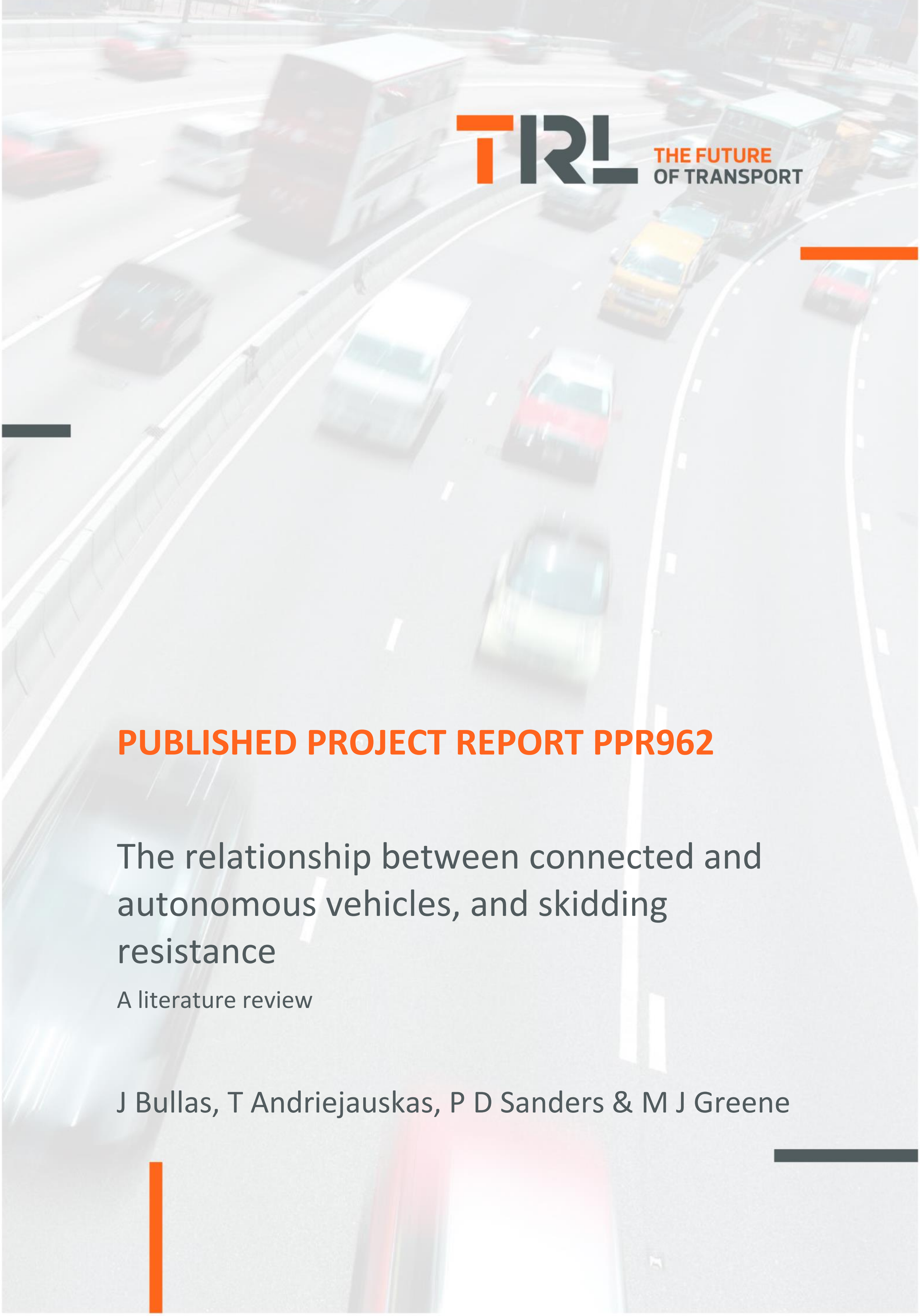

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The relationship between connected and autonomous vehicles, and skidding resistance

A literature review

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Executive Summary

Modern vehicle technologies are becoming ever more reactive and sensor based. To date the most sophisticated of modern vehicle technologies are capable of assuming full control of the vehicle and reacting to the complex situation that is the road environment. The development of modern vehicle systems poses several challenges and potential benefits to highways and vehicle engineers. This document seeks to outline the state of the art of how modern vehicle systems assess road-tyre interaction and how this might influence current processes for the management of skid resistance on the highway asset in the UK.

This is achieved through:

- A summary of knowledge pertaining to the interaction of road surface skid resistance and vehicle performance.
- A literature review into modern vehicle systems, and how they use road surface information such as skid resistance.
- The presentation of a methodology for the use of data captured by modern vehicles that could aid the management of road assets and the decision making process of autonomously controlled vehicles.

The physical interaction between a vehicle and the road surface is handled entirely through the friction generated between the vehicle's tyres and road surface. This generation of friction is highly complex and is dependent upon many variables relating to the vehicle, road surface, and type of manoeuvre being carried out. The methodology used to characterise road surface skid resistance[1] seeks to simplify the complexity of friction generation by making measurements of friction in a highly controlled and highly specific manner. The way the skid resistance performance of road surfaces in the UK is managed, may therefore not be wholly representative of the friction generated between a given vehicle and the road surface.

The literature review explored the published literature relating to modern vehicles to investigate the current technologies as they pertain to the use of skid resistance data at a vehicle level. The literature review sought to answer the following questions:

- How are modern vehicles likely to measure, predict or infer the skid resistance performance of the road surface?
- How will modern vehicles use this information in different situations, for instance the headway given, or braking times used?

The literature review identified several areas for further development, broadly speaking they can be considered as relating to INBOUND data from vehicles that could be exploited as network management tools or OUTBOUND data from sources maintained by the network manager that are used by vehicles on the network; again these systems will be relevant to modern vehicles assuming autonomous control of the vehicle.

[1] The effect of the road surface only on the generation of tyre surface friction.

The areas for further development are:

1) A methodology for the aggregation of INBOUND data FROM vehicles on the network and the translation of this data into meaningful road friction condition indicators for network management purposes.
2) Calibrated tyre models to enable road surface friction to be accurately estimated from normal manoeuvres. This information to be exploited WITHIN the vehicles own systems in real-time as well as an INBOUND data source for network management purposes.
3) A road friction measurement survey device (to be used in a similar manner to those currently used), that can provide a measure of network wide road surface wet friction that can provide OUTBOUND data to be exploited by modern vehicle systems likely to be operating with maximum friction as the limiting factor in their manoeuvres.

1 Background

The aim of this study was to investigate the current CAV (Connected Autonomous Vehicle)[2] technologies as they pertain to the use of skid resistance and, via a literature review, seek to understand:

1) *How are CAVs likely to measure, predict or infer the skid resistance performance of the road surface?*
2) *How will CAVs use this information in different situations, for instance the headway given, or braking times used?*

In attempting to address these questions, the relationship between HAVs[3] (Highly Automated Vehicles which include CAVs) and the highway infrastructure will be considered from the perspective of the management of Highways England's assets.

Road networks are primarily designed to provide a safe and reliable transport system for vehicles piloted by humans. The advent and adoption of vehicles with various levels of autonomy may result in a markedly different behaviour than that of human piloted vehicles. For instance, automated / autonomous vehicles may assess their environment and interpret risk in ways different from humans and therefore act (conduct vehicle manoeuvres) in different ways.

Understanding these fundamental differences in piloting systems will provide a new appreciation of the demands placed upon a road network by the passage of CAVs. Furthermore, it may offer insight into how the management of the road network could be optimised to take advantage of the changes in vehicle fleet characteristics.

It is important therefore to possess a broad understanding of both the forces acting upon the vehicle, and the way that the contact between tyre and road is managed by control systems to optimise occupant safety and comfort: factors that dictate not only the levels of road surface friction needed but also what can practically be mobilised.

Commercially available Highly-Automated Vehicles (HAVs) are being deployed now in increasing numbers on networks around the world; they will ultimately be joined by significant numbers of Autonomous Vehicles[4] (AV) and CAVs, thus research activity now related to any form of HAV may deliver findings equally applicable to AVs and CAVs in the future. By means of example: research relating to inter-connectivity between vehicles should clearly be considered relevant to CAVs but research currently investigating road surface

[2] Connected Autonomous Vehicles (CAVs)would communicate with each other and their surroundings to identify optimum routes. CAVs could also communicate with roadside infrastructure such as traffic lights and use this information to minimise fuel consumption and emissions (Department for Transport, 2015).

[3] Highly-Automated Vehicles (HAVs) are vehicles in which a driver is required to be present and may need to take manual control for some parts of the journey: under certain traffic, road or weather conditions, the vehicle's automation systems may request the driver to take control (Department for Transport, 2015).

[4] A fully autonomous vehicle, an AV, is truly driverless, a driver does not need to be present (Department for Transport, 2015).

friction estimation is contributing to a better understanding of a fundamental component of AVs and CAVs.

This document presents a review of literature relating to the state of the art of automated and/or autonomous vehicles and considers the results of the review in the context of the skid resistance management of the English motorway and trunk road network.

The following sections provide a summary of the science underpinning skid resistance and provide a brief overview of the current wet friction measurement techniques used on the English motorway and trunk road network and how these measurement techniques relate to the frictional domains of typical manoeuvres made by vehicles.

1.1 The levels of vehicle autonomy

"Surface Vehicle Recommended Practice: Taxonomy and Definitions for Terms Related to Driving Automation Systems" (SAE, 2018) describes motor vehicle driving automation systems that perform part, or all of, the Dynamic Driving Task (DDT) on a sustained basis. It provides a taxonomy with detailed definitions for six levels of driving automation, ranging from no driving automation (level 0) to full driving automation (level 5), in the context of motor vehicles (hereafter also referred to as "vehicle" or "vehicles") and their operation on roadways.

The SAE guidance recommends against **using terms that make vehicles, rather than driving, the object of automation**, because doing so tends to lead to confusion between vehicles that can be operated by **a (human) driver or by an ADS** (**Automated Driving System)** and **ADS-DVs** (**ADS-Dedicated Vehicle), which are designed to be operated exclusively by an ADS**. It also fails to distinguish other forms of vehicular automation that do not involve automating part or all of the DDT.

An ADS-DV is a truly "driverless" vehicle. However, the term **"driverless vehicle"** is not used in the SAE document because it has been, and continues to be, widely misused to refer to **any vehicle equipped with a driving automation system**, even if that system is not capable of always performing the entire DDT (within given Operational Design Domain (ODD) limitations, if any) and thus requires a (human) driver for all or part of a given trip (see Section 3).

A vehicle may be equipped with a driving automation system that is capable of delivering multiple driving automation features that operate at different levels; therefore the level of driving automation exhibited in any given instance is determined by the feature(s) engaged, thus:

- A vehicle *with* driving automation capability is a "**level [1 or 2] driving automation system-equipped vehicle**" or "**level [3, 4, or 5] ADS-equipped vehicle.**"
- A vehicle *with an engaged system* (vs. one that is merely available) is a "**level [1 or 2] driving automation system-engaged vehicle**" or "**level [3, 4, or 5] ADS-operated vehicle**."

The above statements are directly relevant to the level of automation on offer in current HAVs in the UK, but it is still important that the appropriate industry terminology is used in future dialogues to avoid confusion.

The AVs and CAVs we refer to in this document may correspond to the **level [3, 4, or 5] ADS-*equipped* vehicles or level [3, 4, or 5] ADS-*operated* vehicle**.

1.2 The vehicle and road surface as a complex system

1.2.1 Fundamental forces

Frictional forces between a vehicle and a road surface are always present, whether at rest[5] or in motion. The following figures summarise these forces. It is not proposed to describe in detail all the technical content associated with the figures, rather simply to graphically illustrate the complexity of the interaction between a vehicle and a road surface.

Figures 1a, 1b and 1c (Kritayakirana, 2012), illustrate how braking (with its inherent longitudinal weight transfer), driving on a gradient, and driving on a road with crossfall, change the longitudinal acceleration profiles a_x and the longitudinal forces, (F_x^{Front} and F_x^{Rear}) that are experienced by a vehicle.

In these Figures:

- xˆ and yˆ represent vehicle body-fixed coordinates,
- $m.a_x$ the braking forces,
- $m.a_y$ the side forces,
- m.g the force due to gravity,
- F_y^{Left} and F_y^{Right} the lateral forces, and,
- F_z^{Front} and F_z^{Rear} the normal loads.

As can be seen from these Figures, the direction and magnitude of the main forces acting on a vehicle can change significantly depending on its trajectory even before any braking takes place.

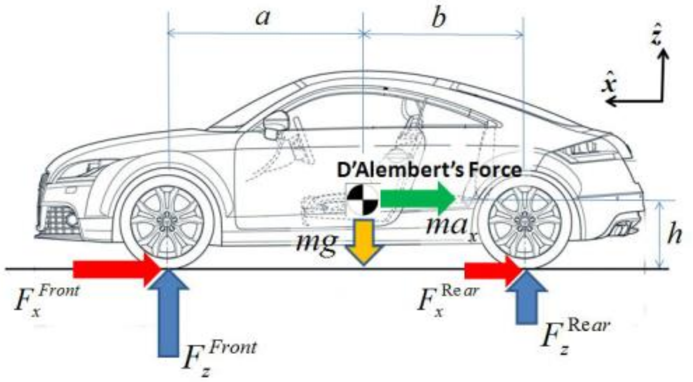

Figure 1a: Weight transfer during braking (Kritayakirana, 2012)

[5] Except in the very rare case that a vehicle is at rest and on a perfectly flat and level surface.

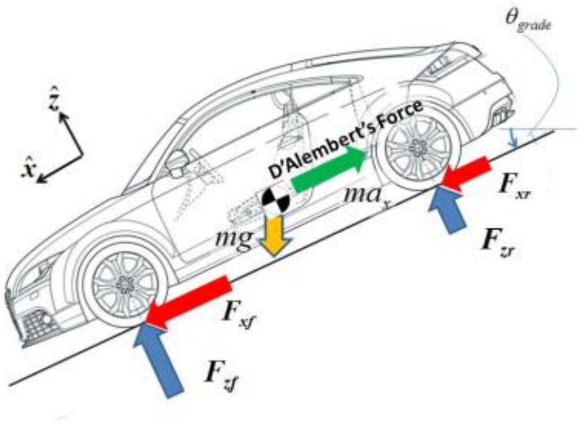

Figure 1b: The effect of gradient (Kritayakirana, 2012)

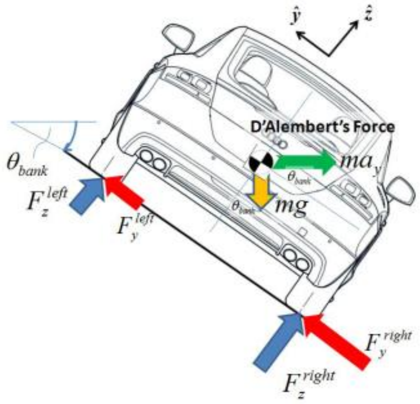

Figure 1c: The effect of cross fall (Kritayakirana, 2012)

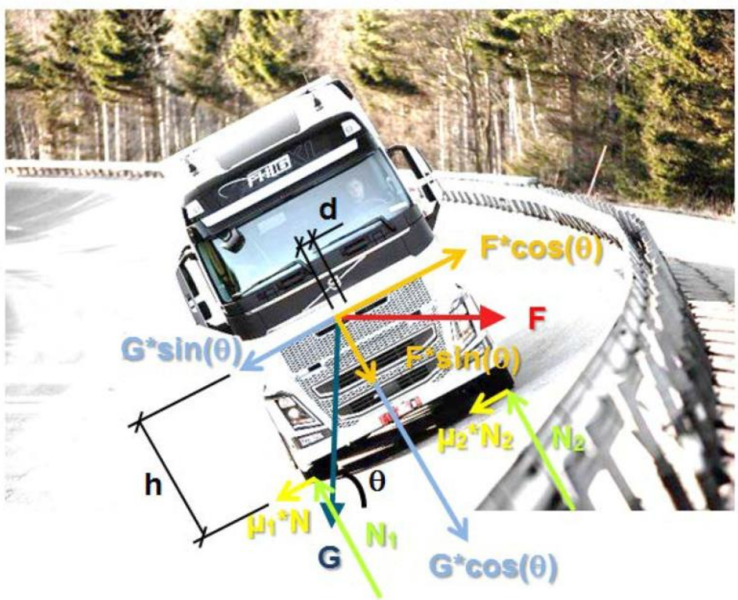

Figure 1d: Analysis of cornering forces in heavy vehicles (Granlund, 2014)

It should be observed that, by virtue of their higher centre of gravity (CoG), the modelling of forces active when heavy goods vehicles (HGVs) are cornering on super elevated bends departs from the traditional analysis of cornering forces acting on a point-mass model of a vehicle (where the CoG is assumed to be located at the tyre footprint, see Figure 1c). This traditional approach may be relevant for low passenger cars, however work undertaken by Granlund, J. et. al. (2014) showed that super elevation demand increases with the height and lateral displacement of the CoG, and peaks when the curve has less friction under the outer wheels than under the inner wheels; in such circumstances the traditional point-mass "car model" can underestimate the super elevation needed for safe HGV operations.

Figure 1d, above, illustrates the complex model of forces acting on a HGV, where torque equilibrium at the wheel under the driver corresponds to Equation (1):

$$F*cos(\theta)*h - F*sin(\theta)*(b/2 + d) - G*sin(\theta)*h - G*cos(\theta)*(b/2 + d) + N_1*b = 0 \quad (1)$$

At the rollover threshold, N_1 equals 0 (zero). Then all normal forces are acting at N_2. After division by cos(θ) and rearranging the terms, Equation (1) can be written as Equation (2).

$$h_{rollover} *(F - G*tan(\theta)) = (b/2 + d)*(F*tan(\theta) + G) \quad (2)$$

By solving for maximum CoG height *h* without rollover, the result is given by Equation (3).

$$h_{rollover} = (b/2 + d)*(F*tan(\theta) + G)) / (F - G*tan(\theta)) \quad (3)$$

After inserting definitions of centrifugal force, F = m*v^2 / R, and of gravity G = m*g, Equation (3) can be rewritten as Equation (4).

$$h_{rollover} = \frac{\left(\frac{b}{2}+d\right)*(\frac{v^2}{R}*tan(\theta)+g)}{\frac{v^2}{R}-g*tan(\theta)} \quad (4)$$

Granlund then applies this analysis of rollover to three cases; "The Roundabout", "The Modern Highway Curve" and "The Old Road Curve".

1.2.2 *Road surface friction*

Every road vehicle requires adequate friction from the tyre/road interaction in order to safely complete manoeuvres. As overviewed in (Sanders, Militzer, & Viner, 2017) the major friction demands can be divided into rolling resistance, straight line braking, cornering, and combined manoeuvres. The latter can be very well explained using the friction circle (Figure 2) showing the relationships between the different friction demands.

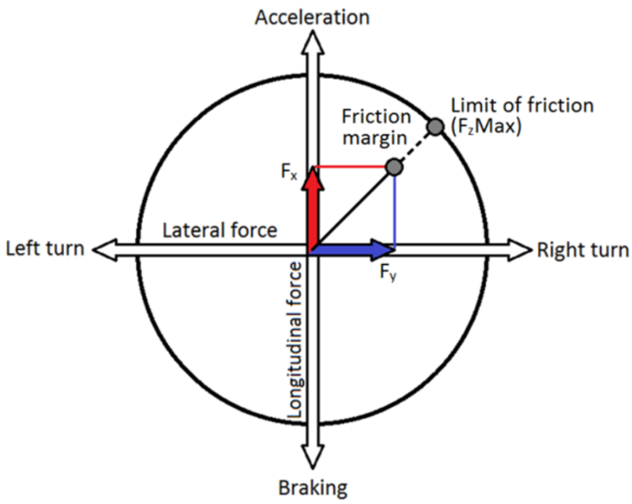

Figure 2: Friction circle (Sanders, Militzer, & Viner, 2017)

At the level of the individual tyre/wheel contact, friction performance can be represented via a three-dimensional interrelationship, with available friction, vehicle velocity and percentage tyre slip as the controlling factors.

Though shown as a circle in Figure 2, it is important to be aware that there would be a unique shape to the friction circle for any combination of road surface type, road surface condition, road alignment, vehicle braking system and tyre design.

A common feature of these circles is that as friction demand increases and with the onset of wheel slip, firstly a sharp peak in friction is experienced (peak friction or μ_{peak}) and then as wheel slip continues to the point at which the wheel is locked and the tyre sliding along the road, a lower level of sliding friction (μ_{slide}) is reached.

1.2.3 Tyre/road interaction

To understand the complexity of the tyre/road interaction, and the continuum of friction parameters it creates, it is useful to visualise a three dimensional 'map' of friction known as a friction profile. Friction profiles present the friction generated by a given surface/tyre combination in relation to vehicle velocity[6] and percentage slip[7]. Figures 2a, 2b and 2c show a friction profile generated from measurements made using the Pavement Friction Tester (PFT[8]).

The friction profiles clearly show the two elements traditionally used to characterise friction, i.e. peak and locked-wheel friction. Peak friction characterises the largest amount of friction generated at any given vehicle speed; it can be present at any slip percentage, but typically

[6] Vehicle velocity is the speed of a vehicle travelling in a given direction.

[7] Percentage slip represents the difference in the vehicle velocity and the rotational speed of the tyre.

[8] A locked wheel friction tester that makes measurements over a full wheel braking cycle at a single test speed.

occurs between 15 and 25 % slip. Locked-wheel friction characterises the friction of a fully sliding tyre, a tyre at 100% slip, at any given vehicle speed.

Using the friction profiles from Figures 2a, 2b and 2c, an attempt has been made to illustrate the complexity of typical manoeuvres made by road vehicles, via several notional paths superimposed on the friction surface: these paths represent the variation in friction/grip experienced by a vehicle conducting various manoeuvres.

It should be noted that the paths marked on the friction profiles are only notional representations of the speed/slip pathways, **they are not based on real test data, and may not be representative of real vehicle performance**. **An initial speed of 100 km/h is assumed in all cases.**

On each of these three profiles:

- Solid lines represent the potential friction domain experienced by uncontrolled emergency manoeuvres without driver aids resulting in loss of control with sliding tyres,
- Long broken lines represent the potential friction domain of emergency manoeuvres where driver aids are active,
- Short broken lines represent the potential friction domain of manoeuvres associated with normal driving.

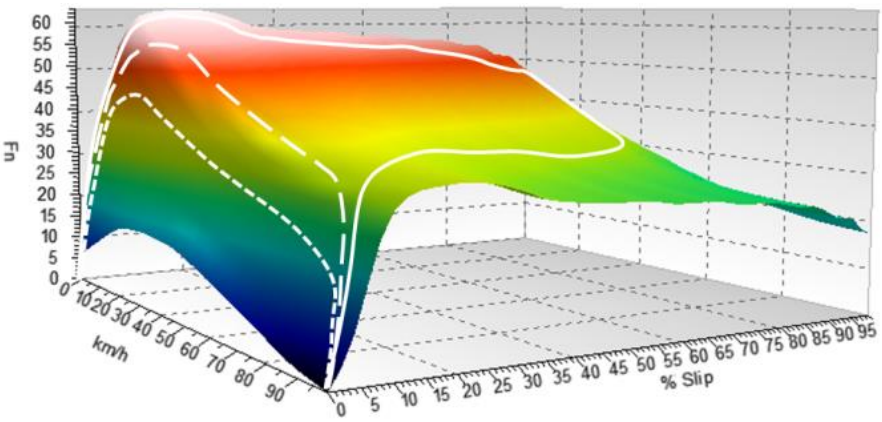

Figure 2a: Straight line braking events

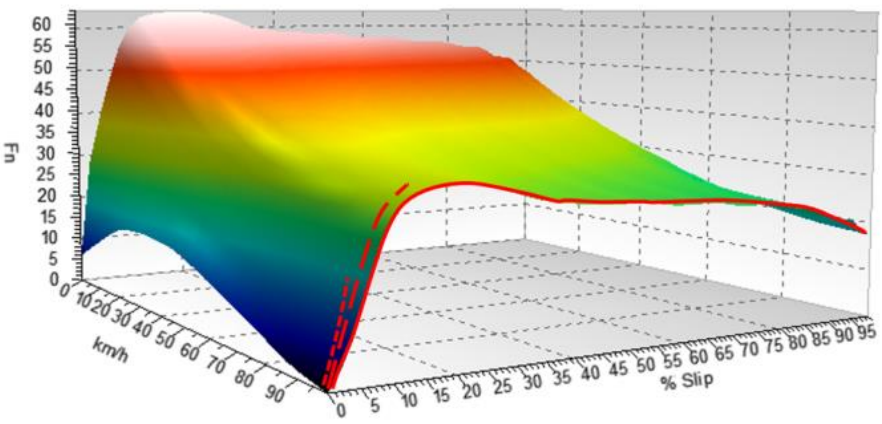

Figure 2b: Turning events without braking

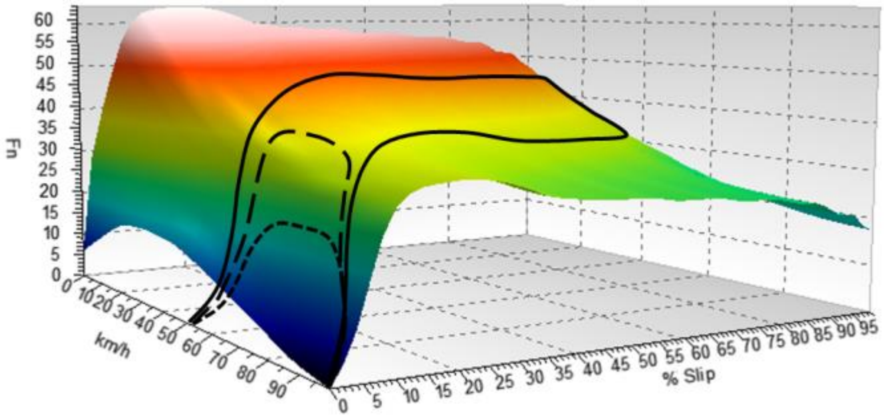

Figure 2c: Turning events with braking

These estimations of typical manoeuvres highlight the complex interplay of vehicle dynamics, braking systems and road surface friction already taking place on the road network. In parallel with the development of autonomous vehicle systems, the measurement of road surface friction has become commonplace with a number of different testing devices available for routine friction measurement; primarily for asset management purposes, and in response to road traffic collisions where the frictional properties of the surface require investigation.

1.3 Road surface friction measurements and real-world braking

Measurements of road surface friction are typically undertaken using standardised test tyres, controlled forward velocities, standardised vertical loads and with water being fed via an integral water feed ahead of the test tyre.

The Sideways-force Coefficient Routine Investigation Machine (SCRIM) is the standard skid resistance measurement device for trunk roads in the UK. SCRIM, like many other friction testing devices, was developed long before the advent of driver aids such as ABS or ESC (Electronic Stability control). SCRIM, as with many other skid resistance test devices, was therefore not designed to measure the levels of peak friction that can be mobilised by the anti-lock braking systems of even the most basic of new vehicles: braking systems delivering controlled levels of wheel slip to ensure both steering and braking can be maintained without skidding.

Road surface friction is typically measured under controlled conditions that represent a worst-case scenario for vehicles without ABS and without visible tyre tread. With the mandatory provision of ABS braking on all new vehicles sold in Europe since 2004, and ESC (Electronic Stability control) on all new vehicles from 2014 onwards and with legislation enforcing a minimum 1.6mm tyre tread depth requirement Europe-wide since 1992, the predominant worst-case scenario for the modern vehicle is likely to be ABS-controlled emergency braking with treaded tyres , rather than locked-wheel braking with bald (smooth) tyres.

The introduction of additional controls to regulate the friction demand on the road (such as ESC) further distances where the modern vehicle frictional demand lies on the friction profiles in Figures 2a to 2c relative to where friction is being measured.

Quantifying the distribution of vehicles with various levels of technology allows the friction demand on the network to be more accurately anticipated. The vehicle fleet still includes older vehicles without the provision of ABS or ESC, however the total mileage driven per year by these vehicles (as a proportion of all vehicle miles driven) is likely to be decreasing as vehicles are scrapped or take on less intensive (lower mileage) uses.

1.4 MOT data and the typical UK fleet

In the UK, annual tests on non-HGV (heavy goods vehicle), non-PSV (public service vehicle) vehicles for basic roadworthiness and emissions control (historically known as the MOT test for Ministry of Transport) have been stored electronically since 2005. This database includes vehicle odometer readings.

The MOT odometer mileage data enables the distribution of vehicles by age to be proportionally represented based on miles driven, since it is highly likely that the older the vehicles the fewer the miles driven year on year.

By interrogating a random sub-set of the MOT test database, a comparison of the total miles driven between MOTs against year of first registration can be made. The graph below (Figure 3) clearly shows the declining number of miles driven by older vehicles. This analysis was undertaken on a dataset of MOT test results for 2006-2016 which was incomplete for 2006 and 2016 and is subject to verification.

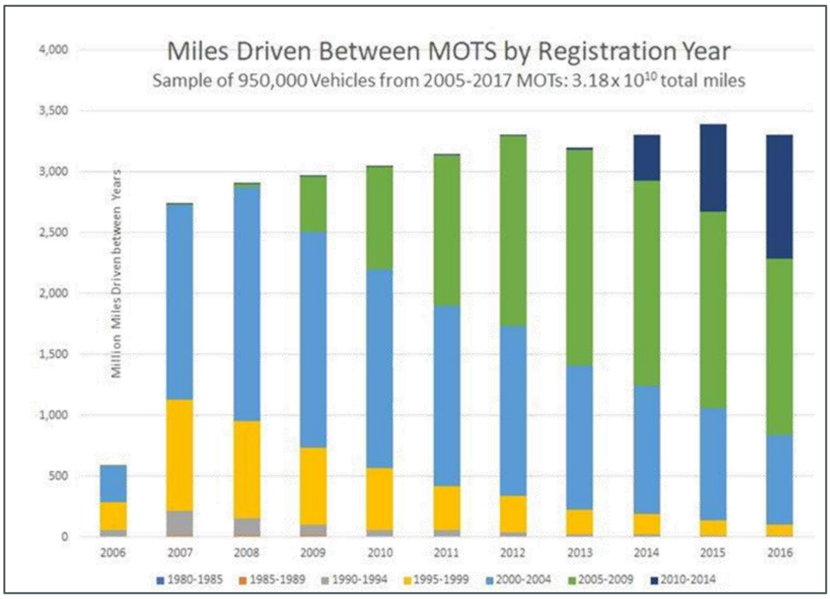

Figure 3: Miles driven between MOTs for Class 4 & 5 vehicles by test year and year of first registration (pers. com. Dr J.C.Bullas[9])

2004 marked the introduction of compulsory ABS, thus the blue, yellow and grey areas of Figure 3 represent the vehicles likely to be without ABS

[9] The graph shown is from an independent analysis of MOT data for Class 4 & Class 5 vehicles for 2006-2016 undertaken by Dr J.C.Bullas in 2019

From Figure 3, pre-2004 vehicles that are unlikely to be equipped with ABS brakes comprise less than 25 percent of the miles driven for the current fleet. It is important to note that the inclusion of mileages prior to the first MOT test have not been included in the above figure.

When the operating ranges of typical wet friction testing devices are considered with reference to the friction profiles described in section 1.2.3, it can be readily seen that no single test device directly emulates the behaviour of modern vehicles:

- Longitudinal fixed slip or sideway-force coefficient devices (such as GripTester, SCRIM etc) sample the friction at a single fixed point on the friction profile. Because vehicle manoeuvres would not conform to a single point on the friction profile, these types of friction measurement systems do not characterise the friction demand of vehicles.
- The PFT measures friction in 2 dimensions through a complete friction/slip cycle at a single speed (the red solid line on Figure 2b) but does not hold its measurement at near-to-peak and so provides a measurement of peak friction that may be highly variable.
- Brake-to-stop tests follow a complete braking cycle at decreasing speed in 3 dimensions (the white solid line on Figure 2a), however they record deceleration and not friction.

In summary, there is evidence to suggest that **over 75% of network miles may be driven by vehicles equipped with ABS braking**, and with an understanding of the commonly used wet friction measurement techniques, one also may conclude that road surface wet friction is not being routinely recorded in a manner that reflects the levels of friction being mobilised by the ABS braking systems fitted to the majority of vehicles on the road.

2 The literature review

The literature review explored the published research relating to HAVs; as already stated, it aimed to investigate the current technologies as they pertain to the use of skid resistance data at vehicle level, on the understanding that the technology can be applied to AVs and CAVs as a subset of the HAV population.

It should be noted that confidential research and development activities by motor manufacturers or their suppliers that may be interfacing vehicles with skid resistance on a network level was not available for review.

It was the aim of the literature review to answer the following questions:

- How are CAVs likely to measure, predict or infer the skid resistance performance of the road surface?
- How will CAVs use this information in different situations, for instance the headway given, or braking times used?

2.1 Structure of the literature review findings

Owing to the large number of references examined, each of the papers has been summarised in the table in the Bibliography (see section 5). The Bibliography table includes several columns identifying:

- Whether the content is a valuable source of background information (Background) and relevant to HAVs. The number of 🕮 symbols indicates a measure of the importance and/or relevance of this content. These papers have not been summarised further.
- Whether the technical content (Tech) may be valuable in the future direction of CAVs interaction with the skidding resistance of the network, the number of 🛠 symbols indicate a measure of the importance and/or relevance of this content. These references have not been summarised further.
- Whether the subject matter of the reference appears to provide a way forwards (Future) for further investigation, or a technology to be adopted soon. The number of ➪ symbols indicates a measure of the importance and/or relevance of this content.

Each reference is accompanied by a summary (in some cases this may be reproduced from the abstract). A number of wide-reaching references have been identified that provide background information, technical content and that also describe future developments. These are summarised in the following sections.

2.2 Specific references of interest

Guanetti, J. and Borrelli, F. (2017) proposed a cloud-aided scheme for electronically controlled suspensions. The cloud hosts a position-dependent road model estimated from car measurements, which is used on the vehicle to parametrize a stochastic model predictive controller (MPC). They show how a stochastic MPC can meaningfully handle these compromises, and how a cloud-aided update of the road model helps to maximize performance. Friction data could be added as another parameter in the road model, work is in progress in this area.

This reference has identified a key area for investigation as a proven pre-existing framework could be exploited with a new data stream: friction

Grimm et al. (2016) described the sensing of road friction conditions by vehicles, collection of the friction data from a large number of vehicles by a central server, processing the data to classify friction conditions by roadway and locale, and sending notifications of the friction conditions to vehicles as appropriate.

Du, Z., Chaudhuri, B.H. & Pisu, P. (2016). In this work, a controller based at an intersection calculated the desired average velocity and optimally assigned reference velocities to local CAVs. Each vehicle uses model predictive control (MPC) to track their individual reference velocity. Though only considering the rolling friction coefficient in the modelling, this work may provide a starting point for modelling CAV behaviours considering road surface friction.

Fors, V, Olofsson, B & Nielsen, L. (2018) investigated the optimal braking and steering patterns in completely autonomous (in the sense that no driver or driver model is assumed) safety-critical manoeuvres in the relevant scenarios of optimal braking and steering in a left-hand turn, in an ISO double lane-change and an avoidance manoeuvre. They examined the effect of different road friction conditions: the braking and steering behaviours remained consistent over different scenarios and different road conditions, suggesting that a single control framework could handle a multitude of situations.

Kane, A. & Koopman, P. (2013) examine the use of ride-through, a technique to reduce the frequency of safety shutdowns by allowing small transient violations of safety rules. In the case of friction data, a missing reading could potentially trigger a similar shutdown response.

2.3 Recommended background reading

Keller (2018) and Allen & Overy LLP (2017) provide a useful background to the legal implications of autonomous vehicles, Johnson (2017) and Pucher et al. (2018), describe the readiness (or otherwise) of the road network for connected and autonomous vehicles. Car Design Research (2016) describes the history of autonomous transport.

Albinsson et. al. (2016), is a recommended read for its technical content of tyre force modelling and Garcia (2019) for its explanation of the Pacejka '94 tyre model parameters.

Domenichini et al. (1996) classifies the SCRIM tyre using the Pacejka Magic Formula, while Cabrera et al. (2018) modelled tyre behaviour from SCRIM using a modified Pacejka Magic Formula with three new parameters.

Chen et. al. (2016), propose a means of estimating tyre/road friction without the need for steering torque or side force. Kritayakirana (2012), describes the development of an autonomous vehicle control system to keep a vehicle at the limits of handling, our present worst-case scenario.

Andriejauskas et al. (2014), for its overview of friction measurement devices, Atkins PLC (2016) for its summary of the impacts of autonomous vehicles. Gee et al. (1996) and Browne (2013), describe the relative advantages of the different levels of autonomy with respect to emergency braking.

Vinnova/Drive Sweden (2017) describes one of the best multi-sensor informatics projects to date.

Panahandeh et al. (2017) used artificial neural networks to estimate road friction from other data.

Song (2014), presents three aspects of autonomous driving near the limit of friction: testbed, estimation and control.

Andersson et al. (2007) investigated three methodologies available to estimate the tyre to road friction, the first based on the forces and torques that are produced at the front tyres at cornering manoeuvres, the second using a physical model of the tyre behaviour to estimate road friction from information on the forces that are produced at straight driving and the third on an optical sensor that classified the road surface ahead of the vehicle. Mention was also made on the potential to feedback sensor data to highways authorities.

2.4 Results of the Literature Review

2.4.1 How are CAVs likely to measure, predict or infer the skid resistance performance of the road surface?

The literature review failed to identify any specific use by HAVs of measurements from pre-existing skid resistance surveys, this somewhat simplistic approach does not appear to have been researched or adopted as a "quick win" by any workers.

From the literature review, road friction parameters within HAV systems are either:

(a) assumed to be fixed (e.g. Zhang et. al, 2018).

(b) measured on the road surface using methods such as ramp turns (e.g. Albinsson et al. 2016).

(c) directly measured "on the fly" in the case of vehicles designed to operate at the point of loss of controls (e.g. Kritayakirana).

(d) measured or estimated using non-contact sensors (Andersson et al., 2007).

(e) measured using validated models of the tyre/road interaction plus information from vehicle sensors during normal running over the network (e.g. Domenichini et al. 1996; Cabrera et al., 2018).

In order to minimise road user delay, by determining appropriate headways, skid resistance data at traffic speed could theoretically be obtained using:

- Validated tyre models and subsequent analysis of CAV sensor data collected from normal driving manoeuvres (such as turning manoeuvres, where a controlled degree of managed tyre slip is expected).
- The use of static or vehicle-mounted non-contact sensors to determine road surface friction (at this point in time this technology should be considered capable of delivering indicative rather than documentary measurements of road surface friction).

2.4.2 How will CAVs use this information in different situations, for instance the headway given, or braking times used?

No evidence was found of any consideration for changes in road surface friction in the calculation of headway or braking times.

As well as being sensitive to component materials and surfacing type, the severity of braking manoeuvres has a well-documented negative impact on the measured wet road surface friction. Junction approaches, downhill gradients and sharp bends are also at high risk of reduced wet road surface friction relative to straight line (so named “non-event” sections).

An integral part of the effective management of networks aimed to deliver a uniform level of wet skidding collision risk is the maintenance of appropriate levels of wet road friction. These may be at a minimum for sections of low wet skidding risk (for example mainline dual carriageways: non-event sections in the UK) and may be at a maximum for sections of high wet skidding risk, such as junction approaches and sharp bends.

When considering how CAVs may use asset information it is important to consider the limiting factors in safe braking manoeuvres:

- If the HAVs maximum rate of controlled deceleration is limited to ensure passenger comfort, then this level of deceleration could be below that delivered by the skid resistance management policy and the manoeuvre could be completed safely.
- If the risk-managed skid resistance falls below the HAVs maximum rate of declaration in emergency braking, this could result in the HAV undertaking a manoeuvre, the friction demand of which exceeds the roads ability to supply it.
- One might infer that a system that assumed a consistently conservative level of wet friction (one less than the network could provide) would, despite ensuring safe completion of braking/deceleration manoeuvres, lead to artificially extended headways.
- Should a circumstance arise whereby the level of wet friction used in headway calculations is greater than the network can provide, this could potentially result in conflict with other traffic on the road.
- Any interplay between required braking demand and the available skidding resistance would necessitate a common reference between the vehicular braking system and the performance of the highway network.
- Should a network operator ultimately possess a database of compatible road surface friction measurements along with road alignment data for each 10 metre section (as provided by TRACS/SCANNER or indeed the HAVs themselves), relatively simple mathematics could be applied to infer the possible effect of these characteristics on the behaviour of a vehicle traversing any given section of road.
- With this comprehensive dataset, **downhill gradients** could have extended safe stopping distances, **radius of curvature** and **crossfall** could dictate some limits on cornering speeds and **levels of available friction** could generate safe stopping distances.

- Thus with a sufficiently detailed understanding of the dynamic behaviour and braking system of an HAV, the forces shown in Figures 1a to 1c could be rationalised and contribute towards **a design envelope for the combined road/vehicle system.**

There is clearly potential to interface two very disparate worlds: those of the infrequent measurements of road surface friction made by asset managers and of the many, many passes of HAVs over the same network, generating data as they go.

The world of the highly-automated vehicle (HAV) is now developing into one of complex data manipulation that should include the frictional properties of the highway.

The HAV world will use information in a proactive manner when and where reactive responses can best be avoided. This form of information transfer should be one of the goals when exploring the future of friction measurement.

The literature review undertaken must realistically be assumed to be but a part of the ever-increasing resource of literature regarding HAV, AV and CAV development. The elements of the review that intersect the realm of routine road surface friction measurement can be viewed as potential alternatives to routine testing with specialist testing devices.

The following chapter uses the common elements described above to map out one particular scenario:

- The traditional role of specialist custom-made survey vehicles (delivering occasional high-precision datasets with a relatively high cost per kilometre) being complemented or replaced by HAVs delivering a semi-continuous data stream at virtually zero-cost, 24hrs per day, 365 days a year.

3 A vision for HAVs, CAVs and skidding resistance

As vehicle systems become more sophisticated the level of autonomy is likely to increase and Table 1, reproduced from the SAE Recommended Practice for Surface Vehicles (SAE (2018)), summarises the levels of vehicle automation. The Recommended Practice sets out the division of roles between vehicle and driver for the different levels of autonomy as follows:

- **This division of roles corresponds to levels 1 and 2:** If the driving automation system performs the sustained longitudinal and/or lateral vehicle motion control subtasks of the Dynamic Driving Task (DDT), the driver does not do so, although s/he is expected to complete the DDT.
- **This division of roles corresponds to level 3**: If the driving automation system performs the entire DDT, the user does not do so. However, if a DDT fallback-ready user is expected to take over the DDT when a DDT performance-relevant system failure occurs or when the driving automation system is about to leave its operational design domain (ODD), then that user is expected to be receptive and able to resume DDT performance when alerted to the need to do so.
- **This division of roles corresponds to levels 4 and 5:** If a driving automation system can perform the entire DDT and DDT fallback either within a prescribed ODD or in all driver-manageable on-road driving situations (unlimited ODD), then any users present in the vehicle while the ADS is engaged are passengers.
- **Level 5 is full automation.**

As fewer legacy vehicles share the network the more efficient the operation of AVs and CAVs may become. Unconnected vehicles should be considered “wildcards” when compared to the level of control that network operators can potentially enforce on AVs and CAVs.

National decisions may need to be made concerning whether the scrapping of older and less autonomous vehicles is incentivised, or made compulsorily, in order to accelerate uptake of AVs and CAVs and provide a more standardised vehicle fleet.

Table 1: Summary of levels of driving automation (after SAE, 2018)

SAE Level	SAE Name	SAE Narrative Definition	Execution of steering / acceleration / deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capability (driving modes)	BASt Level	NTHSA Level
Human driver monitors the driving environment								
0	No automation	The full-time performance by the human driver of all aspects of the driving task.	Human driver	Human driver	Human driver	N/A	Driver only	0
1	Driver assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration / deceleration.	Human driver & systems	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial automation	Part-time or driving mode-dependant execution by one or more driver assistance systems of both steering and acceleration / deceleration. Human driver performs all other aspects of the dynamic driving task.	System	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system ("system") monitors the driving environment								
3	Conditional automation	Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task – human driver **does** respond appropriately to a request to intervene.	System	System	Human driver	Some driving modes	Highly automated	3
4	High automation	Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task - human driver **does not** respond appropriately to a request to intervene.	System	System	System	Some driving modes	Fully automated	3/4

SAE Level	SAE Name	SAE Narrative Definition	Execution of steering / acceleration / deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capability (driving modes)	BASt Level	NTHSA Level
5	Full automation	Full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.	System	System	System	All driving modes		

In terms of the motor industry vision for Connected and Automated Mobility (CAM) for Europe, Pucher (2018) predicts 2020-2030 for the release of Level 4/5 Autonomy vehicles on the European road network (see Table 2).

Table 2 Overview of technology forecasts (after Pucher et al., 2018)

Institute	Aspect	By
European Commission COM (2018) 283 final	Provided the regulatory and enabling framework is in place, vehicles driving themselves under specific driving conditions.	On market by 2020 Commonplace by 2030
Boston Consulting Group	Automated vehicles should represent 20% of global vehicle sales.	2025
ERTRAC	Differentiates three main markets: • Passenger cars • Lorries and freight vehicles • Urban mobility vehicles "In one sentence: in 2050, vehicle should be electrified, automated and shared."	Level 4: mid to late 2020s Level 5: after 2030 Target 2050 exclusively CAM
Honda	"Production vehicles with automated driving capabilities on highways sometime around 2020"	2020
Ford Motor Company	"Fully autonomous vehicle" coming in 2021	2021
Mazda Motor Corporation	"Dreams to be realised until 2030"	2030
Hitachi Ltd.	Autonomous car industry will be worth 50 BEUR in 2030.	2030
Stanford University	"In two years, we'll have 10 million self-driving cars on the road."	2020
Toyota Research Institute	"it is very likely a number of companies will within a decade have level 4 cars operating in specific areas" "none of […] the automobile or IT industries are close to achieving true Level 5 autonomy, we are not even close."	2020-2030

The following sections set out one of many possible timelines for the interplay between HAVs and skid resistance over a 15 year plus period, during which the numbers of un-instrumented, un-connected and ageing vehicles will shrink year-on-year, and the new data streams from HAVs, AVs and CAVs could evolve to a continuous data feed.

3.1 The first 5 years: a time for listening and learning

This initial phase of data exploration will be unidirectional; data collected from vehicle systems will provide a large but relatively uncontrolled dataset, and this data will need to be filtered to provide any measure of correlation with existing controlled highway asset measurement tools.

ABS activation data may highlight where frictional issues exist; such areas may be identified solely by a concentration of ABS triggers or by more complex combinations of vehicle sensor outputs revealed by data mining or the application of machine learning techniques. During this first phase of collection, the assumptions are:

- OEM buy-in is essential for this phase to be successful.
- During this initial phase, there will be very few HAVs on the highway network.
- The vehicle fleet will still include many un-instrumented vehicles, a few lacking even ABS braking.
- The network will have many vehicles fitted with ADAS.
- HAVS will provide the data; asset managers will not be providing data to the vehicles.
- Asset managers will need to develop business models for data exchange and governments will need to establish legislative boundaries/frameworks for data sharing and management.
- The way in which HAVs make use of internally-generated friction data will need to be established via collaborative research between the highways industry and the OEMs.

The exploration of the dataset will identify:

- If HAVs are measuring friction in a way that is meaningful to highway asset managers.
- If highway asset managers are measuring friction in the same way that HAVs are exploiting it.

3.2 +5 Years - the secondary phase: a time for better understanding

At the start of this secondary phase, asset managers will already be aware of how HAVs/ADAS-equipped vehicles are interpreting road surface friction during extreme events; this secondary phase of work will now extend to the collection of routine vehicle data to attempt to establish if the same relationships apply over the whole network and to use these events as the early indicators of road surface friction issues. During this phase:

- OEM buy-in is again essential for success.
- The vehicle fleet will now include far fewer non-HAVs (incentives to scrap/upgrade?).
- Nearly all miles will be are driven by vehicles fitted with ADAS.
- The network will have an increasing proportion of HAVs some of which will be autonomous, a limited number will be connected and autonomous.
- A continuous data stream will be transmitted by all ADAS-equipped vehicles and HAVs.
- HAVS will provide the data, asset managers will not be providing data to the vehicles at this stage.
- Asset managers will increasingly use data from non-survey vehicles to identify changes in pavement condition.
- Asset managers will increasingly be measuring road surface friction in a manner that can be directly interpreted by future HAV systems using the next generation of friction measurement devices.
- Certain routes may be restricted only to vehicles meeting a minimum level of automation.

3.3 +10 Years - the tertiary phase: a time for change and exchange

During this third phase, asset managers will be collecting continuous data from the majority of suitable sensor-equipped vehicles and will start to provide filtered data back to the HAVs for their systems to use.

Asset managers will be monitoring changes in data from vehicle systems as the early indicators of road surface friction issues, with those areas identified being investigated using traditional pavement testing equipment. During phase 3:

- The network will have a significant number of HAVs with many AVs and CAVs
- The network will have close to 100% of vehicles fitted with ADAS.
- Vehicles without sensors (the oldest part of the fleet) will be compulsorily decommissioned.
- Asset managers will now understand how HAVs use road friction data.
- HAVs will be picking up filtered data from highway asset databases maintained by asset managers.
- HAVs will be feeding back road condition data to highway asset databases to supplement or replace formal survey-based datasets.
- Many routes will be restricted to vehicles meeting a minimum level of automation.

3.4 +15 Years - the final Phase: a time for adaptation and sharing

Machine-learning based data mining of sensor information from HAVs will identify the early indications of many road surface issues and automatically generate maintenance requests and trigger immediate alerts sent out to HAVs to moderate their behaviour on these sections. During this final phase:

- The vehicle fleet will be approaching 100% HAVs with more AVs and CAVs in service
- HAVs will be feeding back road condition data to highway asset databases.
- HAVs will be picking up filtered data from highway asset databases maintained by asset managers
- Data from HAVs will replace traditional pavement survey devices.
- Data from HAVs will be used to identify pavement defects and trigger maintenance interventions.
- Most routes will be restricted to only vehicles meeting a minimum level of automation.

4 Conclusions

The literature review has identified several areas for further development; broadly speaking they can be considered as relating to INBOUND data from vehicles that could be exploited for network/asset management or OUTBOUND data from sources maintained by the asset manager that could be used by vehicles on the network. These systems will be relevant to HAVs long before network dominance by AVs or ultimately CAVs.

The areas for further development are:

1) A methodology for the aggregation of INBOUND data from vehicles on the network and the translation of this data into meaningful road friction condition indicators for network management purposes.
2) Calibrated tyre models to enable road surface friction to be accurately estimated from normal manoeuvres. This information to be exploited WITHIN the vehicles own systems in real-time as well as an INBOUND data source for network management purposes.
3) A road friction measurement survey device (to be used in a similar manner such as SCRIM or GripTester is used at present), that can provide a measure of network wide road surface wet friction that can provide OUTBOUND data to be exploited by HAV systems likely to be operating with peak friction as the limiting factor in their braking manoeuvres.

Taking any of these areas forward will require the involvement of both highway authorities and automotive engineering which will require buy-in from manufacturers, whether of the vehicles or of the technology used in their construction.

The proposed timeline, spanning 15 or more years, is comprised of the following phases:

- The first 5 years: a time for listening and learning
- +5 years - The secondary phase: a time for better understanding
- +10 years - The tertiary phase: a time for change and exchange
- +15 years - The final phase: a time for adaptation and sharing

Elements of the above timeline could be completed in shorter times; however when one considers the impact of the legacy fleet and any inertia in the uptake of new technologies (whether due to cost or otherwise), legislation and/or financial incentives may be necessary to move things forward apace.

In any case, the stages of evolution of the network would remain the same regardless of the timescale.

Collection of data from vehicle systems will always require the creation of secure systems to hold data that identifies the time and location of a vehicle at any given time.

From a broader perspective, the integration of friction asset management, road safety and vehicle information systems clearly could present the following benefits:

- Non-subjective HAV sensor data could eliminate the current uncertainty with respect to whether a vehicle experienced low surface friction relative to the levels of in-service friction (according to local management of wet friction standards) or whether the frictional demands were exceptional and exceeded these levels.

- HAVs capturing local temperature and rainfall would provide a valuable resource in the winter when the icing of wet roads in freezing conditions is of greatest concern. Typically, only a few weather stations are installed along a given route; the HAV data stream could deliver a global, metrological data feed.
- Wheel slip caused by ice, snow or surface water could be identified as the data stream would depart from that typical of dry weather conditions.
- HAVs could provide data capable of localising areas where non-injury collisions were occurring, which may be the precursor to future personal injury collisions.
- HAV vehicle-to-vehicle data-streams may, for the first time, identify near-misses between vehicles which may be analysed and acted upon in a way akin to that of the aviation industry.

In order to maximise these benefits highways engineers should be seeking to integrate their systems and methodologies with the data delivered by todays HAVs and to try to keep pace in a fast-moving technological environment that will ultimately be responsible for the rip tide of data unleashed when the network is flooded with AVs and CAVs.

5 Bibliography

The following bibliography documents the references examined in the course of this literature review that were found to include relevant content.

In a departure from tradition, the Bibliography below has been augmented with a measure (via symbols) of the value of the content against three areas of interest: background information 🕮, technical content 🛠 or “the future”⇨. Though subjective rather than objective, the greater the number of a symbol, the greater the relevance to that area of interest.

Reference	Summary of content	Back-Ground	Tech	Future
Acosta, M., Kanarachos, S., Blundell, M. (2017), “Road Friction Virtual Sensing: A Review of Estimation Techniques with Emphasis on Low Excitation Approaches”. Appl. Sci. 2017, 7, 1230; doi:10.3390/app7121230	In this paper, a review of road friction virtual sensing approaches was provided. This work attempted to address whether the road grip potential can be estimated accurately under regular driving conditions in which the vehicle responses remain within low longitudinal and lateral excitation levels. As the detection of μ_{max} was not the main aim of this work, additional results or discussion on this topic were not provided.	🕮		
Albinsson, A. et al. (2016), “Design of tyre force excitation for tyre–road friction estimation”. Vehicle System Dynamics, November 2016.	This paper investigated different excitation strategies for tyre-road friction estimation using active tyre force excitation. Optimized excitations were compared to other excitations that could be implemented in real-time in a vehicle with limited information about the road surface. Depending on the tyre-road combination, the required utilization varied between 40 and 65% in a noise free environment. Hence, without any measurement noise, 65% friction utilization will give a friction estimation error of below 0.1 in normalized force for all of the tested tyre-road combinations using a real-time implementable excitation strategy.	🕮	🛠🛠🛠	⇨
Alharbi, F. (2018). "Predicting pavement performance utilizing artificial neural network (ANN) models" (2018). Graduate Theses and Dissertations. 16703. https://lib.dr.iastate.edu/etd/16703	In this research, historical climate data was integrated with pavement condition data to include all related variables in prediction modelling. An artificial neural network (ANN) model was used to predict the performance of ride, cracking, rutting, and faulting indices on different pavement types. The goodness of fit of the ANN prediction models was compared with multiple linear regression (MLR) models. The results showed that ANN models were more accurate in predicting future conditions than MLR models. The contribution of input variables in prediction models were also determined and discussed.			⇨⇨
Allen & Overy LLP (2017), “Autonomous and connected vehicles: navigating the legal issues”. Allen & Overy LLP, London E1 6AD	Not since the days of Henry Ford has the automotive industry been at such a point of opportunity and disruption. – Uber and Volvo Cars signed a USD300m deal for Volvo to provide SUVs to Uber for autonomous vehicle research.	🕮🕮		

Reference	Summary of content	Back-Ground	Tech	Future
	– General Motors invested USD500m in Uber rival Lyft to develop a fleet of autonomous electric taxis. – Google and Fiat Chrysler are working together to build 100 autonomous minivans, doubling the size of Google's autonomous test fleet. – BMW and Israeli company Mobileye teamed up to build and commercialise driverless cars. – Audi, Mercedes, BMW bought Nokia's mapping company for USD3 billion to deliver more precise maps in their connected vehicles. Market players wanting to take advantage of the opportunities presented by the connected car will, however, need to consider a wide range of legal issues, including regulatory challenges, data protection and security issues, technology standards and interoperability, IP ownership, antitrust aspects and liability questions.			
Andersson, M., Bruzelius, J. et. al. (2007), "Road Friction Estimation", IVSS Project Report, Saab Automobile AB, Reference2004:17750.	This document investigated three methodologies available to estimate the tyre to road friction, the first based on the forces and torques that are produced at the front tyres at cornering manoeuvres, the second using a physical model (the Brush model) of the tyre behaviour to estimate road friction from information on the forces that are produced at straight driving and the third on an optical sensor that classified the road surface ahead of the vehicle. Mention was also made on the potential to feedback friction sensor data to highways authorities.	🕮	🛠	
Andreasson, E. (2017) "Validation of Friction Estimating System", BSc Thesis, Department of Engineering Sciences and Mathematics, Luleå University of Technology,	Investigation of the relationship between the commercially-developed NIRA Dynamics TGI (Tyre Grip Indicator), the ROAR and the ViaFriction devices. Poor content as regards correlation coefficients or statistical analysis.			⇨
Andriejauskas T. et al. (2014), "Evaluation of skid resistance characteristics and measurement methods", 9th International Conference, Environmental Engineering, 22–23 May 2014, Vilnius, Lithuania	Useful overview of skid-resistance measurement devices.	🕮🕮	🛠🛠	

Reference	Summary of content	Back-Ground	Tech	Future
Ars Technica (2019), “Waymo announces 7 million miles of testing, putting it far ahead of rivals”, online reference, https://arstechnica.com/cars/2018/06/waymo-announces-7-million-miles-of-testing-putting-it-far-ahead-of-rivals/	AV stats: It took Waymo (then Google) more than a year to get from 1 million to 2 million miles. Then it took about six months each to get to 3 million and 4 million miles. Waymo logged its next million miles in about three months, three and a half months later, the company had racked up 2 million additional miles. No one else in the industry is close to matching the scale of Waymo's testing. Uber had logged roughly 3 million miles before it was forced to suspend testing in March due to a fatal crash in Tempe, Arizona. GM's Cruise drove only 131,000 miles in California between December 2016 and November 2017.	🕮		
Atkins PLC (2016), “Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow”, Summary Report, Atkins PLC for Department of Transport, May 2016.	VISSIM Modelling of CAVs- The potential for reductions in network performance, rather than improvements Substantial benefits may not be achieved until high levels of connectivity and automation Benefits to congested networks Low speed urban areas may benefit most from low-tech driver assistance capability Reliability is likely to improve Benefits are not constrained to one class of user	🕮🕮		
Beal, C.E. (2016), “Independent Wheel Effects in Real Time Estimation of Tire-Road Friction Coefficient from Steering Torque”, IFAC-PapersOnLine 49-11 (2016:) 319—326, International Federation of Automatic Control	The use of steering torque to identify the surface friction coefficient of the road was presented as a possible way to perform estimation of friction in real time using only the normal driving dynamics of the vehicle. There are many applications that can benefit from improved accuracy in on-board friction estimates. The large variability in the steering torque measurements due to variations in the left and right tyre forces and moments can be significant leading to model mismatches - particularly in the key region of low to medium lateral acceleration. The paper illustrates the weak signal-to-noise ratio for steering torque in carefully controlled experiments and demonstrates that the lumped—axle		🛠🛠	⇨

Reference	Summary of content	Back-Ground	Tech	Future
	assumption may lead to poor estimates of the front axle peak force value when attempting to predict it at slip angles less than those required for full saturation of both wheels			
Best, A. et al. (2017), "AutonoVi: Autonomous Vehicle Planning with Dynamic Maneuvers and Traffic Constraints". IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). https://doi.org/10.1109/IROS.2017.8206087 http://gamma.cs.unc.edu/AutonoVi/video.avi (video included)	The modelled sensing module in this project provided a reasonable value of the friction coefficient μ, this approach required computing new vehicle dynamics functions for different values of μ, the authors planned to address this limitation in future work by learning a transfer function between various road frictions to produce more general data-driven vehicle dynamics functions. In addition, they have assumed perfect sensing in the current technique, and it would be useful to consider sensing errors and uncertainty in their approach.			⇨
Best, A. et al. (2017), "AutonoVi-Sim: Autonomous Vehicle Simulation Platform with Weather, Sensing, and Traffic control", 31st Conference on Neural Information Processing Systems (NIPS 2017), 31 October 2017	AutonoVi-Sim is a platform for autonomous vehicle simulation with the capacity to represent various vehicles, sensor configurations, and traffic conditions. AutonoVi-Sim facilitates training of deep-learning algorithms by enabling data export from the vehicle's sensors, including camera data, LIDAR, relative positions of traffic participants, and detection and classification results. AutonoVi-Sim allows for the rapid prototyping, development and testing of autonomous driving algorithms under varying vehicle, road, traffic, and weather conditions			⇨
Bezzina, D. and Sayer, J. (2015), "Safety pilot model deployment: Test conductor team report". (Report No. DOT HS 812 171). Washington, DC: National Highway Traffic Safety Administration.	The U.S. Department of Transportation undertook the Safety Pilot Model Deployment (SPMD). The objective of the SPMD was to support the evaluation of dedicated short-range communication technology for V2V safety applications, which operate at 5.9 GHz in a real-world, concentrated environment. The focus was to collect data to support (1) the functional evaluation of V2V safety applications, (2) the assessment of the operational aspects of messages that support vehicle-to-infrastructure (V2I) safety applications, and (3) comprehension of the operational and implementation characteristics of a prototype security operating concept. The host-vehicle outgoing signals included GPS location, heading, speed, and quality along with vehicle CAN information (only the devices in CCV-IT		⚒⚒	

Reference	Summary of content	Back-Ground	Tech	Future
	program had a CAN interface) like speed, yaw-rate, throttle, steer, brake, wiper, and turn-signal state.			
BhaiTech (2017), “Autonomous vehicle tires”, www. Automotive Testing Technology International.com, March 2017	BhaiTech Intelligent Tyre (BIT) is now available and is currently undergoing testing. BIT technology recognizes the tire forces and delivers real-time information about tire-road interaction and changing conditions, from the reaction to the type of asphalt to the grip and skid margins. Among several other important quantities, limit road-tire friction coefficients are calculated and seamlessly conveyed to the car’s active safety systems to guarantee safe vehicle operation in relation to the actual environment conditions.		🛠	⇨
Bian, M. et al (2014), "A Dynamic Model for Tire/Road Friction Estimation under Combined Longitudinal/Lateral Slip Situation", SAE Technical Paper 2014-01-0123, 2014, Society of Automotive Engineering, doi:10.4271/2014-01-0123.	A modified tire model to estimate the friction force between tire and road interface based on the original Dugoff model could calculate both the longitudinal and lateral tyre friction forces under different wheel slip conditions with results that are comparable to those of the commonly used Magic Formula tyre model, while the modified tire model needs less computation load than the MF. Simulation was done under longitudinal, lateral and combined wheel slip/sideslip situations, and the tyre-road forces were consistently estimated quickly and close to the simulation values. The proposed model can capture the dynamic characteristics of tyre forces along with the change of various tyre dynamics states. Therefore, it is considered that this modified Dugoff model is valid for vehicle dynamics analysis and simulation.		🛠🛠	
Browne C. (2013), “Autonomous Braking: A Comparative Study of Human, Hybrid and Autonomous Braking Control for Cars”, ANU College of Engineering & Computer Science, Australian National University, Canberra, Australia. Online: users.cecs.anu.edu.au/	Advantages of autonomous braking / cost of autonomous sensors. Potential of autonomous braking to improve fuel efficiency for cars by 10-20% and reduced congestion as cars can stop closer to one another.	🕮	🛠	

Reference	**Summary of content**	**Back-Ground**	**Tech**	**Future**
~Chris.Browne/ ..student_work/.../15_2226_lp_jamesl.pdf				
Bullas, J. C. (2007) “Bituplaning: A Low Dry Friction Phenomenon of New Bituminous Road Surfaces”, Thesis for the Degree of Doctor of Philosophy, Transportation Research Group, School of Civil Engineering and the Environment, University of Southampton.	A useful study of the skid-to-stop test procedure routinely used by the police, and analysis of the data created and an investigation of the nature of low dry skidding events and the factors causing them.	🕮	🛠🛠	
Cabrera, J. A. et al. (2018) “A Procedure for Determining Tire-Road Friction Characteristics Using a Modification of the Magic Formula Based on Experimental Results” Sensors 2018, 18, 896	Modelling tyre behaviour from SCRIM. Tests were conducted in a straight line and with the road in two different conditions: wet and dry. No ABS was used, so the wheels locked during the tests. Therefore, the linear speed of the wheel was taken as the longitudinal speed of the vehicle. A Rotating Wheel Dynamometer model P625 by Kistler used to measure vertical and longitudinal tire forces. SCRIM and road tyre characteristics were calculated for modelling friction The modification of the equation of the longitudinal friction coefficient of the Pacejka Magic Formula by means of the proposed three new parameters fits the test data adequately. Besides, it provides better estimates of the friction coefficient vs slip ratio. Therefore, the tire-road interaction has been characterized more realistically. It is well-known that the longitudinal force vs slip ratio curves are of great importance in the design of active safety systems such as ABS, Traction Control System (TCS).		🛠🛠	
CDR (2016), “Autonomous Car Design Contexts By Car Design Research for GATEway Driverless Car Project”, Car Design Research, March 2016	Historical context of autonomy in transport, Self-guided torpedoes and guided missiles, Autopilot – automatic flight control system (AFCS), Autonomous space vehicles, Military autonomous vehicles, automatic train operation, personal rapid Transit – podcars, key autonomous car developments, DARPA Challenge, 2009 on Google, 2014 on Tesla,	🕮🕮		
Centre for Connected & Autonomous Vehicles (2018), “UK Connected & Autonomous Vehicle Research & Development Projects 2018”. Centre for Connected & Autonomous Vehicles, HMSO.	CAV implementation will help unlock the potential benefits which could include:		🛠	

Reference	Summary of content	Back-Ground	Tech	Future
	• Improved safety – automated technologies which reduce and/or remove the need for human driver input will help improve safety • Optimised use of travel time – as driver attention is no longer needed for the driving task, the driver's time can be utilised on other tasks on their journey • Improvements to transport network performance • Increased mobility, enhanced quality of life and improved social inclusion – for those who may not have access to a vehicle or do not have a driving license.			
Cheatham, B. et al (2019), "Confronting the risks of artificial intelligence". McKinsey Quarterly, April 2019.	The interface between people and machines is a key risk area. Among the most visible are challenges in automated transportation…… accidents and injuries are possibilities if operators of …vehicles…. don't recognize when systems should be overruled or are slow to override them because the operator's attention is elsewhere—a distinct possibility in applications such as self-driving cars.	🕮		
Chen, L. et al. (2016), "Wheel Slip-Based Evaluation of Road Friction Potential for Distributed Electric Vehicle", SAE Technical Paper 2016-01-1667, 2016, doi:10.4271/2016-01-1667	A 'wheel slip based' maximum road friction coefficient estimation method based on a modified Dugoff tire model for distributed drive electric vehicles was proposed in this paper. It aimed to evaluate the road friction potential using standard sensors equipped on production vehicles. The simulation and a test vehicle test show that this method has short convergence time and higher estimation accuracy.		🛠	⇨⇨
Chen, L. et. al. (2016), "The relationship between the resonance frequency of a steering system and the tire-road friction coefficient", The 13th International Symposium on Advanced Vehicle Control, Munich, Germany, September 2016	In this paper, a relationship between the resonance frequency (RF) of a steering system and TRFC (tyre-road friction coefficient) is observed by studying the dynamic characteristics. An equation of steering system resonance frequency is deduced, which is related to TRFC. As a future research direction, it can be used to propose an estimation method of the road condition without the information of the sideslip angle and aligning torque.		🛠	⇨⇨

Reference	Summary of content	Back-Ground	Tech	Future
Cuerden, R. (2019), “Advanced Driver Assistance Systems”, A Direct Line and Brake Survey Report, Impact Journal Spring 2019, The Journal of the Institution of Traffic Accident Investigators.	A survey of 2010 drivers on ADAS and an overview of ADAS systems accessible in 2019.	🕮	🛠	
Deligianni, S.P. et al (2017). “Analyzing and modelling drivers' deceleration behaviour from normal driving”. Transportation Research Record, 2663, pp.134-141	This paper studies the deceleration events, observed from normal driving, and models the braking behaviour. The most used deceleration profile, which is felt as “natural and comfortable”, was defined. The initial speed, the distance, the estimation of the deceleration profile and the reason of braking are the most significant variables affecting those events. This paper concentrated on the comfort of autonomous vehicles, by imitating human behaviour and incorporated various driving scenarios. It is important for the acceptance of the autonomous vehicle to guarantee not only the safety of the passengers but also the comfort in order to gain their trust. What should be noted is that the values of deceleration observed are typically well below the values commonly assumed as normal for dry or wet roads.	🕮	🛠🛠	
Department for Transport (2015), “The Pathway to Driverless Cars”, Summary report and action plan, HMSO February 2015.	This document lays out the Government’s plans to facilitate the testing and production of vehicles in which the driver can choose to use their travel time in ways that have never previously been possible. It sets out a framework to support the testing of automated vehicles, to encourage the largest global businesses to come to the UK to develop and test their technologies.	🕮		➪
Domenichini L. et al. (1996),” Significance of SCRIM-Measurements in Vehicle Motion Simulation Models”, Proceedings of the Third International Symposium on Pavement Surface Characteristics; Christchurch, New Zealand. 3–4 September 1996; pp. 81–97.	A method of describing the SCRIM test tyre characteristics in terms of the Pacejka model (Magic Formula) and establishing a correlation between the Pacejka’s parameters describing the SCRIM tyre on one hand and different commercial tyres on the other.	🕮🕮	🛠🛠	➪

Reference	Summary of content	Back-Ground	Tech	Future
Du, Z. et al (2016), “Distributed Coordination of Connected and Automated Vehicles at Multiple Interconnected Intersections”, World Academy of Science, Engineering and Technology, International Journal of Computer and Information Engineering, Vol:10, No:6, 2016	A distributed control solution was proposed where, in the higher level, the intersection controller calculates the desired average velocity and optimally assigns reference velocities to each CAV. In the lower level, every vehicle is considered to use model predictive control (MPC) to track their reference velocity obtained from the higher-level controller. Though only considering rolling friction coefficient the modelling may provide a starting point for modelling CAV behaviours considering road surface friction.		🛠	⇨⇨⇨
Elmas C. et al. (2015), “Tire-Road Friction Coefficient Estimation and Experimental Setup Design of Electric Vehicle”, Balkan Journal Of Electrical & Computer Engineering, Special Issue 2015, Vol.3, No.4	The Burckhardt tyre model was used as it is particularly suitable for analytical purpose while retaining a good degree of accuracy in the description of the friction coefficient		🛠	
eMove360 (2019), “Rain, Snow and Ice – Continental Uses Road Condition Detection for Active Driving Safety”, – eMove360° Online, https://www.emove360.com/rain-snow-and-ice-continental-uses-road-condition-detection-for-active-driving-safety/ 1	“We use sensors available in the vehicle for the Road Condition Observer to gain information on the grip of the road surface,” says Bernd Hartmann, Head of the Enhanced ADAS (Advanced Driver Assistance Systems) & Tire Interactions project group within the Advanced Engineering Department of Continental’s Chassis & Safety Division. “This knowledge allows us to adjust the functions of advanced driver assistance systems to the actual road conditions. To prevent an impending collision, automatic emergency braking for example must be initiated considerably earlier on a wet road than on a dry one.” Continental has managed to develop a system that recognizes the road condition and allows a classification in dry, wet, snow-covered and icy. In addition to the vehicle dynamics sensors in the car, a mono camera is also used.		🛠	⇨⇨
EuroRAP (2013), “Roads that Cars can Read (A Quality Standard for Road Markings and Traffic Signs on Major Rural Roads)”, Eurorap, Nov. 2013, Basingstoke.	Peripheral to road surface friction but ESSENTIAL for the operation of autonomous vehicles, effective road markings must be clearly visible to the driver, day and night, and in all weathers. Their effectiveness depends on their luminance (how well the marking stands out on the road), and their retro-reflectivity (the amount of light reflected to the driver to make the marking visible).	🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
	There are European standards that stipulate different levels of retro-reflectivity in varying weather conditions. The performance level a "good" road marking should achieve under both wet and dry conditions has been proposed by ERF. This level is already in place in some European countries, is realistic, technically feasible and cost effective. For their part, the vehicle manufacturers (ACEA) have identified and prioritised high, medium and low factors that could adversely impact on the operation and performance of lane departure and lane keeping systems: • High Factor: Road surface condition (wet, ice etc), worn out markings, multiple confusing road markings, old road markings not completely obscured even if blacked out • Medium Factor: Road gradient, road curvature, boundaries between multiple lanes • Low Factor: Lane width (too narrow, too wide), visibility (e.g. fog)			
Fleet News (2019), "Weather data service launched for autonomous vehicles", https://www.fleetnews.co.uk/news/manufacturer—news/2018/07/31/weather-data-service-launched-for-autonomous-vehicles	Bosch has announced a partnership with global weather information provider Foreca, which will deliver road condition prediction services for autonomous vehicles. The new services will help automated vehicles emulate the 'feel' of the road sensation that drivers use when behind the wheel, allowing vehicles to adapt driving style and decision-making in anticipation of hazards. This means an automated vehicle will know exactly where it can drive in automated mode, and how.			⇨
Fors, V (2018), "Formulation and interpretation of optimal braking and steering patterns towards autonomous safety-critical manoeuvres", Vehicle System Dynamics, DOI: 10.1080/00423114.2018.1549331	Investigated the optimal braking and steering patterns in completely autonomous (in the sense that no driver or driver model is assumed) safety-critical manoeuvres in the relevant scenarios of optimal braking and steering in a left-hand turn, in an ISO double lane-change and an avoidance manoeuvre. Examined the effect of different road friction conditions: the braking and steering behaviours…. remain consistent over different scenarios and different road conditions, suggesting that a single control framework could handle a multitude of situations.		🛠🛠	⇨⇨

Reference	Summary of content	Back-Ground	Tech	Future
Freixas, M. R. (2016) “Effects of driving style on passengers comfort: Research on the influence of the bus driver’s style on public transport users”, School of Architecture and the Built Environment, Department of Transport and logistics, Kungliga Tekniska Högskolan	A detailed analysis of the nature of sources of discomfort on public transport (buses)	🕮	🛠	
Garcia A. (2019). “Pacejka ’94 parameters explained – a comprehensive guide”, online: https://www.edy.es/dev /docs/ pacejka-94-parameters-explained-a-comprehensive-guide/	Though targeted at the simulation of vehicle tyre/road interaction behaviour in the video game domain, this resource provides a clear explanation of the Pacejka 1994 model parameters.		🛠🛠	
Gee T. A. et al. (1996), “Braking analysis for collision avoidance – autonomous braking system performance modelling and benefits analysis”. Report No. 95-007, Contract No. DTNH22-94-Y-07016, Eaton Corporate R&D Detroit Center for the U.S. Department of Transportation, National Highway Traffic Safety Administration, Office of Crash Avoidance Research, Washington, D.C	The accident reduction simulations presented in this report indicated that a potential existed for reducing the stopping distances of heavy commercial vehicles equipped with a collision warning system and an autonomous braking system. The accident reduction modelling also predicted that such a system could be responsible for preventing a large percentage of certain types of rear end crashes where the lead vehicle is stationary. The simulation effort showed that over 78% of these crashes could be prevented with a collision warning system and some measure of autonomous braking. Dry friction (mu) was assumed to be 0.75, wet friction (mu) was assumed to be 0.50.	🕮🕮	🛠	
Gordon T.J. and Lidberg M. (2015) “Automated Driving and Autonomous Functions on Road Vehicles”, Vehicle System Dynamics International, Journal of Vehicle Mechanics and Mobility Volume 53, 2015 - Issue 7: State of the Art papers of the 24th IAVSD	A review of the evolution of the intelligent vehicle and the supporting technologies with a focus on the progress and key challenges for vehicle system dynamics. Several relevant themes around driving automation are explored with special focus on those most relevant to the underlying vehicle system dynamics. One conclusion is that increased precision is needed in sensing and controlling vehicle motions. Also, a discussion on mapping accuracy, last time to brake (LTTB) calculations & estimated surface friction and Automatic Control at the Limits of Friction is also discussed.	🕮🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
Granlund, J. et. al. (2014), "Lowered crash risk with banked curves designed for heavy trucks". 13th International Symposium on Heavy Vehicle Transportation Technology - HVTT13, San Luis, Argentina.	The study used a vehicle model including both vertical and lateral position of Centre of Gavity (CoG), as well as road split friction under left/right wheels. The results showed that super-elevation demand increases with height and lateral displacement of CoG, and peaks when the curve is more slippery under outer wheels than under inner wheels. A conclusion was that the traditional point-mass “car model” can underestimate the super-elevation needed for safe HGV operations. The paper recommends some improvements in road design codes for new curves, as well as some actions to improve safety in existing curves.	🕮	🛠🛠	
Grimm et al. (2016), United States Patent No: US 9,475,500 B2: *“Use Of Participative Sensing Systems To Enable Enhanced Road Friction Estimation”*, Oct. 25, 2016 GM Global Technology Operations LLC, Detroit, MI (US).	Methods and systems are disclosed for participative sensing of road friction conditions by vehicles, collection of the friction data from many vehicles by a central server, processing the data to classify friction conditions by roadway and locale, and sending notifications of the friction conditions to vehicles as appropriate. Many vehicles use participative sensing systems to identify road friction estimates which are reported to the central server where the vehicles use sensor data and vehicle dynamic conditions to estimate friction. The central server stores and aggregates the friction data, filters it and ages it. Vehicles requesting advisories from the central server will receive notices of road friction conditions which may be significant based on their location and heading. Driver warnings can be issued for low friction conditions ahead, and automated vehicle systems may also respond to the notices.		🛠🛠	⇨⇨
Guanetti, J. and Borrelli, F. (2017) *“Stochastic MPC for cloud-aided suspension control”,* 2017 IEEE 56th Annual Conference on Decision and Control (CDC), December 12-15, 2017, Melbourne, Australia	A cloud-aided scheme for electronically controlled suspensions was proposed where the cloud hosts a position-dependent road model estimated from car measurements, which is then used on the vehicle to parametrize a stochastic model predictive controller (MPC). It is shown how a stochastic MPC can meaningfully handle these compromises, and how a cloud-aided update of the road model helps to maximize performance.		🛠🛠	⇨⇨⇨
Guanetti, J. et al. (2018), *“Control of connected and automated vehicles: State of the art and*	Review of system components, automated vehicle control architecture for connected and connected and automated, on-board real-time control and planning, challenges and opportunities for CAVs.		🛠🛠	⇨⇨⇨

Reference	Summary of content	Back-Ground	Tech	Future
future challenges" , Annual Reviews in Control, Volume 45, 2018, Pages 18-40	In the deployment of cooperative driving controls, known challenges included the diversity of communication topologies and protocols, communication delays, packet losses, and complex dynamics. While progress has been made to systematically analyse these complex and heterogeneous systems (at least in the highway platooning case), a comprehensive framework was still lacking at present. A Model Predictive Control (MPC) approach for a plug-in hybrid electric CAV and a cooperative adaptive cruise control collision avoidance system were proposed.			
Gupta S. et. al. (2011), *"Estimating Road Friction for Autonomous Vehicles",* CS229 Machine Learning Final Report, Stanford University, California, USA	Ramp steering at discrete locations to estimate Mu. Data was collected on a production Audi TTS fitted with a high precision integrated GPS/INS unit and drive-by-wire capabilities. The vehicle was part of Stanford's Dynamic Design Lab and was used to research autonomous driving at the limits of handling. Friction estimation was not used on the vehicle but having a real-time estimate of friction could drastically improve the speed and safety of its autonomous driving at the limits of handling. Soft Max and Gaussian discriminant analysis (GDA) were tested, however neither classifier performed well enough to be acceptable as an in actual implementation on the car. A support vector machine (SVM) algorithm was implemented using the C-Support Vector Classifier and several SVM Kernels tested. These results indicate that ramp steers are not general enough to use as training data for a classifier to predict friction during any driving manoeuvre (which would have been ideal); instead, the algorithm must be trained with the manoeuvres that the vehicle would experience.		🛠🛠	
Haresh, R., and Harri, J. (2016), *"Coordinated Braking Strategies Supporting Mixed Autonomous and Conventional Vehicles",* Research Report RR-16-321, August 22nd, 2016, EURECOM, Sophia Antipolis cedex, France	Modelling of AV interactions using a maximum acceleration of 1.4 m/s^2 and a maximum deceleration of 0.6g m/s^2 (note the addition of g here). First and second approaches assume decent road conditions. If a road surface "with some oil or sand spill (roads considered dirty)" was considered", maximum deceleration was physically restricted to $4m/s^2$ and the maximum speed limited to 80km/h (50mph).	📖	🛠🛠	

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	The Intelligent Driver Model (IDM) used in Adaptive Cruise Control (ACC) is a typical driving strategy, originally a microscopic traffic flow model falling in the case of Follow-the-Leader models, and which therefore adjusts vehicle acceleration according to the driving dynamics of the vehicle immediately following it. IDM has been shown to avoid creating accidents with preceding vehicles, and through subsequent extensions (IIDM, IDM+). Considering a mixed traffic scenario, IDM was evaluated for its ability to not only avoid collision with the obstacle, but also with the preceding vehicle: IDM couldn't assure collision avoidance of the following vehicle onto itself whereas the proposed algorithm did: a dynamic braking strategy with a first phase avoiding strong braking to mitigate read-collision, and a second phase performing a conventional braking to avoid forward collision.			
Highways England (2017), *"Connecting the Country, Planning for the long term"*, Highways England, Guildford GU1 4LZ UK, December 2017	Theme 2: Connected and autonomous vehicles: Areas of Focus 1. Supporting connected cars – where HE will focus on maximising the benefits of the increase in connectivity of the fleet, given the projected rates of uptake of connected technology 2. Preparing for the operation of a mixed fleet – where HE will seek to understand and address the challenges around safe operation and communications that come through the presence of early adopters of CAV technology on the network, likely to be from Road Period 2 onwards 3. Developing HE's role in supporting and enabling CAVs – where HE will develop its approach to ensure that it maximises the capacity and safety benefits that CAVs offer, using the volume of data available to HE as a network operator and the intelligence and sophistication of the fleet. Theme 5: Operations Areas of focus HE will focus on (including): 2. Data-driven operations – where HE expects to collect better data on their assets and how their network is performing in real time. HE will aim to use	📖📖📖		

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	this data to inform their asset management operations as they aspire to move towards predictive condition monitoring and maintenance.			
Hildebrand, E.D. and Lewis J (2010), *"Driver tolerance of lateral accelerations on horizontal curves"*, Can. J. Civ. Eng. 37: 1–7 (2010)	Ball-bank measurements of curve severity (one acceptable method of determining safe cornering speed used in USA).		🛠	
Horst J., and Barbera A. (2005), *"Trajectory Generation for an On-Road Autonomous Vehicle"*, NIST IR, Gaithersburg, Maryland, USA, September, 2005	This Paper describes an algorithm that generates a smooth trajectory (position, velocity, and acceleration at uniformly sampled instants of time) for a car-like vehicle autonomously navigating within the constraints of lanes in a road. The technique models both vehicle paths and lane segments as a straight line. The algorithm moves a vehicle in lane safely and efficiently within speed and acceleration maximums. The algorithm functions in the context of other autonomous driving functions within a carefully designed vehicle control hierarchy. "Due to the radial warping of paths, our approach to vehicle trajectory generation is always safe, but sub-optimal with respect to efficiency, while gaining elegance, simplicity, and some computational efficiency."		🛠	⇨⇨
Husch, B. and Teigen, A., (2017), *"LegisBrief - Regulating Autonomous Vehicles"*, National Conference of State Legislatures (NCSL), APR 2017, Vol. 25, No. 13	To date in 2017, 28 states have introduced legislation related to autonomous vehicles. The Federal Autonomous Vehicle Policy includes no new rules or regulations—only guidance for states. Tennessee allows drivers to view a visual display, like a television or movie screen, in "Level 3" autonomous vehicles (which can be driven by both humans and technology) because research showed that drivers could re-engage, or take over, more quickly when visually stimulated. Florida's law does not require that an operator be in the vehicle, but the remote operator	🕮		

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	must have a means to engage or disengage the autonomous technology if necessary.			
Jin Xu, J. et al. (2015), *"An Experimental Study on Lateral Acceleration of Cars in Different Environments in Sichuan, Southwest China"*, Discrete Dynamics in Nature and Society, Volume 2015, Hindawi Publishing Corporation	The lateral accelerations of highways with six lanes were found to be less than 3.5 m/s^2, and most were less than 1.8 m/s^2: in a mountainous area, an increasing number of lateral accelerations exceeded the limits of the comfort limit, and a small part of the data exceeded the medium comfort limit (3.6 m/s^2). For highways with two lanes, the amplitude of the lateral accelerations was positively related to the terrain undulation and negatively related to the design speed. With a design speed of 30 km/h in a mountain area, a large proportion of the lateral accelerations exceeded the discomfort limit of 5 m/s^2.		🛠	
Jin, L. et al. (2017), *"Tire-road friction estimation and traction control strategy for motorized electric vehicle"*. PLoS ONE 12(6):e0179526. https://doi.org/10.1371/journal. pone.0179526	This paper attempts to identify in real-time the optimal longitudinal slip ratio and the corresponding maximum available road friction when drive torque exceeds or was close to the available road friction. It proposes the identification of the peak longitudinal force based on the sign change of the derivative of calculated longitudinal force. Although the algorithm is relatively simple, it can enhance the speed and computing efficiency. Furthermore, the non-skid minimum wheel velocity was used to estimate the chassis velocity, a key parameter of the TCS (traction control system). Finally, the simulation and experimental results show that the proposed algorithm can identify the variation of road surface adhesion characteristics without wheel and chassis velocity sensors. [the work appears to relate to tyres at peak friction state]		🛠	⇨⇨
Jo, K. et al. (2018), *"Simultaneous Localization and Map Change Update for the High Definition Map-Based Autonomous Driving Car"*. Sensors 2018, 18, 3145; doi:10.3390/s18093145	Proposes that a pre-built High Definition (HD) map could be used to provide information to the vehicle, such as lanes, traffic signs, traffic lights, barriers, and road surface marking, within 10–20 cm accuracy. By searching the nearby physical features on the HD map, the autonomous car can access the information. without the sensor visibility limitations. The paper includes a discussion of management of the HD map changes by individual autonomous vehicles (Simultaneous Localization and Map Change Update (SLAMCU).	🕮	🛠	⇨

Reference	Summary of content	Back-Ground	Tech	Future
Johnson, C. (2017), *"Readiness of the road network for connected and autonomous vehicles"*. RAC Foundation, London, April 2017	There is a myriad of other implications for road infrastructure, some requiring detailed highways engineering expertise to articulate, including, for example: A fully automated transport system can be expected to reduce the need for sharp braking and could be operated on a surface with only a modest level of friction. Potentially this could allow current Polished Stone Values and texture depth requirements to be relaxed (Dunford et al., 2014). Lamb (2015) notes that because CAVs will run consistently in the same lane positions there will be greater wear and tear in the wheel tracks, and that either the road area beneath the wheel tracks will need to be strengthened, or maintenance repairs will need to be more frequent in those areas. It has already been noted that AVs are likely to require road markings, signs and signals to be maintained to a much higher level than is currently the case. It is also possible that road surfaces, too, will need to be maintained to a higher standard. For example, a pothole in a traffic lane carrying vehicles in a platoon, where vehicles follow each other very closely, could be extremely dangerous, particularly at high speed. Current sensor technology cannot 'see' as far as humans and has a 150-metre limit, which is close to the braking distance at motorway speeds. (Michal Aeberhard – BMW engineer quoted in Bowles, 2016). Standard GPS is only accurate to within 3.5 metres, so using GPS to guide road positioning of vehicles will need augmented systems such as differential GPS or space-based optical clocks. As with any safety-critical communications system, there is a need for triangulation.	🕮🕮	🛠	
Kane, A. and Koopman, P. (2013), *"Ride-through for Autonomous Vehicles"*, CARS 2013 (Safecomp Workshop)	CAV systems: Safety critical systems often have shutdown mechanisms to bring the system to a safe state in the event of a malfunction. This work examines the use of ride—through, a technique to reduce the frequency of safety shutdowns by allowing small transient violations of safety rules.	🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
Kang, Y. S. (2018), *"Development of Predictive Vehicle Control System using Driving Environment Data for Autonomous Vehicles and Advanced Driver Assistance Systems",* Virginia Polytechnic Institute.	Overview of autonomous vehicles and ADAS. Collision Avoidance Systems (CA), Lane Departure Warning (LDW), Lane Keeping Systems (LKS), Yaw Stability Control/Electronic Stability Control Systems, the objective of the research was to develop a predictive vehicle control system for improving vehicle safety and performance for autonomous vehicles and ADAS. In order to improve the vehicle control system, the proposed system utilised information about the upcoming driving conditions such as road roughness, elevation grade, bank angle, and curvature. The driving environment is measured in advance with a terrain measurement system. An optimized Speed Profile (OSP) of maximum allowable speeds (and cornering speeds) are calculated based on ISO road roughness and gradient and/or cross-slope. *"There exists a maximum allowable speed at which a vehicle can be kept on the road while traversing curved roads. This threshold depends on geometric parameters (bank angle, radius of curvature, and acceleration due to gravity) and the friction coefficient between the road surface and tire. "*	📖	🛠	⇨⇨
Kavitha C. et al. (2017), *"Braking distance algorithm for autonomous cars using road surface recognition"*, 14th IOP Conf. Series: Materials Science and Engineering 263 (2017)	This study used a low cost Arduindo-based solution to estimate friction from road surface roughness. A displacement plot from a vehicular ultrasonic sensor was used to find roughness using standard deviation. A constant was obtained, which was specific to tyre compounds to convert roughness to friction coefficient. Rough surfaces gave high friction coefficient values while smoother surfaces, lower. The values obtained for the braking distance on a smooth tarmac surface were consistent with the actual values of braking distance for the car.		🛠	
Keller, P. (2018). *"Autonomous Vehicles, Artificial Intelligence, and the Law",* RAIL - The Journal of Robotics, Artificial Intelligence & Law, Volume 1, No. 2, March–April 2018	Autonomous vehicle technology and the artificial intelligence used to "drive" along our roads is a staggering achievement. Their use, however, raises significant legal issues that will need to be considered and addressed as these technologies become more prevalent.	📖📖📖		

Reference	**Summary of content**	**Back-Ground**	**Tech**	**Future**
Khaleghian, S. et. al. (2017). *"A technical survey on tire-road friction estimation"*. Friction 5(2): 123–146 (2017) ISSN 2223-7690	Summary of experiment-based and model-based approaches to estimating road friction. Several summary tables are provided in which the overall features of different approaches are reviewed and the different algorithms, widely used in friction estimation studies, are discussed.	🕮	🛠🛠	
Koskinen, S. and Peussa, P. Eds (2009), *"EU Project FRICTI@N, Final Report"*, FP6 - IST - 2004 - 4 – 027006, 26 March 2009, Information Society Technologies (IST) Programme.	The objectives of the FRICTI@N project were: • To create a model for on-board estimation of tyre-road friction • To build a prototype system using a minimum number of sensors • To verify the system benefits in selected vehicles • To enhance the functionality of preventive and cooperative safety applications in parallel running Integrated Projects. (in practice with SAFESPOT). Tyre sensors coming from a previous project APOLLO, provided accurate tyre forces to improve VFF (Vehicle Feature Fusion) measurements such as friction used, wheel load and slip. Additionally, it was used to calculate the risk of aquaplaning. Algorithms were tested for robustness against false detections: in a driving test lasting 2 minutes on dry asphalt road, using low acceleration only (under 0.4, normal driving), the environmental sensors were able to classify the road surface 94 % of the time.	🕮	🛠	⇨⇨
Kritayakirana, K. (2012), *"Autonomous Vehicle Control at the Limits of Handling",* Ph. D. Dissertation. Stanford University. Stanford, California, USA.	Many road accidents are caused by the inability of drivers to control a vehicle at its friction limits yet race car drivers routinely operate a vehicle at the limits of handling without losing control. If autonomous vehicles or driver assistance systems had capabilities like those of race car drivers, many fatal accidents could be avoided. To advance this goal, an autonomous racing controller was designed and tested to understand how to track a path at the friction limits.		🛠🛠	⇨

Reference	**Summary of content**	**Back-Ground**	**Tech**	**Future**
Kutila, M. et al. (2015) *"Towards Autonomous Vehicles with Advanced Sensor Solutions"*. World Journal of Engineering and Technology, 3, 6-17. http://dx.doi.org/10.4236/wjet.2015.33C002	A useful outline of the major innovations introduced by the DESERVE (DEvelopment platform for Safe and Efficient dRiVe) project in the area of driver monitoring including the integration of this with wider systems	🕮	🛠	
Layton, L. and Dixon, K. (2012) *"Stopping Sight Distance Discussion Paper #1"*, The Kiewit Center for Infrastructure and Transportation, Oregon State University, April 2012	The selection and application of a sight distance criteria required that several questions be addressed, these included: Should a safe coefficient of friction or acceptable deceleration rate be used to define the deceleration of vehicles? What deceleration rates are implied by the coefficient of friction used for design? What deceleration rates are typical and comfortable for drivers? What deceleration rates are acceptable for stopping of trucks?	🕮	🛠	
Lex, C. et al. (2016), *"On-board determination of the friction coefficient between tire and road using standard-application vehicle dynamics sensors",* In book: "The Dynamics of Vehicles on Roads and Tracks", April 2016, DOI: 10.1201/b21185-78	The work focussed on standard sensors as installed in a vehicle with electronic stability control (ESC), the sensor information required included: wheel speeds, longitudinal and lateral chassis acceleration, the yaw rate, the steering wheel angle and the longitudinal velocity. Using real vehicle measurements, possibilities and limitations of the presented approach are discussed. It is demonstrated that the tyre and road conditions can be estimated in many driving conditions with a high confidence.		🕮	⇨⇨
Li B. et al. (2014). *"Comparative study of vehicle tyre-road friction coefficient estimation with a novel cost-effective method",* Vehicle System Dynamics: international journal of vehicle mechanics and mobility, vol. 52, (8) pp. 1066-1098, 2014	Four methods of vehicle-based friction measurement were considered: ABS used to measure wheel angular velocity Traction/brake torque measurement system from CAN bus Accelerometer used to measure vehicle acceleration GPS based vehicle speed measurement Ultimately a method to estimate the vehicle absolute velocity by using the available measurements of traction/brake torque, wheel angular velocity and longitudinal acceleration was adopted. Considers the wheel rolling resistance, wind drag force and road gradient. The preferred method only needed to measure the wheel angular velocity, the traction/brake torque and the longitudinal acceleration.	🕮	🛠	⇨⇨

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Mansfield, N.J. and Whiting-Lewis, E. (2004), *"Low frequency lateral acceleration and subjective ratings of acceleration intensity and driving confidence in production cars".* Journal of Low Frequency Noise Vibration and Active Control, 23 (4), pp.221-230.	The mean peak lateral acceleration obtained in the cars was approximately that considered to be the peak lateral acceleration before tyres lose grip (i.e. 8 to 10 m/s^2).	🕮	🛠🛠	⇨
Marcelino P. et al. (2017) *"Machine Learning for Pavement Friction Prediction Using Scikit-Learn".* In: Oliveira E., Gama J., Vale Z., Lopes Cardoso H. (eds) Progress in Artificial Intelligence. EPIA 2017. Lecture Notes in Computer Science, vol 10423. Springer, Cham	Using data from the Long-Term Pavement Performance (LTPP) database, 113 different sections of asphalt concrete pavement, spread all over the United States, were selected. Two machine learning models were built from these data to predict friction, one based on linear regression and the other on regularized regression with Lasso. Both models were shown to be feasible and perform similarly.		🛠🛠	⇨
Mataei, B. et al. (2016) "*Pavement Friction and Skid Resistance Measurement Methods: A Literature Review*". Open Journal of Civil Engineering, 6, 537-565. http://dx.doi.org/10.4236/ojce.2016.64046	This paper presents a review on the research studies that have been done on characterization of the frictional properties of the pavement surface and discussed methods used for the measurement and evaluation of texture characteristics and the strengths and weaknesses of these methods. Finally, some ideas were suggested to develop new methods for better and proper measurement of skid resistance: using light reflection, thermal imaging and sonic methods.	🕮🕮	🛠🛠	⇨
Matilainen, M., and Tuononen, A. J. (2001), *"Tire Friction Potential Estimation from Measured Tie Rod Forces"*, 2011 IEEE Intelligent Vehicles Symposium (IV) Baden-Baden, Germany, June 5-9, 2011	An open loop observer was proposed to estimate the friction potential on the front left and front right wheels using the Brush tyre model. The tyre self-alignment torque was obtained from the axial forces measured by strain-gauge sensors attached to the tie rods. A simplified steering and suspension kinematics model was employed to translate the previous forces from the tie rods to the wheel-ground contact. The observer was validated experimentally under steady-state mu-split and ramp mu-transition manoeuvres. The observer exhibited a good performance and was able to infer the friction potential of high and low mu		🛠🛠	⇨

Reference	Summary of content	Back-Ground	Tech	Future
	surfaces (μmax = 0.9, μmax = 0.4) for tyre friction levels ranging from μ = 0.6 to μ = 0.4. The estimation method presented here requires a certain amount of slip before it can give reasonable estimates of friction potential.			
McKenna, I. et al. (2018), *"The Future of Autonomous Vehicles: Risk with Privacy and Tracking"*. Envista Forensics, Atlanta, USA	A valuable overview of: Privacy and security in a new era of autonomous vehicle innovation. What the levels of automation mean for these vehicles. How autonomous vehicles work. Collision avoidance systems and accident prevention. Manufacturing liability and legal concerns.	🕮🕮		
Mizrachi, B. (2018), *"Tactile - The Missing Sense: Enable Autonomous Vehicles to 'Feel' the Road"*, Tactile Mobility, October 18th 2018, Tel-Aviv	Joint venture between Tactile and nVIDIA – teaching AVs to feel the road using AI. Tactile Language Building Blocks are used in a reactive manner to mark hazards over video records.		🛠	⇨
Muller, S. et al. (2003), *"Estimation of the Maximum Tire-Road Friction Coefficient"*, Journal of Dynamic Systems, Measurement, and Control December 2003, Vol. 125	The method is based on the hypothesis that the low-slip, low-μ parts of the slip curve used during normal driving can indicate the maximum tire-road friction coefficient, μ_{max}. The friction estimation algorithm uses data from short braking manoeuvres with peak accelerations of 3.9 m/s^2 to classify the road surface as either dry (μ_{max} ≈1) or lubricated (μ_{max}≈0.6). Significant measurement noise makes it difficult to detect the subtle effect being measured, leading to a misclassification rate of 20%. To begin to see a difference between so termed "soapy" (lower friction) and dry roads using slip curves from individual braking manoeuvres, the friction demand needed to be increased to 0.4, or accelerations of about 3.9m/s^2. This corresponds to somewhat aggressive driving, but it is still well below the μ_{max} values of 0.6 and 1.0 for the roads in question. For this friction demand, the slope of the linear fit to the μ versus slip data correlated with the maximum friction coefficient.		🛠	⇨

Reference	Summary of content	Back-Ground	Tech	Future
NIC (2016), *"Connected Future"*, National Infrastructure Commission (NIC), UK.	5G is expected to deliver a step change of ultrafast, low latency, reliable, mobile connectivity, able to support society's ever larger data requirements as well as wide ranging new applications. Connected and Autonomous Vehicles (CAVs) need mobile connectivity for driver assistance, in vehicle connectivity and Vehicle management, ensuring the necessary digital infrastructure is in place will be critical if the UK is to take advantage of this technology. Only 8% of A and B roads have complete 4G coverage with 47% having no 4G coverage at all. Independent mobile coverage experts OpenSignal found in their 'State of LTE' report that mobile customers across the UK's four networks were on average able to access 4G just 53% of the time.	🕮	🛠	
NIRA Dynamics (2019), *"On board: Tire Grip Indicator"*, NIRA Dynamics promotional literature, NIRA Dynamics AB, Linköping, Sweden	Uses a small software component plugged into a vehicle (ODB socket), either as original installation in cooperation with the car manufacturer, or as an aftermarket solution on an external but vehicle-bus (ODB) connected device. Claimed to measure friction and road roughness.		🛠	⇨⇨
Nisenbaum, A. (2019), *"3 Steps to Making Autonomous Vehicles a Reality"*. Innovation and Tech today (online). https://innotechtoday.com/. 13 March 2019.	Human drivers need to "feel" the road to drive safely and efficiently, and that's no less true of autonomous vehicles. Tactile sensing fills this critical need, going beyond visual capabilities to provide a more comprehensive analysis of vehicle-road characteristics, like grip level, road friction, and individual road and vehicle signatures.		🛠	⇨
Nitsche, P. (2018), *"Safety-critical scenarios and virtual testing procedures for automated cars at road intersections"* Doctor of Philosophy Thesis, Loughborough University.	For each scenario, some of the simulation parameters remain static and some are varied within a certain range, such as the lateral position in the lane and the speed of the opponent, the friction coefficient of the road surface or the level of collision avoidance systems to study their impact. In a survey, the role of the road infrastructure was rated as "very important" by 76% of the respondents.	🕮	🛠🛠	
Norton Rose Fulbright (2018), *"UK, Autonomous vehicles, Technology and innovation"*, Norton Rose Fulbright,	The Automated and Electric Vehicles Act (the "Act") became law in July 2018. It extended compulsory motor insurance to autonomous vehicles.	🕮🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
https://www.aitech.law/publications/2018/q1/av-uk/	It illustrates the UK Government's commitment to progressing autonomous vehicle technology: monitoring and updating this list will require significant resources and close relationships with the manufacturers to stay up-to-date with new developments. The Act also addresses the unique aspects of autonomous vehicles — the computer software and the issue of tampering. Insurer liability under the Act is excluded if the software in an autonomous vehicle is not updated or if it has been adapted to a standard outside of the policy limits. This provision ensures that insurers are not responsible for autonomous vehicles with unauthorized modifications. It raises the question of how manufacturers will disseminate software updates to their customers. Expecting customers to carry out updates themselves could create issues if the update is not received or if the customer does not install it.			
Sanders, P.D. et al. (2017), "Better understanding of the surface tyre interface", TRL Published Project Report PPR815, TRL, Crowthorne.	• The friction prediction model developed performs well overall in predicting friction over a wide range of slip ratio and vehicle speed, from inputs of low speed skid resistance and texture depth. However, it is less accurate at low slip (below 5%) and low, low speed friction (around 0.30 units SC(50)). • Whilst low speed skid resistance and texture depth both contribute to the braking performance, the importance of texture depth seems particularly significant and texture depth is better able to compensate for lower levels of low speed skid resistance than vice versa. • There appears to be an optimum contribution of low speed skid resistance and texture depth to braking distance, taking account of the vehicle speed and the performance of different surfacing materials. • The use of driver aids designed to exploit peak friction has a substantial benefit on the braking performance of vehicles. A wide uptake (approaching 100%) of driver aids could allow for a reduction in the friction requirements on the SRN. However, information on the current			

Reference	Summary of content	Back-Ground	Tech	Future
	and projected distribution of vehicles with driver aids would be needed before making changes to specifications.			
Panahandeh, G. et al. (2017) *"Road Friction Estimation for Connected Vehicles using Supervised Machine Learning"*. IEEE Intelligent Vehicles Symposium (IV), 2017:	From a fleet of connected cars, the following measurements were used in a prediction model: estimated friction values and their corresponding confidence/quality of measurement, wiper speed, ambient temperature, time stamp, and the road segment ID where the measurements accrued. Logistic Regression (LR), Support Vector Machine (SVM) and Artificial Neural Networks (ANN) classification methods were used. The experiments show that an error rate in the order of 20-30 % can be obtained while the prediction accuracy slightly changes for different road segments. Although no single method leads to the best results in all conditions, the ANN method results in more stable results considering different conditions.		🛠	⇨
Patel, R. H. & Bonnet, C. (2017), *"Braking Strategy for an Autonomous Vehicle in a Mixed Traffic Scenario".* Conference: VEHITS - Vehicle Technology and Intelligent Transport Systems, April 22-24, 2017, Porto, Portugal	Various braking strategies and vehicular mobility models are used to simulate different scenarios for front-end and rear-end collision avoidance in longitudinal motion. Maximum braking strength (b_{max}) -0.6g m/s^2 is used.		🛠	
Powell, J.P. & Palacı R. (2015) *"Passenger Stability Within Moving Railway Vehicles: Limits on Maximum Longitudinal Acceleration"* Urban Rail Transit (2015) 1(2):95–103 DOI 10.1007/s40864-015-0012-y	Measured levels of comfortable acceleration in rail transport.	🕮	🛠	
Prokeš, J. (2015), *"Realtime estimation of tyre-road friction for vehicle state estimator"*, MSc thesis, Department of Applied Mechanics, Chalmers University Of Technology, Göteborg, Sweden 2015	Summary of driving modes and friction measurements possible using a vehicle. Here, μ_{TR} is introduced in order to denote the actual tyre-road friction coefficient. To obtain the correct friction estimate using the Brush tyre model and the Magic Formula, in general friction utilisation needed to be higher than 80%. The friction estimates with accuracy of ±0.1 can be identified for friction utilisation around 70%.	🕮	🛠🛠	

Reference	**Summary of content**	**Back-Ground**	**Tech**	**Future**
Pucher, J. et al. (2018), *"State of play of connected and automated driving and future challenges and opportunities for Europe's Cities and Regions"*, Commission for Territorial Cohesion Policy and EU Budget, Catalogue number: QG-03-18-417-EN-N; ISBN: 978-92-895-0998-5; doi:10.2863/856014	The Study sought to provide a tentative outline on the main challenges and opportunities for Local and Regional Authorities (LRA) related to Connected Automated Mobility (CAM). It focussed on CAM in road transport, i.e. on transport with cars, lorries and busses, addressing passenger as well as freight transport. CAM – as potentially disruptive technology – is expected to trigger many developments with economic, social and environmental impacts. Consequently, the Study sought to address the range of issues to be considered from the perspective of LRA in order to support a debate on important aspects for technology monitoring in the upcoming years. Report provides a valuable overview of OEM readiness for CAV technology, and future challenges and opportunities for LRA in connection with CAM, the legal implications of CAM for LRAs.	🕮	🛠	⇨
Rado, Z. and Wambold, J.C. (2012), "*Why Fixed Slip Devices cannot Measure the Speed Gradient due to the Pavement*", SURF 2012: 7th Symposium of Pavement Surface Characteristics, Sept 19-22 2012, Norfolk, USA.	This paper covers why measurements at various speeds with continuous friction measurement equipment (CFME) are not able to measure the speed - friction gradient of the pavement as determined by the macro-textural features of the surface. Most CFMEs measure friction in the slip ratio range of 10% to 18%. In this range it is shown that the friction versus slip speed of these devices are mainly determined by the coupled properties of the surface micro-texture and relevant tire properties and to a minimal extent only by pavement macro-texture properties.		🛠	
Saarikivi P. et. al. (2011) *"Mobile Observation Methods for Road MOBI-ROMA (2011) – "*, Maintenance Assessments, Deliverable Nr 1 – State of the Art of Floating Car Measurements",30.12.2011	The Slippery Road Information System (SRIS) test in Sweden was performed by use of 100 cars, 90 of them were located in the Gothenburg area and 10 cars in Stockholm. The car models used in the test were Volvo V70s and Saab 9-5s. "SRIS increases the possibilities to identify severe road conditions. The field test with 100 cars has shown a good result and that it is possible to apply SRIS to more vehicles and gain a growing profit for the society, both for drivers and road maintenance. "		🛠	⇨⇨
SAE (2018), *Recommended Practice J3016: "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor*	This Recommended Practice provides a taxonomy describing the full range of levels of driving automation in on-road motor vehicles and includes	🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
Vehicles", Society of Automotive Engineering, June 2018	functional definitions for advanced levels of driving automation and related terms and definitions.			
Segata, M. and Cigno, L. (2013), *"Automatic Emergency Braking: Realistic Analysis of Car Dynamics and Network Performance*", IEEE Transactions on Vehicular Technology (Volume: 62 , Issue: 9 , Nov. 2013), Page(s): 4150 – 4161, 08 August 2013	This work considered a version of Emergency Braking (EB), that used warning messages to feed an Adaptive Cruise Control (ACC) that was used to perform automated braking if the driver did not intervene. The leader (or the leaders, in the multi-lane scenarios) brakes with a constant deceleration of 4 m/s^2, Benefits are obtained when as few as 5-10 % of cars are equipped with cruise control and communication devices; cars not equipped with cruise control and communication devices benefit from the presence of cars whose reaction is smoother and anticipated with respect to the standard human reaction.		🛠	
Seif, H.G. and Hu, X. B. (2016), *"Autonomous Driving in the iCity—HD Maps as a Key Challenge of the Automotive Industry"*, Engineering 2 (2016) 159–162	Autonomous driving is on its way to becoming a reality. Advanced driver assistance systems (ADAS) are based on optical and radar sensors that can scan the near-car environment. The results are input to steering, accelerating, and breaking actuators that permit automated driving in situations with low complexity. This is the first step toward autonomous driving. When transferred into urban traffic situations, the information from these sensors is insufficient to enable fully autonomous driving. Additional input such as the exact location, speed, and direction of the car, as well as the current traffic situation and the behaviour of other traffic participants, is required. The basic references for this multi-dimensional information are HD maps with an accuracy of ± 10 cm, enhanced by updates on the real-time status of the wider car environment (to a range of about 1 km). Thus, HD maps are a key challenge for the automotive industry, especially because this topic has not been known as a core competence of car manufacturers until now.		🛠	⇨
Shao L. et al. (2018): *"Robust road friction estimation during vehicle steering"*, Vehicle System Dynamics, DOI: 10.1080/00423114.2018.1475678	In this study, a framework was developed to estimate road friction coefficient with stability and robustness guarantee by using total aligning torque in the vehicle front axle during steering.		🛠	⇨

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	Both front and rear axle information was used to estimate front axle lateral force and achieve a better result compared with classical UIO with only front axle information. Then, combined with an indirect measurement based on estimated total aligning torque and front axle lateral force, a non-linear adaptive observer is designed to estimate road friction coefficient with stability guarantee. To increase the robustness of the road friction estimation result, criteria are proposed to decide when to update the estimated road conditions. Simulations and experiments under various road conditions validate the proposed framework and demonstrate its advantage in stability by comparing it with method utilising EKF.			
Singh, B. K. and Taheri, S. (2015) *"Estimation of tire–road friction coefficient and its application in chassis control systems"*, Systems Science & Control Engineering, 3:1, 39-61, DOI: 10.1080/21642583.2014.985804	This paper aims at estimating the tyre–road friction coefficient by using a well-defined model of the tyre behaviour: the physically based brush tyre model. In its simplest formulation, the brush model describes the relationship between the tyre force and the slip as a function of two parameters, namely, tyre stiffness and the tyre–road friction coefficient. Knowledge of the shape of the force–slip characteristics of the tyre, possibly obtained through the estimation of both friction and tyre stiffness using the brush model, provides information about the slip values at which maximum friction is obtained. This information could be used to generate a target slip set point value for controllers, such as an ABS or a traction control system. To be of greatest use to active safety control systems, an estimation method needs to offer earlier knowledge of the limits. In order to achieve the objective, an integrated approach using an intelligent tyre-based friction estimator and the brush tyre model-based estimator is presented.	🕮	🛠	
Song, S. (2014), *"Towards Autonomous Driving at the Limit of Friction"*, Thesis, Master of Applied Science, Waterloo, Ontario, Canada	This thesis presents three aspects of autonomous driving near the limit of friction: testbed, estimation and control. The architectures presented improve on current vehicle estimation and control methods and pave the way for further developments on autonomous driving at the limit of friction.		🛠	⇨⇨
Tibljaš A.D. et al. (2018), *"Introduction of Autonomous Vehicles: Roundabouts Design and Safety - Performance Evaluation"*, Sustainability	In this paper, roundabout safety level is analysed in circumstances where different numbers of AVs vehicles are mixed with Conventional Vehicles (CVs). Field data about speed and traffic volumes from existing roundabouts	🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
2018, 10(4), 1060; https://doi.org/10.3390/su10041060	in Croatia were used for development of the model. A trajectory file generated in VISSIM and the simulations done with the Surrogate Safety Assessment Model (SSAM) to give some relevant highlights on how the introduction of AVs could change both operational and safety parameters at roundabouts. To further explore the effects on safety of roundabouts with the introduction of different shares of AVs, hypothetical safety treatments could be tested to explore whether their effects may change, leading to the estimation of a new set of Crash Modification Factors. With the introduction of AVs, the average travel speed increases (by about 20%). The increase of speed is more significant with the increase of percentage of AVs and it can be explained or connected with better performance of traffic conflicts management by AVs.			
Torchinsky, J. (2018), *"How Autonomous Cars See The World",* Jalopnik, Online: https://jalopnik.com/how-autonomous-cars-see-the-world-1826147310 1/16	An online resource providing a synthesis of the autonomous vehicle art, unofficial but informative.	🕮🕮	🛠	
U.S. Department of Transportation (2018), *"Preparing for the Future of Transportation Automated Vehicles 3.0"*, U.S. Department of Transportation, Sept 2018.	"The United States Department of Transportation (U.S. DOT) has established a clear and consistent Federal approach to shaping policy for automated vehicles, based on the following six principles: 1. We will prioritize safety. 2. We will remain technology neutral. 3. We will modernize regulations. 4. We will encourage a consistent regulatory and operational environment. 5. We will prepare proactively for automation. 6. We will protect and enhance the freedoms enjoyed by Americans."	🕮🕮	🛠	
Umeno, T. (2002), "Estimation of Tire-Road Friction by Tire Rotational Vibration Model", R&D Review of Toyota CRDL37-3	In this paper, the frequency characteristics of wheel speed vibration are shown to be related to tire-road friction. An estimation method based on these characteristics is proposed. The method is compared to experimental results, and friction change, including that resulting from hydroplaning, can be detected even at constant speed. Friction condition can be estimated		🛠	⇨

Reference	Summary of content	Back-Ground	Tech	Future
	when the vehicle is not necessarily performing any dynamic or handling manoeuvres, and wheel speed sensors are the only sensors that are required. The instrumental variable (IV) method is the most useful.			
Vinnova/Drive Sweden (2017), *"Autonomous Driving Aware Traffic Control – Final Report".* July 2017. Volvo Cars, Ericsson, Carmenta, Trafikverket, and the City of Gothenburg.	This report is the concluding document of a joint public private project run over a period of ten months through to the end of June 2017 financed in part by Vinnova. The partnership included Volvo Cars, Ericsson, Carmenta, Trafikverket, and the City of Gothenburg. The goal of the project was to define and propose a traffic control cloud for automated vehicles with interfaces to vehicles, road authorities and city authorities, along with the associated information flows for connected vehicles. In addition, the project proposed solutions on required services including traffic control and information sharing. Volvo Cars specific findings included: extending the "RFI probe sourced" (Road Friction Index, no more information) concept to include transmitting data from one car to others based on location/time details to increase safety.		🛠	➪➪
Walker, R. et al. (2018), "Future Transport Visions: T01 - Connected and Autonomous Vehicles", Published Project Report PPR864, TRL Academy, Wokingham, UK	Regardless of uncertainty, spatial planning and infrastructure investment decisions today will determine the development of the UK for decades. To avoid wasting money or preventing the development of CAV, it will be important for authorities to employ an on-going adaption of the UK's road infrastructure by: Aligning all new investment to systems that are based on open, interoperable data standards and this may reduce the likelihood of roadside clutter and multiple reinstatements. Maintaining traffic modelling and traffic planning capability to be able to plan and prepare for anticipated changes in traffic Considering the impact of future changes in transport in the design and procurement of new traffic management systems. Potentially addressing the backlog of existing maintenance needs for road infrastructure (estimated to be 14 years with estimated cost of £11.8 billion), should urban CAV systems require improved levels of maintenance	🕮🕮	🛠	

Reference	Summary of content	Back-Ground	Tech	Future
Wall, M. (2015). "What's putting the brakes on driverless cars?", BBC News (online)	2015: While driverless cars could offer valuable mobility to the elderly and people with varying degrees of disability, most experts believe such vehicles will be restricted to urban settings on prescribed routes only. "Full autonomous driving, where you programme your car to drive somewhere and read the paper in the back, that's science fiction to me to be honest," concludes Accenture's Mr Gissler.	🕮		
Wang, Y. and Wei, H. (2018), *"Safe Driving Capacity of Autonomous Vehicles".* IEEE 88th Vehicular Technology Conference (VTC-Fall) August 2018	This paper models AV interactions for Perception-based vehicle (PBV): a vehicle that makes decisions based only on the data obtained from its perception system and for Cooperative-based vehicle (CBV): A cooperative-based vehicle is a vehicle that makes decisions mainly based on the data obtained through inter-vehicular communication. It assumes for a vehicle equipped with ABS (Anti—lock brake system), the maximum acceleration and deceleration are 2.2 to 4.0m/sec^2 and around 9.0m/sec^2 respectively.		🛠	⇨
Worth, D. (2019), *"Robot cars will make UK roads better, Well, tolerable"*. The Inquirer. https://www.theinquirer.net/ inquirer/news/3002064/robot-cars-will-make-uk-roads-better-well-tolerable	The study for DfT found that on a simulation of a major road, where traditional vehicles outnumbered automated cars there was not much change in traffic flow. However, once driverless cars outnumbered normal vehicles traffic flow improved. So much so in fact, that when the simulation was modelled to be nothing but driverless cars, journey times fell by 11 per cent and delays were cut by 40 per cent. This is because driverless cars are able to travel much closer together due to superior reaction times if the car has to break.	🕮🕮		
Zhang, Y. et. al. *"Toward a More Complete, Flexible, and Safer Speed Planning for Autonomous Driving via Convex Optimization"*. Sensors 2018, 18, 2185	Stated constraints for speed planning with a fixed value of Mu of 0.7, Longitudinal acceleration threshold for comfort 0.4µg m/s^2, Lateral acceleration threshold for comfort 0.4µg m/s^2, Max. Longitudinal acceleration of the car. 0.5µg m/s^2		🛠	⇨
Zmud, J. et al. (2018), "*Providing Support to the Introduction of CAV Impacts into Regional Transportation Planning and Modeling Tools*", NCHRP 20-102(09), National Cooperative	CAV and AV are distinct but complementary technologies. Need to Adapt strategic models to CAVs. While different agencies have unique needs, all should develop new planning and modelling processes for CAVs in the transportation environment.	🕮		

Reference	Summary of content	Back-Ground	Tech	Future
Highway Research Program (NCHRP) June 30, 2018				

The relationship between connected and autonomous vehicles, and skidding resistance

Road based transportation is undergoing a dramatic and dynamic change. The advent of connected and autonomous vehicles, the continual development of vehicle sensors, and, the introduction of high-speed communication networks (4G and 5G) present challenges and opportunities to all areas of transportation. This work explores how these technological advances, combined with innovative thinking will be used in the future to improve the way in which the skid resistance properties of highways are measured.

This report seeks to outline the state of the art of how modern vehicle systems assess road-tyre interaction and how this might influence processes for the management of skid resistance on the highway asset in the UK. The work also considers the highway and vehicle system as a whole and explores how highway asset data and vehicle data could be combined to improve highway safety through the focussed and timely prioritisation of maintenance.

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PPR815 Better understanding of the tyre surface interface. P D Sanders, M Militzer and H E Viner. 2017.

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PPR957 Characterising the measurement characteristics of sideways-force skid resistance measurement devices - a desk study and proposal for an experimental study. P D Sanders and C Browne. 2020

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