ABS performance evaluation taking braking, stability and steerability into account

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Abstract

Extensive research on the design and development of antilock brake systems has been done in the past. ABS has been developed not to reduce stopping distance, but rather to stop as quickly as possible whilst maintaining some directional stability and steering control during hard braking. There is however not a single, quantifiable, scientific method in which the performance of these ABS control systems can be compared with one another that takes all the important aspects into account. This investigation proposes an evaluation technique that considers the ABS control system's exploitation of the entire friction circle. Five scenarios are investigated and the performance of two ABS algorithms are compared with one another and with a conventional brake system without ABS. The resulting technique is a clear and concise, multi-parameter comparative tool that can be used to critically compare the performance of various brake systems under the same testing conditions.

Keywords: Antilock brake systems; ABS performance evaluation; braking simulations; braking tests; friction circle

Nomenclature

Symbol	Description	Unit
$ABSIP$	ABS Index of Performance	[-]
$\bar{a}_{ABS}$	Mean longitudinal deceleration of vehicle equipped with ABS	[m/s^2]
$\bar{a}_{no\ ABS}$	Mean longitudinal deceleration of vehicle not equipped with ABS	[m/s^2]
$ITAE$	Integral of the Time multiplied by the Absolute Error	[m/s^2]
j_x	Longitudinal vehicle jerk	[m/s^3]
m	Number of metrics being compared	[-]
n	Number of tests being compared	[-]
R_i	Radius of curvature at time step i	[m]
t	Time	[s]
$\lvert v_i \rvert$	Vehicle speed at time step i	[m/s]
x	Comparison matrix	[-]
$x_{i,\dots}$	ith row of comparison matrix	[-]
x_{ij}	ith metric of jth manoeuvre	[-]
$x_{ij,norm}$	Normalised ith metric of jth manoeuvre	[-]
μ_x	Longitudinal tyre friction	[-]
μ_y	Lateral tyre friction	[-]
$\dot{\psi}_i$	Yaw rate at time step i	[rad/s]
ω_{max}	Maximum wheel speed	[rad/s]
ω_{min}	Minimum wheel speed	[rad/s]
ω_{peak}	Peak-to-peak wheel speed percentage	[%]

1. Introduction

Antilock braking systems (ABS) were conceived originally for trains in the early 1900s (SAE, 2014). These systems were first applied to passenger vehicles and light trucks by Bosch in 1936. The original Bosch system used an electric motor that controlled the opening and closing of an orifice on each brake circuit (SAE, 2014). Kelsey-Hayes began an automatic braking system development plan in 1957, concluding that the system should prevent loss of vehicle control and reduce stopping distance (SAE, 2014). The first commercial systems entered production in the 1960s and Bosch began supplying a hydraulic ABS system to Mercedes-Benz in October 1978. Subsequently, the prevalence of ABS on passenger and light commercial vehicles has increased significantly (SAE, 2014). Research on improving ABS systems continues today with the development of hybrid and full electric vehicles where regenerative braking may be used to recover some of the kinetic energy that would otherwise be lost to heat due to the application of friction brakes (Savitski et al., 2016, Savitski et al., 2015, Ivanov et al., 2015a, Ivanov et al., 2015b). The application of ABS to off-road vehicles is also becoming prevalent, adding additional complexity to the evaluation of ABS performance (Penny and Els, 2016).

According to the Society of Automotive Engineers (SAE), the goal of ABS application is:

‘The application of ABS to a vehicle can provide improvements in the vehicle performance under braking compared to a conventional brake system. Improvement is typically sought in the areas of stability, steerability, and stopping distance … In addition to minimizing stopping distance, vehicle stability is another aspect to straight line braking that must be considered. For the case of straight line braking with the steering held fixed in the straight ahead position, the vehicle should brake in a straight line in the presence of external disturbances … Preservation of steering control and stability during braking are prime goals of the application of ABS to vehicles.’ (SAE, 2014)

There are several test procedures described by the Society of Automotive Engineers (SAE, 2014) to evaluate the performance of ABS, namely:

a) straight line braking on high and low friction surfaces
b) stability and controllability in response to steering inputs
c) braking in a turn
d) split friction coefficient braking

The utilisation of the available friction force is a fundamental aspect of any brake system design. The yaw velocity (or yaw rate) response to steering may be used as a measure of both stability and steerability. For the case of braking in a turn, lateral load transfer occurs from the inside to the outside wheels. The ABS algorithm’s control of the longitudinal slip on the inside and outside wheels at similar slip values usually results in a rigid body motion that increases the radius of the turn. The split coefficient braking scenarios typically occur when the road surface friction coefficients differ between left and right, not an uncommon scenario. Emergency stop manoeuvres under these conditions will exceed the friction available on the low coefficient side, once again resulting in imbalanced longitudinal forces. The resulting rigid body moment will tend to steer the vehicle to the higher coefficient surface (SAE, 2014).

Because there are so many scenarios, many of them with conflicting requirements, it is unavoidable that a compromise in the performance of ABS systems under each scenario will have to be made. ABS is also often closely interconnected with traction control and stability control. It thus becomes difficult to isolate the ABS effect. No single metric or evaluation method exists that compares the performance of different antilock brake systems with one another.

2. Exploiting the tyres' physics

As mentioned by the SAE in their review of antilock brake systems (SAE, 2014), there is an unavoidable trade-off between the different requirements of ABS. The ABS control algorithm has to balance the braking as well as the directional control requirements. This is inherently due to the longitudinal and lateral force generation characteristics of tyres. The tyre friction circle is the ideal tool to visualise this trade-off. Figure 1(a) shows a typical plot of the longitudinal friction as a function of longitudinal slip (negative friction indicates it is in the braking direction). Figure 1(b) indicates one quadrant of the friction circle. This relationship was described semi-empirically by Bakker and Pacejka (Bakker et al., 1989) in their landmark paper on modelling the tyre properties for vehicle dynamics studies. The trade-offs the ABS control system designer is faced with are indicated in Figure 1 as well. The first scenario indicated is where 100% braking is achieved. This occurs when the wheel slip is controlled so that the friction force is at its peak. In this case, the driver will not be able to steer and the vehicle may become unstable if a lateral disturbance is present. The second scenario is the case where no braking force is generated, but the maximum possible side force is achieved (this is indicated as 100% side force in Figure 1). A third scenario is also shown, the case where the wheel is locked – i.e. the longitudinal slip is at 100%. The aim of the ABS control system is to find an acceptable compromise between scenarios one and two.

Ideally, the ABS controller must be able to rapidly switch between 100% braking and 100% side force. In such an ideal case, the friction force will follow the black line (labelled as "Ideal ABS) in Figure 1(b). Physically, this relates to the speed at which brake pressure can be decreased and increased from 100% to 0% and back to 100%. If the ABS system is capable of doing this faster than the tyres can switch from 100% braking force to 100% side force (due to the relaxation length effect of the tyres, see (Maurice and Pacejka, 1997)), the ABS performance will be limited by the tyre friction force generation characteristics. Further improvements to the ABS performance will in such a case be due to the fitment of tyres with a shorter relaxation length and not by tuning the ABS algorithm or updating the ABS hardware. In such an ideal case, the braking half (the negative μ_x and entire μ_y sector, i.e. quadrants three and four) of the friction circle will be available to the driver to exploit during an emergency manoeuvre.

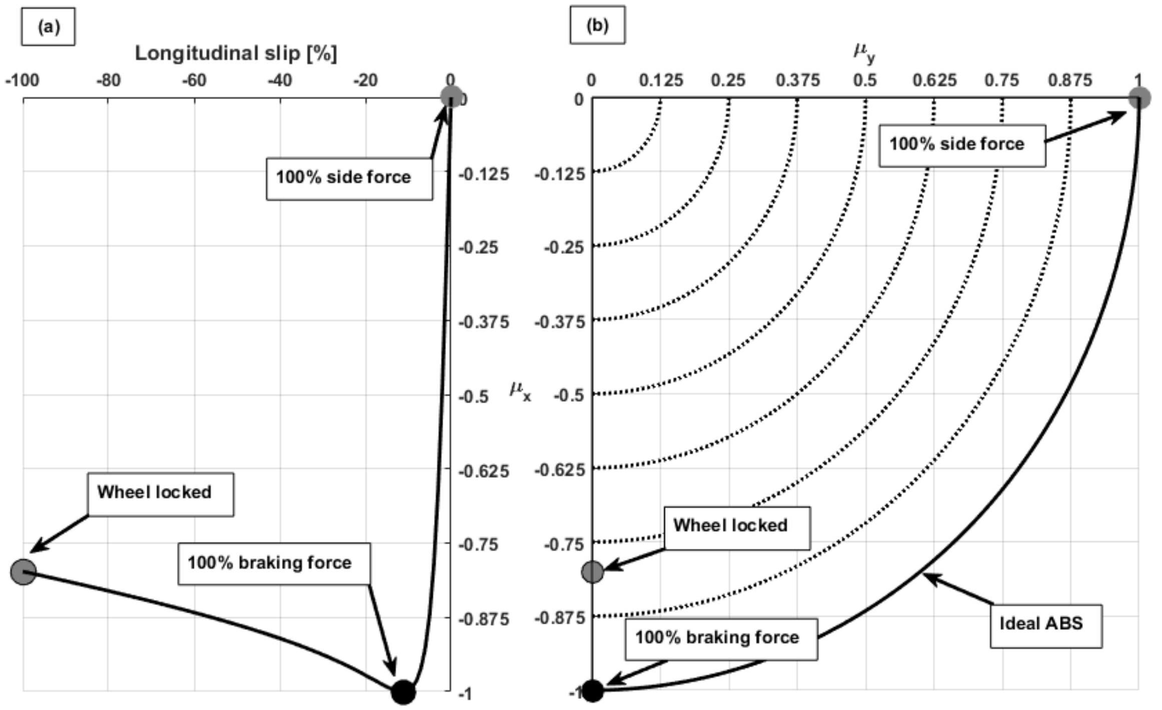

Figure 1. Tyre longitudinal friction (a) and Tyre friction circle (b)

3. Existing ABS performance assessment criteria

Savitski et al. (2015) experimentally evaluated the performance of three ABS algorithms with straight line braking tests on a low friction surface. The experimental surface consisted of wet tiles with an average coefficient of friction of 0.2 (Ivanov et al., 2015a). They divided the assessment criteria into three categories, namely:

a) the braking performance
b) the ABS control performance
c) the driving comfort

The braking performance was evaluated using the brake distance, average deceleration and the ABS index of performance. The ABS index of performance, or ABSIP, shows the ratio between the average deceleration of the vehicle with ABS and without ABS. The ABSIP is given by:

$$ABSIP = \frac{\bar{a}_{ABS}}{\bar{a}_{no\ ABS}} \tag{1}$$

A value of one indicates that the ABS system does not improve the average vehicle deceleration. Values larger than one indicates an improvement in the braking performance. The algorithms investigated by Savitski et al. (2015) resulted in ABSIPs in the range of 1.34 to 1.74, indicating significant improvements in the average vehicle deceleration. It is assumed that the driver of the non-ABS vehicle is passive and brakes with all the wheels locked, rather than a good driver reacting to the vehicle feedback and modulating the brakes (also known as cadence braking).

The ABS control system's response to differing wheel slip dynamics was evaluated by determining the amount of wheel lockup occurring before the control system was able to reduce brake pressure and thus reducing wheel slip. A peak-to-peak value was used to evaluate the performance for each wheel during the first control cycle of the ABS. The worst case value for the left and right wheels on each axle was used to compare different ABS algorithms. The peak-to-peak value was determined with Equation (2):

$$\omega_{peak} = \frac{\omega_{max} - \omega_{min}}{\omega_{max}} \times 100\% \tag{2}$$

Typical values ranged from 6% to 57% for the front wheels and 8% to 36% for the rear wheels (a lower value indicates better performance). The average slip percentage was also used as an ABS control system performance assessment criteria. The best case resulted in 14% for the front wheels and 8% for the rear wheels. In their study it may be seen that the values are almost identical between the left and right wheels on the same axle; this indicates that there is very little lateral load transfer during the straight line brake manoeuvres, as expected. There is however a problem associated with using this metric to determine ABS performance. By tuning the ABS performance to reduce the peak overshoot or to minimise the variation in longitudinal slip, the designer is in effect approaching an optimal slip controller. Kienhöfer et al. (2008) developed a gain-scheduled slip controller that aims to control the longitudinal slip at the longitudinal friction force peak. Using the stopping distance and the ABS pressurised air consumption (their ABS was applied to a heavy vehicle) to evaluate their system's performance, their slip control resulted in an improvement on conventional rule-based ABS by 10% on stopping distance and 30% on air consumption. Kienhöfer et al. (2008) did however not take the yaw stability or steerability of the vehicle into account.

Apart from the safety-related performance criteria, comfort and refinement is becoming of greater importance in modern vehicles. The shock and vibration experienced on the vehicle during ABS operation is therefore also becoming an important consideration, especially on top-end luxury vehicles. Savitski et al. (2015) postulated that jerk was a good indicator of driver perception. The lower the jerk, the better the ABS performance in terms of comfort and driver perception. The integral of the time multiplied by the absolute error (ITAE) of the vehicle jerk in the longitudinal direction was determined with Equation (3):

$$Jerk\ ITAE = \int_{t_1}^{t_2} |j_x| t \, dt \tag{3}$$

The smallest ITAE value recorded during their experiments was 2.92m/s^2 and the largest 12.0 m/s^2.

To visualise their results, Savitski et al. (2015) normalised their assessment metrics (the test with the best score was normalised to 100%) and the resulting metrics were visualised on a radar plot, as shown in Figure 2. In the example of Figure 2, ABS system 1 (the black dashed line) may be seen to be better than the alternatives.

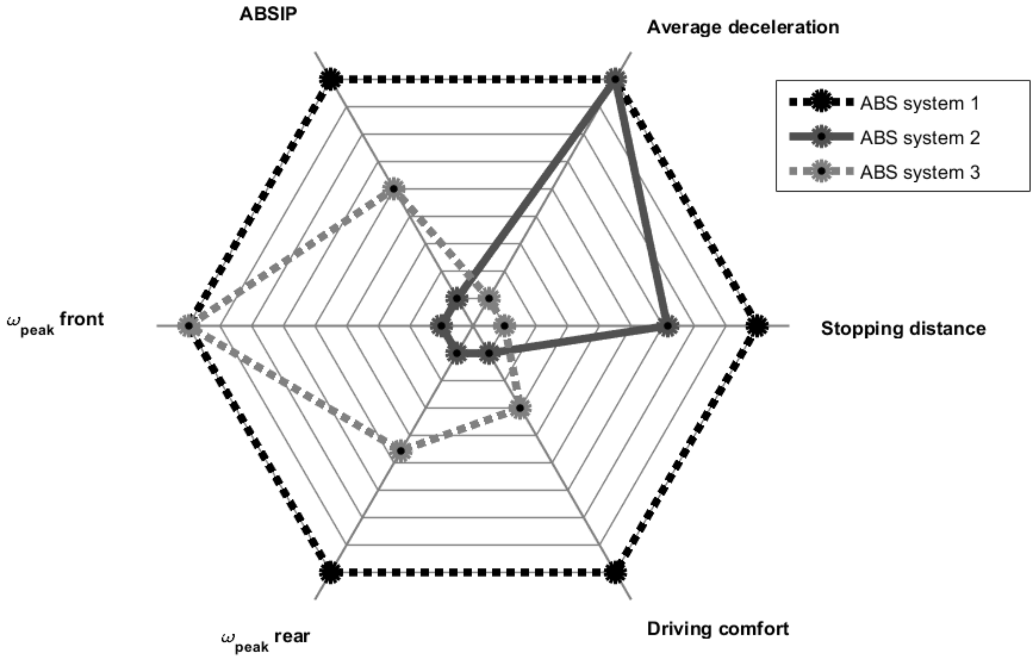

Figure 2. Radar plot used to compare ABS system performance as developed by Savitski et al. (2015)

The study by Savitski et al. (2015) was limited to straight line braking tests. The Antilock Brake System Review by the SAE (2014) specifically mentioned the contribution ABS makes towards a vehicle's stability when braking on split-mu road surfaces and when braking in a turn. Lee et al. (2003) evaluated the performance of a commercial ABS on split-mu roads. The road they tested on had a friction coefficient of 0.35 on the left and 0.6 on the right. The ABS braking performance was compared with the performance of a conventional braking system under these conditions. To compare the braking performance, they considered steering angle input, vehicle deceleration, vehicle yaw rate and the stopping distance. From their results it may clearly be seen that the vehicle equipped with ABS stops in a shorter distance, the steering angle input by the driver required to keep the vehicle driving in a straight line is significantly smaller and the yaw rate indicates better stability when compared to the vehicle without ABS. All of their comparisons were done in the time domain.

Day and Roberts (2002) compared the braking performance of a vehicle with ABS and one without ABS when braking during a severe lane-change manoeuvre, as described by ISO 3888-1 (International Organisation of Standardisation, 1999). The vehicle's ability to maintain the desired path was not described in detail, it was merely stated that the vehicle equipped with ABS stayed within the cones. The vehicle without ABS skidded straight ahead and was not able to stay within the cones (the steering input preceded the application of a force to the brake pedal).

The radar plot of Figure 2 may be less useful when evaluating the performance of the ABS under split-mu manoeuvres or when braking in a turn or during a lane change manoeuvre, because it merely compares averages and does not consider vehicle stability or steerability. The current investigation aims to formulate a method of comparing different ABS algorithms with one another that will guide the design engineer in selecting the most appropriate ABS for their application by taking into account all the requirements as discussed by SAE (2014).

4. Existing directional stability assessment criteria

Quantifying the straight line braking performance by limiting it to stopping distance and average deceleration is easy, but directional control is more challenging to define quantitatively. Directional control is often studied with the aim of developing a driver steering model to be used in conjunction with vehicle simulation models. Thoresson et al. (2014) and Kapp and Els (2015) controlled two vehicle states to develop such a driver model, namely the desired yaw acceleration and the lateral offset from the path. The desired yaw acceleration was related to the desired steering wheel input velocity (which is directly proportional to the yaw rate) and was used as the main path following controller. When using only the yaw rate to perform path following, a lateral offset from the desired path will eventually occur due to integration drift. To rectify this, the lateral path following error was controlled with a PID controller.

The use of both yaw rate variation and lateral path offset error is applicable to evaluating the performance of an ABS. The reasons for a driver to steer during braking is to avoid an obstacle or obstruction in the vehicle’s path or to maintain the trajectory to prevent the vehicle from veering out of its lane. The average driver will at this stage not be too concerned with the yaw rate of the vehicle (unless the vehicle is spinning already) and will attempt to avoid the obstacle by changing the vehicle’s lateral position. The driver attempts to do this by steering, which in turn generates a yaw acceleration and a corresponding change in the yaw rate. If the yaw acceleration is high enough, the vehicle will steer quickly enough to avoid the obstacle, but this “obstacle avoidance” is due to the lateral offset from the original path of the vehicle due to the induced yaw acceleration. It is highly unlikely that an average vehicle will be able to move from its trajectory laterally without generating a yaw acceleration (this is possible with four wheel steering, but there are few examples of four-wheel steer vehicles on the road). Similarly, the lateral path error cannot be considered separately from the yaw rate. The SAE’s antilock braking system review mentions that it is not uncommon for a vehicle to spin about its yaw axis while the CG maintains a straight line when braking on a split-mu surface (SAE, 2014).

5. Proposed ABS performance evaluation technique

A suitable ABS performance evaluation technique must be able to objectively compare different possibilities and make it easier for the control system design engineer to identify the best ABS control system for the application. A compromise cannot be avoided, but the aim of the performance evaluation technique is to clearly and quantitatively compare the braking performance from a practical vehicle dynamics point-of-view. The literature discussed in the preceding sections highlighted the need for the ABS control system to minimise the stopping distance while allowing the driver to maintain directional control. The proposed metrics to evaluate ABS performance are thus:

a) Stopping distance and its standard deviation (if more than one test is carried out for the same algorithm). The stopping distance can be measured easily with a differential GPS such as a Racelogic VBOX 3i (Racelogic, 2014).

b) Mean and standard deviation of vehicle deceleration during the braking manoeuvre. The vehicle deceleration can be measured with an accelerometer or an Inertial Measurement Unit (IMU).

c) Mean and standard deviation of absolute vehicle yaw rate error during the braking manoeuvre. For the case of straight line braking, the desired yaw rate is easy to define, since it should be zero. Defining the desired yaw rate when the vehicle is braking in a turn needs some explanation. The proposed method is to determine the radius of curvature of the turn. In the case of a constant radius turn, as is often found on proving grounds, this is easy to define. If the turn consists of multiple radii (such as a tightening turn or S-curve), an approach similar to that used by Hamersma and Els (2014) may be used. This approach discretised the trajectory and then fitted arcs with constant radii to three consecutive points. The end result is the radius of the curve as a function of the arc length and was found to give accurate results when the radius was larger than 5m. Knowledge of the curve radius allows one to use the vehicle's velocity magnitude at that point (measured with a differential GPS) and the radius of curvature at that point to determine the desired yaw rate at that point with Equation (4). Equation (4) will generally be valid if the vehicle is moving tangent to the curve. This desired yaw rate thus assumes that the vehicle perfectly follows the path. If the vehicle were to under- or oversteer, the onus would still be on the driver to maintain the correct trajectory by providing the corrective steering input. This is similar to a real-world scenario where a driver must attempt to stay within the lane it is driving in. Measurement of the vehicle yaw rate is possible with a gyroscope or with an IMU.

$$\dot{\psi}_i = \frac{|v_i|}{R_i} \tag{4}$$

d) Mean and standard deviation of absolute lateral path following error. It is of paramount importance to include the lateral path following as one of the metrics. This point can be illustrated with two examples where only considering the yaw rate would have been insufficient. The first example is a straight-line, split-mu braking test. During the braking manoeuvre, the vehicle starts to yaw, spinning about its z-axis, but the vehicle continues to proceed in an almost straight line. It is mentioned in the SAE literature on ABS braking that this is scenario is encountered quite often (SAE, 2014). The second scenario is almost opposite to the first. The vehicle starts side-slipping from the intended path. While the yaw rate may be close to that what was desired, the vehicle may end up in a lane different from that in which it started, possibly even in the oncoming traffic. The lateral path error combined with the yaw rate error thus gives more detailed insight into the steerability of the vehicle during the braking manoeuvre. The lateral path following error during the braking manoeuvre is measureable with a differential GPS such as the VBOX 3i (Racelogic, 2014).

The comfort effect discussed by Savitski et al. (2015) is excluded, as ABS is only active during emergency braking. The comfort requirement is thus of secondary importance when considering vehicle occupant safety. The proposed comparison technique does however provide room for the easy integration of additional requirements the control system designer may want to include.

The evaluation technique assigns a single value to each of the four abovementioned metrics' means. A comparison matrix containing m rows and n number of columns, where m represents the number of metrics being used (the abovementioned four is recommended, but additional metrics can be added) and n represents the number of tests being compared, is assembled. Each row in the comparison matrix is normalised relative to the best value in the row. Two possible normalisations exist:

a) A higher value is better, for a case such as the mean deceleration during the braking manoeuvre. In such a case, the metric is normalised by:

$$x_{ij,norm} = \frac{x_{ij}}{\max\left(x_{i,\ldots}\right)} \times 100\%, i \in 1,2,3,\ldots,m;\ j \in 1,2,3,\ldots,n \qquad (5)$$

b) A lower value is better, for cases such as stopping distance or absolute lateral path following error. In such a case, the metric is normalised by:

$$x_{ij,norm} = \frac{min\left(x_{i,\ldots}\right)}{x_{i,j}} \times 100\%, \qquad i \in 1,2,3,\ldots,m;\ j \in 1,2,3,\ldots,n \qquad (6)$$

The standard deviation of each of the metrics during the braking manoeuvre is also taken into account. The standard deviation of each metric is also normalised using Equation (5), resulting in the worst case scenario being assigned a value of 100%.

An illustration technique similar to that shown in Figure 2 is used to compare the ABS performance of different algorithms with each other. Additionally, the standard deviation of each metric is also illustrated. Figure 3 shows how two ABS algorithms using the proposed performance evaluation technique are compared. At the first glance, it may be seen that ABS algorithm 1 performs better than algorithm 2 in all four of the metrics when considering the mean values and when considering the standard deviation. This is the advantage of using the ABS proposed evaluation technique, as it provides clear and quantifiable evidence to support the selection of an ABS algorithm to another. Additional metrics can be included by modifying the radar plot of Figure 3 with addition of more axes.

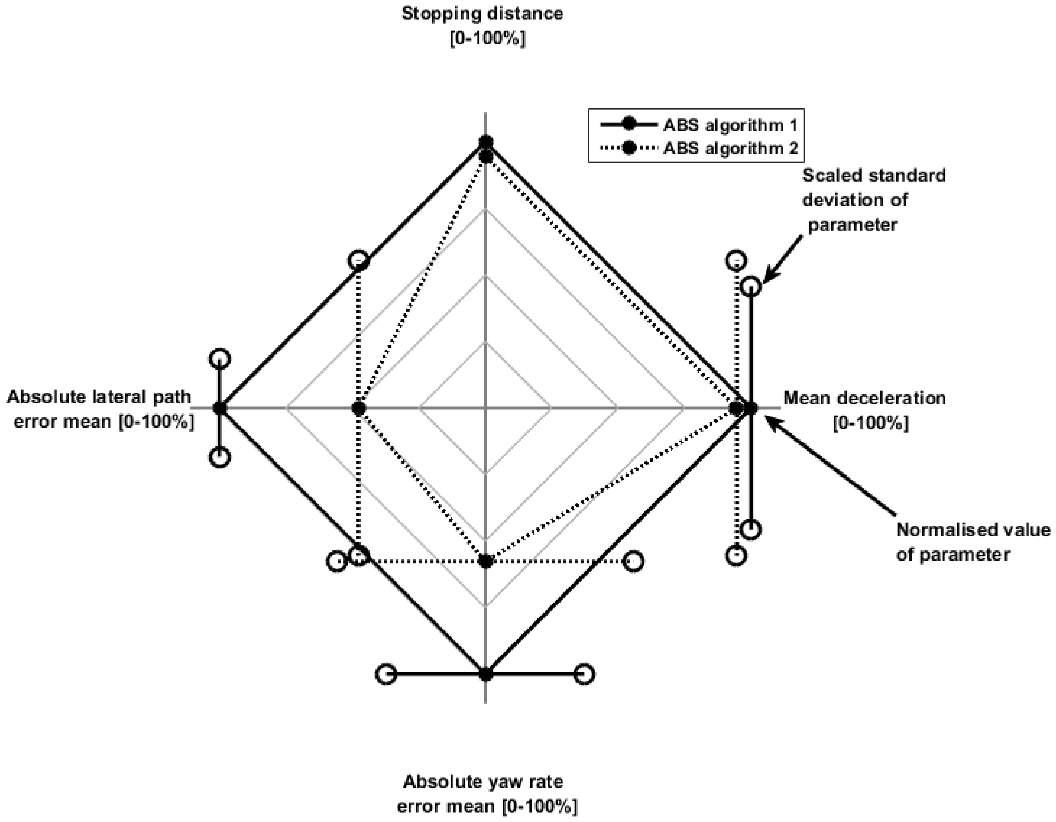

Figure 3. Comparing the performance of two ABS algorithms with the proposed performance evaluation technique

6. Illustrating the ABS performance evaluation technique

Simulations are used to illustrate the proposed ABS performance evaluation technique. The simulations were performed on a lumped mass parameter model utilising kinematics and compliance lookup tables to model the vertical wheel travel relative to the vehicle body. The model contains 14 degrees of freedom (six for the vehicle body, four for the wheels' vertical translations and four for the wheels' spin). A smooth road was used for all the simulations, with various friction coefficients (this is discussed later, specific to each simulation). The vehicle was modelled in VI-CarRealTime (VI-Grade GmbH, 2016). The ABS algorithm is rule-based and is illustrated schematically in Figure 4.

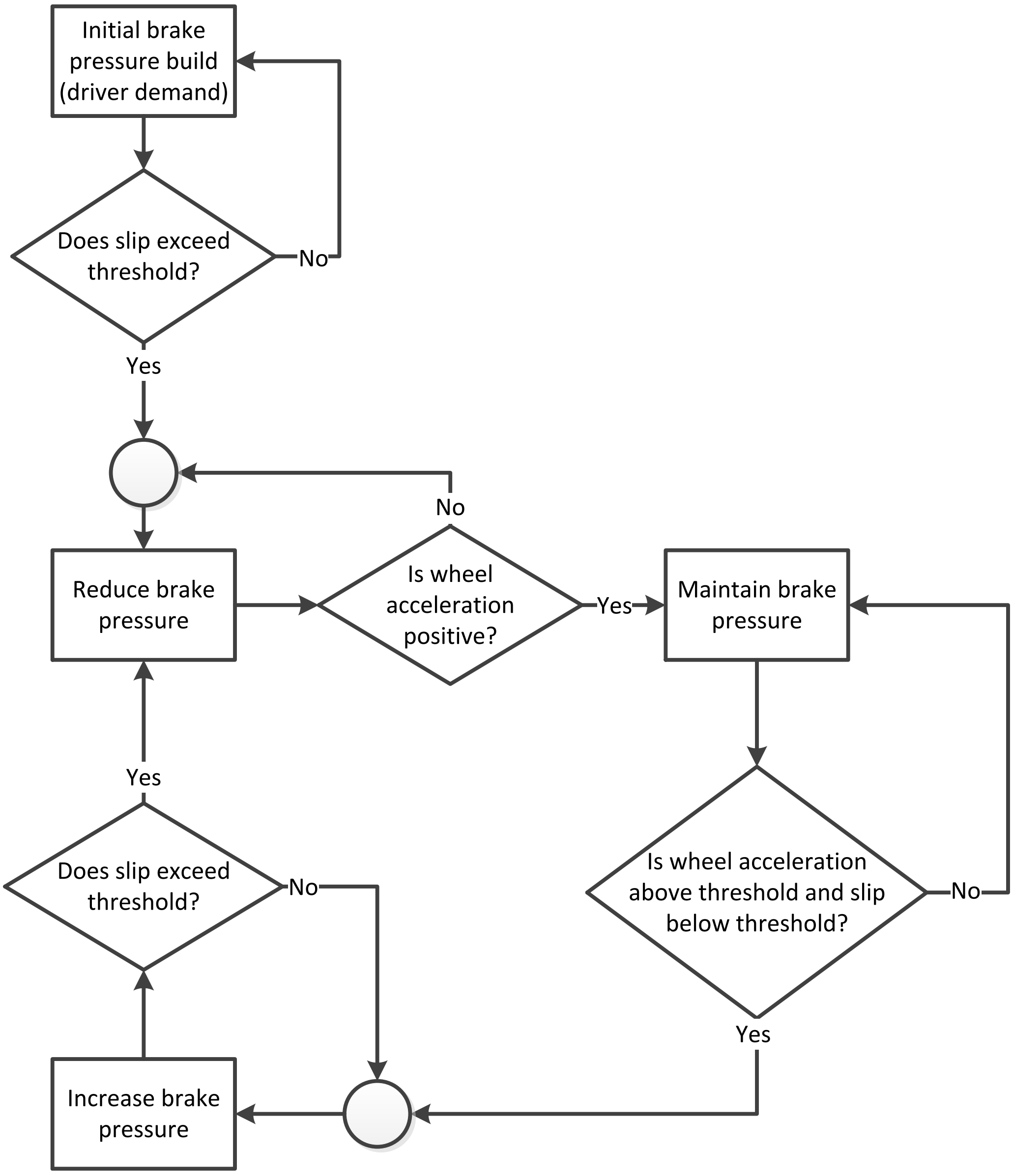

Figure 4. Schematic representation of ABS algorithm

Five braking scenarios were simulated:

a) Braking in a straight line on a high friction surface.
b) Braking in a straight line on a low friction surface.
c) Braking in a turn on a high friction surface.
d) Braking in a turn on a low friction surface.
e) Braking in a straight line on a split-mu surface.

The straight line braking manoeuvres were simulated with an initial speed of 80km/h. The brake-in-turn manoeuvre was simulated with an initial speed of 60km/h. The high friction surface had a friction coefficient of 1 and the low friction coefficient surface had a friction coefficient of 0.3. The high friction brake-in-turn simulation had a constant radius of 50m and the low friction surface a constant radius of 120m. The split-mu surface had a coefficient of friction of 0.8 under the left side and 0.3 under the right side of the vehicle. All of the simulations were terminated when the vehicle reached 15km/h, as the tyre model gives unreliable results at low speeds. The steering model used to follow the prescribed path was the built-in steering controller implemented in VI-CarRealTime (VI-Grade GmbH, 2016). The steering controller attempts to track the prescribed path's yaw requirements and has a compensator to minimise the lateral path following error (VI-Grade GmbH, 2016). The simulations were repeated for three different vehicle configurations: two different ABS implementations and the vehicle without ABS. These are indicated as ABS 1, ABS 2 and No ABS in the figures in the following sections. The two ABS simulations used the same algorithm, but ABS 2 included sensor delays with a resulting delayed response emulating the delays encountered when frequency to voltage converters are used to measure the wheel speed. It is thus expected that ABS 1 will outperform ABS 2, since the response to wheel lockup should be faster.

6.1 Straight line braking results

Figure 5 and Figure 6 show the straight braking results on high (Figure 5) and low (Figure 6) friction surfaces. The differences are clearly visible, with the stopping time increasing from 2.2s to 7.3s for ABS algorithm 1. It is worth noting that on the high friction surface, the stopping time of the vehicle without ABS was better than that of ABS algorithm 2. On the low friction surface, however, the opposite was true. The lateral path error in both cases was very small, equivalent to approximately a tyre width on the high friction surface and even less on the low friction surface. The yaw rate deviated very little from the desired yaw rate, as is expected for a straight line brake test on a constant friction surface.

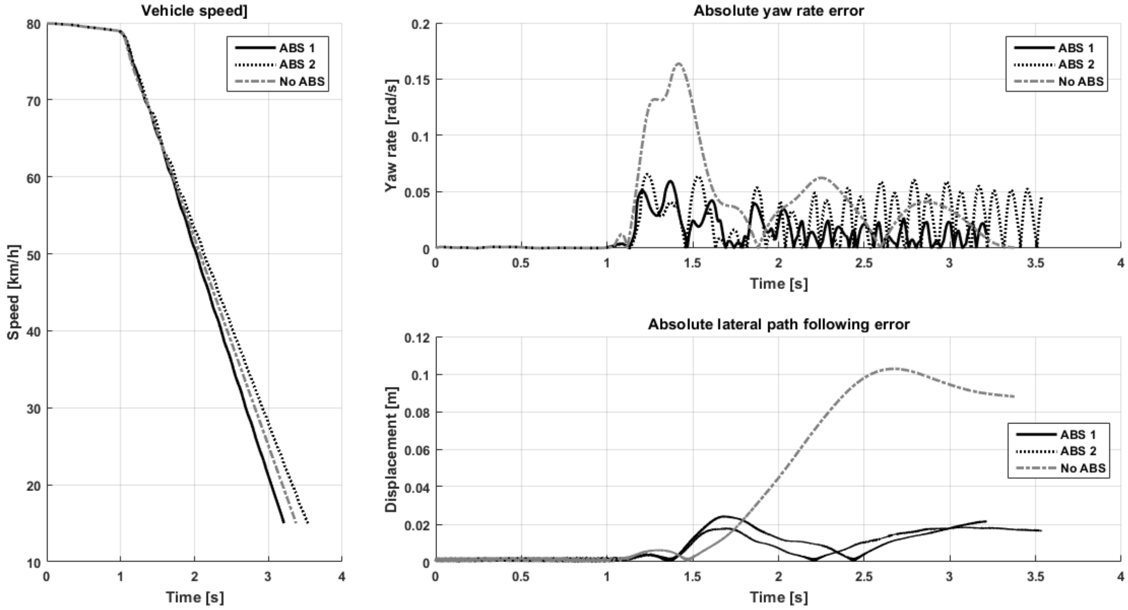

Figure 5. Straight line, high friction braking simulation results

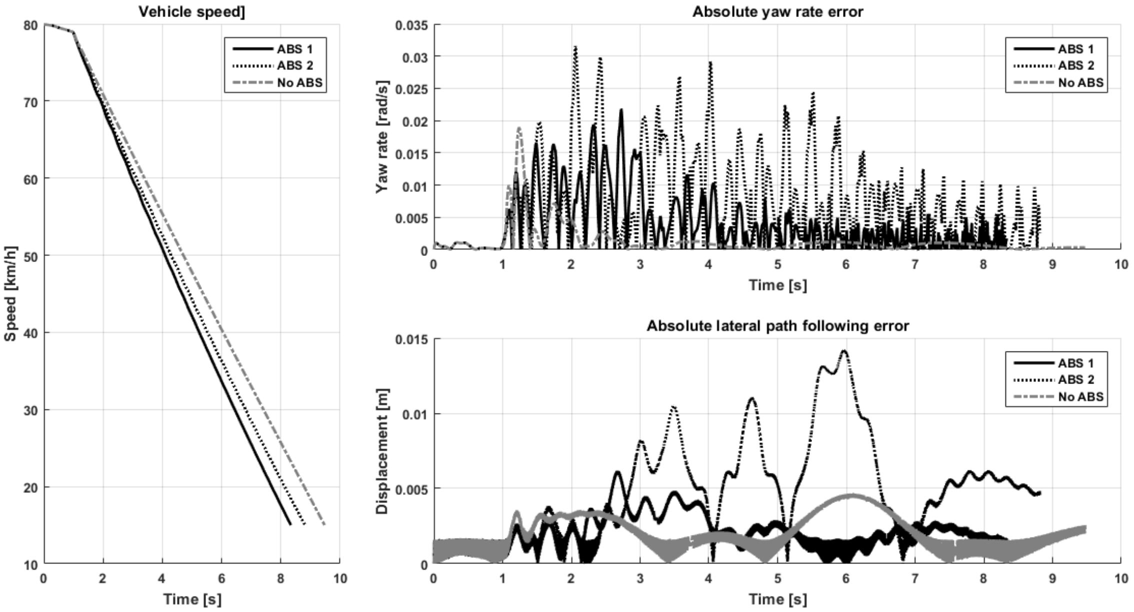

Figure 6. Straight line, low friction braking simulation results

The simulation results of ABS algorithm 1 and 2 and the conventional braking simulation are processed with the evaluation technique discussed in Section 5 and the results for the high friction surface are shown in Figure 7 and for the low friction surface in Figure 8. Figure 7 clearly shows that ABS algorithm 1 performed the best for the high friction surface straight line brake tests. It scored the best for three of the four metrics considered, namely stopping distance, mean deceleration and absolute yaw rate mean error. ABS algorithm 2's performance was better than that of the conventional braking system when considering the directional stability of the vehicle, as may be seen with the better performance in the lateral path following mean error and in the absolute yaw rate mean error. There is however very little to choose between all three simulations with regard to stopping distance and mean deceleration on the high friction surface. It may also be seen that the variation in the metrics used to evaluate the directional stability was significantly lower for the two simulations with ABS enabled.

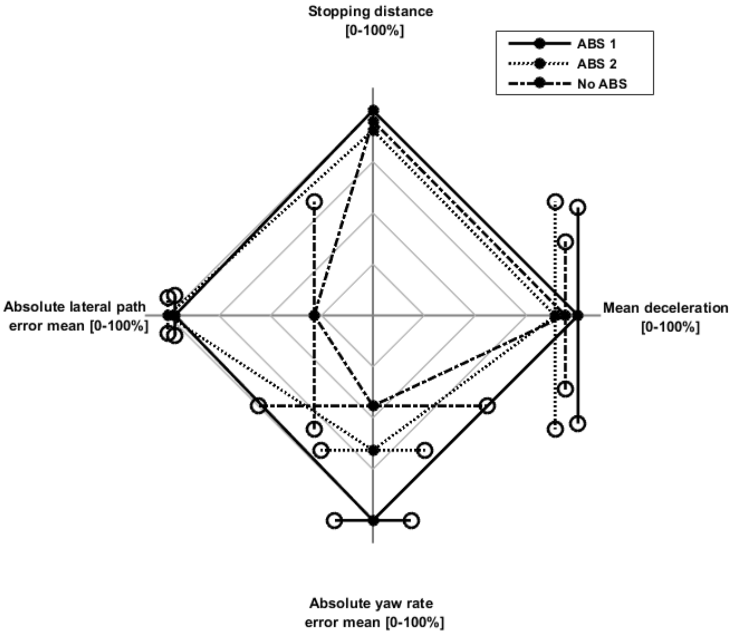

Figure 7. Comparing ABS perofrmance for straight-line braking on low friction surface

Figure 8 shows some interesting results when comparing the low friction simulations' braking performance. Both the simulations with ABS active resulted in improved stopping distances and mean decelerations when compared to the conventional brake system. This indicates that the ABS enabled simulations utilised the longitudinal friction available to the driver better than the conventional brake system. The directional stability for these two ABS enabled cases was however worse than the directional stability of the simulation without ABS. This indicates that the simulation without ABS merely locked the wheels and the vehicle skidded to a halt, while the modulation of the brakes resulted in some directional stability issues. This may be attributed to the yaw moment generated by asymmetrically modulating the left and right wheel's brakes or to the steering controller. Because the simulation is a straight line brake test, the directional stability of the vehicle seemed to be improved when the ABS was deactivated. The steerability was however reduced significantly, as the wheels locked and skidded for the duration of the test. This illustrates the importance of using more than one scenario when evaluating the braking performance of a vehicle; limiting the analysis to straight line, constant road friction tests is not sufficient to evaluate braking performance.

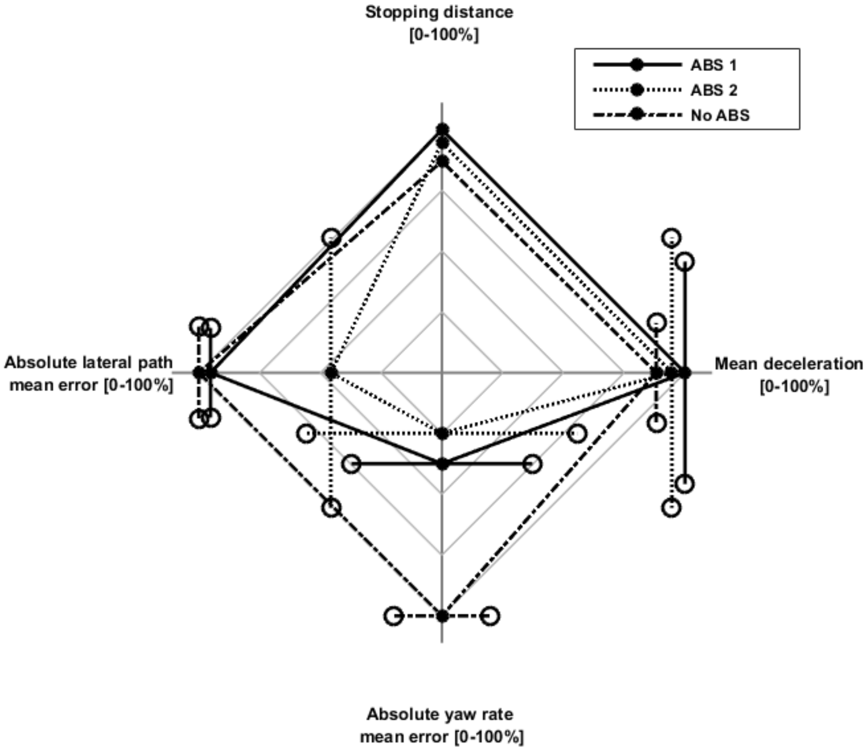

Figure 8. Comparing ABS perofrmance for straight-line braking on low friction surface

6.2 Brake-in-turn results

The brake-in-turn simulation results are shown in Figure 9 and Figure 10. The brake-in-turn results clearly show the advantage of having an ABS equipped vehicle, specifically on the low friction surface in Figure 10. For the case of the high friction surface (Figure 9), the lateral path error made by the vehicle without ABS is significant. The lateral path error was 3.65m when the vehicle reaches 15km/h at the end of the simulation. However, when comparing the yaw rate error on the high friction surface, at first glance there seems to be little difference between the three simulations. This highlights the importance of including the lateral path error and not using the yaw rate on its own. Both the ABS equipped vehicles managed to track the desired yaw rate and path quite accurately, the only difference discernible is in the stopping distance. The ABS algorithm 2 vehicle's stopping distance was 17.1m, compared to 16.1m for ABS algorithm 1 vehicle's stopping distance.

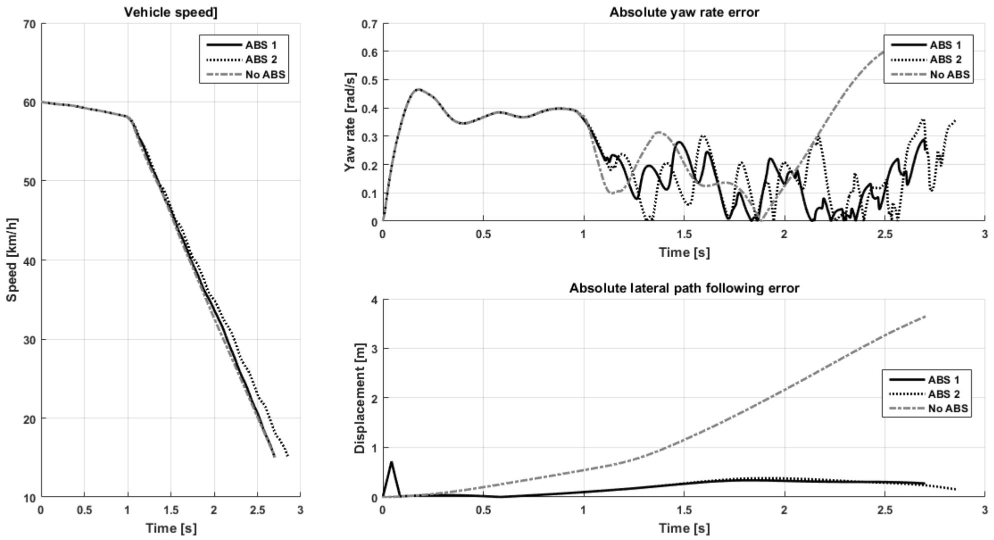

Figure 9. Brake-in-turn on high friction surface simulation results

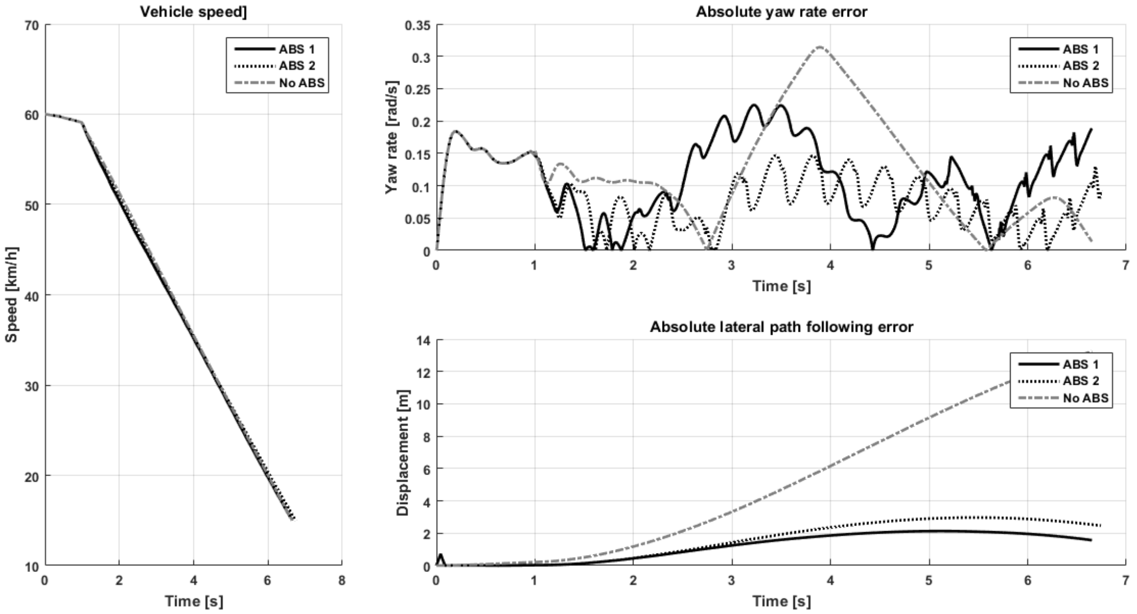

Figure 10. Brake-in-turn on low friction surface simulation results

Processing the simulation results with the steps outlined in Section 5 results in the radar plots of Figure 11 (for the high friction brake-in-turn manoeuvre) and Figure 12 for the low friction brake-in-turn manoeuvre. Similar to the high friction results of Section 6.1, the stopping distances and mean deceleration don’t differ as significantly as the directional stability results. Both the ABS algorithms’ directional stability during the brake-in-turn manoeuvres were significantly better than that of the conventional brake system. The low friction brake-in-turn manoeuvre gives similar results to that of the high friction brake-in-turn manoeuvre, with a slight discrepancy between the lateral path following and yaw rate tracking ability of the ABS enabled simulations.

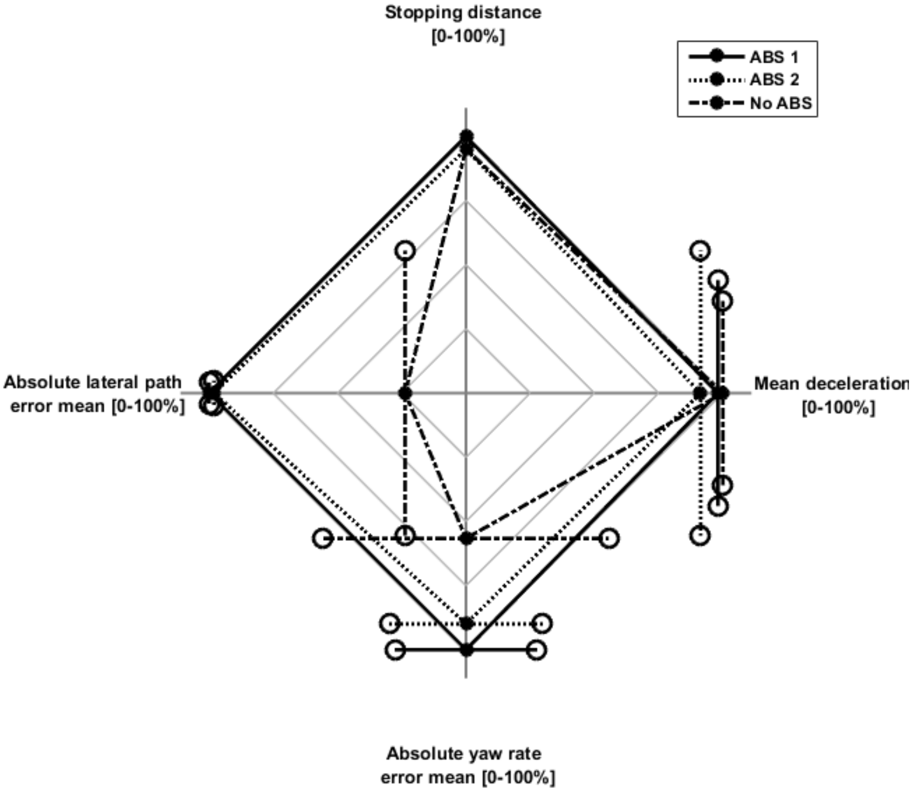

Figure 11. Comparing ABS perofrmance for brake-in-turn on high friction surface

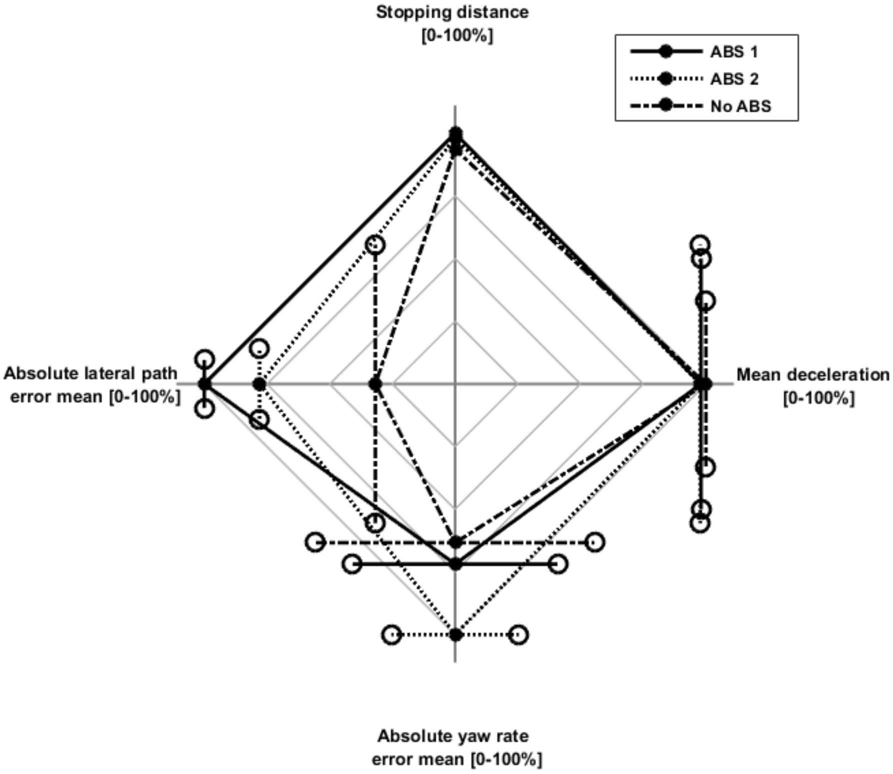

Figure 12. Comparing ABS perofrmance for brake-in-turn on low friction surface

6.3 Split-mu braking results

Figure 13 shows the split-mu braking results. As is the case for the brake-in-turn simulations, the advantage of having ABS is evident on the split-mu surface. The yaw rate error of the vehicles equipped with ABS is negligible when compared to the yaw rate error of the vehicle without ABS. The ABS equipped vehicles also managed to stop in a shorter time than the vehicle without ABS.

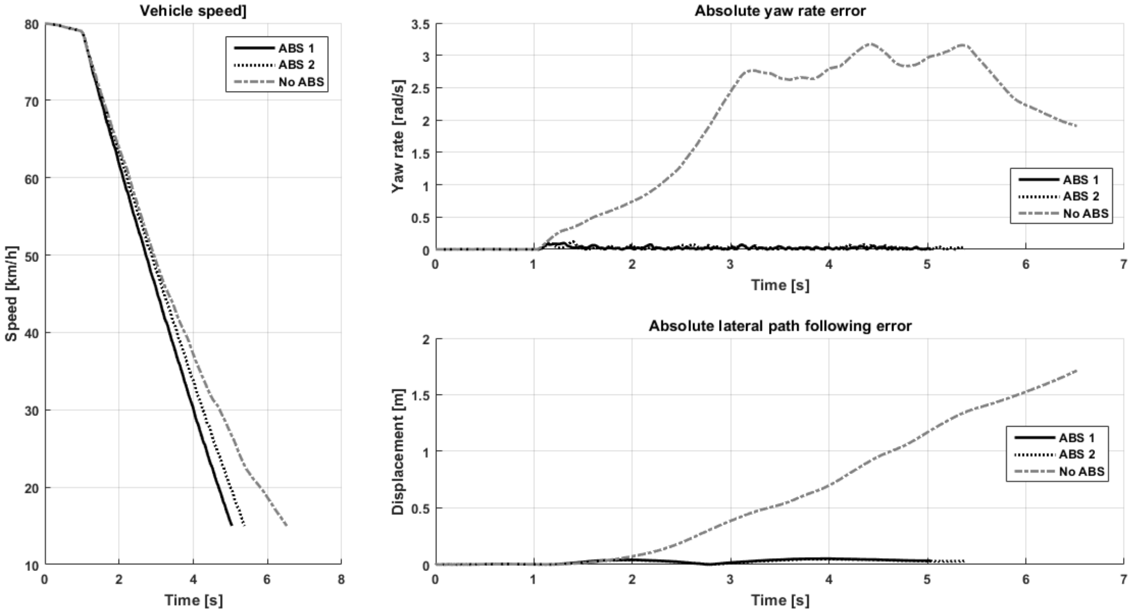

Figure 13. Split-mu braking results

Comparing the simulation results in Figure 14 shows the significant advantage ABS braking has under split-mu conditions. The ABS enabled simulations outperformed the conventional braking system significantly with all four the metrics investigated. Similarly, the variations in each of those metrics were significantly less for the ABS simulations compared to that of the conventional system.

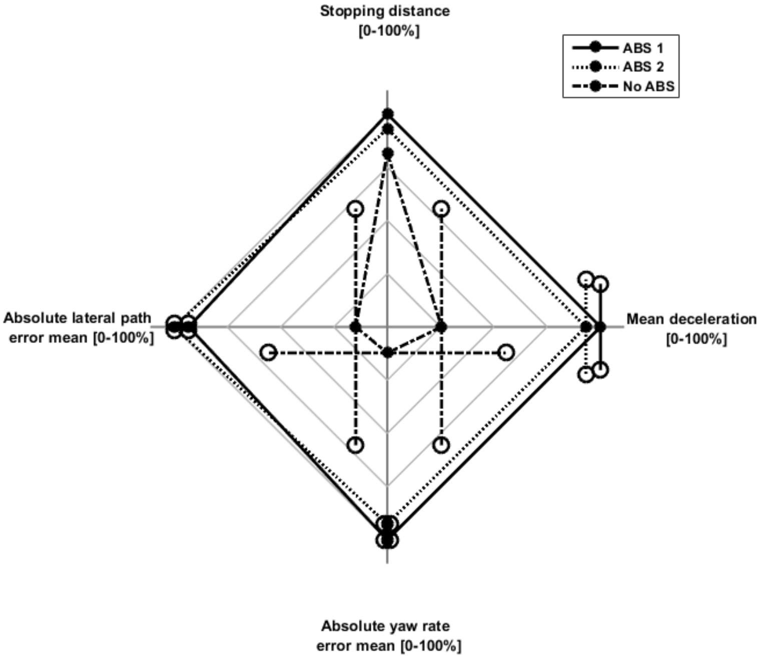

Figure 14. Comparing ABS perofrmance on split-mu surface

6.4 Discussion of the proposed performance evaluation technique

The proposed performance evaluation technique provided a quick and concise way of comparing the braking performance of vehicles with different braking configurations. In many of the radar plots shown throughout Section 6, it is sometimes difficult to identify the ABS algorithm that performed the best. A contributing factor to this is that in all of the discussed cases, the ABS algorithms' performance was compared with a conventional braking system's performance. The advantage of using the proposed evaluation technique is that it scales the comparison of the variation for each metric automatically. To illustrate this, Figure 15 is a reproduction of Figure 14, but with the conventional brake system omitted from the comparison. It is clear in Figure 15 that ABS algorithm 1 outperforms ABS algorithm 2 in three of the four metrics, with the standard deviation of the mean deceleration and the absolute yaw rate mean error lower than that of ABS algorithm 2.

The performance evaluation technique was illustrated throughout Section 6 by comparing different braking system configurations' performance with one another for the same test. The same comparison technique can however be used for a single brake system configuration, but with multiple tests compared on the same radar plot. This may give some insight into the braking performance of the brake system with different manoeuvres, but it is recommended that the surface friction coefficient of the tests compared on the same radar plot are kept close to one another. Failure to do so may result in unrealistic comparisons for all four metrics and their standard deviations.

Finally, the proposed evaluation technique is intended as a first step in the process of evaluating the performance of braking systems. It may be used to easily identify braking systems that perform inadequately when compared to the other systems the designer is considering. If it becomes difficult to decide which of the systems performance is the best, the designer is encouraged to either add additional metrics or to delve deeper into the actual performance of the vehicle by investigating the test or simulation results in the time domain.

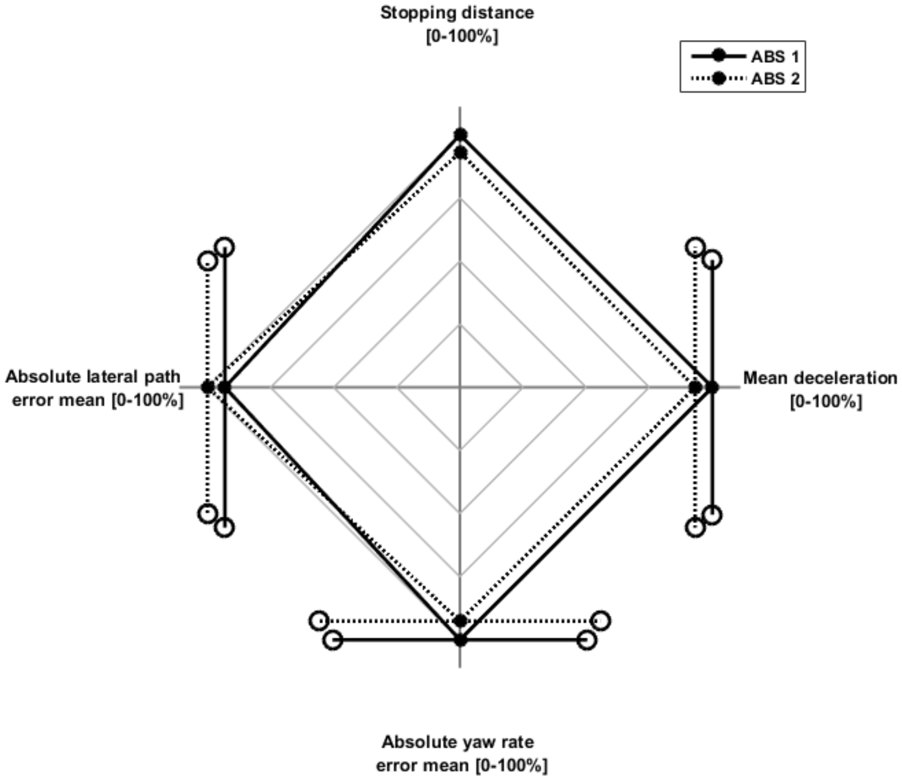

Figure 15. Comparion of ABS performance on split-mu surface

7. Example of experimental evaluation of ABS braking performance

The final step in the development of the ABS performance evaluation metric was experimental implementation. Two vehicles were instrumented with Racelogic VBOX 3i v3 100Hz GPS Data Loggers (Racelogic, 2014). The VBOX data loggers were used in conjunction with a differential GPS Base Station and Inertial Measurement Units (IMUs). The experimental setup allowed the highly accurate capturing of vehicle position, velocity, and yaw rate. Data were sampled at 100Hz. Braking tests were performed on a split-mu surface with an initial vehicle speed of 80km/h. The right wheels were on the lower friction surface. Figure 16 shows an example of the measured data. The brake point was chosen to be 75km/h and the stopping point 2km/h. The brake tests were repeated three times for each vehicle.

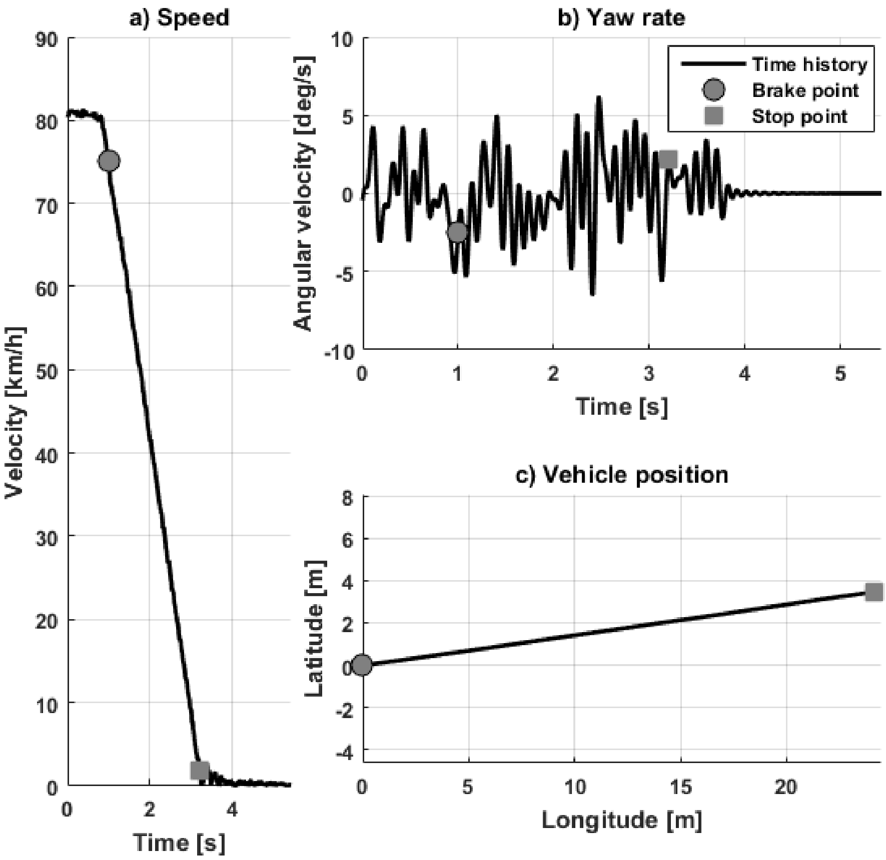

Figure 16. Experimental data captured on split-mu test track

Since a brake test is seldom exactly repeatable due to external factors such as driver reaction delays or ambient conditions (such as a headwind), the average of each of the metrics discussed in Section 5 was calculated. These average values are shown in Figure 17. It may clearly be seen in Figure 17 that the performance of Vehicle 2's ABS is superior to that of Vehicle 1.

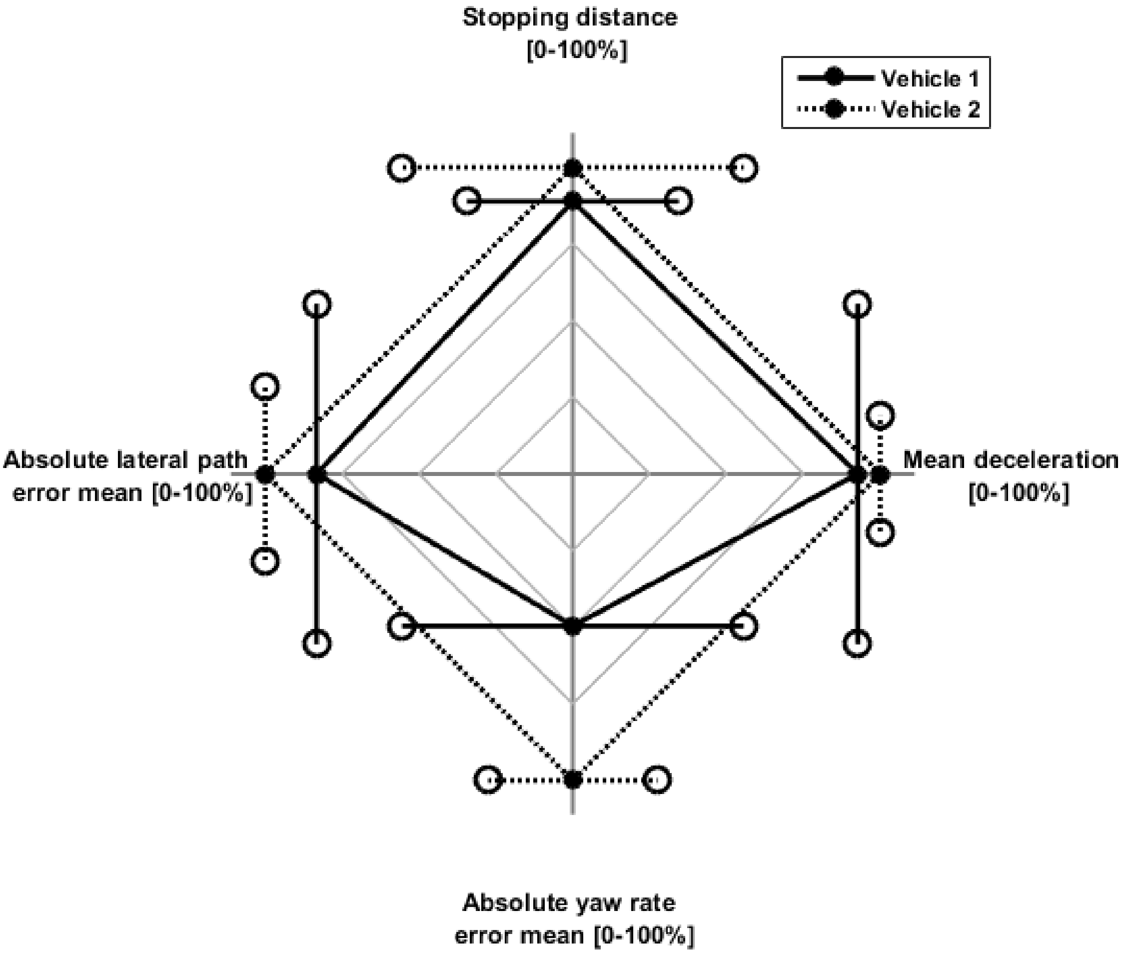

Figure 17. Comparison of experimental ABS performance on split-mu surface

8. Conclusion

The aim of the paper was to formulate an evaluation technique that can be used to clearly and concisely compare the performance of various antilock brake systems with one another taking both stopping ability and directional stability into account. An extensive literature review was performed and several examples of existing metrics used were critically discussed. The requirements as stipulated by SAE International was also investigated. The optimal utilisation of the friction available to the driver, as limited by the tyre's friction force generation characteristics, was discussed to illustrate the compromise the ABS aims to achieve optimally.

Five braking scenarios were chosen to represent the requirements of SAE International of ABS equipped vehicles. These five scenarios were simulated with two different ABS implementations and with a vehicle equipped with a conventional brake system using a full vehicle real-time model developed in VI-CarRealTime. Significant differences in the performance of these systems were noted.

The proposed evaluation technique defined four metrics to evaluate the braking performance of a vehicle, namely:

a) Stopping distance and its standard deviation (if more than one test is carried out for the same algorithm)
b) Mean and standard deviation of vehicle deceleration during the braking manoeuvre
c) Mean and standard deviation of absolute vehicle yaw rate error during the braking manoeuvre
d) Mean and standard deviation of absolute lateral path following error during the braking manoeuvre

These metrics were normalised, with the best performing brake system for each metric being assigned a value of 100%. The metrics were then illustrated on a radar plot to enable quick and clear comparisons. The proposed evaluation technique provides a clear and logical method in which the performance of ABS algorithms can be compared.

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