Investigation into regenerative braking systems

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Executive summary

The United Nations Economic Commission for Europe (UNECE) Regulation for the type-approval of braking systems, Regulation 13-H, sets out the technical requirements, test methods and limit values for the braking systems of all vehicles of category M1 and N1 (passenger cars and light commercial vehicles).

The numbers of electric, hybrid and plug-in hybrid vehicles in production are rapidly increasing. In recent years, the braking regulation has been amended to incorporate provisions relating to regenerative braking systems, which are commonly fitted to such vehicles. However, as experience has built up since introduction of these requirements it has highlighted the need to review the requirements to ensure that they reflect the current state of the art.

The Department for Transport (DfT) commissioned TRL to examine the requirements for regenerative braking systems. The scope was limited to regenerative braking systems intended to be fitted to vehicles of category M1 (passenger cars) and N1 (light commercial vehicles), i.e. those covered by Regulation 13-H. The main aim of the study was to establish whether or not the existing regulatory requirements, test methods and limit values for regenerative braking systems could still be considered adequate in light of the first few years of experience with such systems and any development of new technology likely to be implemented in the foreseeable future.

For system developers, future challenges will include reducing costs, increasing vehicle range and meeting stricter safety and emissions standards. The braking legislation will need to be applied (in current or amended form) to advanced systems that not only stop the vehicle but recover lost braking energy. One particular challenge for manufacturers might be how to maximise energy recovery without impacting on some aspects of braking performance and/or driver feel. This study has endeavoured to anticipate and identify some of the main potential opportunities within UNECE Regulation 13-H that system developers may seek to exploit in the future. Information from some stakeholders, published literature and from a short series of track tests has informed the study.

The analysis suggests that current, “first-generation” regenerative braking systems do not compromise braking safety. The tests carried out on one such system, fitted to a hybrid vehicle, did not raise any safety issues. However, the study has highlighted a number of ways in which the existing Regulation 13-H could need strengthening to maintain this position with regard to more advanced and/or powerful systems.

The main areas in which the study suggests Regulation 13-H may need strengthening can be summarised, prioritised by their safety implications, as:

   a) Regenerative braking systems tend not to be effective at very low speeds (indeed stakeholders have advised that they may actually have to take energy from the battery/energy storage system to further slow or stop the vehicle). Current systems thus work around this by disconnecting the regen system at low speed. This disconnection speed is not regulated. The more powerful the regen system, and the lower the disconnection speed chosen, the higher the potential loss of deceleration is when disconnection occurs, and the greater is the potential for the driver to notice this sudden drop in deceleration, without having changed the braking demand as set by the brake pedal position/force.

   b) The Regulation (sections 5.2.7 and 5.2.10) appears to require compensation by the service (friction) brake for disconnection of the regenerative braking (e.g. when the battery is fully charged), but the wording is unclear as to whether this applies only if the regenerative system is acting alone to provide braking torque, or more generally, including when the friction and regenerative braking are acting together. The Vehicle Certification Agency (VCA) interpret R13-H to require compensation in all conditions, but it is not known if their interpretation is shared by all approval authorities. There is, therefore, room for uncertainty as to
whether there is a requirement for the friction brakes to always compensate for the loss of the regenerative component if it is suddenly disconnected or gradually deactivated.

c) R13-H contains requirements for secondary braking in the event of a failure in the service brake system. However, information from stakeholders has suggested that these requirements may not be fully adequate to prevent adverse effects from a failure in a regenerative system. They have suggested that the most likely failure for an electric motor is a torque variation. This can be a loss of braking torque when the driver is demanding braking but could also be an unwanted surge in braking torque either when the brake pedal is or is not pressed. This problem may become more significant if a distributed drive system was used. In this case, the torque variation may occur on only one wheel, potentially generating a significant yaw moment.

d) In the event that the regenerative system is the sole source of braking torque, the Regulation requires the friction braking system to compensate if the regen system is disconnected. However, section 5.2.10 of R13-H only specifies that this compensation achieves 75% of its final value within 1 second. It does not, therefore, require full compensation, or define how long it should take to achieve its final value. There is potential for adverse driver feel effects if the compensation is inadequate or takes too long to be achieved.

e) The Regulation is focused on the ultimate capability of the vehicle’s braking system to bring the vehicle to a safe, stable halt in an emergency-type, high pedal force and/or rapid brake application. Non emergency brake performance in general is not regulated. By their nature, e.g. variations in power capacity as SOC varies, regenerative systems may increase risk of performance variability and/or driver feel unpredictability at low brake force levels.

f) The Regulation currently only covers electrical regenerative braking systems. It does not cover other potential options such as flywheels and hydraulic accumulators.

g) The Regulation only covers battery-based electrical energy storage systems. It does not cover other forms of electrical energy storage such as ultra-capacitors.

h) It is also believed (based on VCA’s interpretation) that the Regulation does not currently allow for the service braking to be provided exclusively by a regenerative braking system.

i) The test programme has highlighted difficulties in meeting the requirement to conduct the type 0 and type 1 tests when “the contribution of the electric regenerative braking system to the braking force generated shall not exceed that minimum level guaranteed by the system design”. For battery-based systems this should mean zero regenerative effort because if the battery is full it cannot take any further charge, but the “maximum” SOC as indicated by the vehicle may not remove all regenerative braking, because this full charge state has not been achieved.
1 Introduction

The United Nations Economic Commission for Europe (UNECE) Regulation for the type-approval of braking systems, Regulation 13-H, sets out the technical requirements, test methods and limit values for the braking systems of all vehicles of category M1 and N1 (passenger cars and light commercial vehicles).

The numbers of electric, hybrid and plug-in hybrid vehicles in production are rapidly increasing. In recent years, the braking regulation has been amended to incorporate provisions relating to regenerative braking systems, which are commonly fitted to such vehicles. However, as experience has built up since introduction of these requirements it has highlighted the need to review the requirements to ensure that they reflect the current state of the art.

The Department for Transport (DfT) commissioned TRL to examine the requirements for regenerative braking systems. The scope was limited to regenerative braking systems intended to be fitted to vehicles of category M1 (passenger cars) and N1 (light commercial vehicles), i.e. those covered by Regulation 13-H. The main aim of the study was to establish whether or not the existing regulatory requirements, test methods and limit values for regenerative braking systems could still be considered adequate in light of the first few years of experience with such systems and any development of new technology likely to be implemented in the foreseeable future.

This involved a desktop study intended to identify the most likely issues, supplemented by a short programme of dynamic vehicle testing to further explore those issues and inform an assessment of the suitability of the current 13-H test procedures. The desktop study phase included engagement with industry experts/stakeholders and a literature review.

This report describes the project methodology, results and conclusions in full.
2 Methods

This section outlines the methods used during the study. Two approaches were adopted – the first, a theoretical analysis based on a literature review and information from stakeholders and, second, an experimental track-test programme. The elements are further described in the following sub-sections.

2.1 Literature review

The literature review was intended to identify information about the design and operation of regenerative braking systems. Studies on the safety characteristics of regenerative braking were the main focus for the review, but other topics were included if it was possible to draw some conclusions about safety. Searches of the internet were undertaken in addition to searches of specific databases of scientific literature such as the International Transport Research Documentation Database (ITRD), Elsevier Science Direct and TRL’s own in-house library.

2.2 Gathering information from stakeholders

During the project, TRL contacted a small group of brake experts from an original equipment manufacturer (OEM), two tier-one brake system suppliers and an approval authority. The aim of this consultation process was to help:

- Describe the technologies and techniques used by current, near market and future regenerative braking systems;
- Identify any potential problems or weaknesses in either the design of regenerative braking systems or the wording or application of the regulations, particularly the test procedures required to evaluate different systems where the regenerative function can or cannot be deactivated;
- Provide evidence or analysis already in existence that relates to these problems;
- Inform the design of the experimental programme.

2.3 Experimental design

The findings of literature review were combined with the information from stakeholders to design a series of experiments. The aims of the experiments were to:

- Investigate further potential for braking problems to occur within the current regulatory regime;
- Identify difficulties in applying the current regulatory tests to existing vehicles;
- Explore the feasibility of any potential solutions (i.e. new or amended test procedures or limit values) to the problems identified during the literature review and stakeholder consultation.

2.4 Test programme

2.4.1 Test vehicle preparation and instrumentation

A currently available hybrid passenger car was chosen as the test vehicle for this project. It is a hybrid petrol vehicle with a continuously variable transmission, regenerative braking system and electric motor. The vehicle is a 5 door hatchback capable of carrying 5 passengers and luggage.
As previously stated, the purpose of this study was to assess the suitability of the current 13-H requirements and test procedures. Full details of the specific test vehicle are not given in this report because:

\[\text{a)}\] Testing was not carried out on any other regen-equipped vehicle, so it would not be possible to provide proper context for the test results;

\[\text{b)}\] The test vehicle was provided (by the manufacturer) purely as an example of a vehicle/regen system that is approved to R13-H, for the purposes of aiding this assessment of how the Regulation, in general, applies to regen-equipped vehicles, not to attempt to find particular issues with the vehicle itself;

\[\text{c)}\] Any future developments of the Regulation would need to be manufacturer-neutral, so the only issues relevant to this study are generic ones with the potential to affect any manufacturer, rather than any specific to the test vehicle alone.

The test vehicle uses a DC electric motor mounted between the transmission and the crankshaft to assist the petrol engine when required. The energy for the electric motor is collected when the regenerative braking system is activated, this works by the electric motor running in reverse to act as a generator, this energy being then stored in a Nickel-Metal Hydride (NiMH) battery. The nominal system voltage is around 100V.

The vehicle was tested in an unladen condition with a test driver weighing 68kg and 10kg of instrumentation. The fuel tank of the vehicle was at least ¼ full at all times.

The high friction testing took place on the stone mastic asphalt (SMA) surface of the large loop at the TRL test track in Crowthorne. The low friction and transitional tests took place on the basalt tiles at the straight line wet grip area at MIRA in Nuneaton. A full description of these procedures and the rationale for choosing them is given in the results section of this report.

Before testing was started each day, a series of vehicle checks were completed including tyre pressure and tread depth, with the minimum tread depth 3.2mm. A visual inspection of the brakes was also performed, for signs of excessive overheating, cracks and separation of the friction material, excessive discoloration and/or cracking of the brake discs, and to check that the pad friction material had a thickness of at least 4mm.

During the testing, the test surface was approached in the straight-ahead position and the accelerator and steering wheel position kept constant. Approach speeds for the tests, were defined in the test matrix developed during the study and agreed with DfT before testing began. After reaching the steady state conditions the steering wheel was held in the straight-ahead position. The accelerator pedal was then released and the brake pedal pressed as described in the test matrix to achieve the brake pedal force specified for that test run.

Three different types of pedal actuation were used; slow (constant force) was intended to apply the brake pedal, without activating the Brake Assist System (BAS) and holding a constant force, with movement of the brake pedal permitted to achieve this if necessary; slow (constant position) was to apply the brake pedal without activating the BAS and up to a set force, and once this force was reached the brake pedal was held in the same position, even if that meant the pedal force then varied up or down; and fast (constant force), which was intended to apply the brake pedal and activate the BAS while holding the constant force on the pedal set for that particular test run.

All the tests in this vehicle were completed with the vehicle in gear (D - Drive) and were completed with the battery state of charge in one of two conditions, minimum or maximum.

It was not feasible within the scope of the project to decode the CAN bus of the vehicle in order to obtain precise data relating to the state of charge of the batteries or the power flow to or from the batteries, nor to acquire and fit a bi-directional DC Watt-hour
meter (as prescribed in Regulation 13-H for monitoring battery state of charge). Instead, the dashboard display provided for the driver was used to identify between minimum and maximum state of charge. In order to obtain this state of charge, the vehicle was accelerated hard in drive between 20km/h to 45km/h with the electric motor assisting the petrol engine, neutral was then selected so the regenerative braking system is disengaged and the vehicle was braked to 20km/h, this was then repeated several times until the correct state of charge was achieved.

In order to achieve the maximum state of charge, as indicated by the dashboard display, the vehicle was driven in such a way as to try to avoid using any electric motor input by careful use of the throttle and using the brakes or coasting to allow the batteries to recharge via the regenerative braking system.

The vehicle was instrumented with a data logging system. This data logging system included a Racelogic VBox 3i with IMU Integration. This logged the following parameters at 100Hz with a brake stop accuracy of ±2cm:

- Velocity (accuracy 0.1km/h)
- Position (accuracy <1m)
- Distance (accuracy 0.05%)
- X, Y and Z Acceleration (accuracy ±0.01g)
- Yaw, Pitch and Roll rate (accuracy 0.1%)

In addition to this system the vehicle was also equipped with two linear potentiometers measuring brake and throttle pedal position, a brake pedal force sensor and 4 brake line pressure transducers fitted between the ABS Modulator and the calliper at each wheel.
3 Results

3.1 Principles of regenerative braking

When the service brakes of a traditional vehicle, powered by an internal combustion engine, are applied to slow a vehicle down, then the foundation brakes convert kinetic energy to heat energy. The heat energy is dissipated to the atmosphere. There is only one source of energy on such a vehicle, the chemical energy held in the (usually) diesel or petrol fuel. Thus, every application of the brakes represents fuel and energy wasted. The basic principle of regenerative braking is to capture the kinetic energy lost when speed is reduced so that it can be re-used to accelerate the vehicle again, thus reducing the overall energy use (and carbon emissions) of the vehicle.

While the basic principles are the same, the energy capture and storage can be achieved in a number of different ways, for example:

- Mechanical systems – may involve mechanisms whereby the rotation of the road wheels accelerates, for example, a heavy fly wheel converting the kinetic energy of the vehicle to the kinetic energy of the flywheel. The direction can then be reversed so that the flywheel is used to help accelerate the rotation of the road wheels.

- Hydraulic systems – may involve mechanisms whereby the rotation of the road wheels pumps hydraulic fluid into a high pressure accumulator, thus acting to resist the rotation of the road wheels. Kinetic energy is converted to mechanically stored energy. Releasing the hydraulic fluid from the accumulator helps to power the road wheels.

- Electrical systems – where the road wheels are connected to an electric motor, which is in turn connected to batteries (or possibly ultra-capacitor arrays in some vehicles). In braking mode, the electric motor becomes a generator converting kinetic energy into electrical energy. Applying the throttle reverses the process allowing the electrical energy in the batteries to be used to help drive the wheels.

Each type of system has been used in a variety of applications from formula one cars to heavy trucks, but all current mass production systems for vehicles of category M1 and N1 are of the electrical variety.

For the purposes of this study, electric vehicle (EV) includes both hybrids and purely-electric vehicles. Hybrid vehicles combine electric power from an on-board battery with an internal combustion engine. Different degrees of hybridisation are possible:

- A “mild hybrid” switches the engine off when the vehicle is stationary and then restarts when the accelerator is pressed, using the electric motor. Energy from braking is stored and can be used, through the motor, to support the internal combustion engine during acceleration.

- A “full hybrid” is capable of running on battery power alone, although usually for short distances only. The vehicle runs on electric power at low speeds and under low loads and switches to the internal combustion engine for higher speeds and hard acceleration.

- A “plug-in hybrid” can be charged directly from the grid and can run on electric power for longer distances. This requires greater battery capacity than other hybrids.

- An “extended range hybrid” uses a small internal combustion engine to charge the battery rather than drive the wheels. All drive is provided by the electric motor.
Current EVs all have one or two centrally located motors providing drive via a conventional transmission system, with or without an internal combustion engine providing drive through essentially the same route. In-wheel motors are a potential future development that could remove the need for transmissions, drive-shafts and gear boxes and that could, potentially, allow regenerative braking to all wheels as the main, or even sole, source of braking torque.

UNECE Regulation 13-H, which prescribes braking requirements for vehicles of category M1 and N1, defines two types of electric regenerative braking system:

- Category A - means a system that is not part of the service brake system, for example, a system activated upon release of the throttle.
- Category B – means a system that is part of the service brake system, so a system that is activated automatically when the service brake control (pedal) is depressed.

It is quite possible for one vehicle to be equipped with regenerative braking of both category A and category B. In terms of the regulation, phased braking is defined as a means which may be used where two or more sources of braking are operated from a common control, whereby one source may be given priority by phasing back the other source(s), so as to make increased control movement necessary before they begin to be brought into operation. As such this describes the situation for a category B system, where the regenerative braking and service braking need to be suitably phased to ensure smooth, stable and progressive braking for the driver.

Although in theory regenerative braking could be applied to any or all axles, current mass production versions act on the driven axle only, via the driveshaft and transmission. It is believed that most systems in use are currently Categories A and B, with a small, constant regenerative brake torque applied whenever the throttle is released, but with modulated additional torque applied when the brake pedal is pressed.

Category A systems are used on less mainstream vehicles such as the Tesla Roadster, whereby the regenerative torque is applied purely on throttle release and remains independent of brake pedal position. The power electronics control system optimises energy flow back to the battery, whilst retaining vehicle stability and modulating the hydraulic brakes. High levels of category A regenerative electrical braking would be undesirable, from a vehicle stability point of view, particularly if the torque is applied to the rear wheels (as it would be on rear wheel drive cars).

### 3.2 Theoretical analysis

#### 3.2.1 Behavioural factors in braking

It is well documented that many typical drivers fail to fully exploit the potential of the braking system in an emergency. Typically, they might apply the brake quickly but not sufficiently hard. Then as the hazard approaches and the risk is more fully appreciated the brake is applied up to maximum, resulting in a delay between the first perception of the hazard and reaching maximum braking. Brake Assist Systems were developed to detect when a driver intended an emergency brake application and to boost the braking to reduce this delay. Dodd and Knight (2007) found that the thresholds of pedal force and application speed that characterised an emergency depended on the pedal “feel” characteristics of the particular vehicle being driven. Several of the regulatory requirements and/or system design characteristics for disconnection of regenerative braking and compensation by brake phasing could have an effect on pedal feel, which may have the potential to effect the way in which the drivers brake in an emergency and interact with the operation of the BAS.
Curry et al. (2003) studied drivers’ reactions to failures within hydraulic braking systems that resulted in reliance on the secondary brake functions of the vehicle. They studied two failure types:

- A servo failure resulting in loss of assistance, which required the pedal to be pressed much harder to achieve the same level of deceleration
- A hydraulic failure, requiring the pedal to be depressed further to engage the secondary circuit in the master cylinder and to be pressed harder to achieve the same level of deceleration.

They found that in both cases many drivers failed to react appropriately and around two-thirds failed to stop within a distance that the defective vehicle was capable of stopping within. With a failed circuit many drivers reacted by releasing the brakes and then either re-applying them steadily or pumping the pedal.

When a regenerative brake is disconnected and the deceleration is compensated by the service brake, for example because the surface friction is low and the regenerative braking acting on one (the drive) axle has activated ABS on that axle, then the regulation would permit the pedal travel to increase suddenly. If this occurred, it may well be similar to the pedal feel experienced in a circuit failure as assessed.

### 3.2.2 Existing Regulatory Framework

**State of battery charge**

When a simple electric motor is used as a generator, then the torque required to turn it will be proportional to the electrical load, or the current drawn from the generator. In the case of regenerative braking the electrical load will, therefore, depend on the state of charge of the batteries and a low charge will result in a high current draw and high torque. Thus, the maximum braking deceleration that will arise as a result of the regenerative brake system will vary according to the state of charge of the battery. In the absence of more sophisticated control this will mean that the relationship between pedal force and braking deceleration will vary with battery state-of-charge (SOC). It is possible to use the concept of phased braking such that the service brake compensates for any variation, but this may affect the feel of the pedal. Such compensation is a requirement of R13-H, if a category B system is designed to use the electric regenerative braking alone in any circumstances.

UNECE Regulation 13-H states that vehicles equipped with a category B regenerative braking systems may phase the braking input from other sources (such as the service brakes) to allow the regenerative braking system alone to be applied. However, two further conditions must be met. Firstly, variations in the torque output of the regenerative braking system must be compensated automatically by varying the phasing relationship. Secondly, the (phased) braking must act on all wheels to ensure that the braking rate remains related to the driver’s demand. With regards to the first condition, the regulation also specifies two paragraphs in subsequent annexes (one of) which must be met. These requirements essentially demonstrate that the stability of the vehicle is not compromised by the phased braking function and that the ABS is able to prevent wheel lock under the tested road conditions (low and high friction surfaces and transitions between them), and under all relationships permitted by the vehicle’s control strategy. The Regulation also requires that electric regenerative braking systems are designed so that an application of the brake pedal does not reduce the braking effect produced by release of the accelerator pedal/control alone.

While phased braking, and thus compensation for variations in the state of charge, is not mandatory in the regulation, it seems likely that most vehicles would be capable of phasing the regenerative braking system with the main service braking system.
Annex 3 of Regulation 13-H specifies the test procedures and conditions. For the type 0 (cold performance) and type 1 (fade and recovery) tests, the Regulation specifies that for category B systems “the contribution of the electric regenerative braking system to the braking force generated shall not exceed that minimum level guaranteed by the system design”. The intention here is that the test is assessing as far as possible the performance of the service (friction) brakes only, to ensure they are capable of bringing the vehicle to a safe stop even when the regen braking component is absent (as would be likely if the battery was already full and could not take any more energy input). The fade test is also about assessing driver “feel” when braking with a hot brake; a vehicle can fail even if it meets the minimum requirements if that performance has faded significantly against its “cold” stop performance. The Regulation, however, does not stipulate that the regen component must be zero for these tests, instead the condition is deemed to be satisfied if the battery state of charge is in one of the following conditions:

(a) at the maximum charge level recommended by the manufacturer, as listed in the vehicle specification,

(b) at a level not less than 95 per cent of the full charge level, where the manufacturer has made no specific recommendation,

(c) at a maximum level resulting from automatic charge control on the vehicle.

No allowance is made for energy that can be stored elsewhere, other than in a battery, e.g. in an ultra-capacitor, which system designers may use as an additional temporary energy buffer.

**ABS**

ABS activates when the wheels begin to lock. This occurs most easily on surfaces with a low coefficient of friction such as ice. However, when ABS activates, regenerative braking is usually switched off to protect the normal ABS function (Zhang et al., 2010). In these circumstances, the friction brakes would need to compensate for the loss of regenerative braking in order to maintain the same level of deceleration. The strategy for integrating regenerative braking with ABS, and in particular, the timing of the transfer to friction braking might affect the braking performance of the vehicle and the pedal feel.

Where vehicles with regenerative braking are fitted with ABS, it is a requirement that the ABS controls the regenerative braking as well as the friction braking in order to enable the system to reduce the wheel torque in the event of lock. However, there is no requirement as to how this should be controlled so in theory it could be modulated in the same way as the service brake system or simply disconnected. If suddenly disconnected there is again a general requirement that the friction brake should compensate for the change in deceleration that would otherwise result from the disconnection, which may affect pedal feel. The Vehicle Certification Agency (VCA, the UK Government agency responsible for granting type approval to vehicles) interpret this requirement to mean that compensation must be provided whenever the regen component is disconnected, but an alternative interpretation is conceivable, namely that this compensation (friction brake achieving 75% of its final value within 1 second) is only required where the regenerative braking system alone is providing braking torque prior to the disconnection. The wording of the Regulation is considered a little ambiguous in this regard.

The range of tests on low or split friction surfaces would effectively limit the time taken to disconnect the regenerative braking because an excessive delay would cause a longer period of wheel lock which is prohibited. However, if there was a delay in the friction brake level increasing its retardation in response to the disconnection then this would not be picked up in the low friction or friction transition tests because there is currently no requirement (in Annex 6 of Regulation 13-H) for stopping distance or mean deceleration, only stability and steerability.
There is no specific requirement in R13-H for vehicles of category M1/N1, including those equipped with regenerative braking, to be fitted with ABS (or BAS). However, EC type approvals for most vehicles of this category require Brake Assist Systems (BAS) to be fitted and R13-H prescribes that if BAS is fitted, ABS must also be fitted. In reality, it is therefore considered highly likely that all vehicles sold in the EU and equipped with regenerative braking will also be fitted with ABS (and BAS).

The main risk mitigated by the requirements of Annex 5 is that represented by wheel lock. Anti-lock braking systems (ABS) prevent this problem directly and for this reason Annex 5 is only applied to vehicles not fitted with anti-lock, which, as previously explained, are likely to be very rare.

Annex 5 considers the distribution of braking amongst the axles. Essentially, for two axle vehicles, this provides a requirement that the front axle shall always lock before the rear axle when braking on a variety of coefficients of friction and in all load conditions. This is because the condition where the rear wheel is locked and the front wheel is rolling is considered unstable and likely to cause the vehicle to spin about its yaw axis. This could, in theory, be particularly relevant for rear wheel drive vehicles equipped with regenerative braking of category B, or even category A in some circumstances. This is because when the vehicle is travelling on a surface with a low coefficient of friction, the torque applied by the regenerative braking could be sufficient to cause the (rear) driven axle to lock generating an unstable condition. For this reason, R13-H requires that where a category B regenerative system is fitted, then the distribution of braking amongst the axles must be assessed by taking account of the minimum and maximum torque that can be applied by the system. However, it could be considered slightly ambiguous if a vehicle with category A and category B systems was being assessed and a literal interpretation was taken to say only the torque associated with the category B system were to be considered. VCA report that they consider this point in their approvals, because of these issues.

**BAS**

Regulation 13-H makes specific provisions for Brake Assist Systems (BAS), where fitted. Such systems are designed to identify a “panic”, emergency brake activation, and automatically apply full brake pressure to the friction brakes. This is to compensate for the common trait of drivers not to apply full braking in an emergency, or at least not to apply full braking as quickly as possible. Regulation 13-H dictates that vehicles equipped with BAS must also be fitted with ABS, and specifies by how much the ratios of brake line pressure to pedal force, or vehicle deceleration to pedal force, shall increase, or the ratio of vehicle deceleration under ABS control (but not BAS) to that achieved under BAS control, depending on the particular category of BAS fitted.

The Regulation makes no provision for the interaction of BAS with any regenerative braking system fitted to the vehicle. The potential exists, therefore, for a momentary loss of deceleration just before the ABS activates if a significant regen braking component is present during the initial, BAS activation phase. It is also conceivable that the very rapid application of the service brake, on top of a substantial regen component, might cause the wheels to lock momentarily before the ABS can take control, though this is likely to be regarded as a failure of R 13-H by the approval authorities.

**ESC**

Regulation (EC) No. 661 2009 (“the general safety regulation”) will mandate the fitment of ESC on all categories of motor vehicle. For M1 and N1 vehicles, ESC is mandatory from 1st November 2011 for new types, and from 1st November 2014 for all new registrations.
UNECE Regulation 13-H prescribes technical requirements for ESC systems, where fitted, but does not contain special provision for an interface with regenerative braking systems.

Dodd (2004) showed that when cornering on a high friction surface at high lateral accelerations (c. 0.7g+) and braking at low longitudinal accelerations (approximately -0.2 to -0.4g) some passenger vehicles could exhibit substantial yaw instability if the braking was applied sharply. This level of longitudinal acceleration could potentially be developed by regenerative braking alone (if the system was powerful enough) and, on a vehicle so equipped, this may mean that the longitudinal deceleration is generated by the brakes of only one axle. It is not known what effect this may have on the behaviours observed by Dodd (2004) but it may depend on whether the regenerative braking is applied to front or rear axles. Some vehicles will control this sort of behaviour using an electronic brake force distribution (EBD) system to adjust the brake ratio, others will rely on ESC to stabilise the vehicle. However, in either case the interaction with the regenerative system is not specifically regulated, only in relation to the general provisions with respect to compensation.

### 3.2.3 Stakeholder comments

#### State of battery charge

An OEM stakeholder contacted during this study suggested that while SOC effects would be unlikely to show themselves in “emergency” braking, i.e. when the pedal is pressed hard (and as used in Regulation 13-H), it is possible that brake performance at lower pedal loads could be affected. He suggested that if starting from a low SOC then with a fixed brake pedal position, the deceleration achieved may reduce during a single stop, e.g. what started as a 0.2g stop could end up a 0.1g stop as the battery charged and thus the regen braking torque was reduced. The compensation required by 13-H would, it is believed (depending on the interpretation), not be relevant here, at least not in the latter stages of the stop – it would only work to ensure that at the start of braking, the service brakes did not apply a braking torque immediately, while the regen component was ramping up. It would not attempt to compensate for any subsequent ramping down of the regen component unless the regen component was the only source of braking torque at the time. It is VCA’s understanding that current systems do not allow a complete stop using electric regenerative braking only.

#### ABS

An OEM stakeholder suggested that there was unlikely to be any problems with a regenerative system’s interaction with the ABS system, because the control algorithms simply switch the regen off as imminent wheel lock is detected by the wheel speed/slip sensors, and the conventional braking system, controlled by the ABS, takes over.

A system developer stakeholder commented that there was a potential problem with the time it takes the conventional system to fully compensate for the regen braking once it has been switched off. Regulation 13-H specifies that for Category B systems, the service brake must attain at least 75% of its final value within 1s of the regen system switching off (if it was the only source of braking torque at the time). He suggested that the longer a system took to attain this level of compensation, the more chance there was for drivers to perceive a loss of braking effort. This effect might become evident not just when braking relatively heavily on a normal, smooth road surface, but might also occur when braking more gently on a pot-holed surface because the wheels would lose grip, and hence the ABS would deactivate the regen system, as they momentarily lost contact with the road.
BAS
Stakeholders made no comment on this issue.

ESC
Stakeholders made no comment on this issue.

3.2.4 Literature

State of battery charge

No previous studies were found on the characteristics of phased braking systems or the
effects of battery state-of-charge on their performance. If regenerative braking is not
used under certain conditions (such as a high state-of-charge), or if the regenerative
braking force is insufficient, the assumption from the literature is that the braking
control strategy would ensure that the service braking system supplies the required force
(Peng et al. 2008; Yeo et al. 2006).

ABS
The National Highway Traffic Safety Administration (NHTSA) received over 1,200
complaints from Toyota Prius owners alleging a momentary reduction in braking
performance on uneven road surfaces (NHTSA, 2010). Toyota received nearly 200
further complaints directly. The company performed brake tests in an effort to reproduce
the phenomena and found that the braking force reduced after ABS activated (Toyota,
2010). Further investigations revealed that many drivers had experienced the
phenomena, particularly in winter, where drivers may maintain a fixed pedal stroke.
Under these conditions, Toyota found that “vehicle stopping distance may increase,
relative to the driver’s expectations for a given pedal force”. The condition was a result
of the ABS software, which was permitting the change in braking force. Although the
ABS was operating as it was designed to, Toyota conducted a voluntary safety recall to
re-programme the ABS control unit in the Prius (and the Lexus HS250H).

It appears that, in this particular system, the transition from regenerative braking to
service (i.e. hydraulic) braking was being perceived by drivers as a change in braking
force. Under certain conditions, the driver would need to press harder on the brake pedal
to maintain the same deceleration.

BAS
No research literature was found relevant to this issue.

ESC
Few studies have been reported on the interaction between regenerative braking and
ESC and the effects on vehicle stability. Hancock and Assadian (2006) investigated the
impact of regenerative braking on vehicle stability during cornering. A full vehicle model
of a hybrid sports utility vehicle was used for the study (in a computer simulation). They
found that applying regenerative braking to the rear axle can reduce stability, depending
on motor size and road surface friction coefficient. With a moderately-sized motor, on a
high $\mu$ surface, the reduction in stability was controlled by the ESC system without a
large increase in ESC brake pressures. However, on a low $\mu$ surface the reduction in
stability was much more severe and could not be compensated for by ESC. Two solutions
were proposed to prevent regenerative braking from causing the wheels to slip; firstly,
switching to friction braking once the longitudinal slip of either rear wheel exceeds a
specified threshold and, secondly, locking the centre coupling. Both solutions were
effective from a stability perspective, but locking the centre coupling had the added
advantage of maximising energy recovery. However, the authors recommended further work to assess the potential effects on ABS/ESC performance.

Kim and Kim (2006) proposed a new vehicle stability control algorithm using regenerative braking (of the rear motor) with an electro-hydraulic brake system. They found improved stability compared with a baseline system with no control and a system with regenerative braking only.

3.3 Test investigations

To explore the above issues in more detail, various dynamic test procedures were developed and implemented, described in more detail in the following sections.

State of battery charge

To better understand how the regulatory requirements for regenerative systems have been applied to the chosen test vehicle, and how effective they are, it is necessary to identify whether or not the regenerative braking is phased and if so whether the service brakes are adequately compensating for variations in torque as a result of different SOCs. Two test procedures were designed and implemented to achieve this, referred to as baseline system characterisation and in-stop deceleration tests.

The baseline system characterisation tests set out to show how the overall braking performance of the vehicle varies with brake pedal effort and with battery SOC. To minimise any possible effects from the deceleration varying during a single stop, a relatively low initial speed of 50 km/h was selected. The brake force was changed in 20N increments from 0N up to 140N, expected to be near to or exceeding the point of ABS activation, and then a final “emergency” brake test at 500N, which represented a comparison with what might be expected if a regulatory type 0 test were to be undertaken at that speed. Two runs at each pedal force were completed, first with all tests with the battery at minimum SOC (at the start of braking) and then all the tests again at the maximum SOC.

The main test results are shown in Figure 1.

It can be seen that the mean decelerations (defined in this case as the average deceleration once the pedal force has achieved its steady-state value, and before the speed drops to about 20 km/h) are very similar, for a given brake pedal force, regardless of SOC. This indicates that either:

- the system does indeed compensate for the varying amount of torque applied by the regenerative braking and ensure that the driver gets the same level of performance for a given pedal input at all SOC levels; or
- The levels of regenerative braking are so low that they cannot be separated from the experimental error (scatter) in the results; or
- The SOC does not in fact have a strong influence on the level of regenerative braking torque, at least at the levels indicated by the dashboard display as being min and max, such that the regenerative component is similar at both SOCs.
Figure 1. Scatter curve of pedal force (mean) vs Mean Deceleration, up to full braking, for min and max SOC (50 km/h initial speed).

The magnitude of any scatter and differences between the two SOCs were examined in more detail by considering the same data but restricted to pedal forces of less than 120N (see Figure 2) Linear trend-lines are also shown. While the two data sets are on almost identical trend lines, there is some suggestion that the minimum SOC data points are slightly more scattered than those with maximum SOC ($R^2$ values of 0.916 and 0.974 respectively), which may indicate that there is slightly more variability/inconsistency in the pedal force to deceleration relationship at minimum SOC. The effect, though, is very slight.

To put this variability in more context, similar testing of conventional vehicles undertaken during an unrelated study generated typical $R^2$ values of around 0.93-0.99.
If the reason for the results identified in Figure 1 was that the service brake system was being used to compensate for the variation in regenerative braking torque, then this should be apparent from differences in the hydraulic pressure applied to the service brakes. Figure 3 shows how the service line pressure\(^1\) and brake pedal force vary with time for two otherwise similar test runs (at nominally the same pedal force) at minimum and maximum SOC. At minimum SOC it is apparent there is a small time delay (0.3s) between the brake pedal force rising and the line pressure also rising, whereas at maximum SOC the delay is only about 0.1s.

In fact, the brake line pressure was slightly lower at the maximum state of charge (probably because of the slightly lower pedal force applied) suggesting that the service brake was not compensating for any substantial change in the regenerative braking torque.

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\(^1\) The line pressure here is the pressure rise in the front brakes, but the pressure rises were generally identical between front and rear.
Figure 3. Time history for two runs at 25N pedal force, of line pressure and pedal force, one at min SOC, the other at max SOC.

Figure 4 shows a scatter plot of line pressure rises vs deceleration, at the two tested states of charge. There is no appreciable difference between the min and max SOC plots, suggesting either that the regen torque is very low or that there is little difference in regen torque at the two SOC.

Figure 4. Scatter plot of brake pressure rises vs deceleration
Throttle-off decelerations, with no friction brake application, were also very similar between min and max SOC (0.04 – 0.05g in both instances). These deceleration levels are, in the authors’ experience, similar to those achievable by conventional passenger cars in high gear with throttle off, further suggesting that any regen braking torque from the test vehicle is likely to be very small, at least in this throttle-off condition.

The baseline tests described above were intended to identify the phasing of the brakes and whether or not the service brakes compensated for the state of charge at the beginning of a brake application. The in-stop deceleration tests were designed to explore whether the SOC increased sufficiently during an individual brake application to have a noticeable effect on the vehicle’s deceleration rate during the stop, for a fixed, constant brake pedal force or position. To maximise the potential for the effect to show itself, a high initial speed of 110 km/h was used. Two runs at each pedal force level were completed, and the force was increased in 20N increments from 0N to 60N. One set of runs was completed with the test driver applying a constant brake pedal force, and then again with the brake pedal held at the same position throughout the stop. All tests were, at the start of braking, at minimum SOC.

The results of the baseline tests, which found no discernible difference between the braking performance at minimum and maximum SOC, suggest that any reduction in deceleration during a stop would be relatively small. In fact, only during the throttle off tests (no friction braking) from 110 km/h was any reduction in deceleration evident at speeds above about 20 km/h, typically from about 0.07g initially down to about 0.04g at lower speeds (50 km/h and below). With service braking applied, even at low pedal forces, the general effect during the main phase of the stop was that deceleration actually rose, even with a steady pedal force, pedal position and/or line pressure. Figure 5 shows a typical example.

![Figure 5. Time history of a 25N stop from 110 km/h](image)

It can be seen that the deceleration was initially about 0.2g (from between 1 and 7 seconds after brake application) and then gradually rising to about 0.26g after 10-12 seconds (by which point the vehicle's speed had reduced to about 23 km/h). This is counter-intuitive because, for example, aerodynamic drag would tend to reduce as the speed fell, suggesting the deceleration might also fall.
However, the trace also shows a quite substantial drop in deceleration, down to about 0.13g in the latter stages of the stop, from a speed of just below 20 km/h (speed not shown in Figure). This drop-off of deceleration as the speed reduced to somewhere just below 20 km/h was evident in various runs, including the baseline characterisation tests, and regardless of state of charge. It is possible that this reduction in deceleration was a result of the regenerative braking system suddenly disconnecting, or at least suddenly changing its characteristics. This would be supported by the suggestion that the pedal force reduced as the driver kept a fixed pedal position. However, contrary to one of the possible explanations of earlier results, this would suggest that the regenerative braking system is in fact responsible for a significant braking torque and that the service brake system is not compensating for its sudden reduction (at least at low speed).

Regulation 13-H requires the line pressures to achieve at least 75% of their final value after regen system disconnection within 1 second of that disconnection. VCA’s interpretation is that this applies in all conditions. The Regulation does not, however, dictate that the vehicle’s deceleration should return to its value immediately prior to disconnection, only that “wherever necessary, to ensure that braking rate remains related to the driver’s braking demand”. Under the test conditions, it appears that both the friction and regen brakes were operating at the point of regen disconnection. As Figure 5 shows, once the regen system was disconnected (or more gradually deactivated), the line pressures remained the same and the deceleration fell steadily to about 0.13g as the vehicle came to a stop, so there is no evidence here that the friction braking system made any compensation for the apparent reduction in the torque provided by the regen system. It should be emphasised, though, that this does not suggest that the system performance is not fully compliant with the regulatory requirements of R13-H, as the line pressures did attain at least 75% of their final value within 1 second (they actually remained constant) and the overall deceleration did remain related to the driver’s braking demand.

Further investigation of possible explanations of these results was undertaken based on theory, literature and consultation with stakeholders. The apparent low speed reduction of the regenerative braking was discussed with a manufacturer of electric motors for electric vehicles and hybrids. They stated that the characteristics of the regenerative system would vary according to its control philosophy. They considered that at high speeds it would be likely that the system would be controlled as a torque machine, that is, the braking system would demand a certain level of torque from the regen system and the electrics would be adjusted to achieve that torque. However, if a significant braking torque was demanded of the motor at low speeds then this would actually draw energy from the battery rather than charging it, thus producing a negative energy efficiency. In this case it would be necessary to switch the control logic to a vehicle speed dependant approach when low speeds were reached. While it should be possible to control everything to maintain energy efficiency and braking, it was acknowledged that a simple solution might be to deactivate the regenerative system at low speed.

The amount of braking torque that the electric motor can produce will depend on the torque curve for the motor, the ratios of any gears in the drivetrain, and the power of the motor. However, it will also depend on the ability of the battery to store the energy, assuming there is no other means of discharging energy. The US Department of Environment (US DoE, 2009) has carried out tests of the battery performance of the test vehicle. It found that the peak pulse charge power in a 10 second charge period was 9.2KW, which is equivalent to storing 9,200 Joules (J) of energy in 1 second.

The Kinetic Energy of a vehicle (KE) is given by the formula below:

\[ KE = \frac{1}{2} m v^2 \]

Where:

\[ m = \text{Mass of vehicle} \]
\[ v = \text{Velocity of vehicle} \]
A 1,325kg car, as tested, will have 9,200J of kinetic energy at a speed of 3.73 m/s (8.34 mile/h). If this speed was reduced to zero in a time period of 1 second by regenerative braking alone, and assuming 100% efficiency in the regenerative system, then the battery would be charged with a power of 9.2KW at an average deceleration of 3.73 m/s² (0.38g). This therefore approximates the maximum deceleration that would be possible if all the kinetic energy was to be successfully converted to battery charge. However, this theoretical maximum for the battery will be speed dependant because of the squared relationship in the kinetic energy equation. That is, a reduction in speed of 1m/s from 30 m/s to 29 m/s implies a considerably greater reduction in kinetic energy than a reduction in speed from 1 m/s to zero. If braking purely regeneratively, this additional energy must take longer to flow into the battery (because its charge power is limited to 9.2 KW), so this 1 m/s speed reduction must take longer than 1 second, and produce a lower average deceleration.

![Graph showing relationship between initial vehicle speed, deceleration and the rate at which kinetic energy is converted.](image)

**Figure 6: Relationship between initial vehicle speed, deceleration and the rate at which kinetic energy is converted (mass=1,325kg)**

It can be seen that for a battery with a rated charge power of 9.2KW, as installed in the test vehicle, then the power ratings will limit the maximum deceleration to less than 0.1g at speeds above about 25 km/h. It therefore seems likely that the control logic for regenerative braking at these speeds with batteries and motors of relatively low power would be set for a constant charge power/current (the precise value of which will vary with SOC) and, in consequence, accept a variable regenerative braking torque (increasing as vehicle speed reduces) to achieve that power. This control may, for example, be provided by a brake-by-wire system that allows the dynamic apportioning of braking between regenerative braking and friction braking to ensure that the regenerative braking system is operated within current/power limits regardless of transmission speed². This would be consistent with the results shown in Figure 6 where the deceleration increased slightly over the main part of the stop and then increased more significantly toward the end of the stop. However, as these lower speeds are

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² An alternative, though less efficient, solution is to install dump resistors in the car that, with appropriate electronics, take diverted current that would otherwise have gone into the battery.
reached the maximum deceleration that will convert kinetic energy at around 9.2KW increases dramatically. At this point it is likely that the control logic would have to change to avoid unintentionally braking much harder than the driver intended. This would also be consistent with Figure 6 where at a little less than 20 km/h the deceleration reduces by about 0.15g.

At 110 km/h the maximum deceleration that would be possible would be 0.025g. The mean deceleration between 110km/h and 20km/h would therefore be expected to be around 0.05g. Between 50 km/h and 20 km/h the mean deceleration would be expected to be around 0.08g. Although these decelerations are relatively low, it would have been expected that the difference would have been visible in Figure 2, if the regenerative braking was not operating at maximum state of charge and the service brakes were not compensating for the difference.

However, investigating the actual charging performance of the battery at different states of charge (as carried out by the US DoE, 2009), shows that the charging power varies between 7KW at 90% charge and a peak of 10KW at 20% charge, with about 9.2KW at 10% (see Figure 7).

![Figure 7: Battery power in relation to state of charge for the tested vehicle (Source: US DoE, 2009)](image)

It is not known exactly what state of charge the dashboard indicated maximum and minimum translate to but if it is assumed that it is 90% and 10% then the mean deceleration attributable to the regenerative braking system would vary between 0.062g and 0.083g, a difference of just 0.02g. Even if there was no compensation from the service brakes at this level it is quite likely that the differences would have been masked by the experimental error inherent in the driver controlled tests.

**ABS**

Two further tests were used to investigate the effects of ABS and its interaction with the regenerative braking system, referred to as low friction and transition tests.

The low friction tests were essentially the same as the in-stop deceleration tests described earlier, but at a lower initial speed (80 km/h) and on a low grip surface. All tests were carried out at minimum SOC and runs were completed both at a nominally
constant brake pedal force (the test driver was allowed to adjust the pedal position if necessary) and with the pedal position held fixed. Pedal forces were incremented at 20N intervals from 0N up to 80N.

As well as potentially highlighting any sudden loss of deceleration or need for compensatory brake pedal application at the point of ABS activation, these tests were also used to identify the “Regen Disconnection Force”, which is the pedal force required, on the low grip surface, to achieve ABS activation (and thus regen disconnection).

This disconnection force determined the brake pedal forces used in the transition tests. These tests, all at minimum SOC, involved braking the vehicle from two initial speeds (to achieve speeds at the surface transition of 120 km/h and 40 km/h) while on a high grip surface and then, during the stop, moving onto the low friction surface (as used in the low friction tests), and vice-versa (transitioning from low to high grip during a stop, though these tests were only carried out at 40 km/h transition speed). Pedal forces at the regen disconnection force were applied (at constant force levels), as well as at 20N below this level and 20N above it. To replicate the testing required by Regulation 13-H, transition tests were also performed at a fast, emergency style, 500N pedal force.

For the throttle off, low friction tests, the decelerations were very similar to those measured in the baseline tests from 50 km/h and the in-stop deceleration tests from 110 km/h, at about 0.05 – 0.06g. Throttle-off decelerations thus increased slightly with speed, from about 0.04 - 0.05g at 50 km/h up to approximately 0.07g at 110 km/h, with the 80 km/h results in between these two values. These findings are in line with those from conventional vehicles, with the higher aerodynamic drag at high speeds giving slightly higher decelerations. This either implies that the regen system is set to deliver very low torque/power in the throttle-off and no service braking condition or that the system is category B only and therefore does not operate at all when the service brakes are not applied. The battery charging indicator on the dashboard suggested that some regenerative braking does take place in the throttle off, no brake pedal application condition, but at a power of about one-sixth that with the brake pedal engaged. This suggests the test vehicle has a Category A and B system, perhaps only delivering 1-2 KW or so to the battery when the throttle is released, which rises to 7-10 KW when the foot brake is applied. A 1 KW energy drain would equate to a vehicle deceleration of only about 0.01g at 20 km/h, and even less at higher speeds, which is likely to be too low to be measurable within the instrumentation accuracy and test run variability. It is also unlikely to be sufficient to counteract the aerodynamic effects (which would be likely to lead to a reduction in aerodynamic drag deceleration of about 0.04g when slowing from 110 km/h down to 20 km/h for a car such as that tested).

On the low friction surface, even the lowest tested pedal forces (20N) were sufficient to cause wheel lock. However, at these low forces, the wheels did not necessarily lock straight away, so some important lessons about the characteristics of the system before and after ABS activation can still be derived. In each test run at this force level, a slight drop in deceleration was measured just before the ABS system activated (as evidenced by a sudden drop-off in brake pressure before then cycling up and down).

Figure 8 shows part of the time history from a typical test run. ABS activation is evident at a time point just after 5 seconds. A drop in deceleration, however, of about 0.04g (from 0.24g down to 0.20g) is evident just before then, at about 4.8 seconds. It is not certain that this drop is a direct result of the regen system cutting out as imminent wheel lock is first detected, but the 0.04g drop is broadly consistent with the likely regen component at this speed (about 70 km/h). Not shown in the Figure, but under ABS control the deceleration gradually builds back up from about 0.15g initially to the pre-activation levels of about 0.25g within about 3 further seconds.
Given the very low levels of regenerative braking torque at high speeds indicated by the in-stop deceleration tests and the theoretical battery energy analysis, it is the low speed (40 km/h) tests that are likely to be of most interest, because they should involve somewhat higher components of regen deceleration. The high-low transition tests were carried out to provide further evidence, to supplement data from the low friction tests, on whether regen system disconnection at ABS activation had a noticeable effect on the vehicle’s deceleration. The data recorded during these tests do indeed confirm the low friction findings, in that at about 0.1-0.2s before ABS activation, the decelerations drop by about 0.06g, broadly in line with the likely regen component at this speed and further indicating that the regen system is deactivated when imminent wheel lock is detected and just before the ABS first starts to cycle the line pressures.

The low-high transition tests were designed to indicate whether the regen system, once deactivated by the ABS, remained deactivated for the remainder of that brake application, or whether the regen component came back into effect once the ABS was no longer needed (because the car had transitioned onto a high grip surface).

Figure 9 shows the full time history for a typical 40 km/h low-high transition test. At the transition point, 6 seconds into the test run, the brake line pressures stop cycling, as the ABS deactivates. The deceleration then increases rapidly, from about 0.3g up to a peak of about 0.55g. Having reached this peak, however, the deceleration then drops off down to about 0.45g (while the line pressures remain broadly constant). This drop occurs at a speed of between 15 and 20 km/h, and its magnitude is about 0.1g. This is consistent with the results of earlier tests and the theory supporting the likelihood of a significant change in characteristics, or disconnection, of the regen system at this speed. If also the case here it would suggest that the regen system was switched back on at or near the point at which ABS deactivated. A video camera fitted to the vehicle also shows the regen charge indicator moving in to the charging zone in the latter stages of the stop, further suggesting that the regen system did reactivate when the ABS cut out.

Figure 8. Partial time history of low friction stop from 80 km/h
BAS

To reduce any risk of the Brake Assist System interacting with the regenerative braking or conventional braking system during the dynamic track tests described above, all the braking (except the “emergency”, 500N applications) were performed at a slow rate of pedal application, up to the required force level. To attempt to deliberately activate the BAS, a series of tests were carried out with much faster brake application rates. The basic procedure for these tests was identical to that described for the brake system characterisation tests, with a 50 km/h initial speed, on a high grip surface, and here with pedal forces raised from 20N to 80N in 20N increments.

Despite brake pedal application rates during these tests being some 3-10 times faster than with the system characterisation tests (measured in N/s), the BAS does not appear to have been activated. The reason for this is not known but if the BAS was purely based on pedal speed it may be that the threshold of pedal speed was higher than achieved in these tests. If a category C system, based on multiple inputs, it may be that the right combination of pedal speed, pedal force and vehicle speed was not achieved. While it is not, therefore, possible to make any deductions about the interactions between the BAS and regen braking system from these tests, the results are directly relevant to the system characterisation tests (because the only difference between those and the BAS tests was intended to be BAS activation – the initial speeds, test surface and pedal forces were all identical). They are, therefore, included in the analyses of those tests described above.

ESC

Braking in a turn tests would be suitable for investigating the stability effects of low levels of longitudinal deceleration in combination with high lateral acceleration when the brake ratio is strongly biased to one axle as a result of regenerative braking. Given the lack of stakeholder concern about potential ESC effects, however, the time and budgetary constraints, and the risk of adverse (winter) weather disrupting the test programme, it was agreed that such a test programme was inappropriate for this study.
3.4 Future technologies

Political and market pressures are leading vehicle manufacturers to introduce a wide variety of energy saving, lower emission technologies across their ranges. Whilst the primary market for regenerative braking systems is for hybrid and battery electric vehicles, particularly to increase the vehicles’ battery-only range, energy recovery from regenerative braking systems are also relevant to conventional vehicles, e.g. to reduce engine use and/or improve driveability. Systems such as BMW’s Brake Energy Regeneration, fitted to a conventional, Internal Combustion Engine vehicle, are thus likely to become increasingly common.

Winkler et al. (2005) conducted a technical assessment of the federal braking standards in the USA and their compatibility with a range of emerging technologies. With regards to regenerative braking, they highlighted two technological developments they believed would find obstacles in the US legislation:

i) Regenerative braking as the primary braking system

Winkler et al. suggested that in the longer term electric vehicles could be fitted with in-wheel drive systems that, when operating regeneratively, could act as the primary braking system. Based on literature reviewed for their study, they believed this could lead to smaller friction brakes that play only a supporting role, or to the elimination of friction brakes altogether (except for holding or parking functions). However, they noted that (at the time of their study) the performance tests in the federal standards assume that the primary brake is a friction brake. It is worth noting here that the energy flow calculations described earlier suggest that, for example, to brake regeneratively-only at 1g from 70 mile/h would produce over 400 KW of power, well beyond the charging capability of current battery technologies (though not of ultra-capacitors which could be used as an energy buffer).

ii) Hydraulic regenerative braking

Winkler also suggested that hydraulic regenerative braking could be a realistic commercial possibility, in conventionally-fuelled vehicles or in heavy vehicles, in the relatively near future. However, there are explicit statements in the federal standards that limit the regenerative braking requirements to electric vehicles and to electric regenerative braking.

In UNECE Regulation 13-H, category B braking systems are considered to be part of the service brake system. There is no concept of a “primary” brake in the regulation, although phased braking is permitted whereby one source of braking may be given priority over another at a particular time. The regulation should not, therefore, present a problem for future vehicles where the service braking function is provided almost exclusively by a regenerative braking system. The Regulation was, though, designed primarily around the assumption that the service braking would be largely friction-based, so there may be detailed aspects that are not compatible with such vehicles.

All references to regenerative braking in UNECE Regulation 13-H relate to electrical systems. The regulation does not include any provisions for hydraulic or mechanical regenerative braking systems. Such a system would, therefore, need to seek approval via the derogation clause for new technology in the EU type approval legislation that states that new technology that does not meet the requirements can be approved if it can be shown to offer at least the same level of safety and environmental performance.

Similarly, Regulation 13-H assumes that an electric, hybrid or conventional vehicle equipped with regenerative braking uses a battery as its energy storage system. The definition of “state-of-charge” refers only to batteries (rather than the more general term “rechargeable energy storage systems”) and there are explicit statements about battery state-of-charge in the brake test procedures. However, ultra-capacitors, hydraulic accumulators and fly wheels all have the potential to be used in hybrid and
non-hybrid vehicle applications (Clarke et al., 2010; Doucette and McCulloch, 2011). Whilst ultra-capacitor systems require energy flow via electricity, and thus would be covered by Regulation 13-H, mechanical (fly-wheel) systems retain the vehicle’s kinetic energy in the same form, and transfer it directly to the wheels in place of, or in combination with, the engine (or motor). They would not need to comply with Regulation 13-H. Hydraulic systems, such as the Bosch Hydrostatic Regenerative Braking (HRB) system, store the energy as hydraulic pressure and would similarly not be covered by Regulation 13-H.

It is unclear from the existing literature whether current regenerative braking systems, in general, remain switched off when ABS has been activated, until the next brake application even if the ABS deactivates during the stop, or if they are simply switched off only when the ABS is activated, and back on again whenever it isn’t. The tests conducted for this study (the low-high transition tests) suggest that the test vehicle’s regenerative braking system is reactivated once the ABS is deactivated. Some designers specify that regenerative braking cannot be used again until the next brake application (e.g. Zhang et al., 2008). However, Zhang et al., (2010) proposed a system in which regenerative braking is reactivated when ABS control is ended.

R13-H contains requirements for secondary braking in the event of a failure in the service brake system. If the service braking was supplied by a regenerative system these requirements would still apply. However, information from stakeholders has suggested that these requirements may not be fully adequate to prevent adverse effects from a failure in a regenerative system. They have suggested that the most likely failure for an electric motor is a torque variation. This can be a loss of braking torque when the driver is demanding braking but could also be an unwanted surge in braking torque either when the brake pedal is or is not pressed. In a hybrid system with centralised motor and geared transmission this would result in a sudden very high braking torque to the driven wheels, which could be sufficient to cause wheel lock. Although the ABS would in theory disconnect the motor the speed at which this would occur is not controlled. This problem may become more significant if distributed drive was used. In this case the torque variation may occur on only one wheel, potentially generating a significant yaw moment. New requirements may be needed to minimise the effects of such a condition.

TRW have developed ESC-R, a modular, hydraulically closed system based on their standard ESC system. It offers “full compatibility for regenerative braking in hybrid vehicles, without change in pedal feel compared to a conventional brake system, allowing for a maximum of energy recovery during braking”. Continental markets their regenerative brake system with the statement “The use of a conventional ESC unit enables the regenerative brake system to perform all known braking interventions and stability functions.” This essentially brake-by-wire system also has a direct hydraulic push-through in case of brake-by-wire failure. The pressure applied by the driver to the brake pedal is measured and converted to a braking torque demand. The ESC unit is enhanced to communicate with the electric motor system (motor(s) + battery + battery management). The electric motor system reports to the ESC unit how much regenerative braking torque is available (depending on state of charge and temperature). The ESC unit sends back a braking torque demand to the electric motor system that does not exceed the available regenerative braking torque and then ensures that the rest of the demand is met by the hydraulic system. There is, therefore, complete flexibility in control to mix braking from the electrical and friction systems, so it is possible to limit the braking to the capabilities of the battery but, at the same time, to maximize energy recapture.
4 Discussion

With the markets for hybrid, electric and highly efficient, low emission conventionally-powered vehicles set to grow rapidly, the pace of development of regenerative braking systems looks similarly set to increase. The two key barriers to the market for battery-electric vehicles (BEVs) are currently their high cost (particularly of the battery packs) and limited range. For system developers, future challenges will include reducing costs, increasing vehicle range and meeting stricter safety and emissions standards. The braking legislation will need to be applied (in current or amended form) to advanced systems that not only stop the vehicle but recover lost braking energy. One particular challenge for manufacturers might be how to maximise energy recovery without impacting on some aspects of braking performance and/or driver feel.

This study has endeavoured to anticipate and identify some of the main potential opportunities within UNECE Regulation 13-H that system developers may seek to exploit in the future. Information from some stakeholders, published literature and from a short series of track tests has informed the study, as described fully in the preceding sections.

In summary, the analysis suggests that current, “first-generation” regenerative braking systems do not compromise braking safety. The tests carried out on one such system, fitted to a hybrid vehicle, did not raise any safety issues. The study has, though, highlighted a number of ways in which the existing Regulation 13-H could need strengthening to maintain this position with regard to more advanced and/or powerful systems (summarised in the following Conclusions section).

The primary determinant of how powerful the regenerative braking system might be is the power capacity of the battery or other energy storage device/system, that is its ability to quickly convert the kinetic energy of the vehicle into its stored form. Basic mechanical engineering theory suggests for current systems, which can only operate at quite low power levels (< 30KW, say), the regenerative braking component is likely to be quite small, particularly at high speeds. Such systems thus need a substantial additional source of braking torque for medium-high deceleration stops from such speeds, i.e. a conventional friction-braking system. Future developments, however, such as ultra-capacitors, flywheels and hydraulic systems could have much higher power capacities, which could open up the possibility to rely more heavily on the regenerative braking system, even for high speed, high g stops and the opportunity to downsize or even eliminate the friction-braking system.
5 Conclusions

The initial focus during this study was on the effects of variations in the state of charge (SOC) of the battery on the regenerative braking component, and on the interactions of the regenerative system with other brake system components such as ABS, BAS and, to a lesser extent, ESC.

The main areas in which the study suggests Regulation 13-H may need strengthening can be summarised, prioritised by their safety implications, as:

a) Regenerative braking systems tend not to be effective at very low speeds (indeed stakeholders have advised that they may actually have to take energy from the battery/energy storage system to further slow or stop the vehicle). Current systems thus work around this by disconnecting the regen system at low speed. This disconnection speed is not regulated. The more powerful the regen system, and the lower the disconnection speed chosen, the higher the potential loss of deceleration is when disconnection occurs, and the greater is the potential for the driver to notice this sudden drop in deceleration, without having changed the braking demand as set by the brake pedal position/force.

b) The Regulation (sections 5.2.7 and 5.2.10) appears to require compensation by the service (friction) brake for disconnection of the regenerative braking (e.g. when the battery is fully charged), but the wording is unclear as to whether this applies only if the regenerative system is acting alone to provide braking torque, or more generally, including when the friction and regenerative braking are acting together. VCA interpret R13-H to require compensation in all conditions, but it is not known if their interpretation is shared by all approval authorities. There is, therefore, room for uncertainty as to whether there is a requirement for the friction brakes to always compensate for the loss of the regenerative component if it is suddenly disconnected or gradually deactivated.

c) R13-H contains requirements for secondary braking in the event of a failure in the service brake system. However, information from stakeholders has suggested that these requirements may not be fully adequate to prevent adverse effects from a failure in a regenerative system. They have suggested that the most likely failure for an electric motor is a torque variation. This can be a loss of braking torque when the driver is demanding braking but could also be an unwanted surge in braking torque either when the brake pedal is or is not pressed. This problem may become more significant if a distributed drive system was used. In this case, the torque variation may occur on only one wheel, potentially generating a significant yaw moment.

d) In the event that the regenerative system is the sole source of braking torque, the Regulation requires the friction braking system to compensate if the regen system is disconnected. However, section 5.2.10 of R13-H only specifies that this compensation achieves 75% of its final value within 1 second. It does not, therefore, require full compensation, or define how long it should take to achieve its final value. There is potential for adverse driver feel effects if the compensation is inadequate or takes too long to achieve.

e) The Regulation is focused on the ultimate capability of the vehicle’s braking system to bring the vehicle to a safe, stable halt in an emergency-type, high pedal force and/or rapid brake application. Non emergency brake performance in general is not regulated. By their nature, e.g. variations in power capacity as SOC varies, regenerative systems may increase risk of performance variability and/or driver feel unpredictability at low brake force levels.

f) The Regulation currently only covers electrical regenerative braking systems. It does not cover other potential options such as flywheels and hydraulic accumulators.
g) The Regulation only covers battery-based electrical energy storage systems. It does not cover other forms of electrical energy storage such as ultra-capacitors.

h) It is also believed (based on VCA’s interpretation) that the Regulation does not currently allow for the service braking to be provided exclusively by a regenerative braking system.

i) The test programme has highlighted difficulties in meeting the requirement to conduct the type 0 and type 1 tests when “the contribution of the electric regenerative braking system to the braking force generated shall not exceed that minimum level guaranteed by the system design”. For battery-based systems this should mean zero regenerative effort because if the battery is full it cannot take any further charge, but the “maximum” SOC as indicated by the vehicle may not remove all regenerative braking, because this full charge state has not been achieved.
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References


Curry at al. (2003). Drivers perception of secondary brake systems. MIRA Report No. MIRA-03-0235036


Investigation into regenerative braking systems

The United Nations Economic Commission for Europe (UNECE) Regulation for the type-approval of braking systems, Regulation 13-H, sets out the technical requirements, test methods and limit values for the braking systems of all vehicles of category M1 and N1 (passenger cars and light commercial vehicles).

The numbers of electric, hybrid and plug-in hybrid vehicles in production are rapidly increasing. In recent years, the braking regulation has been amended to incorporate provisions relating to regenerative braking systems, which are commonly fitted to such vehicles. The main aim of this study was to establish whether or not the existing regulatory requirements, test methods and limit values for regenerative braking systems could still be considered adequate in light of the first few years of experience with such systems and any development of new technology likely to be implemented in the foreseeable future.

This involved a desktop study intended to identify the most likely issues, supplemented by a short programme of dynamic vehicle testing to further explore those issues and inform an assessment of the suitability of the current 13-H test procedures. This report describes the project methodology, results and conclusions in full.

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