# Calibration of advanced driver-assistance systems (ADASs) on modified vehicles

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# Abbreviations and acronyms

| | |
|---|---|
| ADAS | advanced driver-assistance system |
| AEB | advanced emergency braking |
| ASIL | Automotive Safety Integrity Level |
| E/E | electrical and electronic |
| ESC | electronic stability control |
| FCW | forward collision warning |
| FOV | field of view |
| IIHS | Insurance Institute for Highway Safety |
| LDW | lane departure warning |
| LKA | lane keep assist |
| LVV | low volume vehicle |
| NZTA | NZ Transport Agency Waka Kotahi |
| OEM | original equipment manufacturer |
| SAE | Society of Automotive Engineers |
| SEMA | Specialty Equipment Market Association |
| TTC | time to collision |
| VCA | Vehicle Certification Agency |

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# Executive summary

Vehicles equipped with advanced driver-assistance systems (ADASs) – for example, advanced emergency braking (AEB), lane keep assist (LKA) and blind-spot detection – rely on sensors or cameras that are designed and calibrated to operate within specific height ranges by the vehicle manufacturer, with a specific field of view (FOV) and orientation relative to the vehicle body and running condition (thrust angle).

The objectives of this project were to review international literature and experience of the modification and calibration of ADAS-equipped vehicles to assess the consequences of such modifications on ADAS performance and identify any measures that may have already been taken to address issues. This information was then analysed to make recommendations for New Zealand policymakers and regulators for ADASs on vehicles with altered ride height or rake angle (pitch).

A literature review identified 25 sources, which were graded and selected for relevance and further review. Additional sources were also identified by domain experts and/or from discussions with stakeholders. The literature review revealed that ADAS performance (AEB and LKA) is reported to be altered when vehicle ride-height/rake-angle is changed because the electronic orientation of the sensor in the software has a different frame of reference. Therefore, the ADAS warnings or actions occur at a different time compared with the performance of the baseline ADAS or may even be supressed entirely in some circumstances.

After recalibration using the vehicle manufacturer's standard specification, altered performance was in general not materially different to the baseline condition, but the magnitude of the difference appears to vary between vehicles. In some instances, the ADAS functionality was affected significantly.

No objective test results were available that assessed ADAS performance after ride-height changes without recalibration. It would be expected that in these cases the ADAS performance would be influenced (depending on the magnitude of the ride-height change) because the electronic orientation of the sensor in the software has a different frame of reference.

Five stakeholders were interviewed to gather views and review any unpublished data. This flagged that significant test work to assess effects of ride-height modification (within certification limits[1]) and aftermarket accessories (eg, bull bars and additional lights) on ADAS performance is ongoing in the USA (by the Specialty Equipment Market Association (SEMA)) and Australia (by Transport for NSW), although results from these test programmes are not yet available. Experts in recalibration confirmed that changing the height of the vehicle, unless addressed specifically in the recalibration process, is expected to affect the FOV of the sensors and supports the evidence found in the literature that performance effects can result. Within vehicle manufacturer ride-height tolerances, the effect on ADAS performance is expected to be non-material, but insufficient test data exists to objectively validate this.

The project identified the following recommendations.

**Government**

- Clarify or establish explicit ride-height/rake-angle limits that do not require certification in New Zealand. At present, the available information to define this limit is not available. This could be based on requirements in other jurisdictions (eg, New South Wales), or preferably be defined based on the outcomes of targeted test programmes.
  - Review the findings of test programmes underway in the USA (by SEMA) and Australia (by Transport for NSW) when these become available. These programmes have tested 'utes' with

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[1] The changes in ride height that are permitted by national requirements without the need for additional testing.

  altered ride height (within current certification limits) and aftermarket accessories (eg, bull bars and additional lights) and assessed the effect on ADAS performance compared with the standard vehicle. These results may allow a more robust assessment of the effect on ADAS performance of ride-height changes to be made and the appropriate certification limit.
  - If information is not forthcoming from these programmes, physical testing of ride-height changes for a representative sample of vehicles to assess the effect on ADAS performance of ride-height alterations (and other aftermarket equipment) to identify appropriate certification thresholds would provide the information required.
- Provide consumer information to educate hobbyists about the effects of ride-height and rake-angle modification, the addition of aftermarket items located in the sensor FOV (eg, lights, styling or aerodynamic accessories, or altered custom bumper paints) and how this may influence ADAS performance so that an informed choice can be made about changes to the vehicle and the implications for subsequent ADAS functionality.
- The recommendations for ADASs may need adapting for application to highly automated vehicles. Regulation of automated vehicles should ensure that Society of Automotive Engineers (SAE) Level 4+ systems have appropriate functional safety concepts to deliver ‘fail-operational’ capability. This should be regulated specifically for automated vehicles because this is a key aspect of the functional safety concept. Automated vehicles may be able to cope with alterations to ride height without performance effects or not offer autonomous functionality if the vehicle is out of specification.

**Vehicle manufacturers/technology providers**

- Make vehicle ride-height tolerances easily accessible to the aftermarket and vehicle users if this is not already available. Government could influence this by leading a voluntary industry agreement or by making the information sharing a requirement of vehicle type approval (ie, mandatory sharing of the necessary information to the automotive aftermarket).
- Improve on-board diagnostic capability of vehicle systems and their capability to allow adaptation of the system to changes in ride height and rake angle. Government could assist this by regulating the capability of vehicle diagnostic systems.
- Harmonise the recalibration method of the ADAS to include the input of measured ride height so that this is accurately taken into account as part of the recalibration process. Government could encourage this by instigating a voluntary industry standard for ADAS recalibration.
- Provide consumer information about the capability and limitations of the system, including specific information on ride height and how this might affect ADAS performance. Government could make it a requirement to provide such information.

**Repairers**

- Develop a code of practice for vehicle repair/ADAS recalibration that would ensure that:
  - technicians are adequately trained and follow the original equipment manufacturer/technology provider guidance, including mandatory ADAS recalibration after a repair
  - a maximum ride-height change for which the system would be repaired or recalibrated is identified
  - repairers provide information to the vehicle owner at recalibration, either on the potential for effects on ADAS performance or why a repair or recalibration cannot be carried out.

  Government could facilitate this by chairing the development of a code of practice with industry.
- Repairers could monitor and record the frequency and motivations for recalibrations carried out and any issues with vehicle modifications. This would provide an evidence base that could be used by government to understand issues of recalibration in the fleet.

**Aftermarket equipment suppliers**

- Ensure that information on the effects of ride-height changes on ADAS performance are provided to users who are purchasing aftermarket components that affect ride height. Governments could achieve this by regulating labelling requirements for such products.
- Aftermarket diagnostic tool providers can ensure that, where applicable, the ability to enter the vehicle ride height is provided to a repair technician undertaking the recalibration of an altered vehicle.

**Insurers**

- Ride-height modifications that exceed the vehicle manufacturer’s threshold (or another yet to be defined limit) could be made subject to increased premiums or in certain cases invalidate insurance cover. However, this approach may not be proportionate depending on the outcomes of targeted testing to define the effect on performance of ride-height/rake-angle adjustments.

# Abstract

This project reviewed international literature on advanced driver-assistance system (ADAS) performance after changes to vehicle ride-height/rake-angle, to identify any negative effects these changes may have on ADAS performance. This information was supplemented with technical knowledge from key stakeholders.

It was found that the performance of ADASs (eg, advanced emergency braking, lane keep assist) is altered when vehicle ride-height is changed because the electronic orientation of the sensor in the software has a different frame of reference. Limited objective test data was available, but effects were generally non-material in terms of performance and were noted to vary between vehicles. Effects were expected to increase with ride height, but insufficient information exists to define ride-height limits other than vehicle manufacturer tolerances.

The project developed recommendations for New Zealand policymakers and regulators based on the evidence reviewed on the subject of the recalibration of ADASs on vehicles with adjusted ride heights/rake angles.

# 1 Introduction

## 1.1 Background

In New Zealand approximately 6,000 vehicles each year are certified after modifications above a prescribed threshold; the number of vehicles modified below the certification threshold is unknown. These modifications may include those that involve raising or lowering the suspension, thereby changing the ride height and/or rake angle (pitch) of the vehicle. These changes impact the vertical position of advanced driver-assistance system (ADAS) sensors, such as windscreen-mounted cameras or radars on the vehicle front, relative to the ground plane. ADASs (such as advanced emergency braking (AEB), forward collision warning (FCW) and lane keep assist (LKA)) rely on sensors that are calibrated to operate at specific heights and angles by the manufacturers. There is concern that changing the ride height or rake angle of a vehicle through aftermarket modification may influence how well the systems function on the road. For example, this could lead to ADAS activations where the systems would not be expected to warn or act (false positive), delayed warnings, or in some situations no activation where this would be expected (false negative).

Modifications must be certified in New Zealand if they are over the low volume vehicle (LVV) certification threshold, but there is a concern over the effect on ADAS performance for vehicles below the certification threshold.

NZ Transport Agency Waka Kotahi (NZTA) and Te Manatū Waka | Ministry of Transport are considering a mandate for ADAS technologies on all new vehicles entering the fleet. This project aims to identify the extent to which modification of vehicles with ADASs has created problems in other jurisdictions, and how any such problems have been addressed.

## 1.2 ADAS sensors

The vast majority of current vehicles include a range of sensors (radar, lidar, camera, etc.), in addition to rain/light sensors, which provide data on the road and traffic environment surrounding the vehicle. Although most radar sensors are mounted in the bumper or front grille of the vehicle for longitudinal applications, older style lidar and camera systems are more typically located behind the windscreen because this site has the benefits of an improved field of view (FOV), both in terms of siting height and quality of vision within the area swept by the wipers, and because it offers the often very expensive sensors increased protection from the environment and direct impact damage. Vehicle manufacturers with camera-based systems favour the location on the windscreen behind the rear-view mirror, although there are examples of new production vehicles with roof-mounted cameras (eg, Nio). For scanning lidar systems (eg, Audi, Mercedes) these are grille-mounted, and some new production examples are mounted externally on the roof for improved FOV (eg, Nio, new Volvo XC90).

The sensed information required depends on the intended function of the system. Systems designed to avoid or mitigate collisions require information from the road environment in front of the vehicle in order to be able to decide on the appropriate action. For example, AEB systems and lane support systems, such as land departure warning (LDW) and LKA systems, require information on the upcoming environment so that the system can compare this with vehicle data to determine when, or if, to warn the driver or activate autonomous actions. The information collected by the sensors is therefore critical for these systems (and any system that requires information sensed from the environment around the vehicle) to function as they were intended.

In the case of these systems, the vehicle owner’s handbook typically contains warnings for situations that will reduce or prevent entirely the function of the sensors. For example, there are typically statements relating to foggy conditions or other environmental conditions that affect sensor data. Standards for lane departure systems also provide requirements for the system to notify the driver when the system is impaired in the case of system defects or by environmental conditions (International Organization for Standardization (ISO), 2017).

## 1.3 ADAS calibration

The purpose of a calibration is to allow the on-board software to determine the position of the sensor (either radar, lidar, or camera) relative to the vehicle and its immediate environment. For camera systems, this is captured in the electronic control unit as pitch (or rake), roll and yaw angles. For this reason, the reference target (in the case of a static calibration) is positioned at a defined height and distance from the vehicle so this can be used as a reference point. Dynamic calibration processes and fine-tuning while driving use the vehicle’s environment to determine the position; in principle, this is achieved by using sensed data to continually calculate new reference figures, compare them with last-known reference values and to confirm or make incremental adjustments to reduce the variance. However, the detailed information relating to how and which data is monitored is proprietary information and may also vary between vehicle manufacturers.

Calibration procedures are used by original equipment manufacturers (OEMs) to ensure that the sensors are correctly set up so that the decision making of the ADAS is based on accurate data. There are two main strategies employed: static and dynamic calibration. Static calibration involves the use of a specific target board placed in front of the vehicle at a specific height and distance from the vehicle in controlled conditions. The procedure, which differs between vehicle manufacturers, may involve multiple target board positions. Some vehicles also require a subsequent dynamic phase to accept the calibration. Dynamic calibration involves triggering the calibration routine, either using an on-board diagnostics tool to enter calibration mode, or in some vehicles activating it via the human–machine interface menus on the vehicle. The calibration is then automatically done using the driving scene; the length of time required for this depends on the road environment and quality of road markings or other environment features. It is also evident from the experience of testing vehicles after calibration that fine-tuning of the calibration settings occurs during driving to take account of changes occurring in the vehicle running order resulting from variable loading, towing and wear and tear on components. This may vary depending on the vehicle as the on-board diagnostics systems (and their capabilities) vary between manufacturers.

For either static or dynamic calibration, camera recalibration is required in a range of circumstances and is indicated in the vehicle owner’s handbook. Furthermore, one Audi training document (Audi AG, 2008) for static calibration states that the system requires calibration to compensate for effects from deviations of the actual orientation of the camera from the ideal orientation. Other manufacturers state similar requirements, and in general indicate that recalibration is necessary when:

- the windscreen has been replaced or removed
- any relevant system components have been replaced
- modifications affecting body height have been made to the vehicle suspension system.

The recalibration procedure is carried out electronically – that is, without making mechanical adjustments to the camera – with adjustments made in how the visual scene is interpreted by the camera. The orientation angles are determined indirectly by using a calibration board for a static calibration. The calibration board is aligned in a reference position in front of the vehicle. From recording the geometric patterns on the board, the angles are calculated by the on-board safety system software of the vehicle and stored in the control module.

## 1.4 Vehicle modification

The frequency of vehicle modification varies between countries, with this also linked to the types of vehicle present in the fleet. Countries with a greater proportion of ‘pickup’ vehicles, colloquially known in Australia and New Zealand as ‘utes’, are subject to a greater frequency of aftermarket modification compared with other vehicles. A vehicle owner or operator may change the ride height of the vehicle (either up or down) by changing suspension components or modifying their operation to raise or lower the body ride height relative to the ground. Motivations for ride-height changes can include:

- to gain additional under-chassis clearances for operational or recreational purposes
- to increase the vehicle’s load-carrying capability
- for a special need (such as improving access for a disabled passenger)
- to alter the vehicle’s appearance for aesthetic purposes (Leavy, 2016).

Vehicle owners may also alter the rake angle of the vehicle by altering the suspension on one axle.

However, the suspension is integral to the safety of the vehicle design, and modifying the suspension beyond that approved by the manufacturer (ie, officially approved suspension modification) may result in a safety risk. For example, in New South Wales, modifications to the ride height require certification from a licensed certifier if the changes to the vehicle exceed those considered ‘minor modification’. The limits for ‘minor modification’ in respect of those that affect ride height are:

- modifications to the suspension that increase or decrease the ride height by more than 50 mm
- modifications to the ride height up to 75 mm that incorporate a maximum change in the suspension of 50 mm and/or an increase in the diameter of the wheel and tyre combination of up to 50 mm.

The vehicle certifier checklist for safe operation lists ADAS under a single question: ‘Are all safety features, including AEB, still functioning?’ (Leavy, 2016).

In New Zealand, the LVV Certification Threshold Schedule details modifications that do not require LVV certification, but these do not explicitly specify the ride-height changes that require certification after changes to springs and shock absorbers. The limit for the size of leaf spring blocks to adjust ride height without certification is 50 mm.

# 2 Objectives

The objectives of this project were to:

- collate international literature and experience of the modification and calibration of vehicles with ADASs, the consequences of such modifications and measures taken to address any problems that have arisen
- synthesise findings and make recommendations for New Zealand policymakers and regulators to consider in addressing the calibration of ADASs on modified vehicles.

# 3 Literature review

## 3.1 Method

A list of search terms was developed informed directly by the research objectives (see Appendix A). This focused the search to identify information directly related to ADAS calibration and performance for passenger cars with altered ride heights. The final set of search terms was agreed with NZTA prior to commencing the literature review.

The following criteria were chosen to apply to the literature review:

- **Date range:** Publications from 2015 onwards. This ensured the most relevant technology coverage.
- **Language:** Publications in English language.
- **Publication status:** Both peer-reviewed published (eg, journal) literature and unpublished or 'grey' literature such as policy research papers. This ensured that high quality work outside the traditional academic literature was included.
- **Country contexts:** International, but publications from the UK, Europe, North America, Australia and New Zealand were prioritised.
- **Inclusion criteria:** Specific inclusion criteria were used to assess the suitability of the identified literature. The criteria were applied during an initial review of abstracts, and again with the full-text review. Each document identified was given a score for relevance (eg, how useful is it to answer the research questions) and quality (eg, whether it was retrieved from a peer-reviewed journal, non-peer reviewed scientific-based report or non-academic source). The criteria used are provided in Table 3.1 below.

**Table 3.1 Rating of literature**

| Criterion | Score = 1 (green) | Score = 2 (yellow) | Score = 3 (red) |
|---|---|---|---|
| Relevance | Directly relevant to the objectives of the review, or contains many details to inform review | Indirect or transferrable relevance to the objectives, or limited detail of direct relevance | Not relevant to the objectives of the project, and no transferrable details |
| Quality | Peer-reviewed scientific article (eg, journal paper or conference procedure) | Non-scientific article (eg, online source, newspaper or magazine article) with useful detail | Non-scientific article (eg, online source, newspaper or magazine article) with no useful detail |

Literature with a score of at least 2 in the relevance criterion was included so that we did not limit the sources.

TRL used a bespoke literature review tool to search a range of databases and sources. These included transport sector (eg, Transport Research International Documentation (TRID)), in-depth domain research (eg, ScienceDirect), and general sources such as Google Scholar and Bielefeld Academic Search Engine (BASE). Domain experts at TRL also identified relevant material based on their experience and knowledge to supplement the sources to be reviewed.

## 3.2 Results

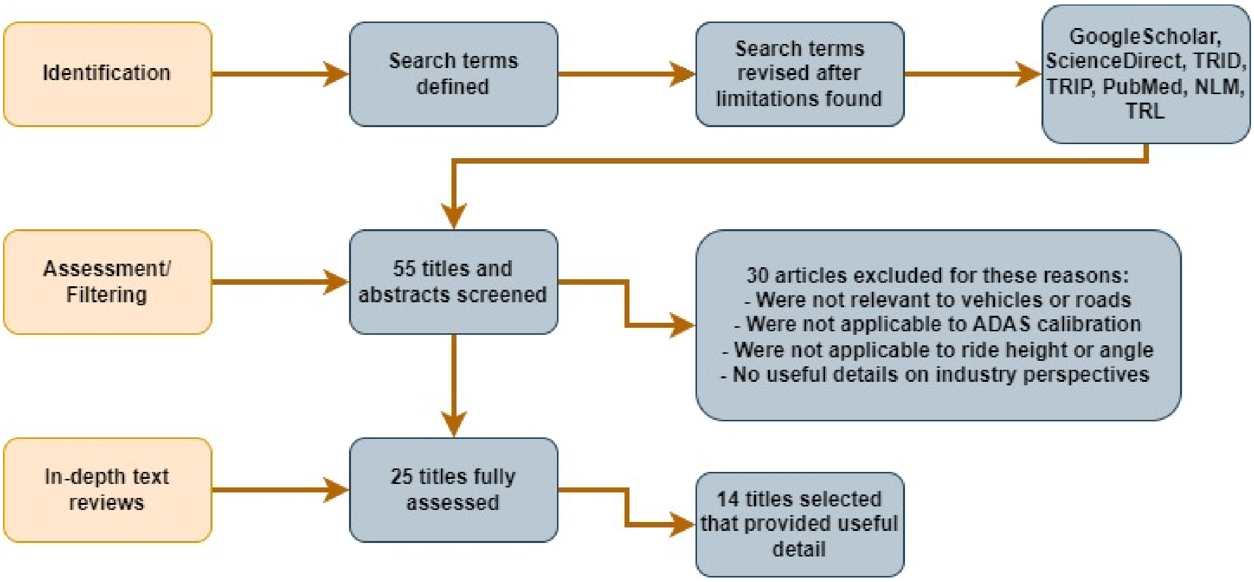
### 3.2.1 Overview

The literature review took a systematic approach consisting of three key tasks:

1. Definition of search terms (see Appendix A).
2. Assessment of quality and relevance (see Table 3.1).
3. In-depth review of full text literature for those selected for inclusion.

A high-level summary of the process and the numbers of sources included in the review are presented in Figure 3.1. These were also supplemented by references identified by domain experts at TRL and sources suggested by stakeholders during meetings.

**Figure 3.1 Literature review: Process and overview of sources included in the review**



### 3.2.2 Research Question 1: Is there any evidence (from international literature and direct technical experience) that modified ride heights on passenger cars affect ADAS performance either before or after calibration?

There were very few peer-reviewed studies or journal articles that discussed ride height, ADAS functionality and calibration in detail. This was likely a result of the specificity of the research questions and the factors being investigated. Much of the literature on calibration of sensors, cameras, lidar and radar were written on unrelated subjects, or in isolation as a technology. Literature on ADAS functionality related to the effects of damage to sensors and life-cycle use, with only peripheral mentions of ride height or rake angle. However, when looking at ‘grey’ literature and industry observations or best practice, this led to a greater amount of material, although by definition this is less evidence-based, including from sections of industry not involved in ADAS development.

As described in section 1.3, calibration procedures define how the vehicle software determines the position and orientation of the sensor relative to the vehicle's environment. Changes to the standard height of the vehicle therefore change the physical position of the sensor relative to the ground plane.

Changing the ride height and rake angle of vehicles can significantly change the FOV of ADASs and therefore cause issues in detection of hazards. The Modern Tire Dealer *Performance Handbook 2023* (Manges, 2023) states that increasing a vehicle's height is likely to increase 'sensor distance' (ie, how far ahead a vehicle sees), which would therefore alter the distances and times used to calculate warnings and reactions for an ADAS. This applies to changes in height to all parts of the vehicle, and changes in ratios of height between areas of a vehicle. The example given in this case is increasing the size of the rear wheels of the vehicle compared to the front (Manges, 2023). This would produce a downward rake angle, and if this was significant enough it could 'eliminate warnings or reactions from the system' since hazards would be outside a vehicle's FOV, or not detected as a hazard due to the change in how the ADAS recognised its location.

The main issue is the perspective; if a vehicle is raised or lowered significantly, sensors and camera data will not be consistent with the expected FOV of the sensors used to calculate proximity and warnings. The points of reference within the perspective of the ADAS will have been shifted, and the critical 'vanishing point' where the sides of a road in a vehicle's perspective meet at a horizon will be in the wrong place. Some information was found on how much this can mathematically change the FOV of a vehicle.

The Specialty Equipment Market Association (SEMA), a trade association for vehicle modification, describes the effects of changing ride height and angle on radar and camera systems (McColloch, 2022):

> *…a vehicle's radar system must be set at a specified level, often +/− 0.1 to 0.3 degrees, or to bubble level ... the floor must also be level—in this case, within +/− 7 millimetres, which equates to changing the angle of the radar sensor 0.4 degree.*
>
> *… Radar height/angle affects the effective range of the radar. For instance, a sensor that's off by 1 degree subtracts approximately 10% of the radar's effective range; a 2-degree misalignment increases that number to 25%; and a 3-degree misalignment subtracts 50% off the radar's effective range.*
>
> *… A camera pitch error of only 2 degrees can result in an inaccurate reading of up to 16 meters; a pitch error of −2 degrees can lead to wrong reading of up to 90 meters.*

Further commentary is given by S&P Global, considered to relate to pitch angle (Parekh, 2023):

> *Even a 1-degree change in the camera position at the windshield could mean a 1.7-meter deviation 100 meters down the road, resulting in the target area being significantly off trajectory. This could lead to the vehicle failing to detect and alert the driver to oncoming hazards.*

It is known that the vertical FOV of camera sensors is sufficient to cover the alterations described above (60 degree vertical FOV), but the ability of the system to recognise how changes in sensor position relative to the scene may influence subsequent ADAS performance. For minor changes (eg, changes due to loading), the on-board diagnostics may make adjustments to the calculated sensor position, but the ability to do so, and to react to the changes described by SEMA, will be affected by the capability of the individual systems.

Information from the Insurance Institute for Highway Safety (IIHS) in the USA showed that misalignment of the camera sensor on a Honda Civic due to poorly fitting sensor brackets resulted in delayed LDW (warning activated 28 cm over the line) and an AEB system that exhibited impaired braking performance (time to collision (TTC)[2] of braking 0.9–1.36 s compared with 1.47–1.48 s for baseline) and sometimes hit the test target rather than avoiding it (O'Malley, 2020). In this case, no warnings were presented to the driver regarding system impairment; with a correctly aligned sensor, LDW was activated before line crossing and the AEB prevented target impacts in all cases. In the case of this vehicle, recalibration of the system returned the AEB system to baseline performance (TTC of braking 1.47–1.53 s compared with baseline of 1.47–1.48 s). Similarly, the LDW performance was improved post-calibration to warn 15 cm before the lane boundary for the comparable test. This demonstrates that poorly adjusted sensors can influence subsequent ADAS performance, and although not directly comparable with ride-height changes, it shows that the position of the sensor is important to achieve the design performance of the system and that an appropriate recalibration can restore performance in at least some cases.

Xu et al. (2014) reported on a study concerning a self-calibration algorithm for a stereo-rigged set of cameras that was intended to closely replicate ADAS camera systems. The algorithm recognised the extreme ends of crosswalks on roadways and used this information to dynamically recalibrate the cameras to the appropriate positions. The self-calibration method was shown to be accurate, but pertinent to this report, the accuracy of the calibration was affected by the angle of the cameras being changed up or down, with the greater angle leading to lower performance. This finding can be extrapolated to infer that ride-height changes may affect the performance of ADASs, since if the algorithm in the study was not as effective after significant angle changes it can be assumed that less significant rake-angle changes may also negatively affect performance of the algorithms and sensors within regular ADASs to a lesser degree.

Furthermore, Cicchino (2017) reported that ADASs are liable to 'drift' or become non-calibrated over a vehicle's life cycle. Leslie et al. (2021) and Cicchino (2023) discussed FCW and AEB, alongside LKA, LDW and other ADAS features, and their general positive effects on driver safety. Importantly, both stated that 'driver usage' over time can affect the accuracy and safety performance of these systems in two ways. This is firstly through the way the driver adapts their driving style to the ADAS, becoming reliant on their functionality. Secondly, 'driver usage' affects ADASs through the repairs and modifications they make to the vehicle, and simple usage of the sensors causing drift, which can reduce the effectiveness of ADASs over the vehicle's life cycle. Though this did not specifically reference ride height, it showed that vehicle repairs and modification were a recognised cause of reduced ADAS performance.

Chipengo et al. (2018) used simulated corner/edge cases to assess the performance and optimal conditions of radar for pedestrian detection in vehicle-mounted antennas. As part of this, they discussed the effect of undulating/steep roads on the effectiveness of radar. They referred to heavily angled streets such as those prevalent in San Francisco, which sometimes exceed 17.5 degrees, and how this can have 'devastating' effects on ADAS and autonomous vehicle safety performance. Travelling at a steep downwards angle would block or reflect radar sensors against the approaching flatter plane and lead to the system missing hazards that were close in frontal proximity. Travelling at a steep upwards angle would lead to the radar 'overlooking' pedestrians and other hazards since they were below the radar FOV at the apex of a slope. This was expected to be 'particularly dangerous' in low-visibility conditions where a vehicle equipped with ADASs would rely more heavily on radar than camera systems. These findings can again be used to make informed assumptions about the effect of ride height. By either raising or lowering the angle of radar on an equipped vehicle without recalibration, the system performance may be affected.

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[2] TTC describes the time it would take for a collision to occur at an instantaneous speed, distance, and acceleration. A lower TTC indicates a later reaction of the AEB system to a hazard.

Stakeholders highlighted anecdotal evidence that the Ford BlueCruise[3] ADAS (a 'hands off, eyes on' Society of Automotive Engineers (SAE) Level 2 automated driving system) utilising adaptive cruise control and LKA had been reported to behave strangely if the vehicle suspension was raised from the OEM standard level in the USA. Aftermarket companies selling or equipping modified suspension note that at least some suspension kits in the USA state that they are 'not compatible with BlueCruise' and advise that the vehicle ride height should not be adjusted if the user wishes to use the BlueCruise functionality.

Commentary about ride height affecting ADASs is noted in industry discussion, especially in reference to recalibration. It is reported that many ADASs 'have built-in sensors that light up or otherwise notify you when the system needs calibrating' (HESAI, 2023) – this comment being in specific reference to ride height. While this source reports that systems notify the driver when out of standard calibration, it should be noted that this is not consistent with general field observations of systems.

It is recognised in the automotive industry that there is a range within which ride height of vehicles can be changed without a negative effect on ADAS performance. Many OEMs (ie, vehicle manufacturers) offer alternative diameter wheel/tyre combinations and also raised suspension height at build, both of which affect ride height, but these specifications offered are not expected to affect ADAS performance since the change is within the remit of the manufacturer's ADAS tolerance (Manges, 2023). However, if aftermarket changes to these vehicles fall outside of the tolerance of the OEM ADAS, such as much larger tyres or heavily lifted/lowered vehicles, then Manges (2023) assumes that it will have a negative effect. The lack of industry standardisation at present for sensors and ADASs, both OEM and aftermarket, also creates problems over a vehicle's life cycle since these produce differing needs for software updates and calibration methods during repairs (McColloch, 2022). In the same vein, the supplier of a particular sensor or camera to a manufacturer may be different depending on the vehicle grade or optional extras specified and may change over time, which further reduces standardisation of fitments and specifications of vehicles. A measure against this issue is again highlighted in support to the above point that manufacturers often build in a tolerance or accommodation for vehicle alterations. This even includes placing sensors in areas where they should not be blocked by additions such as auxiliary lights or winches, on top of changes to ride height and rake angle (Parekh, 2023).

Furthermore, a number of unpublished track test studies carried out by TRL have directly investigated the performance effects of deliberate miscalibration of ADAS camera sensors by moving the target from the position specified by the vehicle manufacturer, both horizontally and vertically. The vertical miscalibration can be thought of as analogous to the effects that might arise from recalibration after changes to ride height.

The performance of LKA was assessed after recalibration with differing static target board positions. The camera calibration procedure was adapted to alter the position of the calibration target board up to 150 mm left, right, and downward, and 50 mm upward from the vehicle manufacturer specified position. Each camera calibration was accepted by the vehicle's electronic control unit as a valid calibration and the LKA system was active, with no warning lights on the dashboard indicating impaired functionality or requirement for further recalibration. The main findings of this piece of research were that these camera miscalibrations significantly changed the response of the LKA from that after a calibration to the vehicle manufacturer's specification. However, the activation of the LKA still occurred within the lane boundary for both left and right lane departures, so it was able to prevent the vehicle from leaving the lane even with altered performance. This was not considered a safety concern since the LKA was still able to perform it's intended function. This indicates that some systems are tolerant to some differences in ride height at recalibration.

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[3] Ford BlueCruise: https://www.ford.co.uk/technology/driving-assistance/ford-bluecruise

In another project that investigated the effect of miscalibrations on AEB performance, using a similar methodology as above, degraded system performance was found. The performance of the AEB system was significantly influenced when the ADAS camera was calibrated with the target board positioned at locations that deviated from the manufacturer's specification. Recalibrations at the downward limit of successful calibration (analogous to increased vehicle ride height) were significantly different to all other conditions tested (including after an OEM calibration). In static tests, this condition resulted in more frequent impacts with the target because the AEB system activated very late or did not activate at all. This corroborates reports by industry stakeholders and Chipengo et al. (2018) that these types of adjustments affect the FOV of the sensor and its subsequent performance.

In addition to these studies that calibrated the ADAS camera at positions that deviated from the OEM specification, a similar effect is seen if the camera position itself is changed. For example, test work in the USA found that ADAS performance was affected by the quality of the ADAS camera-mounting bracket of a replacement windscreen (Insurance Institute for Highway Safety & Highway Loss Data Institute (IIHS-HLDI), 2018) for one particular vehicle model (Honda Civic). In this case, the plastic mounting for the bracket allowed the camera to become skewed (up to 0.4 degrees left and 0.6 degrees right) within the camera mount, which resulted in substantially impaired LKA and AEB performance. This is consistent with the anecdotal data given by representatives from the industry. This performance was demonstrated in track tests and further confirms that the performance of the LKA and AEB systems can be sensitive to sensor alignment. It should also be noted that in this case the vehicle's on-board diagnostics system again did not identify the fault of the camera being displaced from the correct position, so it did not indicate any negative effects to drivers.

Looking at the evidence reviewed, ride height, rake angle and other factors can all affect the 'on the road' ADAS performance of vehicles. The key points from the review are as follows.

- Ride-height and rake-angle changes can have effects on ADAS performance because the software determines the incorrect sensor position(s). Therefore, this can affect when warnings and driver assistance actions are activated or mean that the systems are supressed and, in extreme cases, non-functional.
- Vehicle manufacturers allow for some ride-height changes within specific tolerances (presumably to accommodate changes in loading conditions). At calibration, tolerances also exist, including ride height (some manufacturers offer lift kits for some vehicles). These calibration tolerances vary between vehicle manufacturers, and ADAS performance at the extremes of the tolerances have been shown to be reduced for at least some vehicle models when calibrated using standard procedures.
- ADAS recalibration has been shown in some cases to correct performance to design levels, although in other cases performance differences compared with the baseline remain, suggesting that this factor also varies between vehicles.

### 3.2.3 Research Question 2: If issues have been identified for vehicles with modified ride heights, what measures have been taken to address them?

The review did not locate any legislative measures from other jurisdictions designed to address this issue. Technical measures identified in the review fall into two areas: design considerations and recalibration, both of which relate to ways in which industry has attempted to mitigate any issues.

In the design of the system, OEMs and suppliers usually design in a certain level of accommodation and tolerance to changing ride heights and angles on their vehicles, usually within the remit of the manufacturer approved and provided lift kits and tools (Manges, 2023; McColloch, 2022). This is also considered in the size range of tyres recommended for vehicles at sale and fitment, as the tread difference between the specifications offered is designed to not interfere or cause performance issues for ADASs because of changing ride height. The issue with this measure is that it only accounts for manufacturer approved and sold kits, rather than aftermarket or other OEM-provided modifications. Raising components within suspensions, lifting vehicles, and oversized tyres are particularly popular aftermarket modifications for pickup trucks and sport utility vehicles (McColloch, 2022), and many of these systems are not approved or checked by OEMs. Therefore, it is difficult for technicians or repair/recalibration staff to have awareness of the changes made to vehicles by these modifications and therefore whether the standard recalibration procedure is appropriate.

This measure of design considerations extends to other forms of vehicle modification, such as the addition of winches or bars on bumpers and other areas of the vehicle. Adding features onto the bodywork of a vehicle in proximity to sensors servicing ADASs is very likely to have an effect on the system in that they could obstruct/reflect signals and lead to false positive activations or failures to detect hazards. In a SEMA article titled ‘Modifying ADAS-Equipped Vehicles’, Imlay (2020) explains how manufacturers are attempting to design in measures against this, such as altering bumper geometry, sensor locations and increasing FOV, and also that aftermarket modifiers are doing the same. The article discusses various aftermarket vehicle modification organisations and the methods they take to ensure their vehicle redesigns do not compromise ADASs as far as reasonably possible. Methods mentioned include:

- use of computer-aided design (CAD) to measure FOV cones for ADAS sensors and check the effects of obstructing them
- track and on-road testing of ADASs before and after modifications (up to 500 miles distance travelled)
- pedestrian scenario testing using both adult and child forms.

Though these measures make attempts at ensuring aftermarket modifications do not interfere with ADAS performance, it was noted by Imlay (2020) that not every technician or OEM conducting aftermarket changes will go to these lengths to track test or validate ADASs. This means the problem of misalignment of sensors and cameras after modification and ride-height change still remain for many vehicles.

The main measure taken in the industry to address the effects of modified ride heights is recalibration of sensors post-modification. In Imlay’s (2020) SEMA article discussing aftermarket organisations, each organisation described the multiple stages of recalibration and testing that was undertaken to ensure that the ADAS sensors were properly aligned when the vehicle was delivered:

- American Expedition Vehicles (AEV):

  > *AEV partnered with several third parties to perform proving-ground testing that the company was unable to perform in-house. Final inspection included technicians plugging into vehicle systems using MOPAR software to completely scan ADAS equipment and verify calibration and compliance.*

- Transamerican:

  > *Testing and mapping is repeated, and corrections are made until the systems meet the OE range measured when the vehicle was first delivered to us 100% stock.*

- The Fox Factory:

  > *There are some fundamental calibrations that need to be done even prior to focusing on the camera and the radar systems … [including] speedometer calibrations to account for larger tire sizes, four-wheel alignment, steering angle sensor alignment, FMVSS 126 and 135 testing so that we can ensure that the vehicle is braking, and the electronic stability control systems are all performing like they should.*

> *… During on-road testing, the Titan's lane-departure warning and adaptive cruise control with gap adjustments were validated. Once the truck received its VIN-specific calibration documentation, it was off to TRC for further proving-ground evaluation.*

The approaches used both static and dynamic methods of calibration in combination to achieve the desired performance of ADASs post-modification. Static calibration usually involves the vehicle in a controlled environment with static alignment targets, and lasers are used to position the vehicle/recalibration equipment in order to ensure the ADAS has a correct frame of reference. Dynamic calibration usually involves in-situ testing of ADASs using certain parameters, such as ensuring a vehicle is correctly identifying the lane markings on a road at a certain set speed, or that it is able to detect pedestrian forms during track testing. Both of these are well-trusted methods in addressing issues with ADAS sensors over the life cycle of vehicles and after modifications (HESAI, 2023; Parekh, 2023). These sources also indicate that ADAS-equipped vehicles may alert the driver when the vehicle detects that the camera is miscalibrated. However, it should be noted that this capability is not consistent with practical experience of systems for passenger cars, where such warnings are not communicated to the driver unless there is a major event (ie, power or component failure). This capability also depends on the on-board diagnostics system of the vehicle and whether the sensor data is outside specific tolerances, otherwise systems may not be capable of detecting issues.

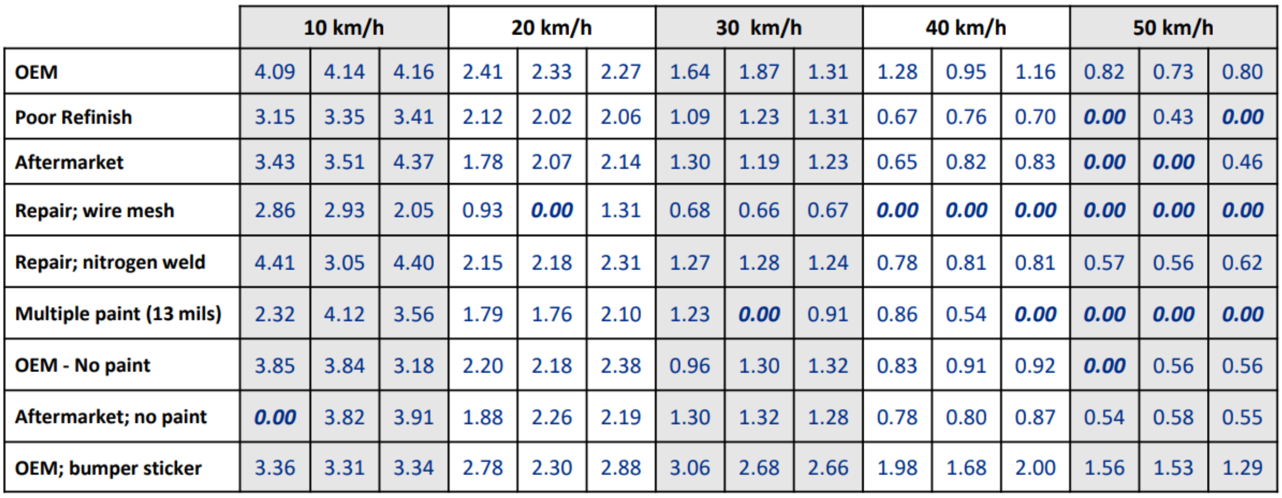
It is noted that even 'routine' vehicle repair procedures can affect ADAS performance, and there appears to be a desire within the repair and recalibration sectors to foster greater collaboration and interdependence between the work of each party (Parekh, 2023): 'For example, wheel alignment shops could examine getting into ADAS inspection because an accurate wheel alignment on most vehicles will require an ADAS reset.' Recalibration as a measure addressing the effects of ride-height changes on ADAS performance is one that is already prevalent, but there is scope for the requirements and provision of recalibration to go further than it currently does. Vehicles that register aftermarket modifications should be notified for ADAS recalibration regardless of whether this made use of manufacturer-approved or provided kits, since (as noted above) even 'routine' repairs could lead to ADAS performance being affected. This goes in hand with the further growth in the number of ADAS-equipped vehicles in the market. As the number of equipped vehicles increases, the number of recalibrations will also increase. This therefore means a larger number of vehicles' safety performance will be affected by the interaction between repairs and ADAS functionality.

The IIHS demonstrated this in its findings (O'Malley, 2020). It found that the number of vehicles being brought in for repair and requiring recalibration requests due to having incorrectly fitted or specified windscreens increased heavily between 2016 and 2019 for multiple manufacturers, including Volvo, Mercedes-Benz, Honda and Subaru. It also found significant differences between calibration procedures from different manufacturers:

- Different requirements for static and dynamic calibrations: Only 27% require both static and dynamic calibration, 42% require only dynamic calibration.
- Only 45% say to check tyre pressure and ride height before process, and only 22% say to check wheel alignment.

The IIHS also examined the relationship between repairs and ADAS performance after repair and recalibration. It tested the performance of a rear cross-traffic detection system of a Toyota Prius with differing bumper status. This included OEM and aftermarket bumper parts, well and poorly painted parts, repair using nitrogen welding or wire mesh, and the addition of a bumper sticker. It was found that many conditions produced no alert sound from the ADAS-equipped vehicle – that is, the TTC of the alert was 0.00 seconds. The results can be seen in Table 3.2 below.

**Table 3.2 IIHS rear cross-traffic detection results: TTC (seconds) of alert (reprinted from O'Malley, 2020)**



| | **10 km/h** | | | **20 km/h** | | | **30 km/h** | | | **40 km/h** | | | **50 km/h** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **OEM** | 4.09 | 4.14 | 4.16 | 2.41 | 2.33 | 2.27 | 1.64 | 1.87 | 1.31 | 1.28 | 0.95 | 1.16 | 0.82 | 0.73 | 0.80 |
| **Poor Refinish** | 3.15 | 3.35 | 3.41 | 2.12 | 2.02 | 2.06 | 1.09 | 1.23 | 1.31 | 0.67 | 0.76 | 0.70 | ***0.00*** | 0.43 | ***0.00*** |
| **Aftermarket** | 3.43 | 3.51 | 4.37 | 1.78 | 2.07 | 2.14 | 1.30 | 1.19 | 1.23 | 0.65 | 0.82 | 0.83 | ***0.00*** | ***0.00*** | 0.46 |
| **Repair; wire mesh** | 2.86 | 2.93 | 2.05 | 0.93 | ***0.00*** | 1.31 | 0.68 | 0.66 | 0.67 | ***0.00*** | ***0.00*** | ***0.00*** | ***0.00*** | ***0.00*** | ***0.00*** |
| **Repair; nitrogen weld** | 4.41 | 3.05 | 4.40 | 2.15 | 2.18 | 2.31 | 1.27 | 1.28 | 1.24 | 0.78 | 0.81 | 0.81 | 0.57 | 0.56 | 0.62 |
| **Multiple paint (13 mils)** | 2.32 | 4.12 | 3.56 | 1.79 | 1.76 | 2.10 | 1.23 | ***0.00*** | 0.91 | 0.86 | 0.54 | ***0.00*** | ***0.00*** | ***0.00*** | ***0.00*** |
| **OEM - No paint** | 3.85 | 3.84 | 3.18 | 2.20 | 2.18 | 2.38 | 0.96 | 1.30 | 1.32 | 0.83 | 0.91 | 0.92 | ***0.00*** | 0.56 | 0.56 |
| **Aftermarket; no paint** | ***0.00*** | 3.82 | 3.91 | 1.88 | 2.26 | 2.19 | 1.30 | 1.32 | 1.28 | 0.78 | 0.80 | 0.87 | 0.54 | 0.58 | 0.55 |
| **OEM; bumper sticker** | 3.36 | 3.31 | 3.34 | 2.78 | 2.30 | 2.88 | 3.06 | 2.68 | 2.66 | 1.98 | 1.68 | 2.00 | 1.56 | 1.53 | 1.29 |

The 'Repair; wire mesh' row demonstrates that when the bumper was repaired in front of a functioning sensor, this affected the ADAS performance. The IIHS found that although manuals and guidance would tell repair staff that certain repairs were not compatible with ADAS features, this advice was not followed or would be contradicted by further guidance informing them that a repair was good practice. By looking at these results together with the fact that only 45% of any of the manufacturer recalibration processes examined even mentioned ride height, it is clear that although recalibration is known to be important to preserving ADAS function and vehicle safety, the processes have scope for improvement.

This improvement is likely to involve further interdependence between repairers and those responsible for recalibration, with the recognition that repairs to ADAS-equipped vehicles are very likely to require recalibration even if they are seemingly 'routine' repairs or small ride-height adjustments. Thatcham Research (2019, p. 2) produced guidelines on best practice when repairs require recalibration of ADASs. Given scenarios are:

- *Repairing, removing, refitting, aligning or replacing parts within the vicinity of ADAS sensors.*
- *Making any geometry changes, or changes to the vehicle's suspension or ride height.*
- *Realigning, replacing or refitting any ADAS sensors or associated vehicle parts.*

As part of this guidance, Thatcham Research also suggests general methods and approaches to take when recalibrating ADASs post-repair. Considerations include:

- assessing for presence ADAS sensors pre-repair and seeking guidance of relevant manufacturer-specific methods
- confirming recalibration sits within relevant vehicle manufacturer ADAS tolerances[4]
- approaching the manufacturer dealership network if no relevant repair guidance exists or is available for a vehicle
- ensuring the correct method of calibration is used (static, dynamic, or both).

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[4] Although this is not easy to achieve as vehicle manufacturers may provide sensor location tolerances, but do not provide tolerances for recalibration of sensors.

Differences in manufacturer calibration methods were also found however, so standardisation or guidance on ADAS calibration after repairs and height changes, and which of these are incompatible, would be a step to avoiding ADAS performance being negatively affected. Thatcham Research (2019) further suggests that vehicle manufacturers and software/equipment suppliers provide clear, consistent advice and procedures and provide or support training for technicians and document capabilities of current calibration methods.

As an overall answer to the research question, there were measures identified to address the effect of ride height and other modifications on ADAS performance. These are, broadly:

- design considerations – design and test vehicle ADAS features pre-deployment to determine the settings most resilient to ride-height modifications
- frequent and targeted recalibration – ADASs should be recalibrated to manufacturer specifications even after minor modifications and repairs to ensure the ADAS frame of reference is correct and will continue to function as required.

However, with each of these main measures, there are the following issues.

- Design considerations only go so far, as aftermarket additions, modifications and repairs can all invalidate the protection that a vehicle’s design provides since they are outside of the range of manufacturer-approved processes.
- Manufacturers and OEMs have different calibration procedures, and often it is difficult to determine what a modification has changed and therefore which sensors to recalibrate. Some repairs can also interfere with calibration and cause ADASs to perform poorly even after recalibration is completed in accordance with vehicle manufacturer guidance and instructions.

# 4 Stakeholder information

## 4.1 Introduction

During June 2023, TRL held online meetings with five stakeholders (see Appendix C) using the topic guide (see Appendix B) as a guide for the meetings. The following sections report the findings.

## 4.2 Research Question 1: Is there any evidence (from international literature and direct technical experience) that modified ride heights on passenger cars affect ADAS performance either before or after calibration?

The Vehicle Certification Agency (VCA), the UK's type approval authority and designated technical service, was not aware of any issues in the field arising from vehicles with modified ride heights affecting ADAS performance. However, aftermarket modifications do not require certification in the UK; any changes made must comply with the Road Vehicles (Construction and Use) Regulations (1986).[5] These requirements ensure vehicles are roadworthy and are enforced by Police and a limited number of specific aspects formally checked at periodic technical inspection. This test – often referred to as MOT in the UK – is mandatory and required annually for passenger cars in the UK over 3 years old. However, ADASs are not currently covered by these in-use regulations and are also not one of the areas that are checked at MOT.[6]

Therefore, in the UK, impaired ADAS performance is most likely to be detected by the driver of the vehicle, who may notice altered performance and report to a vehicle main dealer or a windscreen repair and replacement company if this is the source of the change in performance. TRL considers it unlikely that impaired performance would be detected by roadside enforcement, and some systems (eg, AEB) may not manifest any issues until a critical event occurs. Detectability of ADAS impairment was discussed, and this was considered only likely to be noted by the driver of the vehicle, and it is also likely that performance changes for AEB may be less detectable in normal driving than systems such as LKA, lane centring and adaptive cruise control, unless the vehicle warns of impaired functionality. VCA indicated that in the UK, raising and lowering the suspension is relatively rare in comparison to regions such as the USA, Australia and New Zealand, so overall effects were noted as low from a population perspective.

Australia mandated AEB (ADR 98) and LKA (ADR 107) on new vehicles from start dates in 2023/24. Transport for NSW indicated that in common with New Zealand (and also the USA), aftermarket modifications such as lift kits, bull bars, and antennas/driving lights are 'commonly installed' by vehicle owners. In response to this, test work is ongoing with the objective of assessing the effect of these aftermarket modifications on ADAS performance. Results from this test programme may be shared, but this is not certain at this stage.

The testing programme has included the 2020 Toyota Hilux, 2021 Ford Ranger and 2022 Isuzu D-Max. These models were chosen because they are commonly fitted with aftermarket accessories and subject to a range of loading while in use. They also represent the different types of sensor systems used for ADAS

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[5] Road Vehicles (Construction and Use) Regulations (1986): https://www.legislation.gov.uk/uksi/1986/1078/contents/made

[6] MOT inspection manual: cars and passenger vehicles: https://www.gov.uk/guidance/mot-inspection-manual-for-private-passenger-and-light-commercial-vehicles/1-brakes

technology: dual camera systems (Isuzu D-Max) and single camera combined with a radar (Toyota Hilux and Ford Ranger).

Testing has focused on both AEB and LKA, with AEB being tested in the following test scenarios:

- stationary vehicle target (10–60 km/h)
- moving vehicle target (30–80 km/h; target 20 km/h)
- child pedestrian near side (vehicle speed 10–60 km/h; pedestrian target 5 km/h)
- adult pedestrian far side (vehicle speed 10–60 km/h; pedestrian target 6 km/h).

Baseline performance assessed at running order (kerb mass plus equipment and driver) and gross vehicle mass with load distributed according to axle load limits and the following variations have been assessed for comparison with the baseline conditions:

- rearward pitch – vehicle loaded to rear axle limit and maximum load applied to rear towing ball to simulate trailer loading
- lift – 75 mm combined lift is the limit in New South Wales before certification is required (up to 50 mm from suspension changes and up to 50 mm from wheel/tyre diameter)
- lift and bar – as above with the addition of bull bars
- bull bars – OEM specification with the addition of bull bars
- antennas (no further detail available)
- driving lights (no further detail available).

SEMA also indicated that testing on variations in ride height (on similar vehicle types to Transport for NSW) has been carried out, and that it offers a test facility designed to investigate and recalibrate vehicles with modifications such as ride-height changes. Results from this work are unavailable, but high-level observations of the effect on ADAS performance were comparable with those noted by other sources.

TRL has carried out multiple test programmes that have involved track testing to assess ADAS performance (see section 3.2.2), although these have focused on performance after deliberate miscalibration by adjusting the position of the static target board compared to the vehicle manufacturer's specification. These results indicate that altered recalibration settings (ie, those that deviate from the vehicle manufacturer's specification, the vertical adjustments of which are analogous to recalibration after ride-height changes) result in ADAS performance changes after recalibration, but that generally these differences are non-material in most cases.

The specific issue of lifted vehicles is noted in the glass replacement markets in the USA and Australia, and their policy is that recalibration of ADASs is carried out after windscreen replacement if the vehicle ride height is within OEM tolerances. If it is outside tolerances, then a recalibration is not carried out and the customer is provided with a disclaimer regarding the ADAS functionality. Issues identified by glass repair and replacement companies are the difficulty, in some cases, of determining the OEM tolerance limits for different vehicles, and practical issues regarding identifying lifted or raised vehicles in the field as users may not admit to or be aware of changes that have been made.

Bosch has been involved in the calibration of ADASs for many years and confirmed the general performance differences after miscalibration and also for performance where the calculated sensor position deviates from the expected value. The same general issues affect camera and radar sensors, but systems should recognise when they are outside thresholds at which they function, but this is likely to vary between vehicles because of differing on-board diagnostics capabilities. Dynamic fine-tuning calibration should also detect issues over the course of driving and correct the sensor calibration or, in case of significant errors, deactivate the system and warn the driver.

During recalibration, some vehicles request the ride height as an input to the calibration process (eg, Volkswagen, Nissan, Honda). For these vehicles, if the ride height is outside the vehicle manufacturer tolerances, then the recalibration will fail on the basis of the ride-height inputs not being within specification. However, other vehicles do not request this data, so it is assumed for these cases that a standard value is used. The AEB functionality especially was highlighted as being likely to be impacted by changes to the sensor FOV.

## 4.3 Research Question 1: Summary

Stakeholders highlighted that effects on ADAS performance are acknowledged for at least some vehicles with altered ride heights. The effects may vary between vehicles of different types because they have different ADASs, and also different on-board diagnostic capabilities. Performance effects on ADASs occur pre-recalibration and may also be present post-recalibration depending on the specific vehicle and whether ride height is an input into the calibration process.

In general, the effects on performance are non-material, with ADASs still delivering reasonable performance compared with design performance. However, in some instances (on some vehicles), the effect on ADAS performance appears to be more significant, with a greater number of examples of no, or late, AEB activation and lane keeping activation further over the lane boundary. These have the potential to have a reduced level of safety performance in critical situations compared with the baseline system.

Within the vehicle manufacturer range of ride height, differences in performance have been noted, but the level of ADAS performance is not materially different to the baseline.

At least some vehicles (if ride height is not an input in the calibration process) appear to be able to successfully accept a recalibration in a wider range of conditions but with effects on ADAS performance without any driver warning of changed ADAS functionality. This may vary between vehicles and their on-board diagnostics capability.

## 4.4 Research Question 2: If issues have been identified for vehicles with modified ride heights, what measures have been taken to address them?

VCA did not highlight any issues that it was aware of regarding effects on ADAS performance from raising or lowering the ride height of vehicles. VCA indicated that in principle, during multi-stage approval, it would become aware of modifications made in subsequent stages to aspects that had been already approved (eg, wheelchair accessible vehicles changing the rear suspension). In this case, there is a test to determine whether suspension changes have influenced electronic stability control (ESC) performance. The requirements specified for ESC for special purpose vehicles in Commission Regulation (EU) No 214/2014 are as follows:

> *The requirements shall be fulfilled to the greatest extent. The type-approval authority may only grant exemption(s) if the manufacturer demonstrates that the vehicle cannot meet the requirements due to its special purpose. The exemptions granted shall be described on the vehicle type-approval certificate and the certificate of conformity (remark –entry 52).*
>
> *The fitting of ESC is not mandatory. In the case of multi-stage approvals, where the modifications made at a particular stage are likely to affect the function of the base vehicle's ESC system, the manufacturer may either disable the system or demonstrate that the vehicle has not been rendered unsafe or unstable. This may be demonstrated, e.g., by performing rapid*

> *double lane-change manoeuvres in each direction at 80 km/h with sufficient severity to cause intervention by the ESC system. These interventions shall be well-controlled and shall act to improve stability of the vehicle. The Technical Service shall have the right to request further testing if deemed necessary.*

Although there are no requirements for ADASs, VCA considered it possible that if ADASs were to be considered, this may be treated in a similar way to that used for ESC, in that the authority would need to be satisfied that the systems offered acceptable performance and did not have any unintended consequences, but would not be tested to the extent that systems on a standard vehicle type would be. In two-stage approvals, body builders would be supplied by manufacturers with information on the boundary conditions; unless it is within that tolerance, applicants would probably not be able to provide evidence that the ADAS performance was unaffected, so VCA would likely reject the modification.

SEMA provides test facilities and services to members to allow testing of aftermarket modifications, allowing suppliers to test calibration of ADASs with modified vehicles. This provides the industry with the technical approach to investigate compatibility of modifications with ADASs.

Transport for NSW indicates that thresholds exist for changes to ride height of 75 mm (up to 50 mm from suspension changes and up to 50 mm from wheel/tyre diameter). Transport for NSW's *Light vehicle modification manual – Suspension and ride height* (Leavy, 2016) outlines modifications that require certification in accordance with the Road Transport (Vehicle Registration) Regulation 2007 and the Vehicle Safety Compliance Certification Scheme. These values are based primarily on stability and handling issues rather than effects on ADASs, but the certification checklist lists a criterion for high-level ADAS functionality.

## 4.5 Research Question 2: Summary

No legislative measures to address the issue identified were found from either the literature review or the stakeholder meetings.

Some technical measures have been taken by the industry to improve compatibility of modifications and aftermarket accessorises with ADASs as evidenced by the services and testing offered by SEMA, but no technical measures were identified as being directly applicable to regulators.

# 5 Discussion

## 5.1 ADAS performance and recalibration

AEB and LKA have been studied more extensively than other ADASs (eg, blind-spot detection). No evidence was found regarding blind-spot detection performance being influenced by ride-height changes. The evidence from the literature and from discussions with stakeholders highlights a range of data that shows that ADAS performance is influenced by changes in ride height both without calibration and after a calibration to the vehicle manufacturer's standard specification (ie, calibrated for standard ride height). Although not robust enough to draw definitive conclusions, the information available to date suggests that the effect on performance varies between vehicles. This is perhaps to be expected since different vehicles may be equipped with different ADASs, and different generations of ADASs may cope with these issues more effectively.

During normal use, the loading of the vehicle alters the height and attitude of the vehicle. It is presumed that this is the reason for tolerances of the standard calibration position (from testing of several vehicles), which allows minor deviations from the specified reference point. In these situations, the system reports a successful calibration, and the system will remain functional. As the deviations from the specified position increase, and the tolerance limit is reached, a vehicle will typically not accept a recalibration. When the recalibration is accepted, evidence was found that ADAS performance may not be optimum, but was still functional and, depending on the direction and extent of electronic sensor misalignment at recalibration, may result in an ADAS warning and acting earlier or later compared with the standard system.

However, without recalibration, changes to the sensor positions may also have effects on ADAS performance. This may vary between vehicles and sophistication of the vehicle's on-board diagnostic systems. There was some information that, for early systems at least, the LKA and AEB could be noticeably impaired without the vehicle detecting this and alerting the driver via a malfunction indicator light.

In terms of functional safety design of the systems, ADASs are designed by manufacturers using the ISO 26262 functional safety standard as industry practice (ISO, 2018) and because these systems are typically SAE Level 0 (in some cases Level 1) systems, the systems have the controllability measure as the driver. For greater levels of automation, systems will have more advanced functional safety concepts (see section 5.2)

From the information gathered, it is evident that manufacturers specify a tolerance for ride-height changes, primarily for other issues such as vehicle handling. Within these tolerances, the limited evidence suggests that the performance of the ADAS may be affected, but that performance changes are generally non-material in terms of safety. However, it should be noted that the evidence also suggests that this varies between vehicles, and in some cases ADASs can be more significantly affected. Further test work is required to investigate this issue, and ongoing results from Transport for NSW may allow a more robust assessment of the effects to be made.

It also appears that, for at least some vehicles, ride-height changes that exceed the manufacturer limits may result in degraded ADAS performance without driver warnings. However, the ability of the on-board diagnostics system to detect issues is likely to vary between vehicles, and only anecdotal evidence is available.

Recalibration of ADASs in some cases results in restoration of ADAS performance to design levels. For vehicles that request a measured ride height or for those with special calibration procedures for OEM-approved lift kits, this is expected to be the case. For recalibration that assumes the standard ride height on a vehicle that does not request the measured ride height at recalibration, the limited evidence shows that this may not restore performance to design levels.

Changes to ride height could have two negative outcomes on safety system performance. The changes could:

1. degrade or change the performance of the system so that it does not function as intended
2. cause the system to provide false positive activations where warnings or actions are activated when they are not warranted.

There is no evidence from testing that the more serious false positive responses occur, although these test environments are not a reliable indicator of this aspect because the immediate environment is uncluttered. Anecdotal reports indicate that warnings can be triggered in situations where the system would not be expected to activate, but limited information is available.

## 5.2 Automation and functional safety

The SAE defines six levels of driving automation ranging from 0 (fully manual) to 5 (fully autonomous), depending on the roles in the driving task for the driver and the system (SAE International, 2021):

- Level 0: No driving automation
- Level 1: Driver assistance
- Level 2: Partial driving automation
- Level 3: Conditional driving automation
- Level 4: High driving automation
- Level 5: Full driving automation.

For current ADASs that provide driver assistance in a momentary capacity (eg, AEB, FCW, LDW, LKA), these are Level 0 systems. For ADASs that provide more continuous ongoing support (eg, lane-centring systems and adaptive cruise control) these are considered Level 1 systems. If multiple systems are engaged simultaneously that provide longitudinal and lateral support (eg, lane centring and adaptive cruise control) then the combined ‘system’ is delivering Level 2 automation. One key distinction is the ‘fall-back’ capability of the automation where this falls to the driver (Levels 0–3) or the system (Level 4–5).

As the capability of vehicle systems develops towards greater levels of automation, the system design will have more demanding safety goals and different functional safety strategies to enable effective ‘fall back’ capability. For example, in terms of functional safety design of the systems, ADASs are designed by manufacturers using the ISO 26262 functional safety standard as industry practice (ISO, 2018). This standard was adapted from the International Electrotechnical Commission’s (IEC) 61508 standard (IEC, 2010), and it provides manufacturers with a framework to design a system where safety is at the focal point. It is intended for application to safety-related systems that include one or more electrical and electronic (E/E) systems in motor vehicles to deliver a system that is free of ‘unreasonable risk’ to individuals caused by potential malfunctions in the E/E systems. ISO 26262 consists of 12 parts, which cover the management of functional safety for a system through its concept, product development and production and operation stages. For initial development of a system, the ISO 26262 Part 3 ‘concept phase’ involves a safety risk analysis to develop a functional safety concept that is used to specify functional safety requirements. Vehicle hazards are identified via HAZOP (Hazard and Operability study) and/or STPA (System Theoretic Process Analysis) and a corresponding safety goal determined to mitigate each hazard. Each safety goal is then classified in accordance with one of five possible safety classes:

1. Quality Management (QM)[7]
2. Automotive Safety Integrity Level (ASIL) A
3. ASIL B
4. ASIL C
5. ASIL D.

The safety goal classification is achieved by evaluation of three parameters:

1. exposure – that is, how often the vehicle is in a situation in which the people involved (eg, driver, passengers or other road users) may be put at risk
2. controllability – that is, how well the individuals involved can handle an infringement of the safety goal
3. severity, which quantifies the seriousness of the consequences that may arise from a breach of the safety goal.

Safety goals must be implemented in accordance with the classified ASILs and is done by performing safety analyses to define a functional safety concept that addresses a range of issues, including fault detection and failure mitigation, and transitioning to a safe state. The functional safety concept could be architectural strategies such as ‘fail safe/passive’ or ‘fail operational’ with associated redundant systems.

- **Fail safe/passive:** An electronic system is ‘fail safe’ if any single electronic fault is detected and results in the system transitioning to a safe state to ensure safety of the system. A system is ‘fail passive’ if it disengages after an electronic fault with no further action and does not interfere with operation of other systems.
- **Fail operational:** An electronic system is ‘fail operational’ if any first electronic fault is detected and does not result in a loss of any primary electronic system functionality that is essential to the safety of the system. Following any first electronic fault, if the degraded system is no longer fail operational to any subsequent fault, the system transitions to a status of fail safe. Essentially, the system can safely sustain a minimum of two fully independent faults prior to loss of primary system functionality and transition to an associated safe state.

It should be noted that the redundancy of sensor signals required in the vehicle E/E architecture for fail operational capability can also contribute to potential self-calibration or run-time reconfiguration as and when required (Macher et al., 2019).

As vehicle systems progress to greater automation levels and the ‘fall back’ is the system, the functional safety concept of the system will demand a design with ‘fail operational’ capability. This will, for example, demand much more sophisticated on-board diagnostic capability, dynamic recalibration capability and sensor redundancy than current ADASs. This will mean that systems with greater automation will either be able to adapt to changes in ride-height through improved system capability, or will not offer automated driving if the vehicle is not in specification (eg, altered ride height).

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[7] The rating ‘QM’ indicates that a standard quality management system (eg, in accordance with ISO/TS 16949) and the observance of established standards such as Automotive SPICE are sufficient to achieve the corresponding safety goal and that no additional requirements need to be taken from ISO 26262.

# 6 Conclusions

The main conclusions from this project are as follows.

- The available evidence suggests that ADAS performance (AEB and LKA) is altered when vehicle ride-height and rake angle is changed because the electronic orientation of the sensor in the software has a different frame of reference.
    - Altered performance means that the ADAS warnings or actions occur at a different time compared with the baseline ADAS. Generally, altered performance is not materially different to the baseline condition, but the magnitude of the difference appears to vary between vehicles. In some instances, the ADAS functionality can be affected significantly.
    - There is insufficient evidence on the magnitude of ride-height changes for which ADAS performance changes are non-material compared with baseline. Further data is required to determine a proportionate response to the issue.
- No test results were available specifically on ride-height changes without recalibration. It would be expected that in these cases, the ADAS performance would be influenced (depending on the magnitude of the ride-height change) because the position of the sensor is changed compared to that expected by the system. The ability of the systems to self-correct is not well understood, although stakeholders indicate that irrespective of the recalibration method (static, dynamic, combined), vehicles also have the ability for dynamic fine-tuning. However, based on the evidence collected from stakeholders, this is likely to vary because the capability of on-board diagnostics systems to identify and correct deficiencies also varies between vehicles.
- Vehicle manufacturers allow for some ride-height changes within specific tolerances, presumably to accommodate changes in loading conditions. At calibration, tolerances also exist, including ride height, and some manufacturers offer lowering and lift kits for some vehicles. These calibration tolerances vary between vehicle manufacturers, and ADAS performance at the extremes of the tolerances have been shown to be reduced for at least some vehicle models when calibrated using standard procedures.
- At recalibration, tests that altered the static target position for an ADAS camera (analogous to ride-height changes) showed that:
    - recalibration was accepted by the vehicle for a range of target position conditions compared with that specified by the vehicle manufacturer
    - AEB and LKA performance was altered on a number of different vehicles, while the systems remained active with no driver warnings.
- The evidence suggests that recalibration can restore ADAS performance, and this is likely to be the case for vehicles that demand measured ride-height as part of the recalibration process or have specific recalibration processes for adjusted vehicle ride heights (ie, to accommodate OEM-approved lift kits). However, for vehicles that do not request ride height at calibration, there were examples of both restored and unrestored ADAS performance. The evidence indicates that this may also vary between vehicles.
- For automated driving at SAE Levels 4/5, the functional safety concept of the system will demand appropriate diagnostics capability, sensor monitoring, and sensor redundancy to deliver a ‘fail operational’ safety concept. This will either demand technical solutions that can cope with ride-height changes without influencing performance or detect modifications and deny system activation because the vehicle is outside the operational design domain (or a combination of these). The measures that are applicable to highly automated systems will therefore require adaptation from those applicable to current ADASs.

- In New South Wales, limits on ride-height modification without requiring certification exist of 75 mm (up to 50 mm from suspension changes and up to 50 mm from wheel/tyre diameter). However, it should be noted that these limits have been set in response to more fundamental vehicle stability and handling rather than the potential effects on ADAS performance. Test work is underway by Transport for NSW to assess the effect on ADAS performance of ride-height adjustments up to the current certification limit.
- Within vehicle manufacturer ride-height tolerances, the effect on ADAS performance is, based on the available information, expected to be non-material. However, insufficient test data exists to objectively validate this.

# 7 Recommendations

In response to the conclusions made by this project, the following recommendations are made in terms of measures that government could take to address this topic. These have been presented according to the stakeholder group best placed to implement the measure, and where appropriate, highlighting the action that government could take to directly or indirectly encourage or facilitate successful implementation.

**Government**

- Clarify or establish explicit ride-height/rake-angle limits that do not require certification in New Zealand. At present, the available information to define this limit is not available. This could be based on requirements in other jurisdictions (eg, New South Wales), or preferably be defined based on the outcomes of targeted test programmes.
    - Review the findings of test programmes underway in the USA (by SEMA) and Australia (by Transport for NSW) when these become available. These programmes have tested ‘utes’ with altered ride height (within current certification limits) and aftermarket accessories (eg, bull bars and additional lights) and assessed the effect on ADAS performance compared with the standard vehicle. These results may allow a more robust assessment of the effect on ADAS performance of ride-height changes to be made and the appropriate certification limit.
    - If information is not forthcoming from these programmes, physical testing of ride-height changes for a representative sample of vehicles to assess the effect on ADAS performance of ride-height alterations (and other aftermarket equipment) to identify appropriate certification thresholds would provide the information required.
- Provide consumer information to educate hobbyists about the effects of ride-height and rake angle modification, the addition of aftermarket items located in the sensor FOV (eg, lights, styling or aerodynamic accessories, or altered custom bumper paints) and how this may influence ADAS performance so that an informed choice can be made about changes to the vehicle and the implications for subsequent ADAS functionality.
- The recommendations for ADASs may need adapting for application to highly automated vehicles. Regulation of automated vehicles should ensure that SAE Level 4+ systems have appropriate functional safety concepts to deliver ‘fail-operational’ capability; this should be regulated specifically for automated vehicles because this is a key aspect of the functional safety concept. Automated vehicles may be able to cope with alterations to ride height without performance effects or not offer autonomous functionality if the vehicle is out of specification.

**Vehicle manufacturers/technology providers**

- Make vehicle ride-height tolerances easily accessible to the aftermarket and vehicle users if this is not already available. Government could influence this by leading a voluntary industry agreement or by making the information sharing a requirement of vehicle type approval (ie, mandatory sharing of the necessary information to the automotive aftermarket).
- Improve on-board diagnostic capability of vehicle systems and their capability to allow adaptation of the system to changes in ride height and rake angle. Government could assist this by regulating the capability of vehicle diagnostic systems.
- Harmonise the recalibration method of the ADAS to include the input of measured ride height so that this is accurately taken into account in the recalibration process. Government could encourage this by instigating a voluntary industry standard for recalibration.

- Provide consumer information about the capability and limitations of the system, including specific information on ride height in vehicle manuals and how this might affect ADAS performance. Government could make it a requirement to provide such information.

**Repairers**

- Develop a code of practice for vehicle repair/ADAS recalibration that would ensure that:
  - technicians are adequately trained and follow the OEM/technology provider guidance, including mandatory ADAS recalibration after a repair
  - a maximum ride-height change for which the system would be repaired or recalibrated is identified
  - repairers provide information to the vehicle owner at recalibration, either on the potential for effects on ADAS performance or why a repair or recalibration cannot be carried out.

  Government could facilitate this by chairing the development of a code of practice with industry.
- Repairers could monitor and record the frequency and motivations for recalibrations carried out and any issues with vehicle modifications. This would provide an evidence base that could be used by Government to understand issues of recalibration in the fleet.

**Aftermarket equipment suppliers**

- Ensure that information on the effects of ride-height changes on ADAS performance are provided to users who are purchasing aftermarket components that affect ride height. Governments could achieve this by regulating labelling requirements for such products.
- Aftermarket diagnostic tool providers can ensure that, where applicable, the ability to enter the vehicle ride height is provided to a repair technician undertaking the recalibration of an altered vehicle.

**Insurers**

- Ride-height modifications that exceed the vehicle manufacturer’s threshold (or another yet to be defined limit) could be made subject to increased premiums or in certain cases invalidate insurance cover. However, this approach may not be proportionate depending on the outcomes of targeted testing to define the effect on performance of ride-height/rake-angle adjustments.

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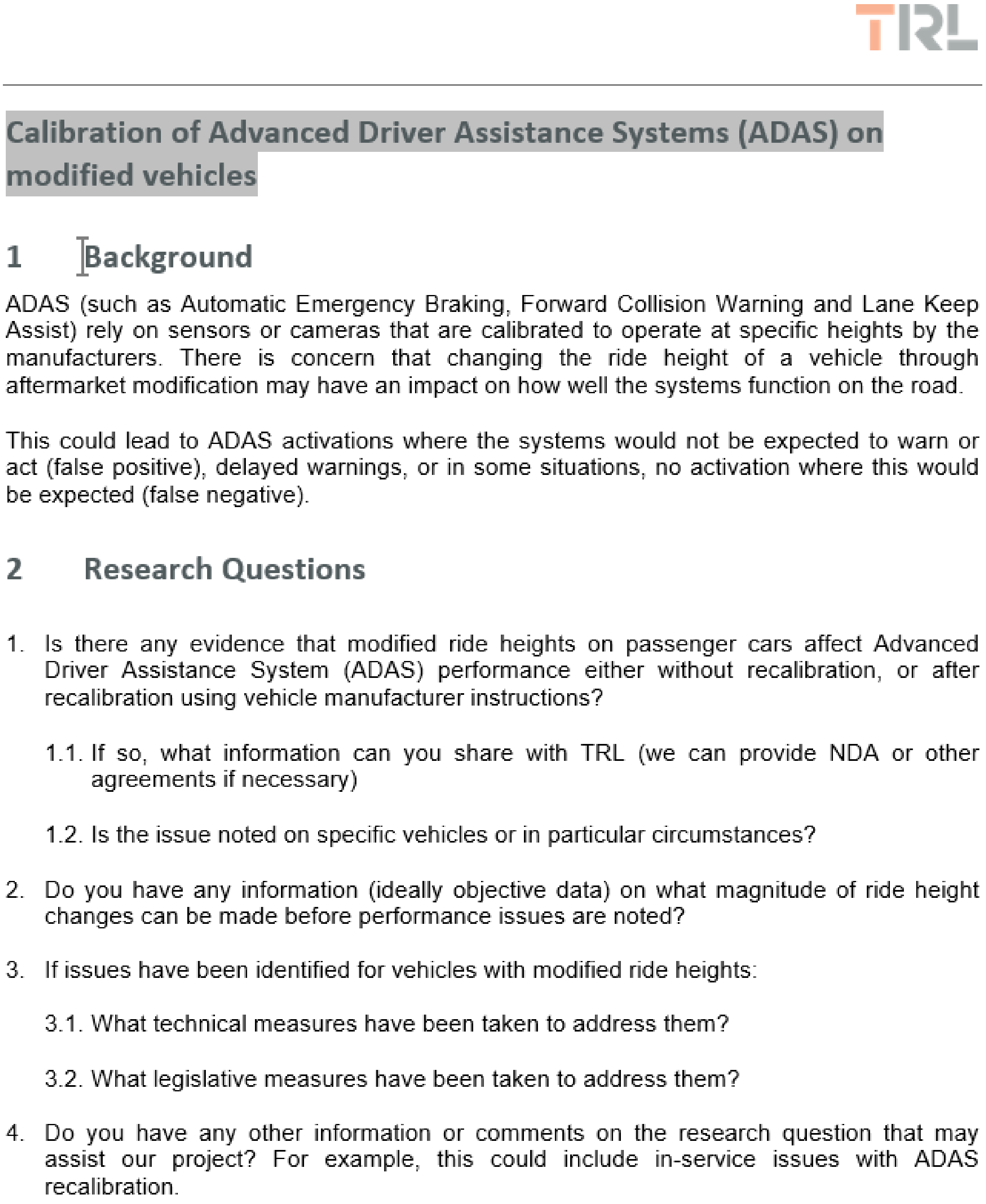
# Appendix A: Literature review search terms

**Table A.1 Literature review search terms**

| Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|
| Ride height/height | Modified | ADAS (advanced driver assistance system) | Performance |
| Rake angle/angle | Modification | AEB (advanced emergency braking) | Error |
| Pitch angle | Adjustment | LKA (lane keep assist) | Malfunction |
| Suspension | Adjust(ed) | Camera | Defective |
| Suspension coil | Change(d) | Sensor | Calibrat(ion) |
| Suspension spring | Lower(ed) | TSR (traffic sign recognition) | Fault |
| Coilover | Raise(d) | Lane support | Validation |
| Shock absorber | Aftermarket | Blind spot monitoring | |
| Leaf spring | Lift blocks | LDW (Lane departure warning) | |
| Shackle | • Strut spacers<br>• Wheel(s)<br>• Wheel size<br>• Diameter | • FCW (Forward collision warning)<br>• CAS (Crash avoidance system)<br>• Lidar<br>• Radar | |

# Appendix B: Stakeholder topic guide



## Calibration of Advanced Driver Assistance Systems (ADAS) on modified vehicles

### 1 Background

ADAS (such as Automatic Emergency Braking, Forward Collision Warning and Lane Keep Assist) rely on sensors or cameras that are calibrated to operate at specific heights by the manufacturers. There is concern that changing the ride height of a vehicle through aftermarket modification may have an impact on how well the systems function on the road.

This could lead to ADAS activations where the systems would not be expected to warn or act (false positive), delayed warnings, or in some situations, no activation where this would be expected (false negative).

### 2 Research Questions

1. Is there any evidence that modified ride heights on passenger cars affect Advanced Driver Assistance System (ADAS) performance either without recalibration, or after recalibration using vehicle manufacturer instructions?
   1.1. If so, what information can you share with TRL (we can provide NDA or other agreements if necessary)
   1.2. Is the issue noted on specific vehicles or in particular circumstances?
2. Do you have any information (ideally objective data) on what magnitude of ride height changes can be made before performance issues are noted?
3. If issues have been identified for vehicles with modified ride heights:
   3.1. What technical measures have been taken to address them?
   3.2. What legislative measures have been taken to address them?
4. Do you have any other information or comments on the research question that may assist our project? For example, this could include in-service issues with ADAS recalibration.

# Appendix C: Stakeholder list

**Table C.1 Stakeholders list**

| Stakeholder | Scope |
|---|---|
| Belron International | Technical – Aftermarket windscreen repair and replacement/ADAS calibration |
| Bosch | Technical – Tier one supplier of ADASs/ADAS recalibration |
| SEMA | Technical – ADAS calibration on vehicles with raised/lowered suspension in USA |
| Transport for NSW | Regulatory – New South Wales (Australia) |
| Vehicle Certification Agency | Regulatory – Vehicle certification in the UK |