure at each wheel, independent of the driver [2, pp. 75].*

2.2.3 Wheel Speed Sensor

Wheel speed sensors are used to measure the angular velocity (ω) of a vehicle’s wheels. This vital information can then used by the ABS control unit to calculate the reference velocity of the vehicle (equation 3), as well as wheel slip (equation 4). The reference velocity calculation may also incorporate information from other sensors such as accelerometer readings (as in [16, 17]) and current braking/acceleration torque (although these are not directly measurable). However, it is also possible to accurately estimate vehicle reference velocity with just wheel speed sensors, as shown in [18]. These calculations are then used to calculate each wheel's current slip (equation 4), and so are vital in the role of an ABS.

Due to the noise inherent in wheel speed sensors (and accelerometers), signal processing is necessary before any wheel slip calculations can be performed, which would traditionally be performed in the ABS module ECU. However, it is becoming common to find ICs (integrated chips) built into modern day wheel speed sensors that perform signal processing, to reduce the amount of computation required of the ABS module [2, pp. 147].

2.3 Design Validation

Because of the inherent safety concerns surrounding construction of vehicle handling control systems, which are directly accountable for the physical response of the vehicle, it is of paramount importance that such systems are developed and tested in an environment that mimics real world physics as accurately as possible. Large companies have the luxury of being able to verify such designs by implementing them in real vehicles and observing them in a safe and controlled environment, such as the Bosch "proving grounds" in Boxberg, Germany [2, pp. 35]. However, it is seldom possible, even for large automotive companies, to confine all such experimentation to this kind of extensive testing due to monetary and time constraints. Furthermore, these hurdles are only exaggerated for researchers with limited access to such equipment. For these reasons, two alternative approaches in particular have become popular among the academic community for prototyping implementations of control software such as ABS and TCS.

2.3.1 Dynamic Testing Rig

The first of these approaches is simulation of vehicle operation via dynamic testing rigs, as described and used in [18]. Through this approach, special testing equipment is used to artificially emulate both tyre and road interaction by running a mechanically controlled tire along a belt mimicking road surface, whereupon real tyre-road dynamics can be directly observed. This approach allows for rapid prototyping as well as considerably accurate results. However, its application is limited by the requirement of specialized testing rigs, which can be quite expensive. Also, the setup and maintenance of such systems only prolongs the time required to perform testing.

2.3.2 Simulation

If procurement the previously defined dynamic testing rig is not possible, as is the case in this paper, then the most feasible alternative is virtual simulation of tyre dynamics. There are many general purpose simulation environments that can be adapted to suit the needs of control systems design, such as Simulink [19]. There are also special purpose simulation environments for vehicle dynamics such as HVE [20], as used in [21]. However, this type of bespoke, specialized simulation software tends to be quite expensive and difficult to learn. Whilst not providing results as informative as testing on real equipment, virtual simulations have the advantage of being much faster to perform. They are also advantageous in that they are not limited in the number of different situations that they can model.

In an interesting compromise, Oniz et al.[18] first evaluates their design of an estimator for vehicle reference velocity in virtual simulations and then further validates the design via a testing rig.

3 Design and Implementation

As mentioned earlier, the goal of this project is to construct an anti-lock brake system that mimics commercial ones in widespread use today. This section will explore the design decisions, theory and implementation level details behind that system.

3.1 Development Environment

Expanding on the discussion outlined in section 2.3, the choice of development environment is a key decision in any software project, but particularly important in this instance. Ultimately, the ABS implementation discussed in this paper is only be able to perform as well as the physics simulation in which it is designed and tested. Hence, it was obvious from the beginning of the project that this decision would be one of the predominant factors in determining the project's success. Of course, the expensive testing facilities mentioned at the beginning of sections 2.3 and 2.3.1 would not be available. Leaving virtual simulation as the only viable choice. However, rather than building a simulation model around a general purpose simulation environment like Simulink [19], which would require a large amount of time spent implementing and debugging complex physics models, the decision was made to use a physics simulator that had already been validated as a reasonably accurate model of real world physics. However, a large proportion of specialized vehicle dynamics simulators were too expensive to be considered for this work, and many of the open source alternatives were not accurate enough.

Ultimately, the open source motorsport simulator “Speed Dreams 2”, [3] was chosen. Although this system is not frequently used in vehicle dynamics literature, the project TORCS [22] (from which the Speed Dreams project was originally forked in 2008) has earned its place in the research community after being the focus of several articles [23] for its application in developing autonomous driving AI. For this reason, TORCS was originally considered for use in development. However, this was not possible as the TORCS project uses a lumped model to describe braking force and thus individual wheel braking is not supported. However, since its split from TORCS in 2008, Speed Dreams has put more of an emphasis on realistic physics, and with its recent release of the SimuV4 physics engine (in version 2.1), Speed Dreams 2 offers simulation of individual wheel braking on certain cars. In fact, the Speed Dreams 2 project comes with its own implementations of both ABS and TCS control systems, however, these are basic in functionality and are not meant to replicate any real life implementations of such systems.

Figure 5: *Speed Dreams 2, main menu [3].*

Although information on the specific physics models underlying Speed Dreams is sparse, by digging through the source code it was discovered that the Pacejka "Magic Formula" tyre model is used, at least in part, to realistically model tire-road interaction.

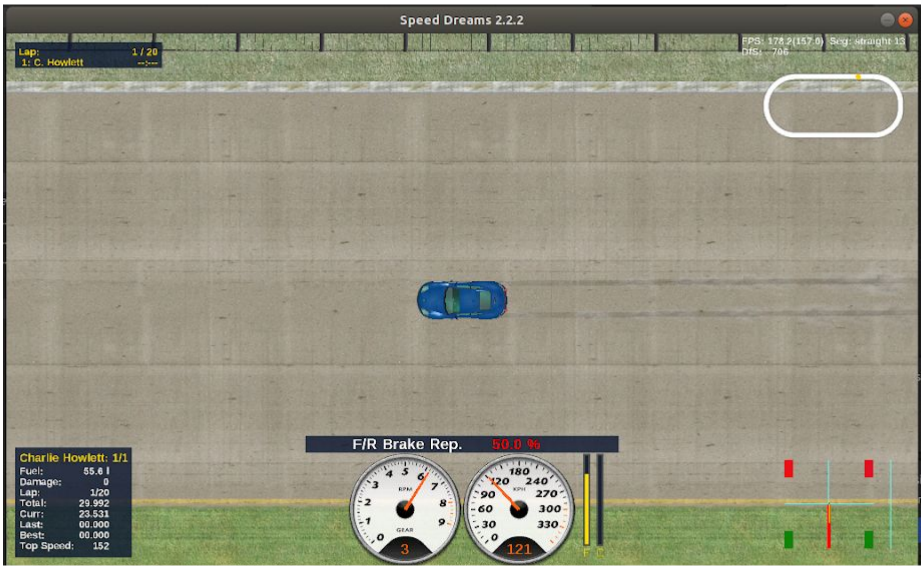

Figure 6: *Speed Dreams 2, during ABS fitted braking simulation [2].*

In fact, the Speed Dreams 2 vehicle model is sophisticated enough to boast glowing brake pad visualisation. And, as can be seen in Figure 6 (above), skid marks of varying depth and intensity even relay details of the intensity of braking patterns during deployment of the ABS.

3.2 ABS Construction

The anti-lock brake system presented here is comprised of 2 major components. Firstly, a replication of the control algorithm presented in [21], the “Bosch Version 1” algorithm. This control loop mimics the ABS control cycle described in [2] (figure 7, below), thus effectively modelling a commercial anti-lock braking system. However, a few modifications were made to this implementation, predominantly, the algorithm presented in [21] neglects how the ABS should determine the vehicle’s reference velocity, key in determining slip values. Among the literature, several approaches have been made to accurately evaluate a vehicles velocity from various sets of sensors (i.e. determining a nonlinear function). I chose to implement an Extended Kalman Filter, based on a simplification of the non-linear, deterministic tyre-force model presented in [11 and 16].

3.2.1 ABS Control Loop

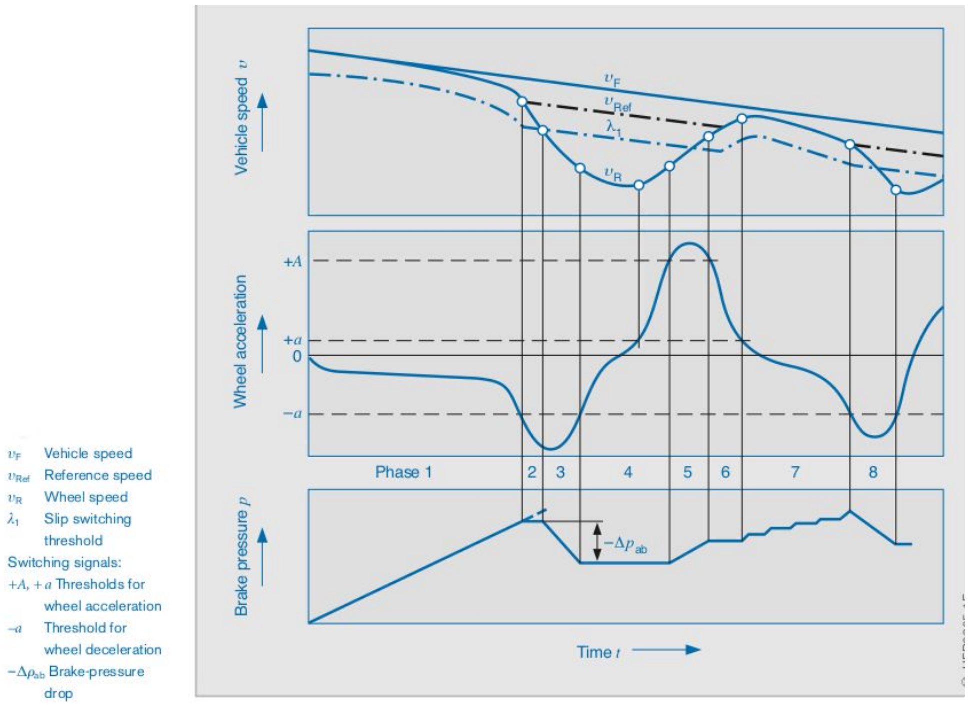

Figure 7: *Typical control cycle for "ABS Bosch 1" [2, pp. 82].*

As previously mentioned, the ABS control loop presented in this work is based on the algorithm known as "Bosch Version 1", introduced by Day and Roberts [21]. This work was supposedly inspired by an older book by Bosch, for which digital copies seem to be very rare, in which the algorithm for producing the control cycle in figure 7 was outlined. This slip control cycle is very straightforward, but is allegedly, "used on many passenger cars" [21, pp. 5]. Fundamentally, the algorithm uses individual tyre slips, as well as wheel accelerations, to determine impending wheel lock up and take appropriate action (increase, maintain or release pressure at each wheel). The algorithm comprises of 8 phases. Each wheel initially starts at phase 1, with the algorithm continuously polling the state of each wheel. In each ABS call, every wheel is considered in turn and progresses through the 8 phases according to specific criteria. The variables required as well as each phase of the algorithm are described in the tables below:

Bosch Version 1 Variables:	
Variable:	**Description:**
Threshold Vehicle Velocity	Minimum longitudinal velocity for ABS to become active (m/s).
Threshold Wheel Velocity	Minimum wheel angular velocity for ABS to become active (rad/s).
Tyre Maximum Slip	Maximum acceptable longitudinal tyre slip (normalized slip).
Wheel Minimum Spin Acceleration	Minimum acceptable wheel angular acceleration, indicates impending lock up (rad/s^2).
Wheel Maximum Spin Acceleration	Maximum wheel angular acceleration, before further braking is applied (rad/s^2).
Apply Delay	Time delay for controlled output pressure increase $(seconds)$.
Primary Application Rate	Initial rate of controlled output pressure increase (Pa/s).
Secondary Application Rate	Secondary rate of controlled output pressure increase (Pa/s), typically 10 times less than the primary application rate.
Release Rate	Rate of controlled output pressure decrease.

Table 1: *Description of Bosch ABS version 1 variables, as presented in [21].*

Bosch Version 1 Control Cycle:
Phase 1 (Initial Application):
The hydraulic modulator sets brake pressure of each wheel equal to that specified by the driver (via the brake pedal). This continues until wheel angular acceleration (negative) drops below the minimum wheel spin acceleration level, where the tyre progresses to phase 2.
Phase 2 (Maintain Pressure):

Brake pressure is maintained (driver input does not affect it). This continues until the tyre longitudinal slip exceeds the slip associated with the max slip threshold (At this point, the current tyre slip is used as the max slip threshold in later phases. The tyre is beginning to lock). Following this, the tyre progresses to phase 3.

Phase 3 (Reduce Pressure):

In this phase, brake pressure is reduced according to the release rate, until wheel spin acceleration exceeds the maximum threshold, where the tyre progresses to phase 4.

Phase 4 (Maintain Pressure):

Brake pressure is maintained for the specified Apply Delay (or until wheel spin acceleration exceeds +A, which is ten times the maximum wheel spin acceleration), where the tyre progresses to phase 5.

Phase 5 (Increase Pressure):

Brake pressure increases according to the primary apply rate. This phase continues until the wheel spin acceleration becomes negative, where the tyre progresses to phase 6.

Phase 6 (Maintain Pressure):

Brake pressure is maintained. This continues for the specified apply delay (or until the wheel angular acceleration again exceeds the wheel minimum spin acceleration), where the tyre progresses to phase 7.

Phase 7 (Increase Pressure):

Brake pressure increases according to the secondary apply rate. This achieves greater braking performance whilst minimizing the potential for wheel lock-up at tyre longitudinal slip in the vicinity of peak friction. This continues until wheel angular acceleration drops below the minimum angular acceleration threshold, where the tyre progresses to phase 8.

Phase 8 (Reduce Pressure):

In this phase, the tyre immediately progresses to phase 3. Where a new control cycle begins.

Table 2: *Description of Bosch ABS version 1 control cycle, as presented in [21].*

3.2.2 Velocity Estimation via Extended Kalman Filter

One of the aspects that [21] fails to shed light on is how commercial ABS solutions calculate vehicle reference velocity under extreme braking. In this way, the only aspect of the complete ABS solution presented here that is not at least claimed to be in widespread use is its method of calculating such velocity. During normal driving conditions, reference velocity can simply be calculated as the average of the circumferential velocities of the undriven wheels (equation 3). However, under heavy braking, large brake slip values invalidate this approach. The ABS presented here employs an Extended Kalman Filter for this purpose, as a simplified version of the EKF presented in [11]. This control technique is particularly alluring as the EKF gracefully accounts for the noise present in realistic wheel speed sensors and the model presented in [11] (an extension of the work provided in [16]) only requires wheel speed sensor readings.

The details of inner EKF workings is beyond the scope of his paper. However, the basic idea is this. Given a state vector (that is not directly observable),

$$x(t) = [v_x,\ v_y,\ \lambda] \tag{5}$$

Where $x(t)$ is the state of the system at discrete time step t and λ is a scalar used in the physics model used to calculate $x(t)$ given the input vector,

$$u(t) = [\delta_f,\ \omega_f,\ \omega_r] \tag{6}$$

Where δ_f is the angle of the vehicle's steering wheel (radians) and the variables ω_f, ω_r are the average front and rear angular wheel velocities. The EKF uses initial assumptions about the state of x at t=0, and gaussian distributions representing the noise present in the input vector variables, state vector variables, and “process noise” (the inaccuracy of the model) to calculate $x(t)$ given $u(t)$. Given enough time, and proper modelling, the EKF will converge on the real values of $x(t)$.

Implementing this facet of the anti-lock braking system was much more complicated than the previously explored slip control cycle. The addition of three open source libraries [5, 7, 9] to the project were required. In practice, the implementation presented here always assumes straight line braking (I.E: $\delta_f = 0$), for simplicity.

4 Simulation and Results

After implementing the previously described anti-lock braking system, a series of straight-line braking tests were performed in Speed Dreams 2. In this section, I will present these results and comment on how they reflect the system's effectiveness. The variables used to define the system are included in the table below.

Simulation Variables:	
Variable:	**Value:**
Threshold Vehicle Velocity	10 (m/s).
Threshold Wheel Velocity	$10(rad/s)$.
Tyre Maximum Slip	0.12 (norm slip).
Wheel Minimum Spin Acceleration	$-95\ (rad/s^2)$.
Wheel Maximum Spin Acceleration	$0\ (rad/s^2)$.
Apply Delay	$0.04\ (seconds)$.
Primary Application Rate	11000000 (Pa$/s$).
Secondary Application Rate	8458000 (Pa$/s$).
Release Rate	50000000 (Pa$/s$).
Car Mass	1265.0 kg.
Car Maximum Braking Pressure (per disk pad)	13000 KPa.
Static Wheel Radius	0.3179m.
EKF λ scaler	1.1

Table 3: *Description of variables values used in following simulations.*

4.1 Velocity Estimation

Firstly, the accuracy of the previously discussed EKF, used to estimate vehicle longitudinal velocity during extreme braking, will be discussed. For this purpose, 3 sets of test data were gathered. For each of these tests the vehicle first reaches an initial velocity of

80kph, 110kph or 150kph. At this point, the car's clutch is disengaged and 100% braking pressure is linearly introduced over the course of 0.08 seconds, simulating a driver applying emergency braking.

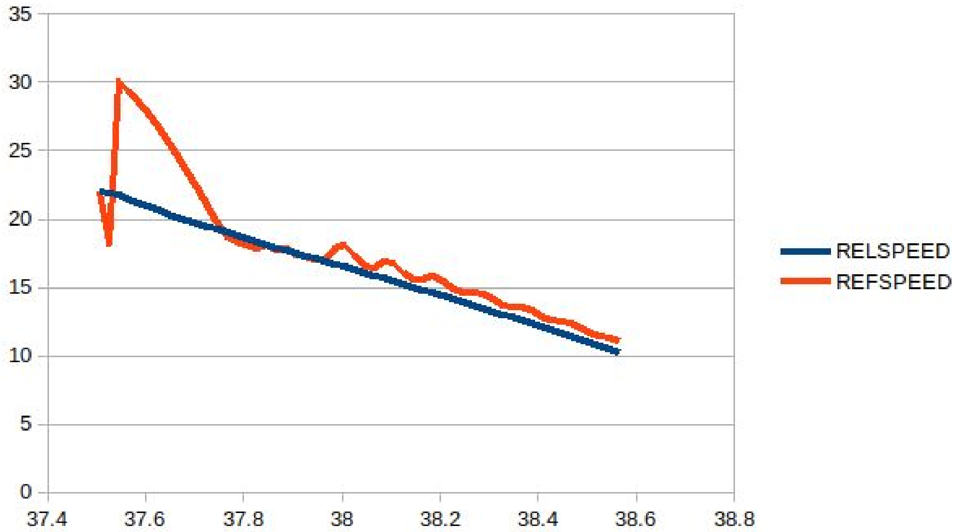

Figure 8: *Real speed and estimated speed vs time for emergency braking sequence starting at 80kmh (~22.2 m/s).*

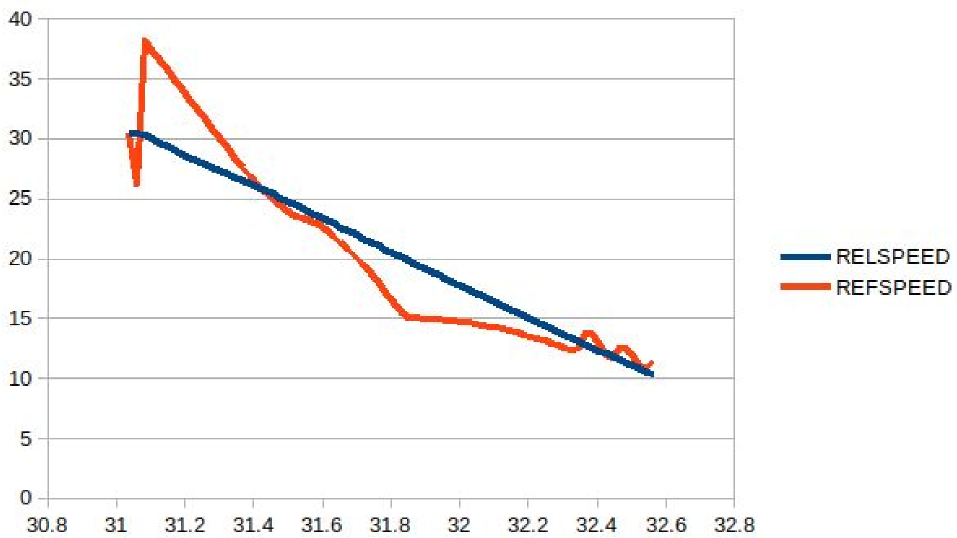

Figure 9: *Real speed and estimated speed vs time for braking sequence starting at 110kmh (~30.5 m/s).*

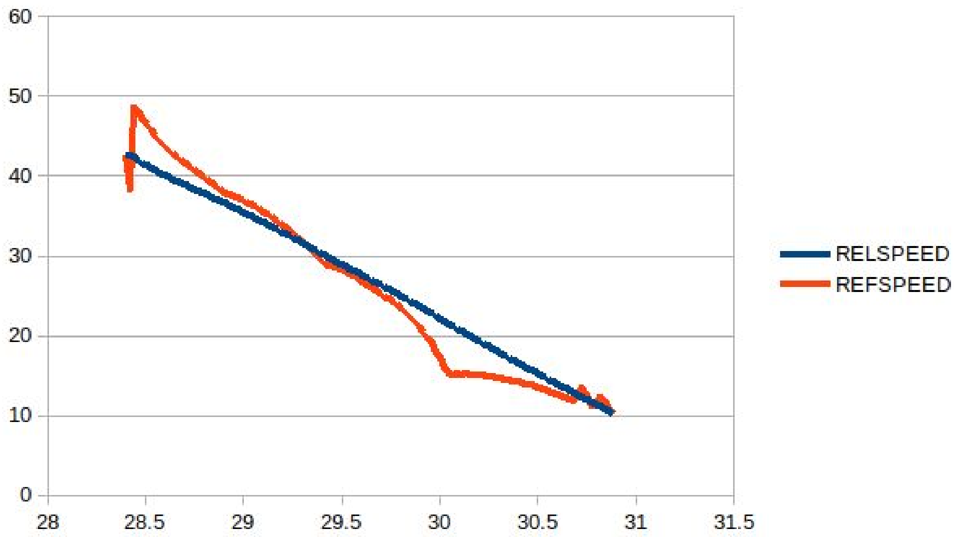

Figure 10: *Real speed and estimated speed vs time for braking sequence starting at 150kmh (~41.7 m/s).*

As expected, these results show a relatively good level of convergence between estimated speed (REFSPEED) and actual speed (RELSPEED), which only improves as simulation time progresses. However, these results are not as impressive as those presented by Alvarez [11]. This is very likely due to the EKF state modelling simplifications made by this paper for simplicity (whereas Alvarez [11] included in his state vector an accurate model of vehicle suspension, which affects normal forces acting at each wheel and thus tyre friction, as described in equation 1).

4.2 ABS Control Loop

In this section, results of a single emergency braking simulation will be used to evaluate the performance of the previously described control cycle to regulate slip levels during braking. so as to not have these results rely too heavily upon the performance of the EKF (which dictates current wheel slip levels in the control loop), these results were collected by feeding the ABS with the vehicle's actual velocity. Due to implementation limitations, this ABS control loop is simulated at only 50Hz.

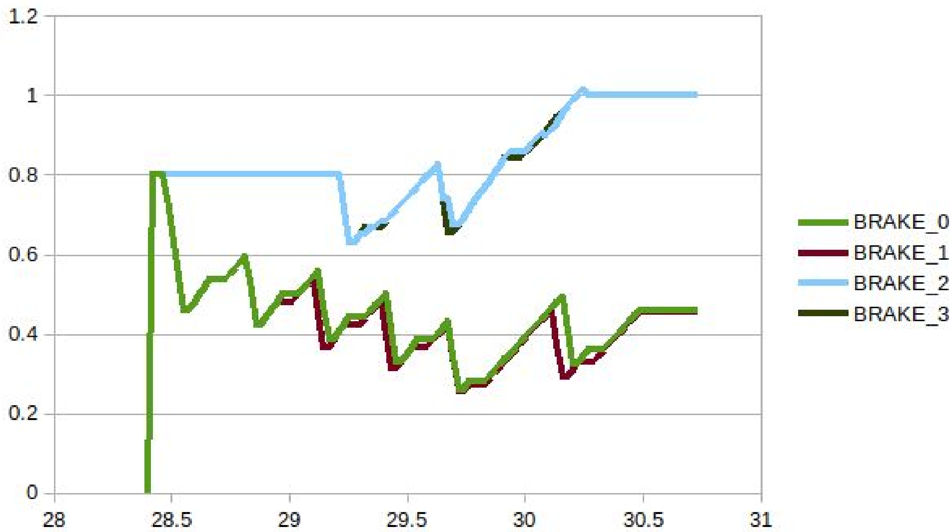

Figure 11: *Normalized braking commands (0-1) vs time for braking sequence starting at 150kmh (~41.7 m/s).*

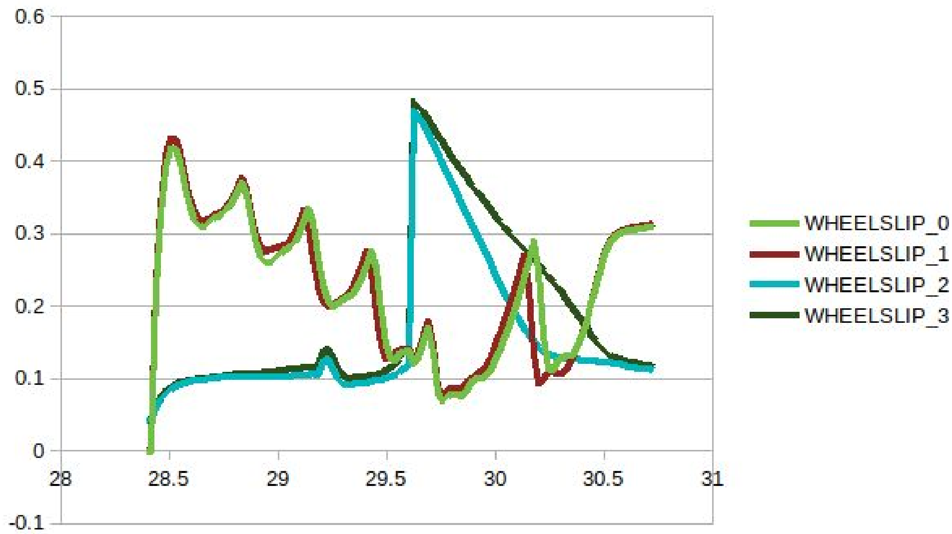

Figure 12: *Slip values vs time for a braking sequence starting at 150kmh (~41.7 m/s).*

The braking levels shown in figure 11 show an encouraging familiarity with the typical control cycles presented by both K. Reif [2] (figure 7) and those presented in the work of *Day and Roberts* [21]. Notice how the front wheel brake values (BRAKE_0, BRAKE_1) are lower than those for the rear wheel brakes (BRAKE_2, BRAKE_3). This is due to sudden braking resulting in a shift of weight from the rear to the front of the car. Appropriately, the ABS control cycle thus applies less brakes to the front wheels to prevent lockup. On the other hand, whilst figure 12 does show wheel slip values clearly being lowered towards the tyre maximum slip threshold (0.12), it begs the question of why slip values were ever permissed to exceed this limit at initial brake application. Not only this, but the reason behind the irregularity of wheel slip values after t=29.5 is unexplained.

5 Conclusion

Throughout this paper an implementation of ABS that attempts to mimic commercial variants is described and evaluated. Promising results in the previous section do indicate good regulation of slip levels, but also clearly show room for improvement. One such area is in vehicle velocity estimation, (as performed via extended kalman filter) which has been shown from past literature [11, 16] to have more effective implementations. Another limiting factor is the simulation platform used to retrieve these results. Whereas the ABS described here is only simulated at 50Hz, a much more realistic implementation would expect to run at around 500Hz. Although this could be achieved via simulation in Speed Dreams, further adjustments to the current testing setup would be required. In future work, it would be interesting to see timing analysis performed on this implementation so as to provide the academic community with ABS benchmarks. Another possible avenue of further work lies in additional testing upon the system to determine how drastically this ABS reduces braking distances, braking times and/or lateral slip values in different driving conditions.

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