ARTICLE:

Brake systems: a mind of their own

By **Dr Michael Ellims**

The electronic car

In the early 1970s the Japanese began introducing integrated circuits to control functions in cars such as windscreen wipers and the dashboard. Eventually spark timing and fuel mixture control replaced mechanical devices such as the distributor and the carburettor. The age of the electronic car had begun. In a 1971 article in Popular Mechanics, Benray,[1] looking at what could be achieved with low cost microprocessors in vehicles, predicted integrated engine control, instrument clusters and 'anti-skid 4 wheel' as potential applications.

The latter is interesting because attempting to prevent wheels skidding on vehicles has a long history, and the microprocessor plays a leading role in reaching a solution. Initial experiments used mechanical systems to modulate brake pressure; the British experimented with systems derived from aircraft anti-lock brakes in the 1950s and 1960s without producing a system that could be widely applied. In the 1960s, Ford, GM and Chrysler were all working on anti-skid systems. Ford introduced a rear wheel system to market in 1968, and Chrysler introduced a four-wheel system in 1970. However, any real progress was slow and it was not until Robert Bosh Gmbh introduced its Anti-Lock Braking System (ABS) in 1978[2] that the adoption and eventually acceptance of ABS became widespread. Between the early systems and 1978, a transformation had taken place in the number of transistors that could be incorporated in electronic devices, which lead to progressively more powerful microprocessors and eventually to complete systems on a chip. To a significant degree it was this transformation that enabled successful anti-skid or anti-lock systems to be introduced.

Anti-lock brake systems

To appreciate what an anti-lock brake system does, it is necessary to understand the purpose of the two sets of wheels in a vehicle. It is generally understood that the front wheels are used to steer a vehicle – that is, they operate to change the direction of the vehicle. What is less well understood is the function of the rear wheels. The rear wheels do not actively control the change of direction of a vehicle, but they are critical in ensuring the vehicle is able to move in a straight line. If the rear wheels lose traction, then it becomes difficult to maintain movement in a straight line. If a vehicle is not equipped with ABS, any sideway motion at the rear of the vehicle requires the driver to counter steer, because the rear of the vehicle attempts to overtake the front.

An example of the worst-case scenario is where the rear tyre has a blowout,[3] which often results in a total loss of control.[4] Loss of control can also occur if a wheel is locked. When this occurs, the lateral (sideways) forces that the rear wheel can produce are minimal. It follows that when a wheel is locked, it can move sideways because there is little force being generated to oppose this motion. A locked wheel is just a bit of rubber sliding on the roadway. If the front wheels continue to rotate, then as the back of the vehicle moves out, the lateral forces on the front wheels increase. This acts to increase the angle, which in turn increases the lateral forces on the front wheels, and the vehicle starts to slide at the rear, which becomes self-reinforcing. The forces in play on the wheels continue until the front wheels become the rear wheels, and a spin occurs.

[1] Ronald M. Benrey, 'Microelectronics in the '70s', Popular Science, (October 1971), 199 (4): 83-5, 150-2.
[2] Ann Johnson (2001) 'Unpacking reliability: The success of Robert Bosch, GmbH in constructing antilock braking systems as reliable products', History and Technology: An International Journal, 17:3, 249-270, DOI: 10.1080/07341510108581994.
[3] A puncture is a 'slow' release of air from a tyre, a blowout is a rapid, often catastrophic failure of the tyre.
[4] For an example, see https://www.youtube.com/watch?v=e1d9e7WsHYg.

In simple terms, the aim of ABS is to attempt to prevent 'wheel lock' from occurring in much the same way as 'pumping the brakes' using the service brake pedal does. More importantly, ABS can do this for each wheel individually, and it can do it much more rapidly than any human. This is achieved by having a wheel speed sensor on each wheel which constantly estimates the rotational speed of the wheel and its acceleration and deceleration. From this information the software also estimates the forward velocity of the vehicle, and under braking, the software can detect if one or more wheels are slowing faster than the others, or if the deceleration of the wheel indicates that traction is about to be lost. The mathematics can get rather involved,[5] which is why advances in electronics were so important to the development of ABS, but the details are unnecessary for our purposes. One aspect of the discussion is important: an ABS system does not know how fast the vehicle is moving or accelerating; it has an estimate (usually a very good one) derived from the wheel speed sensors.

To achieve control of each wheel, there are two valves associated with each brake calliper, an inlet valve and an outlet valve. In normal operation, the outlet valve is closed, and brake pressure is controlled from the master brake cylinder – together with the pressure the driver applies to the service brake pedal. As the wheel slows there is an intermediate state where both the inlet and outlet valves are closed, maintaining a constant pressure. If the wheel continues to decelerate, the outlet valve will open, thus reducing the braking force (strictly torque) applied to the wheel. This cycle can repeat, and the operating frequency of the system varies between 10 and 20Hz, that is it cycles 10-20 times per second.[6]

The first point to note here is that in normal circumstances ABS is not operational, and the brake system defaults to acting as a simple hydraulic system. It is not a simple system, but it acts as if it were. This is a deliberate design feature, because if the system fails, the default state is to revert to the standard hydraulic system. It is rare for ABS to be initiated.

[5] The treatment of slip for a single wheel is presented in the appendix.
[6] Adapted from Robert Bosch GmbH, *Bosch Automotive Handbook* (8th edition, 2011), 806.

How ABS fails

The first thing to note is that all systems fail eventually, everything humans build has a failure rate. Aerospace addresses this issue with legally mandated inspection and maintenance routines. Automotive manufactures address this by recommended maintenance schedules which are only mandatory to keep a vehicle in warranty. In some countries a yearly inspection is required – however, the scope of this is limited and will not necessarily identify latent faults; that is those faults that exist but are yet to cause an issue.

We have to assume that ABS systems can fail, and the manufacturers also assume ABS systems can fail. Probably the most common problem associated with ABS systems is that the wheel speed sensors fail. However, the failure modes of the system are well known (they are designed that way), and in most cases a failure of the wheel speed sensors will take the system offline, and the brake system will revert to a simple hydraulic system with no valve actuation. Should this occur, a red ABS warning lamp will be lit on the dashboard to let the driver know there is a problem with the system.

More problematic are failures that can only be detected during operation, such as stuck or unresponsive valves, or more problematically, errors in the microprocessor or – on occasion – the software.

At this point it is important to recall a point noted above; that the ABS software only has an estimate of what is actually occurring at the wheels, derived from the wheel speed sensors and the brake force being requested by the driver. Because the system does not 'know' what is happening, it can be fooled by unusual situations (we shall return to this point latter).

ABS can occasionally be fooled simply by presenting the software with valid data that is out of the ordinary. One example that has been considered, is where the wheels on one side of the vehicle drive over different surfaces: dry tarmac to the left and ice to the right – there is an ISO validation test for what is termed split-mu braking.[7] Likewise, engineers have also thought of the possibility that an alternative

[7] ISO 14512: 1999 Passenger cars – Straight-ahead braking on surfaces with split coefficient of friction – Open-loop test procedure.

pattern of ice and tarmac would confuse the system: a defined standard checkerboard test has been developed.[8]

One situation that was not covered, and which has been related to the author,[9] occurred in road works where a vehicle transitioned from a complete surface to one where the old road surface had been removed, giving a significant difference in height difference between the two. As the transition between the two surfaces was made under braking, the ABS system was 'fooled' into thinking that a major change in surface friction had occurred as the wheels locked while in the air. The system reacted as programmed – opening the outlet valves and effectively disabling the brakes.

Advances on ABS

Once ABS was implemented, it followed that ABS was improved. Further developments took place, such as: traction control, electronic stability control, brake assist and automated emergency braking. Once software can control brake pressure, and hence brake torque at each wheel, a multitude of things can be accomplished. We now briefly look at some of these systems.

Traction control

The first development to follow ABS was a traction control system (TCS). In its most basic form, traction control is simply a matter of observing on a two-wheel drive vehicle that the drive wheels are rotating more rapidly than the non-driven wheels. If the sensors report that one wheel is spinning, then a brake torque can be applied to that wheel. If the sensors on both wheels report each to be spinning, then the brake system will 'request' that engine power be lowered. If this occurs, it follows that the TCS is now in control of both the brake system, commanding brake actuation, and in control of the engine (or the motor if it is an electric vehicle) power output. There is another difference as well, whereas ABS will be activated in response to the driver commanding a brake actuation; traction control will intervene whenever the system thinks that it is required, without any specific driver input.

Electronic stability program

Whereas ABS and TCS react to road conditions as estimated by the wheel speed sensors, ESP the Electronic Stability Program (ESP) or Electronic Stability Control (ESC) systems attempt to cause a vehicle to undertake the actions that the driver intends when controlling the vehicle. To do this, the ESP system needs to 'know' first, what the driver intends when manipulating pedals or switches, and second, what is actually happening to the vehicle.

The first is estimated from (i) the driver inputs, such as the steering angle and the positions of the throttle and brake pedal, and (ii) the estimated road speed and road conditions derived from wheel speed sensors, which primarily comprise of estimates of the friction between the tyre contact patch and the road surface. An important point to remember is that control of the vehicle is dependent on an area of rubber approximately the size of a man's hand in contact with the road. All the forces controlling the vehicle's movement on the road go through these contact patches.[10]

The second is estimated by a combination of the wheel speed sensors (as for ABS and TCS), and information from accelerometers and a gyroscopic sensor that provides information on the acceleration on each of the x, y and sometimes z vehicle axis (longitudinal, lateral and vertical), and information on the rotation of the vehicle about its centre of mass. Other information can also be taken into account, such as tyre pressure, to obtain a more accurate estimate of the wheels rolling radius.

This data is subject to calculations by two mathematical models: a model of the intended behaviour, and a model of what the vehicle is actually doing, together with the forces that are acting on the vehicle. A discrepancy between the two will cause ESP to react, firstly by controlling the yaw of the vehicle by braking wheels on one side or the other – either to increase or decrease the yaw rate – or by attempting to slow the vehicle by cutting the power to the drive wheels and applying the brakes, or both.

The models involved in estimating the vehicle's behaviour on the road are complex, and the

[8] ISO 21994:2007 Passenger cars — Stopping distance at straight-line braking with ABS — Open-loop test method.

[9] Personal communication from Damian Harty, co-author of; Michael Blundell, Damian Harty, *The Multibody Systems Approach to Vehicle Dynamics* (Butterworth-Heinemann, 2004).

[10] So check your tyres regularly.

explanation above is only the briefest of outlines. It does not discuss complexities such as avoiding roll-over, or the behaviour of a vehicle towing a trailer, which changes the weight distribution on a vehicle. If there is a trailer but no 'trailer attached' sensor, this has to be inferred by the model as a departure from expected behaviour in 'normal' driving circumstances. It also needs to be said that the models, while general in form, are set up in practice to be specific to the vehicle they are used on. This is a laborious process involving an initial setup using data from similar vehicles and a great deal of track testing under various conditions, including winter testing.

Autonomous emergency braking

All the systems discussed above are fitted to light and heavy vehicles. ABS and ESP are mandatory in the EU and over much of the world, and effectively TCS is also fitted, as its functionality is incorporated into ESP. The next system to be discussed is Autonomous Emergency Braking (AEB), which will become mandatory in the EU in mid 2022, along with a number of other 'intelligent' systems.[11]

AEB is a system designed to avoid or mitigate a collision by applying the brakes independently of the driver if necessary. If a collision occurs, the severity of the impact can be mitigated by any reduction in speed. This is done by sensors 'looking' at the road ahead of the vehicle and estimating whether or not a collision will take place, where 'looking' is performed by sensors such as LIDAR,[12] radar and cameras – with the latter two becoming dominant.

The word 'estimate' is used in the discussion of ABS, TCS and ESP. It follows that the word 'look' is used in its most generic sense, something akin to 'detect' rather than how it is often used in a human context of 'understand'. AEB does not understand on any deep level what is going on. It is capable of detecting (LIDAR, radar, camera) and classifying (cameras) various objects that it may encounter; estimating the paths those objects may take and determining if the vehicle path will intersect with the object. If the software detects a probable collision, it will first warn the driver, and if the driver takes no or too little action, the software will activate the braking system. AEB can and will brake on its own accord in a vehicle fitted with it.

What can go wrong

Anything and everything can go wrong, at least in theory. Everything made has a failure rate and will eventually fail.

Electronic systems are no different. The movement of electrons cause heating, and the continued heating and cooling cycles cause stress on the components, and vibration and heat weaken connections. Electronic devices can have very long lives, but they are finite. In addition, not everything can or needs to be made perfectly. In low-cost systems such as automobile systems engineering, a judgement will be used to decide when to halt the process of continual refinement.

This is illustrated in the cost difference between an aerospace alternator and one from a passenger vehicle. For one aerospace project on a light aircraft, an alternator was necessary. An aerospace certified alternator was quoted at US$30,000 per unit, compared with approximately US$50 for an automotive equivalent. To a large extent, the cost of an item reflects the number of devices that development costs can be spread over. A company such as Ford makes millions of cars every year – hence the cost of developing a component is spread over a very large number of parts. In comparison, Boeing have only made a few thousand 737 jets; and even if the 737 is numerically the most numerous jet airliner ever produced, nevertheless the cost of components cannot fall in price in the same way as motor vehicle components.

Counter measures

As with the design of avionics systems, the automotive industry has sets of mandatory regulations, standards and guidelines to which it must conform. For brake systems, including ABS and ESP, the normative regulations that apply are UNECE Regulation 13H,[13] FMVSS[14] 135, and the Chinese equivalent. These standards specify performance requirements for the systems and development requirements. For example, Regulation 13H has an

[11] https://ec.europa.eu/commission/presscorner/detail/en/IP_19_1793.
[12] https://en.wikipedia.org/wiki/Lidar.
[13] UNECE R13H, 'Addendum 12-H: Regulation No. 13-H Uniform provisions concerning the approval of passenger cars with regard to braking Revision 3', 24 Feb 2014, http://www.unece.org/trans/main/wp29/wp29regs0-20.html .
[14] Federal Motor Vehicle Safety Standard.

annex which states ‘to be applied to the safety aspects of complex electronic vehicle control systems’ where ‘complex’ is effectively any system under programmed control. These regulations in turn correspond to the international standard ISO 26262,[15] which sets out the analysis and processes expected for developing complex electric systems.

When designing a system, the analysis begins with defining what a system is intended to do: that is, what functions the device will provide to the vehicle. Once the functions are defined, the standard requires an analysis of what hazard may be presented at the vehicle level e.g. unwanted acceleration, deceleration etc, may result from failure to provide the functions. This analysis uses established hazard analysis techniques,[16] together with an assessment of the associated risk for each of the hazards defined in the context of various driving scenarios. This includes risks that might be apparent at other times, such as during workshop maintenance. The scale used is A to D, with D being the highest rating.[17] Once potential failures, hazards and risks are identified, the standard (as does UNECE R13H) calls for the development of a what is termed a functional safety concept (FSC).

A functional safety concept is a technical plan for (i) how the device is going to deal with the various failures that have been identified and that can lead to a hazard occurring, and (ii) the mitigation of those failures in a way that avoids the hazards. There are various ways in which this can be done.

Consider the example of the simple ABS system. We can suppose a function is ‘measure wheel speed’; a failure of the function could be ‘wheel speed measured low’, leading to ‘inappropriate calliper release’, and resulting in the hazards ‘vehicle yaw’ due to unbalanced braking or ‘extended braking distance’ due to a reduction in brake force. In this instance, simple checks on the values returned by the sensor will identify some errors; other errors can be identified by the software examining the sensor outputs from all four wheels (on a passenger vehicle) and whether the brakes are being applied from the brake pressure measurement. If an error is identified by the software, then remedial action can be taken by the software. In a ‘simple’ system such as ABS, the functional safety concept is to ‘fail silent’ or ‘fail off’; that is to disable the ABS and illuminate the ABS lamp on the dashboard.

On more complex systems, the functional safety concept becomes more problematic. For example, what the failure mechanisms and modes of radar or camera systems might exhibit are extensive. There is also the issue of ‘fusing’ or combining the different streams of information together to provide a view of the vehicle’s environment that makes use of all the information available. Final safe states are also more problematic, as it may not be acceptable for these complex systems to fail silently.

Failures

One way to examine what happens in practice is to examine vehicle recall notices – for example those published by the Driver and Vehicle Standards Agency (DVSA),[18] which have tabulated the data in a CSV file for data collected since 1992.[19] The CSV file has 12,321 rows or records of which 130 can be considered related to ABS, TCS and ESP or AEB systems. This is approximately 1 per cent, approximate because the count does not fully account for duplicates, for instance when several models from one manufacturer exhibit the same issue, there is a record for each model.

If we consider the probable root cause from the recall notice, there are:

32 recalls that were software related, based on the stated need for the software to be updated.

26 recalls for issues with the hydraulic system.

21 recalls for mechanical issues.

[15] ISO 26262-1:2018 Road vehicles - Functional safety.
[16] An overview of 23 different techniques is given in Clifton A. Ericson II, *Hazard Analysis Techniques for System Safety* (2nd edn, John Wiley & Sons, 2015).
[17] The choice of scale is perhaps a little unfortunate. For avionics, the scale is E to A, with A being the highest rating.
[18] Formally The Vehicle and Operator Services Agency (VOSA).
[19] https://www.check-vehicle-recalls.service.gov.uk/recall-type/vehicle/make. The author has previously used this database, notably for the paper; Michael Ellims, ‘On wheels, nuts and software’, *Proceedings of the 9th Australian workshop on Safety Critical Systems and Software - Volume 47* (2004, Australian Computer Society, Inc). At that time the extraction of data had to be performed manually from printed monthly reports. This may be an improvement, however some recall notices appear to be absent.

14 where the electronics hardware appeared to be faulty.

13 for issues with sensors.

12 for issues with the wiring harness (primarily chafing).

10 for water ingress into some part of the system.

Below is a small selection of the recall notices, edited for brevity and with corrected spelling and grammar. The failures noted below are from the following manufactures: Volvo Bus, Mitsubishi, Volvo Car, Peugeot, Hyundai, Scania Truck, Iveco, Land Rover, Vauxhall (Opel), Mercedes Benz, and Toyota.[20] There are a number of fields separated by a dash as follows: the system to which the author assigns the failure – the headline from the recall notice – a description of the cause of the failure – and the remedial action required.

Hydraulic System - Braking Performance May Be Reduced - an unexpected loss of braking performance due to the ABS/ESP Modulator not being correctly filled with hydraulic oil at the factory - replace the ABS/ESP hydraulic modulator and control unit.

Wiring - Incorrect Connection of ABS Sensing - sensor wires may be incorrectly connected. This could result in the sensing system failing to identify which wheel may be locking - inspect and correct wiring.

Software - Faulty Control Unit May Cause Vehicle to Perform Outside Specification - the coding may not correspond to the specification and may trigger unplanned action in the vehicle - update the software.

Sensor - Yaw Rate Sensor May Suffer Internal Delimitation - this could result in actuation of the stability control incorrectly resulting in uneven and unexpected application of the brakes - sensor will be replaced with a quality assured part.

Software - Emergency Braking System May Function Without Warning - the Automatic Emergency Braking System (AEBS) may in certain traffic situations activate itself - Update the AEB software.

Wiring - Vehicle May Catch Fire - the ABS warning light may come on when driving. If ignored the vehicle may catch fire - replace earth wire and grease contacts in ABS module.

Hydraulic System - Loss of Control - In the event of emergency braking or during an ESP regulation phase (e.g. avoiding manoeuvre) the hydraulic block may not prevent the locking of a wheel which could affect control of the vehicle - replace the braking system hydraulic block.

Software - Brakes May Activate Without Warning - the software on vehicles equipped with Advanced Emergency Braking (AEB) system has an error in its programming. This could cause the AEB system to incorrectly register a collision risk with a stationary object and brake the vehicle to avoid a collision. This could result in the driver losing control or an emergency braking situation without the driver's knowledge - upload new software to the AEB system.

Sensor - Unintentional Operation of ABS - at certain temperatures (room temperature or below) the front wheel speed sensors can send faulty signals to a number of control units. It is possible that when braking the ABS could be activated when not needed and the ABS light will be illuminated - replace both front wheel sensors with modified type.

Water – Braking May Be Reduced - It is possible that moisture can enter the front wheel ABS sensors via its wiring due to insufficient waterproofing. This can cause the generation of an abnormal signal to the ABS ECU. In extreme cases it could affect the directional control of the vehicle or reduce the braking efficiency of the vehicle - replace the sensors.

Mechanical – Loss of Stability - Due to the improper shape of a component inside the ABS actuator there is a possibility that a resin component could be damaged during its press fitting assembly creating minute resin fragment(s) which could become stuck in the actuator - replace the ABS Actuator with a new one.

It must be emphasised that a simple flaw in the manufacturing process on what appears to be one

[20] If the reader wishes to establish which manufacturer is responsible for each of the examples, it will be necessary to download the CSV file and conduct a search to identify the example against the manufacturer.

bolt could result in catastrophic failure, for which the following recall notice was issued:

> Mechanical - Steering Column Joint May Not Be Secure - The Steering column may become detached from the rack due to incorrectly tightened bolt - On affected vehicles check for presence of retaining nut. If present tighten nut to specified torque. If nut is absent replace bolt and screw and tighten to specified torque. THE MANUFACTURER HAS ADVISED NOT TO DRIVE THE VEHICLE. [The emphasis is from the recall notice]

Discussion

From the previous section it is obvious that electronic brake systems can go wrong, and they are observed to go wrong. However numerous studies have shown these systems are effective at preventing accidents. For example, a study sponsored by the American National Highway Traffic Safety Administration showed that over the majority of test surfaces and manoeuvres, vehicles fitted with active ABS obtained shorter braking distances, the exception being on loose gravel. On surfaces with different friction levels on each side (split-mu) they observed that 'When the ABS was disabled and a panic brake input applied, each test vehicle deviated from its stopping lane by yawing out of control'.[21]

Traction control has been less studied. This is because, in some ways, it can be considered more of a convenience feature. However, ESC has been extensively studied. Kreiss and others applied statistical methods to 40,000 accidents over the period 1998-2002 on German roads, and concluded that 'results demonstrate clearly and significantly that there in fact exists a substantial benefit of ESP'.[22] Likewise, Lyckegaard and others examined Danish accidents from 2004 to 2011 and concluded that 'ESC reduces the risk for single-vehicle injury accidents by 31% when controlling for various confounding factors related to the driver, the car, and the accident surroundings'.[23]

However, in some regards seeing is believing, and to this end the reader is invited to view the following sets of videos available on YouTube from a driving program produced in the United Kingdom, featuring a former race driver Tiff Needell:[24]

> An early look at the effects of using ABS, TCS and ESP on snow in Finland.[25]
>
> A review of ESC systems on the verge of ESC becoming compulsory.[26] (2012)
>
> What happens with a car without ESP at various speeds.[27] (2015)

The third video amply demonstrates another less understood feature of tyre technology. The vast majority of vehicle manoeuvres on the road take place within what is referred to as the force circle, with acceleration and deceleration normally being under +/- 0.3g (2.8 m/s/s) and likewise lateral forces are constrained within the same limits (+/- 0.3g); this appears to be the 'comfort zone' for 'normal' driving for the vast majority of drivers. In this area of use, tyre behaviour is linear, and the amount of friction between the tyre and road changes in a constant manner, as do the forces. Beyond this limit, the response of a tyre becomes progressively non-linear, which can result in sudden changes in vehicle behaviour.

The author has an MSc in operating system development and a PhD in software testing. He has been working in real-time control systems for 30 years in both automotive and aerospace working on engine and motor control, brake systems and functional safety and contributed to the ISO 26262 standards.

The author may be contacted at mike@ellims.xyz

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[21] Garrick Forkenbrock, Mark Flick and W. Riley Garrott, *A comprehensive light vehicle antilock brake system test track performance evaluation* (SAE Technical Paper No. 1999-01-1287), 7.

[22] Jens-Peter Kreiss, Lothar Schüler and Klaus Langwieder, 'The effectiveness of primary safety features in passenger cars in Germany', in *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles 19th ESV Conference* (No. 05-0145, 2005), 11.

[23] Allan Lyckegaard, Tove Hels and Inger Marie Bernhoft, 'Effectiveness of electronic stability control on single-vehicle accidents', *Traffic Injury Prevention*, 16(4) (2015), 380-386.

[24] A brief Biography can be found on Wikipedia at https://en.wikipedia.org/wiki/Tiff_Needell.

[25] Fifth Gear ABS, TC, ESP Full version https://www.youtube.com/watch?v=wR1SSxpKitE.

[26] Tiff VS Electronic Stability Control | Fifth Gear Classic https://www.youtube.com/watch?v=7-2UAfsbyZo.

[27] Driving Without Electronic Stability Control - Fifth Gear https://www.youtube.com/watch?v=YuUBeJSYg4o.

Appendix

In a pure rotation situation, the longitudinal vehicle velocity and the rotational speed of the wheel is given by:

$$v = r\omega$$

Where v is the velocity of the vehicle (m/s) relative to the centre of mass, ω is the rotational speed of a wheel in radians per second (rad/s) and r is the rolling radius of the tyre (in meters) which changes with load and tyre pressure.

During acceleration $v < r\omega$

During deceleration $v > r\omega$

The slip velocity can be calculated as $v_{slip} = r\omega - v$

And the slip ratio as $R_{slip} = v_{slip} / r\,\omega$

In general, an ABS system will aim to keep the slip ratio between 0.1 and 0.2 (10 - 20%) for optimal braking.[28] The astute reader will have noticed that v is itself estimated from $r\omega$ over all four wheels of a passenger vehicle. This has to be achieved in such a way so that errors are accounted for.

For example, if an electronic component such as a resistor begins to fail, then it is possible that the calculated wheel speed differs from the other wheels. This can be resolved – at least partially – by rationality checks that take into consideration steering angle, brake forces and whether or not the wheel in question is a driving wheel.

[28] Randy Beikmann, *Physics for Gearheads: An Introduction to Vehicle Dynamics, Energy, and Power - with Examples from Motorsports* (2015, Bentley Publishers).