

Integration of Active Braking System in Multi-Body Systems Tool to Improve Prediction of Braking Loads

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ABSTRACT

An increase in data measurement and recording within vehicles has allowed Anti-lock Braking Systems (ABS) to monitor a vehicle's dynamic behavior in far more detail. This increased monitoring helps to improve vehicle response in scenarios such as braking whilst cornering and braking on uneven surfaces.

The Durability and Robustness (D&R) CAE department within Jaguar Land Rover discovered that the lack of a complex ABS system in virtual vehicle models was contributing to poor lateral and longitudinal loads correlation throughout the suspension and mounting systems. D&R CAE started a project to incorporate Continental's ABS system, provided by '©Continental AG' for physical JLR vehicles, into SIMPACK virtual vehicles by means of a co-simulation (2017 n.d.). The work involved collaboration between 3 departments in Jaguar Land Rover and ultimately led to implementation of the ABS into the JLR standard automotive virtual database.

Following successful implementation of the new ABS system; D&R CAE commenced correlation of JLR vehicles over key durability and extreme event surfaces. These surfaces and the correlation techniques are described in detail in this paper. The results highlight significant improvement in wheel rotational deceleration when compared against the original ABS system. An improvement in suspension longitudinal and lateral loads correlation can also be seen. Improved correlation in this area moves D&R CAE forward in their goal to achieving confident predictive ability on durability and extreme braked loadcases which will ultimately reduce the reliance on physical testing and improve JLR's processes.

Phase 2 of this project will focus on an increased number of JLR vehicle platforms and loadcases in order to establish a robust level of correlation, allowing D&R CAE to roll out the new ABS system throughout the business.

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INTRODUCTION

The Durability and Robustness (D&R) Computer Aided Engineering (CAE) department within Jaguar Land Rover (JLR) are responsible for testing new vehicles throughout the engineering process. These tests are designed to catch potential issues due to component-component or system-system conflicts which may not have been picked up in a standalone system or component test. To robustly test the interaction of the Anti-Lock Braking System (ABS) within the complete vehicle, a number of braking loadcases are performed on different surfaces according to a strict test procedure. Areas within the suspension which are likely to see high loads during these braked loadcases are the track rod and lower control arm(s) [Figure 1], with lateral and longitudinal directions often seeing the highest load. D&R instrument and measure these loads throughout the test to determine if they are within the acceptable range.

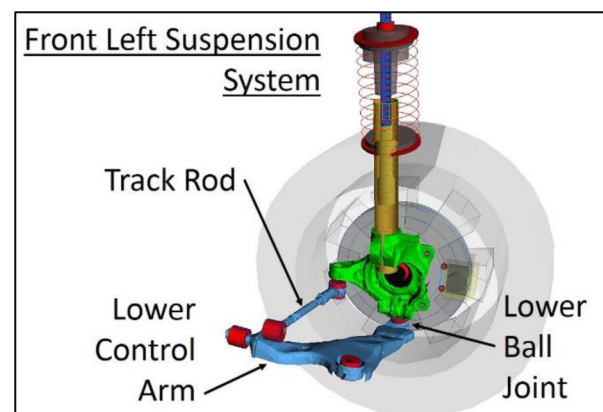


Figure 1. Front left Macpherson strut suspension system diagram

Durability and Robustness CAE department, a sub-department to D&R, has been using Multi-Body Simulation software 'SIMPACK' to perform virtual loadcases with full vehicle models and highly accurate scanned virtual surfaces. Currently, a large number of virtual

loadcases can be used to accurately predict vertical loads throughout the suspension system, this work often negates the need for a physical test on earlier gateways in the engineering process where physical prototype vehicles are expensive and often non-representative.

Before this project, D&R CAE's 'Detection Event' rating for braked loadcases was a 7 or 'DE7'. This rating implied that it was possible to run a virtual vehicle on braked loadcases according to test procedure requirements, however the resulting load was not correlated to physical test data and thus load prediction was not possible. Loadcases with a DE7 rating can be used for an 'A to B' comparison, to determine if a component change would likely reduce or increase the load at certain joints, but prediction of the load is not possible. To achieve this DE7 rating, a simplistic ABS system was created in Simulink and integrated into Simpack via a MATSIM interface technique. This MATSIM ABS looked at the degree of wheel slip and compared it to a 'min' and 'max' wheel slip value which had been entered by the user. The system would then increase or decrease the brake pressure depending on the value of wheel slip. The MATSIM ABS was capable of preventing the wheel from locking up whilst maintaining a good deceleration rate; however comparisons of wheel speed to the physical test showed the simplistic ABS system was too sinusoidal in its approach and the physical vehicle ABS was clearly working on a more complex level.

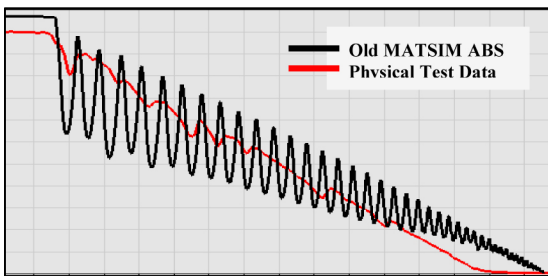


Figure 2. ABS Stop - Front left wheel speed vs time

The effect of wheel speed correlation on component loads was not fully understood when starting this project; it was only assumed that due to the wheel being the first component in the load path, the peak longitudinal and lateral loads on the lower control arm and track rod would be affected. It was also believed that the different frequency of the wheel decelerating and accelerating would alter the system response, altering stiffness values in non-linear compliant mounts. Another issue with the MATSIM ABS was its inability to integrate with other active systems such as Continuously Variable Damping (CVD), Hill Descent Control (HDC), Stability Control System (SCS), Torque Vectoring by Braking (TVBB) and other active systems requiring control of brake pressure to increase vehicle performance. With the increasing use of these active systems in JLR vehicles, the requirement to model them correctly in virtual vehicles is paramount to achieving good predictive capability and ultimately reducing physical testing. The key goal of the work carried out and discussed in this paper was to improve the correlation (during braked events) at the wheel which as a result, was expected to improve longitudinal and lateral loads at the lower ball joint. Implementing the Electronic Braking System (EBS) from the physical vehicle aimed to improve

this wheel correlation whilst also future-proofing the virtual braking system, allowing for further brake related active systems to be added at a later time.

LITERATURE REVIEW

One of the most relevant papers to this work was a master thesis written by Tobias Eriksson studying applied mechanics at the Chalmers University of Technology in 2014 (Eriksson 2014). Eriksson implemented a supplier provided ABS control system in Simulink with a Volvo Car Corporation (VCC) virtual vehicle model in ADAMS Multi-Body Simulation (MBS) software. He discovered the requirement for a settling time of 6s when using his system and also highlighted the need to robustly test the virtual system using physical test inputs in an open loop format.

Other literature used for this project included Simpack documentation such as user guides to better understand the co-simulation techniques available. A short Simpack news article written by Vladislav Drobny on 'ABS Braking with SIMAT Co-Simulation interface' in August 2003 (Drobny 2003) highlighted the benefits of using a SIMAT co-simulation technique to carry out ABS braking within Simpack vehicles. Drobny stated that by using this type of co-simulation it was easier to modify parameters, plot graphical outputs and modify the algorithm without having to change the Simpack model. Although these were not the core reasons as to why a SIMAT co-simulation was used, it was useful to understand the additional benefits.

MODELLING APPROACH

D&R CAE knew that the Electronic Brake System (EBS) logic from Continental and Bosch suppliers was available within JLR and that if the logic could be implemented into Simpack it could drastically improve wheel speed correlation and thus improve lateral and longitudinal lower ball joint correlation. Discussions with the Deceleration and Stability Attribute (DSA) department led to D&R CAE acquiring an EBS logic block embedded within Simulink which was setup to run, via a co-simulation, with Carmaker 1D simulation software. Close collaboration with the DSA department over a number of months allowed D&R CAE to use this Simulink/ Carmaker co-simulation to understand the inputs and outputs required from the EBS system. D&R CAE were then able to cut the logic block down into a more manageable system which consisted of just the ABS. Simplifying the logic block to contain only the ABS caused the system to require a lesser number of inputs to operate and thus reduced the complexity when integrating it for the first time with Simpack vehicle models. Having used Simpack extensively for development work and program support prior to this project, it was obvious to D&R CAE that a complex control system such as ABS could not be easily implemented directly into Simpack without the use of Simulink and a suitable interfacing technique. 3 different interfaces were explored when starting this project; MATSIM, SIMAT and FMU Import.

Simpack Interface Options

A MATSIM interface had been used previously and was the most well-known within D&R CAE. It was used for the original ABS system which allowed D&R CAE to achieve a DE7 rating for virtual braked loadcases. MATSIM works by creating the ABS logic within Simulink before packaging and integrating it within Simpact as a control element. The advantage was that once the control logic had been correctly packaged within Simpact, the Simulink software was not required, removing the need for users to have both Simulink and Simpact installed. Run time was also kept to a minimum with MATSIM since the controller logic was embedded within Simpact and data was not required to pass back and forth between software. The downside of MATSIM interfaces are that they only work with more simplistic, linear control systems and for this reason it was deemed unsuitable for the more complex, non-linear control system provided by the ABS suppliers.

An FMU or Functional Mock-up Unit interface works using a co-simulation. This allows use of an FMU solver, communicating to Simpact modelling elements using the Simpact solver, thus allowing for more complex control logic. FMU co-simulation and SIMAT co-simulation are two different interfacing methods but work in a very similar way. The main difference is that an FMU has the ability to use any software which complies with the FMI or Functional Mock-up Interface. Because the ABS logic was packaged within Simulink and it was complex and non-linear, the only two interfaces possible were FMU and SIMAT co-simulations. A SIMAT co-simulation was the approach chosen for this project because it was built specifically for co-simulation between Simpact and Matlab-Simulink. An FMU approach would have also been suitable however it was logical to use the technique which was more specifically built for the task.

Simpact Virtual Models

After establishing which Simulink interface should be used and reducing the input channels required for the ABS logic; a simple Simpact vehicle model was built consisting of chassis, 4 wheels and linear spring - damper connections at all 4 corners [Figure 3].

The basic virtual model was able to carry out ABS braking on a straight, flat surface using the Simulink ABS logic via SIMAT co-simulation. Wheel speeds were compared against previous Carmaker runs carried out by the DSA department to validate the results. Using this simplistic Simpact model, D&R CAE were able to find and solve issues within the system far faster than would have been possible with the complex, full virtual vehicle models. One issue found using the simplistic model was the inability of the ABS logic to work with a 64bit version of Matlab. 32bit Matlab had to be used, yet this version was incompatible with 64bit Simpact. After collaboration with both Virtual Hub and DSA department, the issue was resolved by installing 32bit Simpact and linking the SIMAT block from this to the 32bit version of Simulink. With the 32bit SIMAT block linked it was then possible to use 64bit Simpact models with 32bit Simulink.

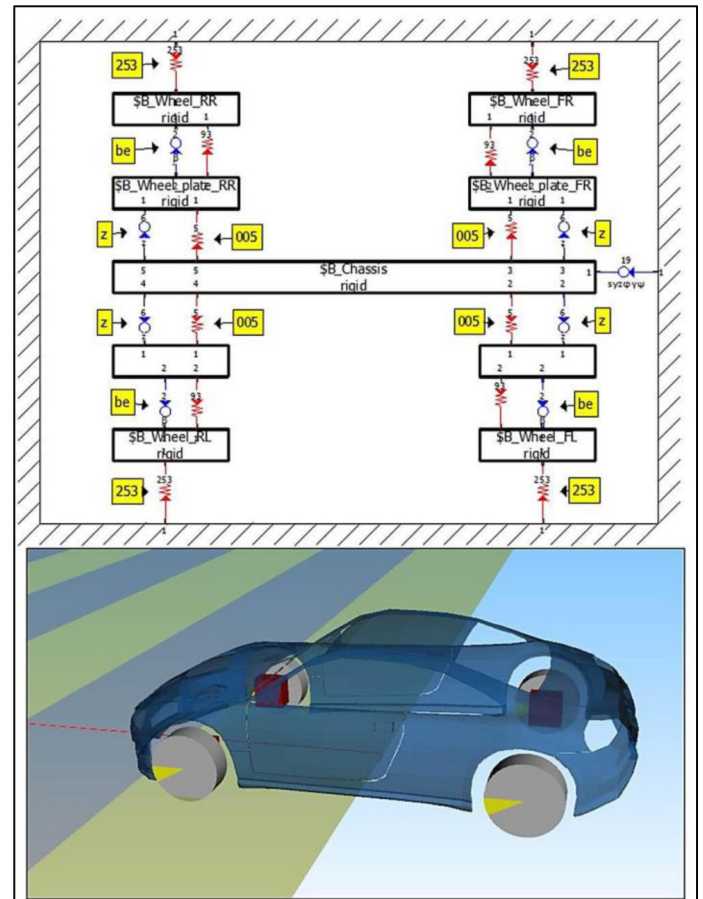


Figure 3. Simple Simpact vehicle model used to test ABS block via SIMAT co-simulation

Another issue first found using the simplified model was the settling time required for the ABS block. Settling time was set to around 5-6 seconds following the study by Tobias Eriksson in his paper (Eriksson 2014). Eriksson gave all his input channels a zero value for the first 2 seconds of the run, he then ramped these values up over the next second until they were 100% of the actual values seen in the simulation, Eriksson then waited a further 2-3 seconds before initiating the vehicle braking. This method was replicated in D&R CAE's ABS brake logic, however after implementing the full vehicle model and carrying out further correlation runs, it was apparent that the brake pressure was increasing before the brake switch had been pressed (discussed further in the 'Settling Time' section of this paper).

Once successful ABS braking with the simplified Simpact model had been achieved with suitable levels of correlation to the Carmaker results; a full virtual vehicle model was taken from Simpact wizard and opened in Simpact Pre-Processor. Simpact wizard is the more user-friendly side of Simpact, its Graphical User Interface (GUI) contains switches as well as information about what the switches change within the model. Wizard allows the user to edit a set of pre-determined parameters using these switches but does not allow alteration of any other parameters. Since the required input and output channels were not readily available in the virtual vehicle model, the pre-processor had to be used instead of wizard. (GmbH 2001 - 2016)

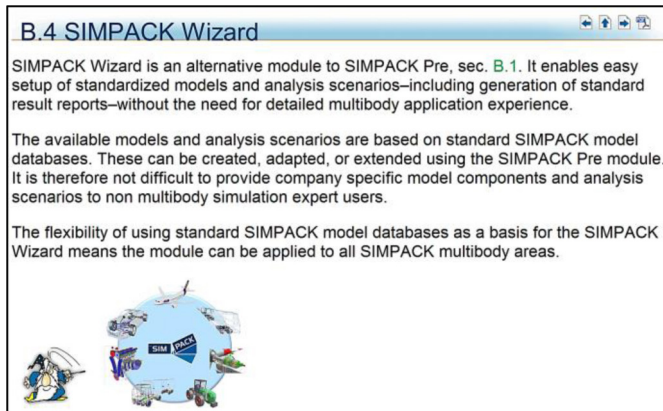


Figure 4. Screen grab from Simpack Documentation describing Simpack Wizard (GmbH 2001 - 2016)

The pre-processor is the 'raw' side of Simpack, used to build the models from scratch using bodies, joints, force elements...etc. By opening the virtual vehicle model in pre-processor it was possible to add the necessary inputs, outputs, senders and receivers which would enable it to correctly talk to the ABS block within Simulink and vice versa. After setting up these input and output channels correctly, the full vehicle model was run via the SIMAT co-simulation with the ABS Simulink block. Results from the first full vehicle ABS stop event showed wheel speeds similar to what was seen in both the simplistic model and the CarMaker results. This implied the ABS was operating correctly. Once D&R CAE had a full virtual vehicle model operating correctly using the ABS block within Simulink, the department requested the help of Virtual Hub. The Virtual Hub department within JLR is responsible for building the virtual vehicles and compiling them to work faultlessly in Simpack wizard. Virtual Hub also maintains the virtual surfaces (known as loadcases) on which the vehicles are run. D&R CAE asked the department to implement the required inputs, outputs, senders and receivers into the virtual vehicle models; this enabled any virtual model to be run on any virtual loadcase with the co-simulation ABS block from Simulink controlling the brake torque. Implementation into wizard allowed D&R CAE to commence correlation against physical test data.

SIMPACK MODEL AND LOADCASE SETUP

Before carrying out correlation activities, the Simpack model and loadcases had to be setup. A number of choices had to be made at this stage to optimise the model and loadcase in order to give the right amount of complexity whilst minimising runtime. Some of these choices required individual studies to be carried out which have been discussed in the sub-sections below.

Model and Loadcase Basic Setup

The virtual vehicle setup was mainly determined by the physical test data available; for example the wheels and tyres on both Evoque and Discovery Sport test vehicles were Continental Cross Contact 245/45/R20 so this tyre had to be used in the Simpack model in order to correlate effectively. Corner weight, spring rates, ride height and

damper tunes were matched wherever possible, however some components could not be used such as 'Continuously Variable Damping' (CVD) dampers due to the active system not being available. It was also unnecessary for D&R CAE to accurately model some systems such as the driveline rotation and engine torque since these loads were not being analysed for the purpose of this work.

After building the model to match the test vehicle, the loadcases were setup to match the test surface as closely as possible. D&R CAE have highly accurate scanned surfaces of all extreme and durability events carried out by JLR vehicles. For this work it was important to use these surfaces, despite the additional runtime, since the wheel vertical undulations would have a large effect on the ABS response and correlation at wheel level was critical for this work. Another important option was to decide whether to run the vehicle with rigid or flexible components. Running with flexible components such as the body and suspension arms allows Simpack to calculate the amount of energy which would be absorbed within that component during an event. It's a reduced form of Finite Element Analysis (FEA) within the Multi-Body Simulation environment. The issue with using flexible bodies is that the calculations are complex and because of this the runtime increases considerably. Due to the nature of this work, requiring numerous re-runs, it was decided that rigid bodies would initially be used for all components to keep runtime to a minimum.

Brake Torque or Disc Caliper Study

A study was carried out to look into the advantages and disadvantages of using the more realistic disc and caliper braking method compared to applying a braking torque to the center of the wheel.

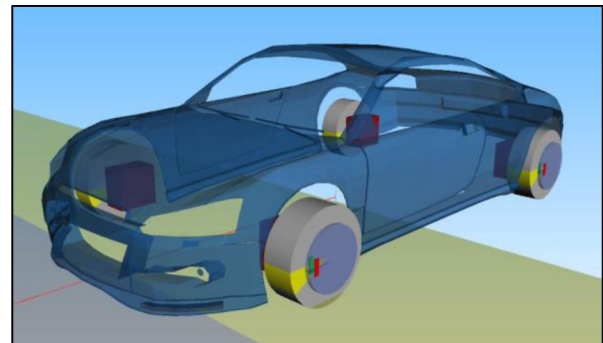


Figure 5. Simple Simpack vehicle model with the addition of disc and pad braking

The study compared two simplified vehicle models; one with working disc and calipers with a pre-defined level of friction between pad and disc and the other with brake torque applied directly to the wheel hub. Both methods were effective in achieving the correct rate of deceleration, however it became obvious that the torque application method required more complex logic to prevent the wheels from being able to spin backwards. One test involving a high level of brake pressure caused the wheels to spin backwards on the torque applied model. This negative wheel speed was picked up by the ABS unit as a positive wheel speed which responded by applying higher levels of brake torque. The resulting effect was an unstable system causing the

model to have higher and higher negative wheel speeds and eventually causing the simulation to abort. Although disc and caliper braking solved this instability issue; the additional information required for it to work correctly was not readily available. Additionally the level of complexity required for a robust disc and caliper system would have significantly increased runtime. After discussions with the Virtual Hub department, a solution to the negative wheel speed issue was created which made it possible to apply any value of torque to the wheel without the system becoming unstable. This was achieved using a velocity dependent torque cap which reduced the brake torque to 0% as the wheel rotational velocity approached 0 rad/s. The logic then reapplied the torque to 100% as the wheel velocity increased. The torque cap was setup to operate within an extremely short time period and velocity range to avoid any unwanted secondary effects.

Tyre Model Study

A tyre model study was carried out between FTire and MF-Tyre to determine which would be most suitable to work with the ABS system. FTire is the standard tyre model used by D&R CAE, it offers good levels of accuracy when simulating high vertical impact events such as kerb drive over. MF-Tyre is used by vehicle dynamics department, this tyre excels in modelling high speed cornering simulations which don't require high levels of vertical displacement. Two runs were carried out on an ABS Stop loadcase using the new Simat ABS block; both models were identical except one used FTire and the other used MF-Tyre. The results [Figure 6] highlight the issue with the MF-Tyre model whereby the wheel speeds, on occasion, rose higher than the total vehicle velocity. A wheel speed rising above the vehicle velocity in the physical world would not be possible and thus it was clear that MFTyre was incorrectly modelling the longitudinal build up and release during the ABS braking event. Results from the FTire model showed the behavior was far more realistic (when compared to test wheel speed data) and thus it was decided that FTire was to be used for all further ABS simulations.

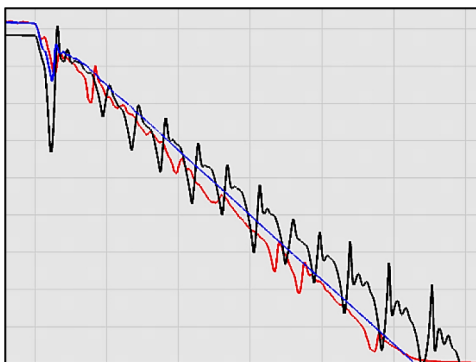


Figure 6. ABS Stop - Front left wheel speed vs time - Test data (red), MF-Tyre simulation (black) and FTire simulation (blue)

ANALYSIS

Analysis was carried out using a Continental Electronic Braking System (EBS) used within JLR's Evoque and Discovery Sport vehicles. Other JLR vehicles use different ABS modules with some using Bosch systems, however due to differences between Continental

and Bosch blocks; swapping the ABS logic within the Simpack models was not straightforward. Discussions with Continental and Bosch suppliers have initiated a standardised delivery structure. This structure will allow Carmaker and Simpack models to easily swap and change EBS modules depending on the vehicle being tested. For the first phase of this project, only the Evoque and Discovery Sport EBS module was used for correlation work.

In this section the key findings encountered whilst carrying out correlation will first be discussed. Following this the status quo of Range Rover Evoque and Discovery Sport correlation on specific loadcases will be shown.

Correlation Criteria

The first physical data set received by D&R CAE had wheel speeds recorded from an Evoque carrying out 3 ABS stop runs. These wheel speeds were viewed in Simpack post-processor to understand the variability between collections [Figure 7].

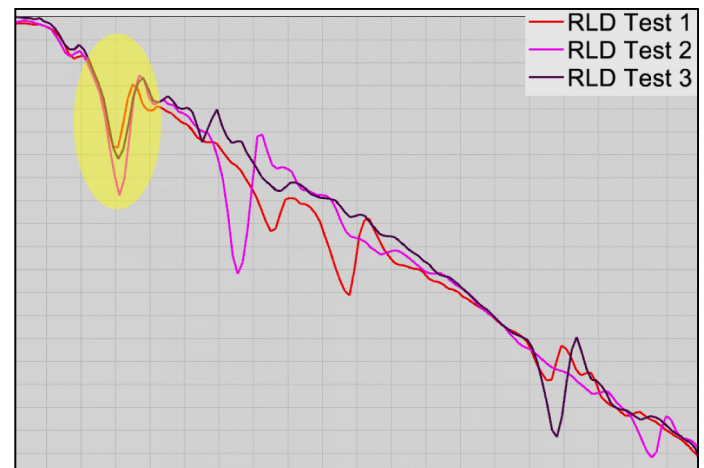


Figure 7. ABS Stop - Front left wheel speed vs time - 3 different physical test results

It was clear by looking at the results that the first wheel speed trough when the brakes were applied was of consistent size. After this initial trough the behavior was more variable which was thought to be caused by friction variability on the surface. The total number of wheel speed troughs over the ABS Stop loadcase was also similar between the 3 runs. The findings from this investigation led to correlation activities focusing on the total number of troughs over the event and the similarity to the first wheel speed trough. As more data was available on later tests such as pothole brake, canted slab and ABS stop on rough road, other correlation points were used such as master cylinder pressure, brake caliper pressure and lower ball joint longitudinal and lateral loads.

Friction Coefficient

Initial simulations run using the Evoque showed deceleration rates higher than those seen in test [Figure 8].

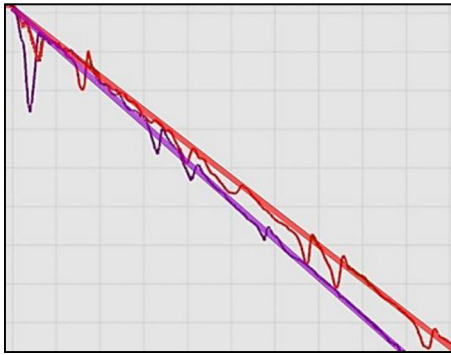


Figure 8. Front left wheel speed vs time for a physical test (red) against a simulation (purple)

From these results it was clear that the level of friction needed to be reduced in the virtual model. Altering friction required an additional parameter to be included within the loadcase which Virtual Hub was able to implement. Once in place the deceleration rate could be altered by adjusting the surface coefficient of friction to better match the test data. Results after reducing the surface friction showed matching wheel speed deceleration rate which also resulted in improved correlation of the first wheel speed trough and total number of troughs.

Master Cylinder Pressure and Rate

Once the deceleration rate and general characteristics of wheel speed had been correlated on an ABS Stop event; a better physical test data set was required which contained a higher number of channels including brake pressures and lower ball joint loads. With this new data, a study was carried out to look into the effect that maximum brake master cylinder pressure had on the ABS response. Results from this study proved that the maximum brake pressure value had a significant effect on wheel speed - altering both the number and size of troughs. It was found that, providing the maximum brake pressure was set above a 'critical value'; the deceleration rate of the vehicle could not be further increased. This showed that the limiting factor for improved deceleration was no longer brake pressure. The limiting factor was instead the tyre/ surface friction in the model which further proved that altering friction was the correct approach since the deceleration rate at this contact limit correlated with the physical test data. As brake pressure was increased above the critical value, the number and size of wheel speed troughs increased. This increase is thought to be due to the ABS system expecting to reach higher pressures before seeing wheel slip and thus increasing brake pressure at a faster rate. The standard maximum brake master cylinder pressure which came within the model provided by DSA department was 195bar, this value was chosen by DSA due to it being the maximum value reached within a number of physical brake tests. The value was rounded to 200bar by D&R CAE and used for initial correlation work. If brake master cylinder pressure was measured in the test data available, the maximum value could be input (in place of the standard 200bar) to better correlate results.

Following the study looking into maximum brake pressure; the brake rate was investigated. The default EBS system had no obvious parameter to tune this brake rate and from initial results the rate seemed to be determined by the co-simulation sample rate which had to be set to 0.001s to operate correctly with the ABS block.

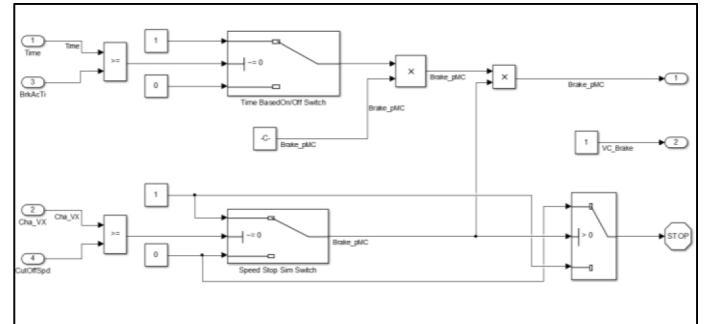


Figure 9. Default EBS system showing input of brake master cylinder pressure with no rate limiters

Rate limiters were added to the ABS system in Simulink which would limit the rate at which the master cylinder brake pressure could increase/ decrease. This rate was then set to a suitable value based on the average rate increase of master cylinder pressure in physical tests. Looking at test data it was clear that one rate defining the whole application of 100% brake pressure was not suitable since the rate during most physical tests dropped after roughly 50% brake pressure had been reached. Two rate limiters were added to solve this issue; one operated up to 50% maximum brake pressure and the second from 50% to 100% max brake pressure. By better defining brake pressure rate; caliper pressure and wheel speed correlation was seen to improve.

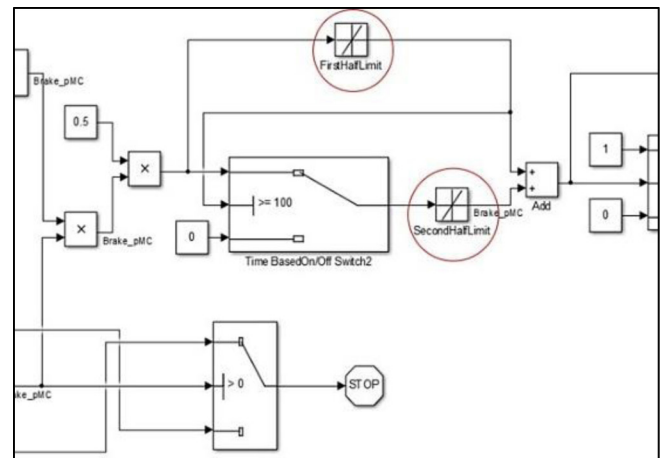


Figure 10. EBS block with addition of rate limiters to better control the input of brake pressure

To further improve correlation of brake pressure rate, a new Simulink 'signal builder' block was added which removed the need to have brake activation switches and rate limiters. The signal used in this new block was taken from the master cylinder pressure time history recorded during the physical test. In order to input the time history from the test it first had to be smoothed since the pressure was recorded by CAN signal at pre-defined time intervals. Using the inbuilt 'LOESS' stepped output instead of a smooth curve.