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# Automated Driving Systems: Understanding Future Collision Patterns

## Development of Methodology and Proof of Concept

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# Contents

# 1 Executive Summary

The concept of self-driving or automated vehicles (often referred to as autonomous vehicles) is increasingly becoming a reality and development of these vehicles is widely reported in the media. There are a number of different avenues through which this development is taking place with increasing competition between the more traditional automotive companies and technology companies such as Google and Apple, to create the first/best fully automated car.

The emergence of automated vehicles (AVs) could have a major impact on society as a whole, including the safety of road users. Research in the US by the National Highway Traffic Safety Administration (NHTSA) (2008) which indicates that 90% of car collisions are caused by driver error was used to predict an 80% reduction in collisions by 2040 (KPMG, 2015).

Before the full adoption of automated vehicles, there will be an interim period where traditional and automated vehicles will need to co-exist. While the collision rate for automated vehicles will be expected to be low, there is potential conflict between these two types of vehicle while they are sharing the road environment.

This study has developed and applied a methodology to investigate the potential effect of the introduction of automated vehicles on the future collision distrubution. The methodology was applied to a limited scope of collisions (one and two vehicle collisions involving at least one car that resulted in fatal or serious injury) to demonstrate proof of concept.

The case analysis from the UK Road Accident In-Depth Studies (RAIDS) suggested collisions at junctions and those involving vulnerable road users would be reduced, accompanied by a reduction in single vehicle run off road collisions. However, there was minimal information available regarding collisions involving automated vehicles and 20% of the collisions were assigned to an “unknown” collision category. Depending on how these collisions could be re-assigned has the potential to change any conclusions drawn from the changes to the distribution of collisions. Therefore it was not possible to identify the high risk collision scenarios for automated vehicles.

To understand the potential consequences of introducing automated vehicles into a mixed fleet, data collection is critical. This should help to understand how collision patterns will change, and identify any “new” collision types.

The output from the analysis included an estimate of the number of collisions that may be avoided by the introduction of level 4 automated vehicles. However, improvements to these estimates could be achieved by:

- Using a larger more representative sample for the in-depth case analysis;
- Giving greater consideration of injury mitigation during the case studies;
- Including a hierarchy of alternative collision types to help determine the outcomes from an automated vehicle intervention during the case review process. This would help to reduce the number of collisions classified as unknown following the analysis;
- Consideration of a mixed vehicle fleet with varied levels of automation;

- Having an improved understanding of the uptake of automated vehicles within the vehicle fleet for the specific market (e.g. GB), including ownership models.

With a more robust estimate of the benefit of the automated vehicles (from a larger more representative sample of case studies), predictions of changes to each category within the collision matrix could be made.

This study was able to develop and demonstrate a methodology to assess the potential impact of a mixed vehicle fleet. However, it has not been possible to fully achieve the research objectives and identify how requirements for vehicle occupant restraint design or vulnerable road user protection may change with the introduction of level 4 automated vehicles. Based on the number of unknowns in this study, it may be beneficial to repeat this analysis once the capabilities of automated vehicles and future uptake/use of these vehicles becomes clearer.

# 2 Introduction

The concept of self-driving or automated vehicles (often referred to as autonomous vehicles) is increasingly becoming a reality and development of these vehicles is widely reported in the media. There are a number of different avenues through which this development is taking place with increasing competition between the more traditional automotive companies and technology companies such as Google and Apple, to create the first/best fully automated car.

The rise of automated vehicles (AVs) could have a major impact on companies, professionals, mobility, economy and society as a whole, including the safety of road users. Automated vehicles could replace company fleets for transporting employees or deliveries. Employees could gain productive hours during daily commutes by utilising their time effectively for working instead of driving. They could also spend quality time with family members or just relax.

It has been predicted that the car insurance industry could completely change, driven by a reduction in collisions estimated to be around 80% once automated cars are universally adopted by 2040 (KPMG, 2015). This estimate is based on research by National Highway Traffic Safety Administration (NHTSA) in the US (2008) that indicates that 90% of car collisions are caused by driver error.

As automated vehicles penetrate the fleet, there will be an interim period where traditional and automated vehicles will need to co-exist. While the collision rate for automated vehicles will be expected to be low, there is potential conflict between these two types of vehicle while they are sharing the road environment. This research aims to develop a methodology to investigate the potential effect of introducing automated vehicles on the types of collision and in turn identify any changes to priorities for future occupant protection. The research aims to highlight the high risk collision scenarios for the first generation of automated vehicles and explores the crashworthiness vehicle design priorities.

# 3 Methodology

An overview of the methodology for the research is shown in Figure 1. The analysis was restricted to consider only the introduction of automated passenger cars.

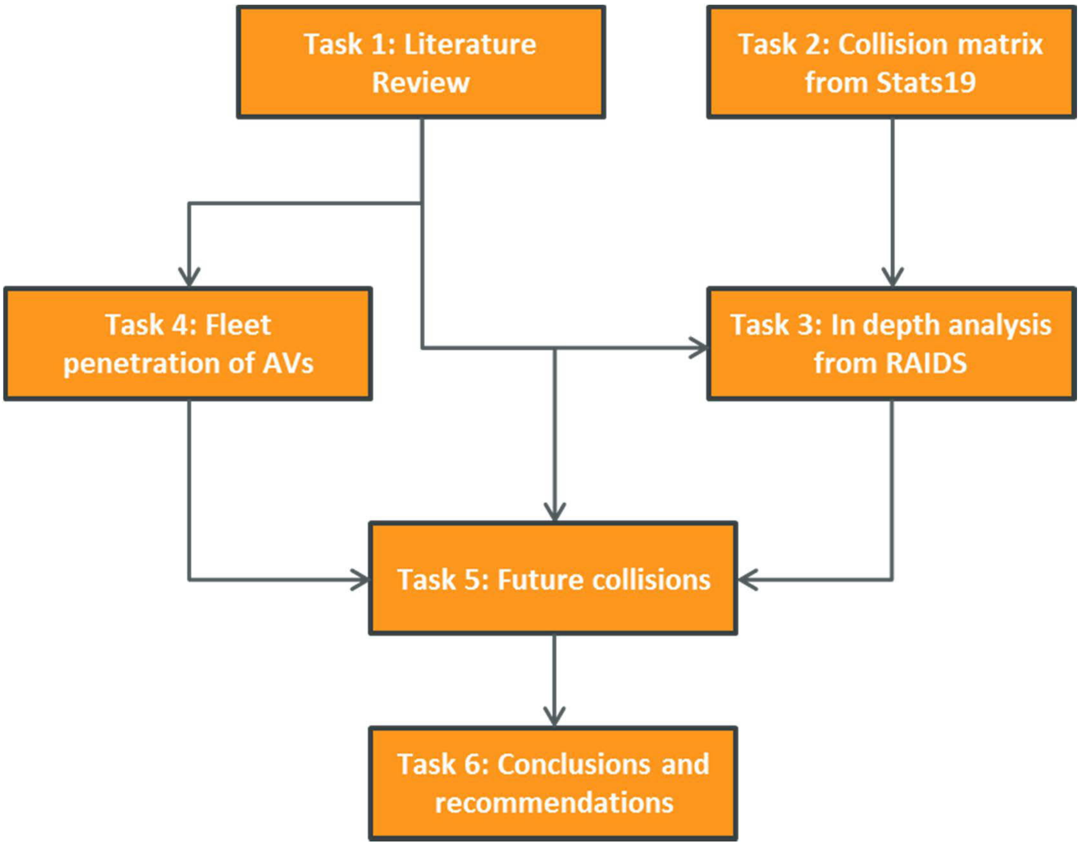


Figure 1: Overview of project methodology

## 3.1 Task 1: Literature review

The literature review aimed to inform the analysis and modelling tasks (Tasks 3, 4 and 5) by identifying information relevant to the following questions:

- What is the most appropriate level of autonomy to consider in the analysis?
- What systems will AVs have in place to prevent or mitigate collisions?
- Are AVs less likely to be involved in a collision (i.e. is collision avoidance better) than conventional cars?
- What collisions have AVs been involved in so far?
- When involved in a collision, do AVs protect their occupants better (i.e. is crashworthiness better) than conventional cars?
- Are there likely to be any new collision types which emerge as AVs are introduced?
- What is the likely fleet penetration of AVs?
- How will AVs influence traffic reliability and flow?

- What problems are foreseen during the transition stage between conventional cars and AVs?

The results of the literature review are presented in Section 4.

## 3.2 Task 2: Collision matrix from Stats19

The aim of this task was to understand the current collision types in Great Britain in order to inform the sample of cases selected from the Road Accident In-Depth Study (RAIDS) for detailed analysis.

The Great Britain (GB) road injury accident database, Stats19, was used for this analysis. Collisions involving cars between 2013 and 2015 were extracted from the database and summarised by type of collision. The collisions types were assigned using a hierarchical approach which is described in more detail in Section 5.

## 3.3 Task 3: In depth analysis from RAIDS

Road Accident In-Depth Studies (RAIDS), funded by the UK Department for Transport (DfT), brings together different types of investigation from earlier studies into a single programme combining existing data with new in a common and comprehensive database. These investigations are designed to understand how people are injured rather than necessarily determine responsibility for the collision. RAIDS collects data from the scene of crashes and examine vehicles that have been involved in police reported collisions in the Thames Valley and Hampshire regions

A sample of 50 collisions from the RAIDS database was selected for case review. The sample was chosen such that it was broadly representative of the distribution of collision types from the Stats19 data. For each collision, the case review considered the following question:

> "If the defined level of autonomy was applied to the vehicle interest (passenger car), how would the outcome of the collision have changed?"

For collisions where there was more than one passenger car, the analysis considered applying the automated vehicle system to the vehicle that would most likely have resulted in a positive outcome for the collision. If it was not clear which vehicle was most likely result in a positive outcome, the automated vehicle system was applied to the vehicle that was identified as being at fault. A new collision matrix was generated for the RAIDS sample based on the analysis and the changes to the types of collision that the cars would have been involved in if they were AVs. Further detail of the methodology is provided in Section 6.

## 3.4 Task 4: Fleet penetration of AVs

The aim of this task was to estimate the future fleet penetration of AVs within the GB passenger car fleet. The method applied uses information on the age and turnover of the passenger car fleet and the rate of uptake of new technologies into this fleet, and combines this in a simple model to predict the uptake of AVs for every year between 2020 and 2040.

## 3.5 Task 5: Future collisions

This task draws together the information gathered in the preceding tasks to provide a prediction of the future casualty scene. The outputs from the RAIDS case review, literature review and fleet penetration tasks, were combined to estimate the total number of casualties for the years 2020 to 2040. This modelling attempted to control for existing background trends in collisions and vehicle use.

The final step was to generate a future collision matrix for Great Britain which details how many collisions of each type are predicted. This was based on estimates of the effectiveness of AVs at reducing (or increasing) each collision type from the analysis of the RAIDS cases.

## 3.6 Task 6: Conclusions and recommendations

Following the completion of the analysis, the methodology and results have been reviewed. The aim of the review was to:

- Assess the quality of the methodology developed for estimating the impact AVs will have on future collision numbers and types, and to assess the quality of the information that is currently available for this type of analysis.
- Understand the limitations of the data sources and make recommendations for improvements to the methodology as more information about AVs becomes available.
- Consider how the future collision matrix could impact upon requirements for the protection of vehicle occupants and pedestrians and pedal cyclists that are collectively referred to as Vulnerable Road Users (VRUs).

# 4 Literature review

A range of literature was identified and reviewed to provide background information and to derive assumptions required to complete the proposed analysis. Literature was identified using search terms such as “automated vehicles”, “self-driving cars” and “autonomous vehicles” in conjunction with terms such as “fleet penetration”, “uptake”, “collisions” and “accidents”. It should be noted that this was not a comprehensive literature review on this subject. Specific objectives of the literature review were to:

- Identify and define the level of vehicle autonomy that would be assumed for the analysis and associated performance of the technology;
- Review information from collisions involving AVs to identify if there were any emerging trends in collision types; and
- Understand the impact of AVs on traffic and the likely fleet penetration of these vehicles.

## 4.1 Levels of autonomy

In January 2014, the Society of Automotive Engineers vehicle standards committee defined six different levels of driving automation to guide industry and consumers to establish principles of safe operation for fully automated vehicles (SAEJ3016, 2014). This document was updated in September 2016 (SAEJ3016, 2016). The six levels are shown in Figure 2.

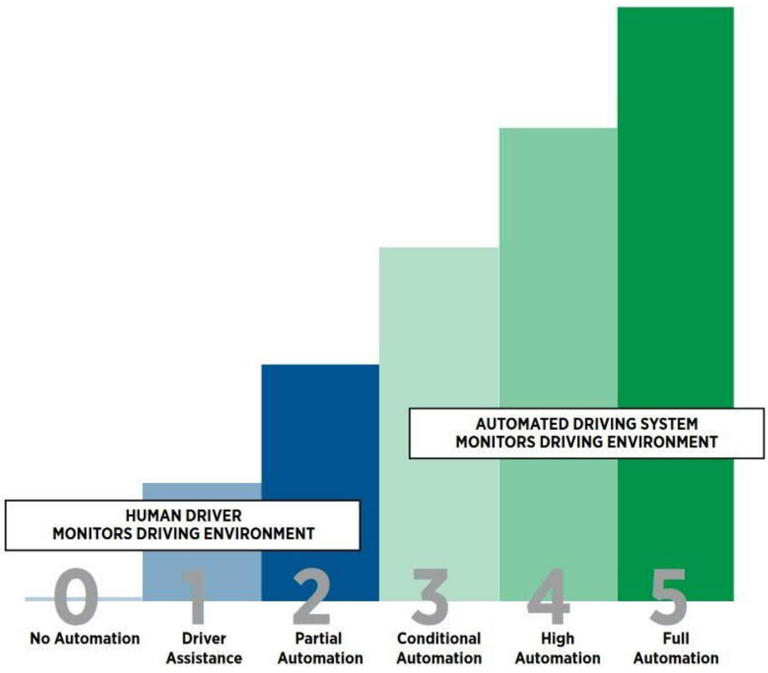


Figure 2: Six levels of driving automation (SAEJ3016, 2016)

The following sections define what is meant by each of the six levels.

### 4.1.1 Level 0 – No Automation

At level 0, the human driver is continuously in full control of the dynamic driving task[1] (e.g. speed and direction); there are no vehicle systems active to intervene. This level of autonomy represents a conventional car with no Advanced Driver Assistance Systems (ADAS), designed to automate/adapt/enhance driving for increased safety or comfort.

### 4.1.2 Level 1 – Driver Assistance

At level 1, the human driver continuously executes either the longitudinal or lateral dynamic driving task (but not simultaneously), whilst the other is executed by a driver assistance system. Examples of this level of automation include cruise control, active parking assist and Advanced Emergency Braking (AEB).

### 4.1.3 Level 2 – Partial Automation

At level 2, the human driver must supervise the driving assistance system which executes longitudinal and lateral dynamic driving tasks. The driver must monitor the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and execute an appropriate response to such objects and events. This driver assistance system only takes over in defined use cases. Examples of this level of automation include Adaptive Cruise Control (ACC), Lane Keeping Assistance (LKA) and traffic jam assist.

### 4.1.4 Level 3 – Conditional Automation

At level 3, the human driver is not required to observe the dynamic driving task nor the driving environment at all times but must always be able to respond appropriately to a request to resume control.

The automated driving system executes the entire dynamic driving task, both longitudinal and lateral control in a defined use case. The system identifies its performance limits in the dynamic driving task and within an appropriate period of time requests the driver to intervene and resume control of the driving dynamic task. One example of this type of

[1] The dynamic driving task includes all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints, and including without limitation:

1. Lateral vehicle motion control via steering
2. Longitudinal vehicle motion control via acceleration and deceleration
3. Monitoring the driving environment via object and event detection, recognition, classification, and response preparation
4. Object and event response execution
5. Manoeuvre planning
6. Enhancing conspicuity via lighting, signalling and gesturing, etc.

system is automated motorway driving where the vehicle requests the user take back control upon exiting the motorway environment.

#### 4.1.5 Level 4 - High Automation

At level 4, the human driver is not required during a defined use case (e.g. motorway driving) and is not expected to intervene within that defined use case.

The automated driving system executes the entire dynamic driving task, both the longitudinal and lateral dynamic control in all circumstances in defined use cases. For example, the Oxbotica pods used for the GATEway Trial in Greenwich, London, are prototype level 4.

#### 4.1.6 Level 5 – Full Automation

Finally, level 5 represents an automated driving system which executes the entire dynamic driving task, both the longitudinal and lateral dynamic control in all circumstances experienced during the entire journey. There is no expectation that a driver will be requested to intervene. Waymo (formerly Google's self-driving car) is working towards this level of autonomy.

#### 4.1.7 Progress from level 0 to level 5

Many of the major automotive manufacturers currently utilise automated technology as support for the driving task, resulting in level 1 and level 2 systems (ADAS) being common place in the current car fleet. However, significant progress is being made by both technology companies and car manufacturers who are dedicated to designing fully self-driving cars, bypassing the intermediate levels of autonomy altogether.

The driving automation level 3, where the car switches between full autonomy and full human control, could be especially difficult to implement with respect to timing of the handover and will require considerable user experience for design and engineering tasks. To avoid this apparent difficulty in navigating level 3 autonomy, Google (Waymo) took the decision to entirely disregard this level and focus on self-driving cars, and to design and build a vehicle from scratch (Davies, 2017).

Similarly, an AV expert at Ford, Jim McBride, said that "the biggest demarcation is between Levels 3 and 4." He's focused on getting Ford straight to Level 4, since Level 3, which involves transferring control from car to human, can often pose difficulties. (Reese, 2016).

### 4.2 System capabilities

There are numerous vehicle safety technologies that have the capability to reduce the frequency and severity of road collisions and trauma. Below is a brief overview of the key technologies, (TRL, 2016). The systems described below either already exist within vehicles or are being developed for future vehicles. Most of these systems work individually at a low level of automation (level 1 or 2), but can be used in combination to fulfil an automated driving task.  This is not a comprehensive list of systems, but those that are not already commonplace on vehicles and are most likely to be used as part of an automated driving system (ADS).

### 4.2.1 Advanced Emergency Braking (AEB)

Advanced emergency braking systems allow a vehicle to detect an obstacle in the environment ahead (without the intervention by the driver), and are able to mitigate or prevent a collision by automatically deploying the brakes. The level of braking automatically differs, however the system may have full potential of anti-lock braking (ABS). These systems are predominantly relevant to situations where the driving task may be interrupted or where the driver is distracted (for example; smartphone usage, distraction from the external environment or other vehicle occupants).

Vehicle-to-vehicle AEB systems have been on the market for some years and have the potential of avoiding or mitigating the front-to-rear shunt collisions. The systems are categorised as “Inter-urban AEB” or “high speed AEB” which may reduce impact speed in higher speed environments.

### 4.2.2 Advanced Emergency Braking – Vulnerable Road User (AEB-VRU)

Pedestrian-capable AEB systems classified as “Urban AEB” or “low speed AEB”, may be effective at reducing the number of collisions and injuries in a city environment and at inner-city driving speeds. These were first introduced into the market in 2013, and are now being introduced into lower budget vehicles.

Cyclist-capable AEB systems will be able to avoid or mitigate cyclist collisions at inner-city driving speeds. Currently this type of system is not commercially available; however existing Urban AEB systems may be able to detect cyclists even though they are not specifically designed for it.

### 4.2.3 Connected vehicle technologies

Connected vehicle technologies use dedicated short-range communication devices to permit vehicles to connect and communicate with each other vehicle-to-vehicle (V2V), to the surrounding compatible infrastructure (vehicle-to-infrastructure or V2I) or to vulnerable road users (V2VRU or V2P). Currently, connected vehicle technologies are not offered on the market and limited safety data has been published.

### 4.2.4 Advanced driver monitoring

Advanced driver monitoring systems, also known as fatigue warning systems, monitor and assess a driver’s alertness and fatigue or drowsiness by watching the driver through cameras installed to the dashboard. If the driver is fatigued or distracted, the system will issue a warning when it has detected that a specific limit has been crossed and will adapt the warning notification of assistance systems or alert the driver to take a break.

Many vehicle manufacturers are studying and developing such systems. Systems can use a combination of sensors to monitor a range of parameters including eyelid movements of a driver, direction of sight, assess the driver’s steering wheel movements, driver’s head position and facial expressions.

### 4.2.5 Emergency Steering Assist (ESA)

ESA systems support the driver in situations where an evasive steering manoeuvre is initiated or is required. During the manoeuvre, the system applies additional steering torque and helps the driver in lateral vehicle guidance. For example, if the driver was to swerve to avoid an obstacle on the road (like a pedestrian), the system will compute the optimal course around the obstacle and the additional steering torque will be applied to help follow the calculated trajectory and stabilize the car. The driver remains in control of the vehicle and can override the system at any given time.

ESA can extend the capabilities of AEB by avoiding collisions where the braking was not enough to prevent the collision with an object.

### 4.2.6 Intelligent Speed Adaptation (ISA)

Intelligent speed adaptation refers to a collection of technologies which are designed to help drivers adhere to the suitable speed for the road environment. Three different levels of control are possible:

- Advisory systems that warn the driver when their speed greater than the limit of the current road environment.
- Voluntary systems where the driver chooses whether the automated system can regulate their vehicle speed.
- Mandatory systems where the driver's speed selection is physically restricted that cannot be overdriven

### 4.2.7 Automated junction management

Automated junction management systems will impede drivers from entering a conflicting route with another vehicle at a junction. The system runs a reservation protocol in which vehicles who wish to cross a junction will contact the server or junction manager agent responsible for managing that particular junction. The vehicle will reserve a trajectory through the junction space-time, much like a landing aircraft will contact an air traffic control tower to reserve space along a specific runway at a specific time for its landing. The junction manager decides whether to grant or reject requested reservations according to the junction control policy.

This system will avoid collisions in two possible scenarios:

1. Collisions during a right turn when crossing the path of oncoming traffic on the opposite lane.
2. Collisions when entering or passing through a junction with cross traffic.

### 4.2.8 Headway monitoring/Adaptive Cruise Control (ACC)

These systems monitor both distance and relative speed to other objects/road users in the vehicle's forward travel path, and the driver is alerted if the safe following distance, relative to the vehicle's travelling speed is breached. ACC systems will maintain and regulate a vehicle's set speed including automatic brake application up to a specified level in order to maintain a safe following distance. The system will also alert the driver if intervention is required.

#### 4.2.9 Lane Change Assistance (LCA)/Blind Spot Detection (BSD)

Lane change assistance systems alert (audible or visual) the driver when potential conflicts with other road users are detected when upon initiation of a lane change manoeuvre. The system can determine whether the driver is intentionally changing lanes or merging into traffic. However, the system is not capable of taking direct action to avoid a possible collision; hence the driver remains liable for safely driving the vehicle.

The proximity of surrounding vehicles is mostly detected by radar sensors, however camera, infrared, and ultrasonic sensors are also utilised. The driver is alerted by visual, audible or haptic means, when a vehicle is drawing near to the rear and when another vehicle is adjacent to theirs.

#### 4.2.10 Lane Departure Warning (LDW)/Lane Keeping Assist (LKA)

Lane departure warning systems monitor vehicle lane positioning and warn the driver when significant deviation is detected due to unintended lane departure. Warnings can be audible, visual and/or tactile so corrective action can be undertaken. More advanced systems (LKA) may apply counter-steer to maintain vehicle lane positioning

### 4.3 Collisions involving automated vehicles

Currently, companies such as Mercedes-Benz, Audi, and Waymo (Google) are running trials of AVs in a range of different use scenarios in order to develop the technology in real-world environments and demonstrate safety credentials. Research by NHTSA in the US (NHTSA, 2008) indicated that 90% of car collisions are caused by driver error, and therefore large safety benefits may be gained by removing the driver from the driving task.

The literature suggests that AVs will not only influence collision rates, but may also reduce the severity of those collisions which do occur (e.g. through reduced speed). The sections below summarise some of these key findings and discuss the challenges faced during the transition phase between 100% conventional cars to 100% AVs.

#### 4.3.1 Changes to collision rates

Crashes involving autonomous vehicles are widely reported by the media; for example:

- “A Tesla driver dies in the first fatal autonomous vehicle crash in US” (New Scientist, 2016)
- “Google’s self-driving car caused its first crash” (Wired, 2016)
- “A Valentine's Day fender-bender involving a Google autonomous Lexus and a public bus shows, cars that drive themselves can make mistakes” (Daily Mail, 2016)

Individual companies are collecting data relating to the performance of their technology when involved in collisions or near misses. However, there are relatively few studies pooling data from multiple AV testing companies and as a result, the true impact of AVs on crash rates and severities in still relatively unknown.

According to a research report commissioned by Google looking at collision rates for automated vehicles compared to conventional cars (VTTI, 2016), self-driving cars were involved in fewer collisions than conventional cars. They showed that self-driving cars have a rate of 3.2 crashes per million of miles, and conventional cars have a rate of 4.2 crashes per million miles. It was noted that the data was adjusted for unreported crashes and accounts for accident severity; however, the investigation did not take account of potential collisions that were avoided when human backup drivers took control.

Other research carried out in the US described a preliminary analysis of real-world collision involving self-driving vehicles (UMTRI, 2015). This research found that self-driving vehicles were involved in more collisions per million miles travelled than conventional cars. However, the distance travelled by self-driving vehicles was still quite low at the time of reporting (around 1.2 million miles, compared with around 3 trillion annual miles in the U.S. by conventional vehicles). It could have been hypothesised prior to this analysis that the self-driving cars would have a lower collision rate because they were to be driven in less demanding or limited conditions (for example: avoiding heavy rain or avoiding snowy areas), which is the opposite of the findings. Consequently the experience of the self-driving vehicles which has not been representative of the experience for conventional vehicles and the lower mileage covered.

### 4.3.2 Changes to collision severity

The UMTRI study (2015) showed that the overall severity of crashes involving self-driving vehicles was also lower than for conventional vehicles. However, these differences should be considered tentative as they could be due to different exposures between the vehicle types.

Technologies such as AEB, which automatically applies the brakes if the driver does not respond in time, have been estimated to reduce collision speeds and the risk of injury. A study by the University of Adelaide in Australia examined 104 crashes using simulation. It concluded that AEB could reduce fatal crashes by 20-25%, and that crashes where injuries occurred could have been reduced by 25-35% (Anderson, et al., 2015).

### 4.3.3 At-fault crashes

The Google study concluded that when the incidents of the AVs were investigated, none of the vehicles in self-driving mode were accountable for the collision (VTTI, 2016). This finding aligned with the UMTRI study (2015) which also demonstrated that the self-driving vehicles were not at fault for the collisions they were involved in.

### 4.3.4 Non-driver related crashes

Sivak and Schoettle (2015) include a discussion around whether AVs will compensate for non-driver factors in collisions. For example, inappropriate actions by other traffic participants, vehicular defects, roadway factors or environmental factors. It was concluded that self-driving vehicles could compensate for some but not all crashes caused by other traffic participants (e.g. the vehicle might not have sufficient time to respond to a pedestrian stepping out in the road). In terms of vehicle defects, some of these may no longer be relevant (e.g. lighting failures because the AV does not rely on visual input); however, given the complexity of the vehicles, it seems likely that defects might occur more frequently on self-driving vehicles than on conventional vehicles. The vehicles should eventually be able to handle most roadway factors (e.g. potholes), but the current sensing technology struggles in fog, snow and heavy rain. Level 4 and 5 automated vehicles are expected to “fail-safe” in the event of a system defect by bringing the vehicle to a stop in a safe place.

#### 4.3.5 Transitional phase: Automated and non-automated vehicles

As automated vehicles penetrate the fleet, there will be an interim phase where conventional and automated vehicles will need to co-exist. While the collision rate for automated vehicles is expected to be lower than conventional vehicles, there is potential conflict between these two types of vehicle, until all vehicles on the road become automated. However, little information has been identified as to the effect of the mixed vehicle fleet with respect to safety.

According to a report by Sivak & Schoettle (2015), the turnover of light-duty vehicles in the US takes a long time, with the average vehicular age currently being 11.4 years. Moreover they state that the distribution of vehicle age has a very long run, citing data from the US Department of Energy which stated that 13.3% of all light trucks sold 25 years ago were still on the road in 2002, with a corresponding percentage for cars of 2.3%[2]. As a result, it could take a long time for AVs to infiltrate the fleet, leading to a long transitional period where AVs and conventional cars need to co-exist.

A major issue during the transitional phase is that driver of conventional vehicles would have particular expectations about the likely response of other vehicles on the road (subject to aspects such as the type of the other vehicle, the location of the interaction, and the age and gender of the driver of the other vehicle etc.). According to a paper by Schoettle (2011), male-to-male crashes are under-represented and female-to-female crashes are over-represented in several types of two-vehicle crashes indicating the possibility that the expectations of male drivers about anticipated behaviours of other male drivers are more veracious than expectations of female drivers about the anticipated behaviours of other female drivers. Moreover, in a lot of recent situations, drivers of conventional vehicles interact with one another by making eye contact and continue according to the response received for other drivers. Said response would be absent in interactions with automated vehicles. The level of importance of both driver expectations and response from other drivers, and the resulting effects on the safety of a traffic system containing both conventional and automated vehicles, remain to be determined.

[2] U.S. Department of Energy (2014), Transportation Energy Data Book, http://cta.ornl.gov/data/index.shtml

#### 4.3.6 Transitional phase: Automated and vulnerable road users

An additional growing worry is observing how automated vehicles will interact with vulnerable road users (pedestrians, and cyclists etc.); this will particularly be an issue during the introduction and transitional phase of automated vehicles. As discussed earlier, there are some safety technologies (V2VRU, AEB, etc.) that specifically assist in avoiding collisions with VRU's which are presently available or under development. Currently vulnerable road users are not equipped with intelligent transport systems (ITS) or safety equipment which would allow them to communicate with automated vehicles, even though there are constant new developments in research in this field (Prospect, n.d.) (Vruits, n.d.).

The use of roads by walkers and cyclists are being encouraged to improve wellbeing and sustainability. However these are the most vulnerable types of road user. According to the European Transport Safety Council, 29% of all road deaths across the EU are amongst pedestrians and cyclists, where pedestrians are 21% and cyclist are 8% (ETSC, 2016).

The lack of means of established communication between pedestrians and automated vehicles is becoming an increasing problem. Information is communicated with human drivers and circumstances are made clear by eye contact or gestures using eyes, head or hands or sometimes even with headlights (flashing). With the introduction of automated vehicles, and without a driver operating the vehicle, this means of interaction will no longer exist.

Another similar problem is that the switch from conventional vehicles to automated vehicles will not happen immediately. It is expected by some that the conversion could take up to 50 years (Litman, 2015) for the vast majority of conventional cars to disappear from the roads, thus both types will co-exist for some time.

There is also a situation where vulnerable road users would pose the question "how would one distinguish between an automated vehicle and a conventional one (from a distance)?

Is it necessary for the automated vehicle to take a different shape, form or colour that would help road users to tell the two apart. Research with new ideas in this field is ongoing, from LED's in the vehicle's grill or windshield to audio concepts and to even sensors detecting gestures or smart wearable devices of the road users. There are also some studies going into the vehicle projecting a dynamic crossing lit up on the road to indicate to the pedestrian that is safe to walk past. (Chalmers, 2015)

The European Transport Safety Council commented regarding ethical issues, which are frequently raised, relating to the full driving automation level (ETSC, 2016). The comments related to how a vehicle should respond when determining to initiate an evasive steering manoeuvre to avoid a vehicle but then instead potentially colliding with a pedestrian. It is evident that ethical matters also require full consideration in the development of automated vehicles.

### 4.4 Effect of automated vehicles on traffic flows

A study for the UK Department for Transport (DfT) on the impact of Connected and Autonomous Vehicles (CAVs) on traffic flow showed that, assuming 100% penetration of CAVs, there would be an improvement in delay of more than 40% for journeys on the strategic road network (Atkins Ltd, 2016). This is associated with a reduction in average journey times and a reduction in the variability of journey time. When CAVs only made up 25% of the vehicle fleet, the benefits were predicted to be negligible.

Similar simulation for urban roads indicated that lower levels of CAV fleet penetration (25%) could result in improvements of 12% in delay, 21% for journey time and almost 80% for journey reliability. This level of improved reliability was considered unlikely to be replicated in all situations, but using a low demand model, an improvement in journey time reliability of 30% was seen, broadly supporting this conclusion (Atkins Ltd, 2016).

A US study (Bierdtedt, et al., 2014), reported that initially AVs will either have no impact or at worst reduce vehicle densities and flows. In the longer term they anticipated that once AVs reach almost full penetration of the fleet, and when vehicles were able to co-operate more with one another to facilitate merging and right of way interpretations, operating efficiencies would begin to improve. Until that time and post-2035, assuming a fleet mix of at least 75% AVs with programming between conservative and aggressive, traffic-flow benefits of 25-35% could be achieved. Beyond then, when much more aggressive algorithms are accepted, vehicle delays could be reduced by 45%.

Bierdtedt et. al. (2014) also suggested that with 50% penetration of the vehicle fleet, AVs are likely to increase the vehicle miles travelled by between 5% and 20% and that this could increase by up to 35% as the fleet penetration reaches 95%. However, there were no dates assigned to these levels of fleet penetration. The paper concluded that any increased efficiency is likely to be offset by the increase in vehicle miles travelled.

It is widely discussed in the literature that AVs may result in increased car-sharing due to the cost of the technology. For example, Morgan Stanley estimate that automated cars could achieve a shared cost per mile below that of owned vehicles by as early as 2030 (Morgan Stanley, 2016). However, the impact of car sharing on miles travelled is unclear: Bierdtedt et. al. (2014) states that if the expansion of AVs does increase car sharing then the overall number of vehicle miles travelled may decrease at a system-wide level. However, it is also acknowledged that if costs reduce then ownership of vehicles may actually increase, leading to an increase in vehicle miles travelled.

## 4.5 Fleet penetration of automated vehicles

Current forecasts for AV market penetration were summarised in a report for the Tampa Hillsborough Expressway Authority in Florida (Pinjari, et al., 2013). These forecasts vary considerably:

- 20–30 million to 95 million automated cars worldwide around 2030 to 2035 – EE Times.
- 15–20 percent of cars globally will be highly automated by 2030, fully automated cars will be in the low single-figure percentages – Market research company
- 75 percent of all light-duty vehicle sales globally by 2035 – Market report
- 75 percent of all vehicles will be automated by 2040 – Institute of Electrical and Electronic Engineers

In the US, (Bierdtedt, et al., 2014) predicted it will be 2050/2060 before automated vehicles make up 50 to 75% of the vehicle fleet.

The interaction between conventional and automated vehicles during the transition period could be expected to be at least several decades long. In addition, a report from the US (Sivak & Schoettle, 2015) stated that some people may want to only drive conventional cars, further adding to the transitional phase.

A study looking at UK opportunities relating to connected and autonomous vehicles (KPMG, 2015) suggested that production vehicles with level 4/5 automation would start to be introduced into the UK fleet from 2025 at a level of 4%. This fleet penetration is expected to increase to 25% by 2030. For level 3 production vehicles, the fleet penetration is expected to rise from 4% in 2017 to 75% by 2030. The predicted take up of the technology is shown in Figure 3.

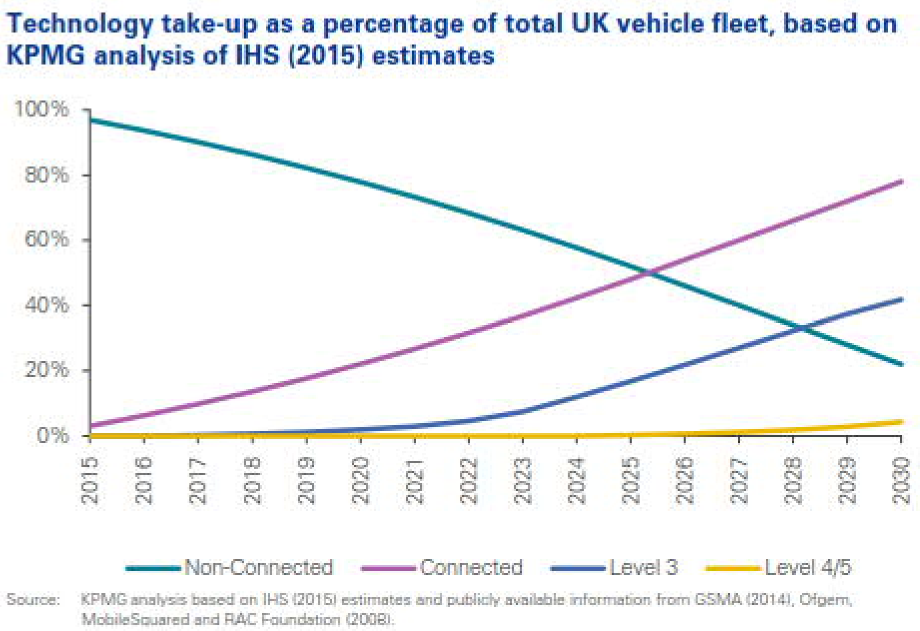


Figure 3: Connected and Automated Vehicle Technology Take Up Predictions for the UK Fleet (KPMG, 2015)

## 4.6 Conclusions

The aim of the literature review was to inform the approach to be adopted in the subsequent tasks of this research. Based on the results presented here, a number of decisions have been made for the analysis that follows.

Firstly, the analysis will assume that the first automated driving systems available in the passenger car fleet in Great Britain will be level 4 'high automation' AVs, which transfer the control from the human to the car in defined use cases. This decision aligns with many of the technology companies and car manufacturers developing AVs, who have made the decision to bypass level 3 'conditional automation', due to the complexities around whether the human or car is responsible at any given moment.

The impact that AVs will have on collision rates is not clear. Some studies suggest that the current collision rates for AVs are higher than conventional cars, and others suggest the opposite. In the long term, the technology should reduce collisions associated with driver error (and perhaps impact on other non-driver related collisions). They should also reduce the severity of the collisions which do occur e.g. through reduced speed. However, in the interim period before AVs make up the whole fleet, there will be challenges for AVs and conventional cars/VRUs interacting with each other. In the absence of clear information on the collision types expected in the future, the decision was made to utilise the RAIDS in depth collision data to estimate this. Task 3 will utilise a case study approach, assessing whether each collision would have occurred if one of the vehicles was a level 4 AV.

The level 4 AVs are predicted to incorporate a broad range of technologies including AEB, AEB-VRU, connected vehicle technologies, fatigue monitoring systems, ESA, ISA, automated junction management, ACC, lane change assistance, and lane departure warning systems. For the purpose of the case analysis and development of the methodology, the systems available on the level 4 automated vehicle were restricted to those contained within the vehicle itself and where information regarding the performance of the system is established.

Similarly to the collision data, the fleet penetration and effect on traffic flow of AVs is not currently clear. Some research predicts that vehicle ownership/traffic will increase, whilst others predict the opposite as we move towards a car-sharing model. This uptake might also differ for different fleets, with commercial vehicles predicted to be among the first to adopt AVs. Either way, the change is not going to happen overnight. As a result, this study needs to include a range of realistic predictions for fleet penetration over the coming years. For the purposes of this study, it has been assumed that cars will continue to be purchased and used for private use, and that the uptake of these vehicles will follow a similar pattern to other new technologies into the fleet (i.e. electric vehicles).

Finally, the DfT study (Atkins Ltd, 2016) identified key knowledge gaps, one of which was that many of the current studies on CAVs consider an idealistic future state with high penetration (around 100%) of CAVs with enhanced capability. There was minimal consideration of that the effect of a lower penetration of CAVs with lesser capabilities mixing with the existing vehicle fleet. This study aims to help fill this knowledge gap.

# 5 Collisions in Stats19

The aim of this task was to understand the current collision types in Great Britain, in order to predict how these might change if AVs were introduced into the fleet. Stats19 data from collisions involving cars between 2013 and 2015 were summarised to understand common collision types.

The collision types are assigned in a hierarchy so that each collision is only included once. The method used is similar to that adopted for the European Road Assessment Programme (EuroRAP). They are assigned in the following order:

1. Collisions involving Vulnerable Road Users (VRUs: pedestrians, pedal cyclists and equestrians);
2. Collisions at a junction;
3. Single vehicle collision where the vehicle left the carriageway;
4. Head on collision;
5. Shunt collision (front to rear);
6. Multiple vehicle collision where at least one vehicle left the carriageway; and
7. Other collisions.

Due to the hierarchy, a collision involving a pedestrian at a junction would be classified as a VRU collision rather than a junction collision. Therefore, the total number of collisions at a junction will be more than is presented here.

In total, between 2013 and 2015 there were over 360,000 personal injury collisions involving a car in Great Britain. One percent of these were fatal, 13% serious and the remainder (86%) were slight. Figure 4 shows how these collisions are disaggregated into the seven collision types.

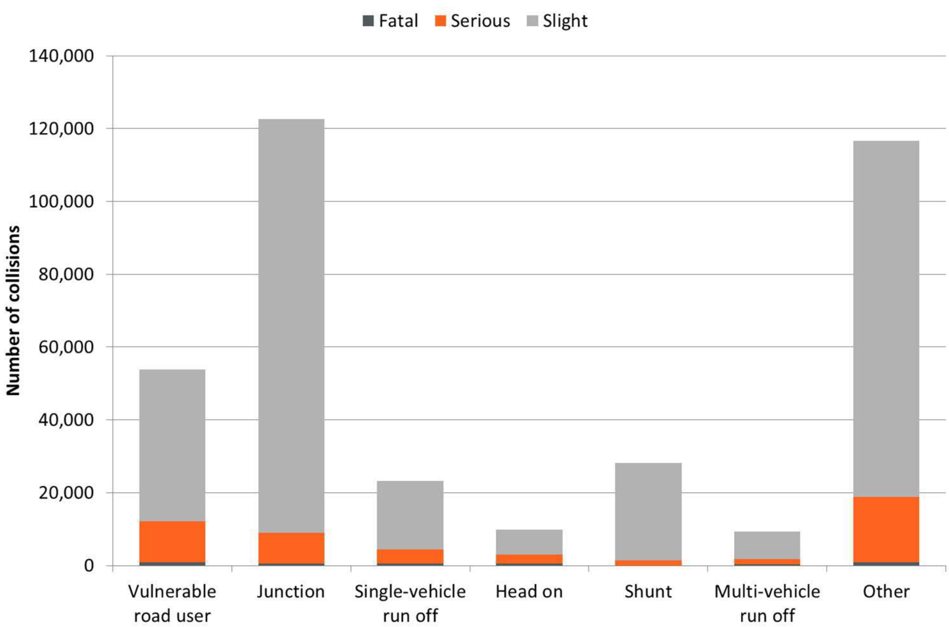


Figure 4: Injury collisions involving a car by collision type and severity (Stats19, 2013-2015)

Over a third (34%) of these collisions involved a junction; collisions involving a VRU accounted for 15% and 32% were classified as 'other' (e.g. some side swipe collisions and rollovers that don't meet the requirements of the other categories).

In order to investigate the impact of AVs on different collision types, it is important to further disaggregate collisions by the number of vehicles involved: single car collisions, 2 vehicle collisions where both vehicles were cars, 2 vehicle collisions where just one vehicle was a car and collisions involving 3 or more vehicles (at least one of which was a car). Figure 5 shows the distribution of all collisions and fatal/serious collisions by this variable. These results show that the vast majority of collisions (88%) involve one or two vehicles.

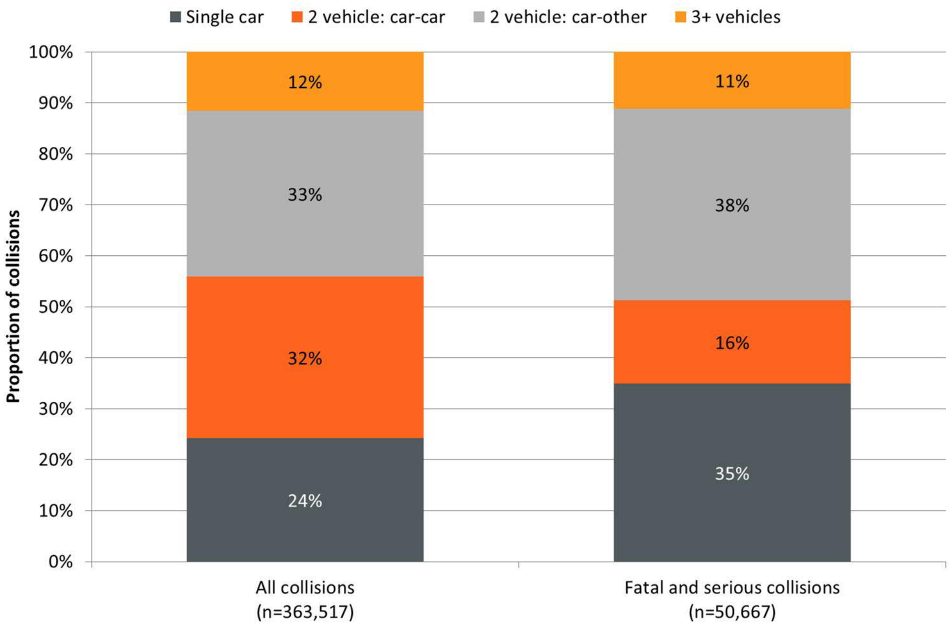


Figure 5: Injury collisions involving a car by severity and number of vehicles involved (Stats19, 2013-2015)[3]

The next task of this research involved studying a sample of these collisions in more detail to determine the impact on the collision if one of the vehicles involved were replaced with an AV. This is more complicated in collisions involving three or more vehicle because there are often multiple interactions to consider. As a result, it was decided to exclude collisions involving more than two vehicles from the scope of this analysis.

In addition, because the RAIDS database is biased towards more serious collisions, the decision was made only to consider fatal and serious collisions within this analysis. Consequently, the analysis that follows is restricted to around 12% of the total injury collisions which occurred in Great Britain between 2013 and 2015. Figure 6 shows how these collisions are distributed between the different collision types.

[3] percentages may not sum to 100% because of rounding errors

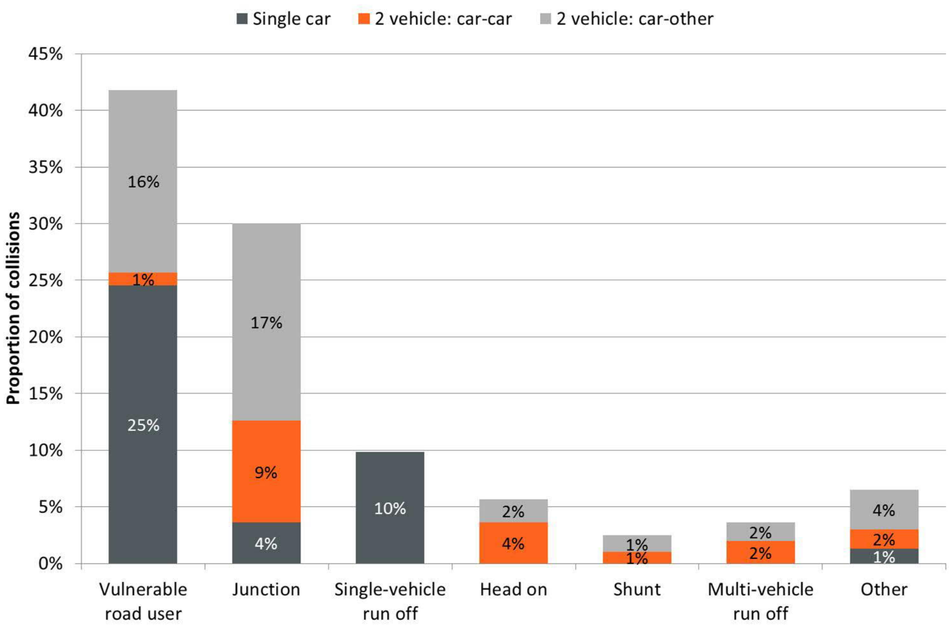


Figure 6: Fatal and serious collisions involving at least one car (one and two vehicle collisions only) by collision type and number of vehicles involved (Stats19, 2013-2015)

One quarter of the fatal and serious collisions involving one or two vehicles are single vehicle collisions with a VRU. Other common collision types are VRU and junction collisions involving a car and another vehicle (16% and 17% respectively) and single vehicle run-off collisions (10%). This collision distribution will be used to select a representative sample of collisions from RAIDS to investigate further (see Section 6).

# 6 In-depth collision analysis

The following sections describe the methodology and outcome from Task 3, the in-depth collision analysis.

Figure 7 shows an overview of the methodology used for the in-depth collision analysis.

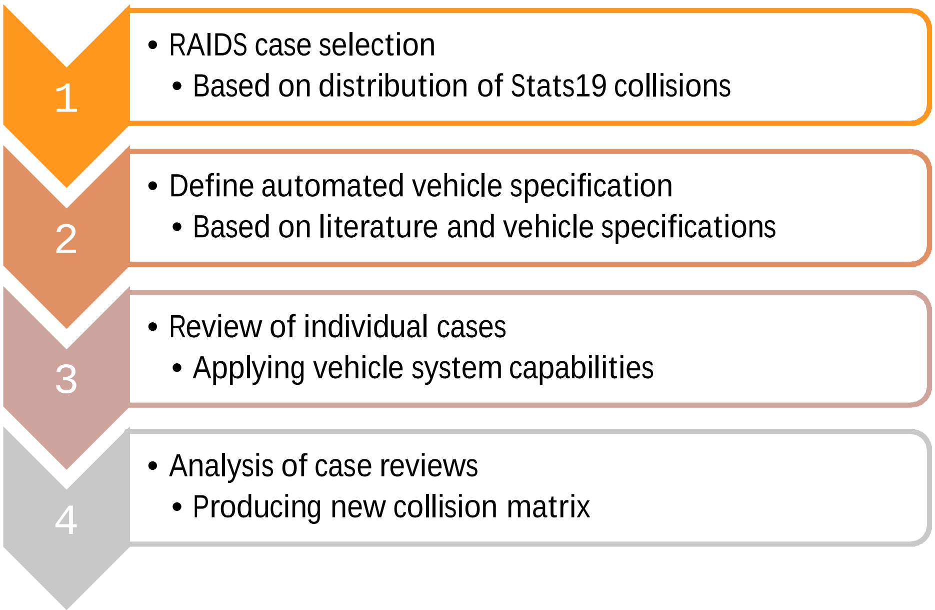


Figure 7: Overview of methodology for in-depth collision analysis

## 6.1 Case selection

In order to identify a broadly representative sample of cases from the RAIDS database, collisions from each of the EuroRAP collision types in Stats19 were cross referenced to the RAIDS databases. The RAIDS cases were then assigned to the relevant EuroRAP collision type.

A sample of 50 in-depth cases were selected for review. The distribution of cases by collision type was intended to match the distribution of the KSI collisions in Stats19 (as described in Figure 6). The final distribution of the cases analysed is shown in Table 1.

Table 1: Distribution of 50 RAIDS cases analysed compared to the Stats19 distribution

| | RAIDS | | | Stas19 | | |
|---|---|---|---|---|---|---|
| | Single car | 2 vehicle: car-car | 2 vehicle: car-other | Single car | 2 vehicle: car-car | 2 vehicle: car-other |
| Vulnerable road user | 14 (28%) | 2 (4%) | 1 (2%) | 25% | 1% | 16% |
| Junction | 2 (4%) | 7 (14%) | 4 (8%) | 4% | 9% | 17% |
| Single-vehicle run off | 9 (18%) | | | 10% | | |
| Head on | | 3 (6%) | 1 (2%) | | 4% | 2% |
| Shunt | | | 2 (4%) | | 1% | 1% |
| Multi-vehicle run off | | 1 (2%) | 1 (2%) | | 2% | 2% |
| Other | 1 (2%) | 1 (2%) | 1 (2%) | 1% | 2% | 4% |

There was some variation from the target distribution because of rounding applied to the total number of cases (50) and availability of cases of the correct collision type. Single-vehicle run off collisions and single vehicle collisions involving vulnerable road users are over-represented. Car to car collisions involving pedestrians, or at junctions or head-on are also over-represented.  Car to other vehicle collisions, especially those involving vulnerable road users or occurring at junctions are under-represented in the RAIDS sample.

## 6.2 Automated vehicle definition

For the purpose of the analysis, a Level 4 automated vehicle has been defined with the capabilities defined in Table 2. The system responsible for the automated driving function will be referred to as the Automated Driving System (ADS). The definition of the ADS is based on known advanced driver assistance system (ADAS) technologies.

Each system (defined below) has its own Operational Design Domain (ODD). This defines the specific conditions under which the ADS or the individual ADAS are designed to function.

The ADS can only be activated when the overall ODD requirements for that system have been met (motorway driving, specified environmental conditions, GPS mapping). Individual ADAS can be applied where the relevant ODD requirements for the individual system has been met.

The following limitations relating to the performance of sensors apply across all systems:

- Not in poor visibility - e.g. snow, fog, spray;
- Not when driving towards a low sun;
- Not in roadworks; and
- Sensor range:
  - <30km/h LIDAR 50m range with 56° Field of View;
  - >30km/h Radar 200 m range with 18° Field of View.

The ODD and performance specifications applied during the case review are described in Table 2.

Table 2: Performance specification of automated vehicle systems

| System | ODD | Performance |
|---|---|---|
| Automated Driving System (ADS) | Motorway driving, all<br>urban driving with high res GPS data<br>Not when snowing, foggy | As defined for each individual ADAS below |
| Electronic Stability Control (ESC) | Always on | Activates when vehicle skids/spin<br>Corrects path of vehicle when loss of control is imminent |
| Advanced Emergency Braking (AEB) | Always enabled in conditions defined below but can be deactivated<br>Active over 5km/h<br>Requires 10km/h speed differential between vehicles | Over-ridden with strong driver input (accelerating/braking/steering)<br>Warning 2.6s Time To Collision (TTC)<br>Light Braking (0.3g) 1.6s TTC<br>Heavy Braking (0.7g) 0.6s TTC |
| Advanced Emergency Braking – Vulnerable Road User (AEB-VRU) | Always enabled in conditions defined below, but can be deactivated<br>Active over 5km/h<br>Not effective/deactivated >50km/h | Over-ridden with strong driver input (accelerating/braking/steering)<br>Warning 2.6s TTC<br>Light Braking (0.3g) 1.6s TTC<br>Heavy Braking (0.7g) 0.6s TTC |
| Emergency Steering Assist (ESA) | Always on | Not active when indicating |
| Intelligent Speed Adaptation (ISA) | Requires drive activation of system<br>Requires road signs to be visible | Restricts speed of vehicle to the speed limit |
| Adaptive Cruise Control (ACC) | Requires drive activation of system<br>Active at speeds >15km/h | Maintains headway to vehicle ahead.<br>Allows up to 0.3g deceleration |
| Lane Keeping Assist (LKA) | Requires drive activation of system<br>Dual c'way/motorway<br>Visible good quality road markings<br>No loss of control<br>Radius of curve >250mm<br>Active at speeds >60km/h | Keeps vehicle in lane<br>Over-ridden by strong steering input<br>Deactivates when indicating |
| Blind Spot Detection (BSD) | Active at speeds >10km/h<br>Not active when reversing | Provides warning when vehicle in blind spot |

## 6.3 Case review

Each RAIDS case was reviewed using an analysis matrix which posed the questions as shown in Figure 8.

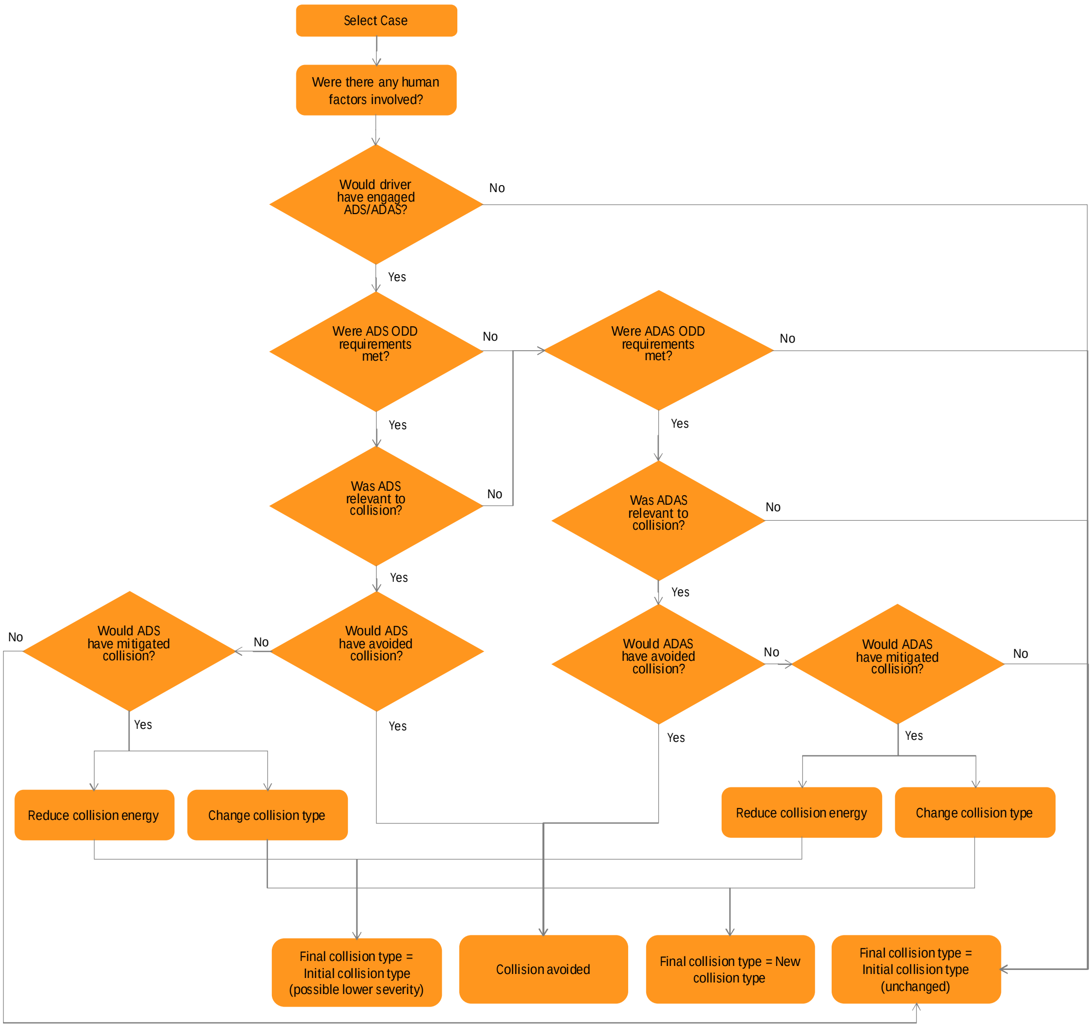


Figure 8: Overview of analysis matrix used for case review

The objective of this process was to identify for each case:

1. If the driver would engage either the ADS/ADAS;
2. Would the ADS/ADAS function in the collision environment (i.e. the ODD requirements were met);
3. Was the ADS/ADAS relevant to the collision type;
4. Would the ADS/ADAS have avoided or mitigated the collision; and
5. How would the collision have been mitigated.

When answering questions one to four, a level of confidence was applied. The level of confidence was generally dependent upon how much information was available in the case record, with a lower confidence applied where information was not available. For some situations, it was not always clear whether the ADS/ADAS would have had the desired outcome and so a lower confidence level was recorded. The confidence was also affected by any human factors that were recorded in the case file.

## 6.4 Analysis and results

Based on the review of each case, the collisions were reclassified into an alternate collision type (Figure 9). The collision types available for selection were the same as those used to select the cases, with the addition of "no collision" and "unknown".

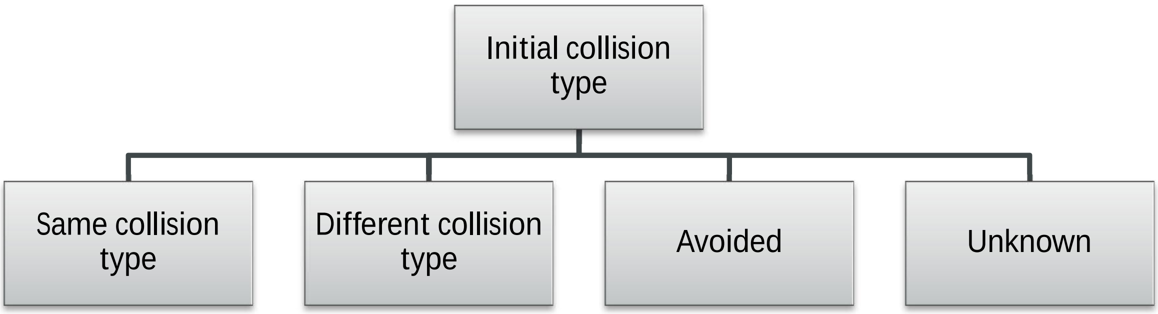


Figure 9: Collision reclassification

For example, taking the nine 'single vehicle rollover' cases then the predictions of outcome indicated:

- two cases would have remained as rollovers,
- one rollover might have become a pedestrian collision instead,
- four of them could have been completely avoided,
- and two were difficult to predict so were left as outcome unknown.

Of the total set of 50 cases analysed, 11 (22%) would have been avoided. In five of these 11 cases, the avoidance of the collision would have been enabled by the ADS. There was either a medium or high confidence in the effectiveness of the ADS for these five collisions. The avoidance of the remaining 6 cases was considered to be attributed to the ADAS systems that would have been active on the vehicle because the ADS could not be engaged. Two of the six ADAS avoided collisions were assigned a high confidence, with the remaining 4 cases being assigned low confidence because of driver behaviour factors.

A further 10 cases (20%) were recorded as 'unknown' collision type. The collision type was assigned as unknown because there could have been a number of different outcomes depending on how the vehicle had reacted during the collision scenario. The methodology did not define an order of preference for the alternate collision types. Four of the unknown collision types were associated with the ADS being used, and two were associated with ADAS. There were four cases where it was unknown if either ADS or ADAS would have had an effect on the collision because of insufficient information in the case file.

Table 3 shows a comparison of the distribution of cases by collision type before and after the analysis of the 50 RAIDS cases.

Table 4 summarises how the distribution of collisions has changed.

Table 3: Comparison of Distribution of Collision Types - RAIDS

| | Single car | | 2 vehicle: car-car | | 2 vehicle: car-other | | Unknown/Avoided | |
|---|---|---|---|---|---|---|---|---|
| | Original | Revised | Original | Revised | Original | Revised | Original | Revised |
| Vulnerable road user | 14 (28%) | 12 (24%) | 2 (4%) | 0 (0%) | 1 (2%) | 0 (0%) | N/A | N/A |
| Junction | 2 (4%) | 2 (4%) | 7 (14%) | 4 (8%) | 4 (8%) | 2 (4%) | N/A | N/A |
| Single-vehicle run off | 9 (18%) | 3 (6%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | N/A | N/A |
| Head on | 0 (0%) | 0 (0%) | 3 (6%) | 2 (4%) | 1 (2%) | | N/A | N/A |
| Shunt | 0 (0%) | 0 (0%) | 0 (0%) | 1 (2%) | 2 (4%) | 1 (2%) | N/A | N/A |
| Multi-vehicle run off | 0 (0%) | 0 (0%) | 1 (2%) | 0 (0%) | 1 (2%) | 0 (0%) | N/A | N/A |
| Other | 1 (2%) | | 1 (2%) | 1 (2%) | 1 (2%) | 1 (2%) | N/A | N/A |
| No Collision | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 11 (22%) |
| Unknown | N/A | N/A | N/A | N/A | N/A | N/A | N/A | 10 (20%) |

Table 4: Change in Collision Distribution - RAIDS

| | Single car | 2 vehicle: car-car | 2 vehicle: car-other | Unknown/ Avoided |
|---|---|---|---|---|
| Vulnerable road user | -4% | -4% | -2% | N/A |
| Junction | 0% | -6% | -4% | N/A |
| Single-vehicle run off | -12% | 0% | 0% | N/A |
| Head on | 0% | -2% | -2% | N/A |
| Shunt | 0% | +2% | -2% | N/A |
| Multi-vehicle run off | 0% | -2% | -2% | N/A |
| Other | -2% | 0 | 0 | N/A |
| No Collision | N/A | N/A | N/A | +22% |
| Unknown | N/A | N/A | N/A | +20% |

The largest effect of applying the ADS/ADAS to the RAIDS cases was changing the outcome of 22% of the cases to “No collision”. There was also a 12% reduction in “Single-vehicle run off” collisions and an overall 10% reduction in “Junction” and “Vulnerable road user” collisions. There was less obvious changes for the other collision types, which may have been expected because of the small number of cases analysed for these categories. It should also be remembered that the 20% of collisions that are now of an "Unknown" type will most likely be distributed within the collision matrix. However, at this time there is insufficient information to consider this further within this project.

As well as eliminating collisions or changing the type of collision that occurs, the ADS and ADAS have the potential to reduce the severity of collisions. There were a total of 18 cases where the ADS/ADAS was considered to offer potential for reducing the energy involved in the collision, nine for ADS and nine for ADAS. The confidence in the possible benefit of the systems was higher for the ADS (mostly high/medium) than for ADAS (mostly medium/low).

# 7 Fleet penetration of AVs

The aim of this section is to predict the fleet penetration of AVs into the passenger car fleet up to 2040. An overview of the methodology is shown in Figure 10.

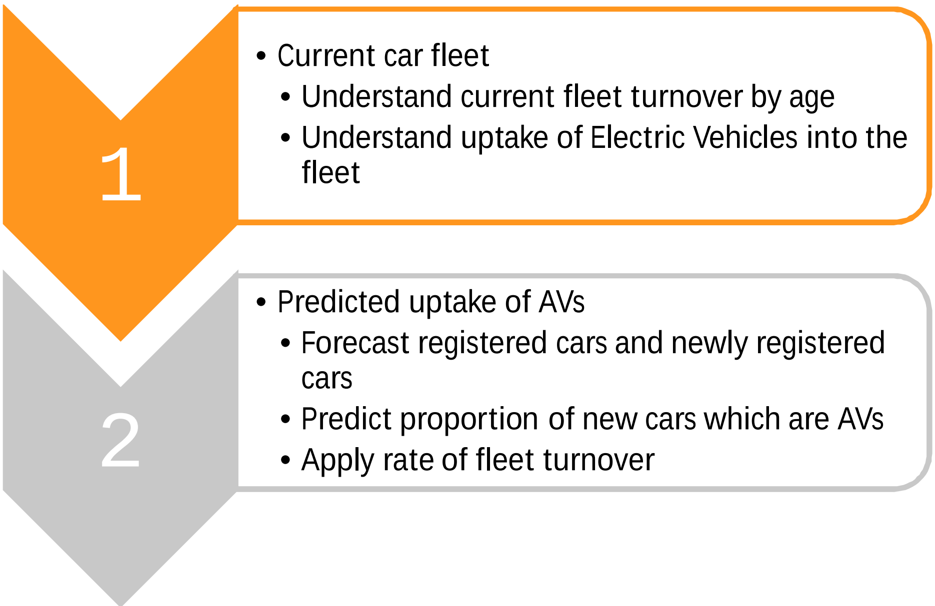


Figure 10: Overview of methodology for fleet penetration estimates

## 7.1 Current car fleet

This section summarises the results of analysis of vehicle statistics which detail the number of licensed cars in Great Britain each year (Department for Transport, 2016). The aim of this analysis is to understand the car fleet turnover, in order to predict future uptake of AVs into the fleet.

Figure 11 shows the average age of the car fleet in Great Britain (orange line, left axis) and the proportion of licensed cars which are registered for the first time i.e. the proportion of cars which are new each year (grey line, right axis).

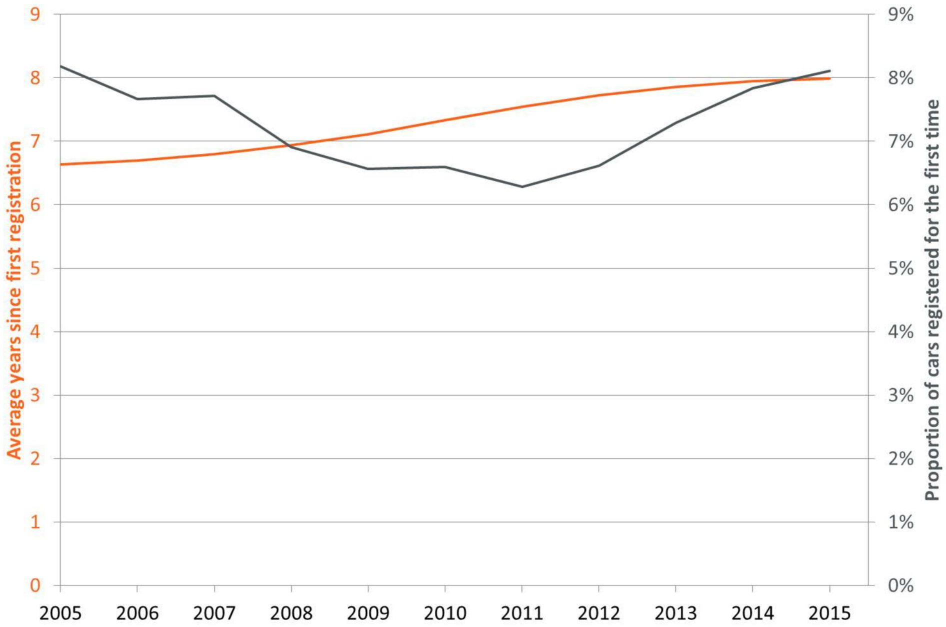


Figure 11: Average age of the car fleet in Great Britain and proportion of cars registered for the first time by year (2005-2015)

On average, the age of the car fleet has been increasing each year, suggesting that the fleet is not being replaced as quickly as it has previously been. However, over the same period, the proportion of cars which are registered for the first time has fluctuated: decreasing between 2005 and 2011 but increasing in recent years. As a result, it would be expected that the average age of the car fleet to be reducing in line with the higher proportion of new vehicles. However, the more detailed vehicle age data shows that the trend for increasing age is driven by an increase in the oldest vehicles (i.e. those aged 13+ years) which are being retained in the fleet for longer.

Figure 12 shows the registered keeper of the cars in the fleet.

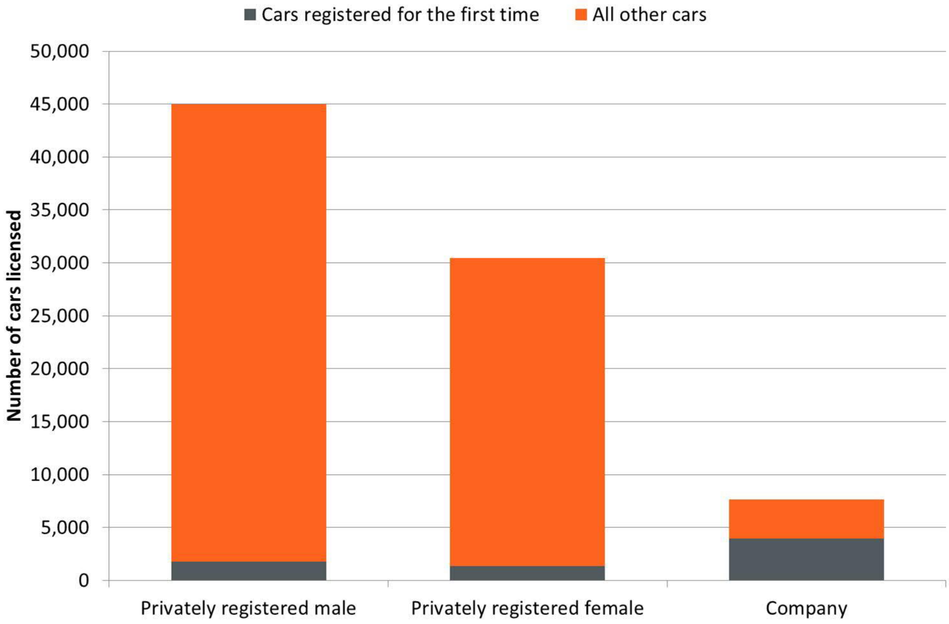


Figure 12: Number of licensed cars by keepership[4] and vehicle age (2013-2015)

Although more cars are privately registered than company registered, a much higher proportion of the company registered cars (52% compared to 4%) are newly registered each year. As a result, this may suggest that when AVs are introduced into the fleet, companies may be among the first adopters of these vehicles.

Electric and hybrid vehicles are a relatively new introduction into the car market. As a result, these might inform the likely uptake of other new technologies such as AVs. Figure 13 shows how the proportion of all cars (and newly registered cars) which are electric or hybrid has changed in recent years.

[4] Unknown registrations have been excluded

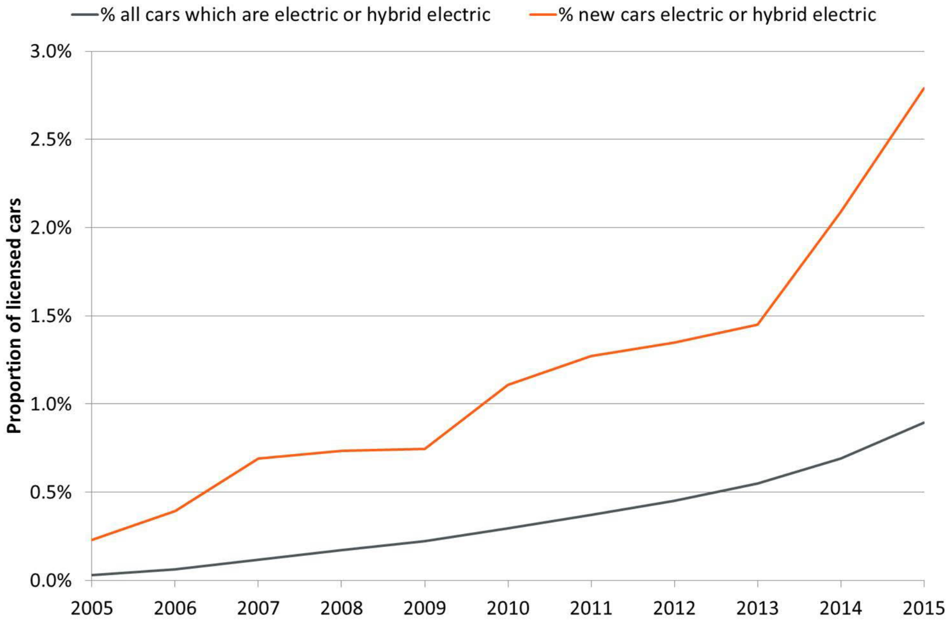


Figure 13: Proportion of cars which are electric or hybrid electric by year (2005-2015)

The proportion of vehicles which are electric or hybrid electric has been increasing year-on-year; however, as of 2015 less than 1% of licensed cars (and fewer than 3% of new cars) were electric or hybrid, despite these cars being an option within the market for more than 10 years. This suggests that the uptake of new technologies into the fleet can be quite slow, although as the chart suggests, this may follow an exponential trend accelerating as the technology becomes mainstream.

## 7.2 Predicted uptake of AVs

The analysis of the current fleet suggests that in recent years the car fleet has been diverging with more of the newest and oldest vehicles. It also suggests that new technologies such as electric and hybrid electric vehicles are taking a long time to penetrate the fleet.

Based on these trends, when AVs are introduced into mainstream purchase, these vehicles have been assumed to penetrate the fleet gradually as older cars are replaced with newer ones, resulting in a long period of time where AVs will interact with conventional vehicles. The key assumption is that the introduction of AVs will not influence the manner in which cars are purchased and used; cars will continue to be privately owned and generally only used by one owner or household, rather than being used as a shared asset. This is a strong assumption of this analysis and it is not currently clear whether this model will be adopted, or whether technology costs will result in a move towards a car-sharing model (see Section 4.4).

In order to estimate the potential effect of introducing AVs on collision types, it is necessary to first estimate the fleet penetration of AVs between 2020 and 2040. This section outlines the methodology to achieve this, presenting a range of estimates of AV fleet penetration alongside the associated assumptions. It has been assumed that the first AVs will be on offer to the consumer market in 2020.

Firstly, it is necessary to estimate how the total number of cars will grow up to 2040. Assuming a linear trend similar to that observed between 2005 and 2015, it is estimated that the total number of cars in Great Britain will exceed 35 million by 2040 (see Figure 14).

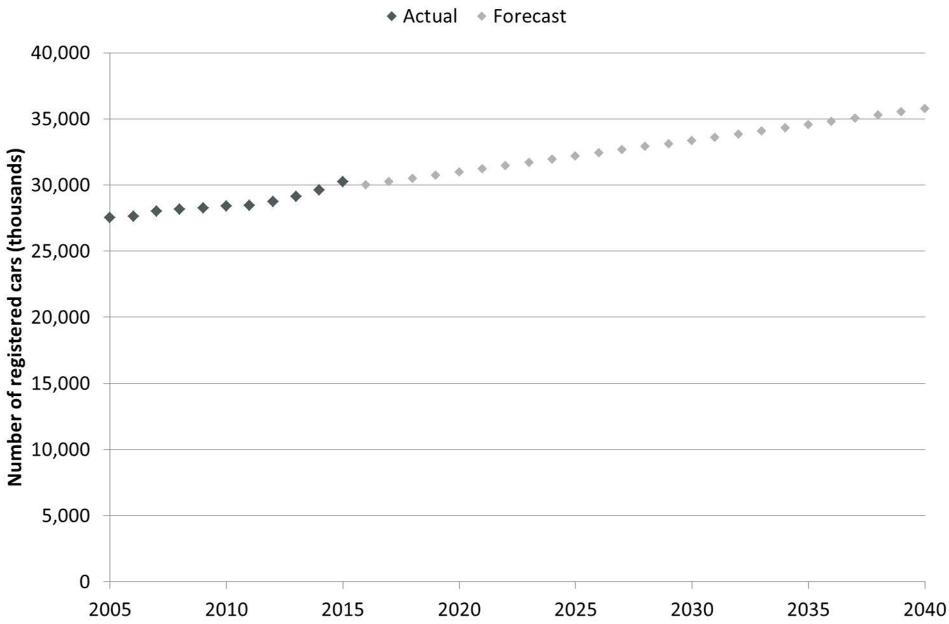


Figure 14: Actual and predicted number of registered cars (2005-2040)

Since the number of newly registered cars each year has tended to fluctuate (as seen in Figure 11), two different assumptions have been applied to provide a range of estimates for the number of newly registered cars up to 2040:

1) A linear extrapolation has been applied to the trend in newly registered cars for the most recent years (2011-2015) – by 2040 this equates to around 19% of cars being newly registered each year.
2) A constant proportion (8.1%) of newly registered vehicles each year.

Figure 15 shows these two forecasts.

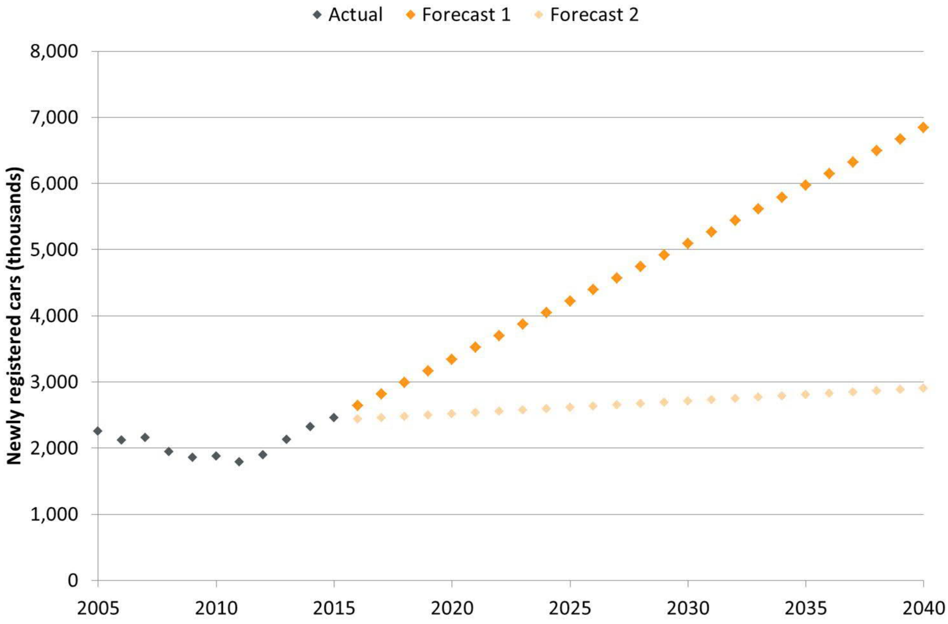


Figure 15: Actual and predicted number of newly registered cars (2005-2040)

In the absence of any conclusive evidence from the literature about the likely uptake of AVs in the future, it has been assumed that the uptake of AVs will follow a similar pattern to the uptake of electric and hybrid electric vehicles into the car fleet. This is a relatively strong assumption to make since there are fundamental differences in AVs and EVs, but both represent new technologies which are unfamiliar to mainstream consumers. As a result, uptake of AVs has been assumed to grow exponentially at the same rate as EVs did between 2005 and 2015 (see Figure 13). It is assumed that this exponential growth in AVs starts in 2020 and continues to 2040 (Figure 16).

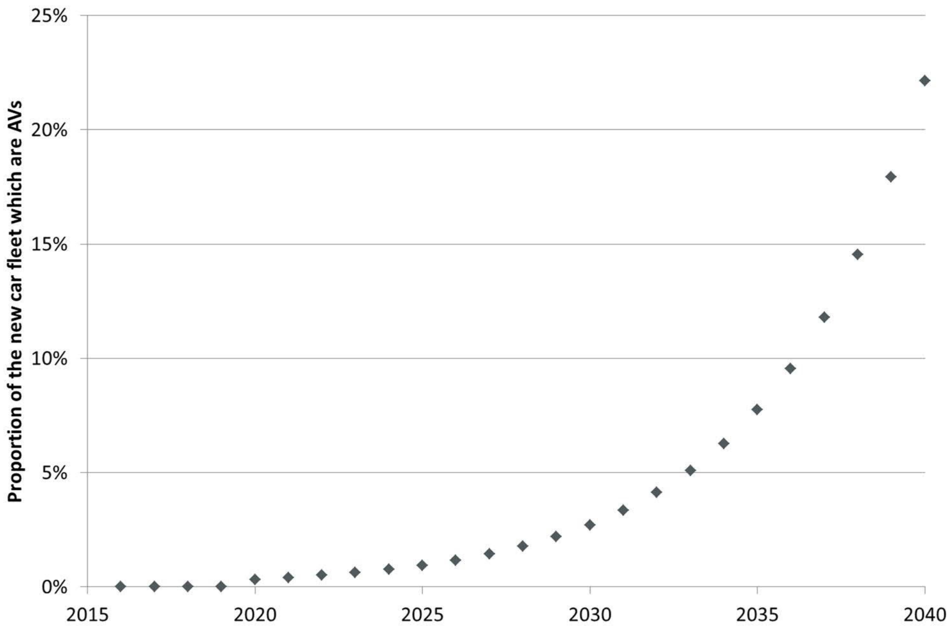


Figure 16: Predicted proportion of new cars which are AVs (2016-2040)

Combing the estimates in Figure 15 and Figure 16 the maximum number of AVs expected in the fleet in any given year can be predicted. However, as vehicles age they are scrapped from the fleet so the calculations for the number of AVs in the fleet also needs to account for this. Assuming the same retention rate of cars by age as seen in the 2015 car fleet, it is estimated that the number of AVs in the fleet will grow as shown in Figure 17.

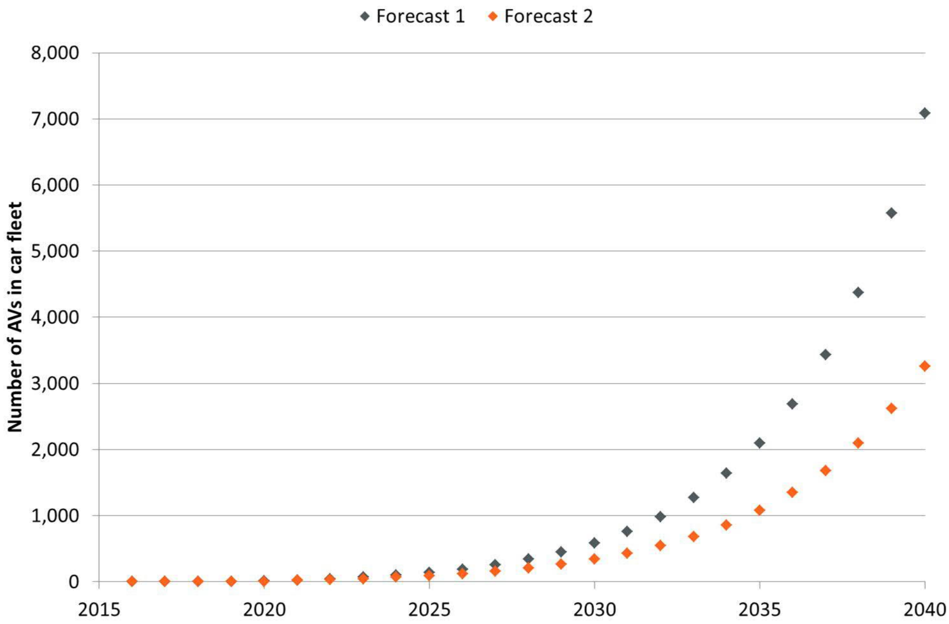


Figure 17: Predicted number of AVs in car fleet (2016-2040)

Forecast 1 equates to approximately 19% of the total car fleet being an AV by 2040 whilst the less optimistic forecast 2 equates to only around 8% of the fleet. Compared to the results from the literature review, which predict that anywhere from 15% of the fleet in 2030 to 75% of all vehicles by 2040 will be AVs (see Section 4.5), the estimates presented here are at the lower end of the predictions, suggesting that they might represent a conservative view.

# 8 Future collisions

This section presents the results of the modelling which estimates how many collisions there will be in 2040 if the uptake of AVs is similar to that predicted in Task 4 (see Section 7) and the effectiveness of AVs at preventing collisions is similar to that observed in Task 3 (Section 6). This modelling also takes into account the background trend in reducing collision rates which has been observed in the collision data in recent years.

As with the analysis is Sections 5 and 6, this analysis is restricted to collisions involving fatal or serious injury and those which only involve a single car or two vehicles, at least one of which must be a car. Therefore the collision numbers presented here are an underrepresentation of the total number of injury collisions, and the impact of AVs is likely to be much higher, especially if commercial vehicle fleets are quicker to adopt the technology than the passenger car fleet.

An overview of the methodology for this modelling is shown in Figure 18.

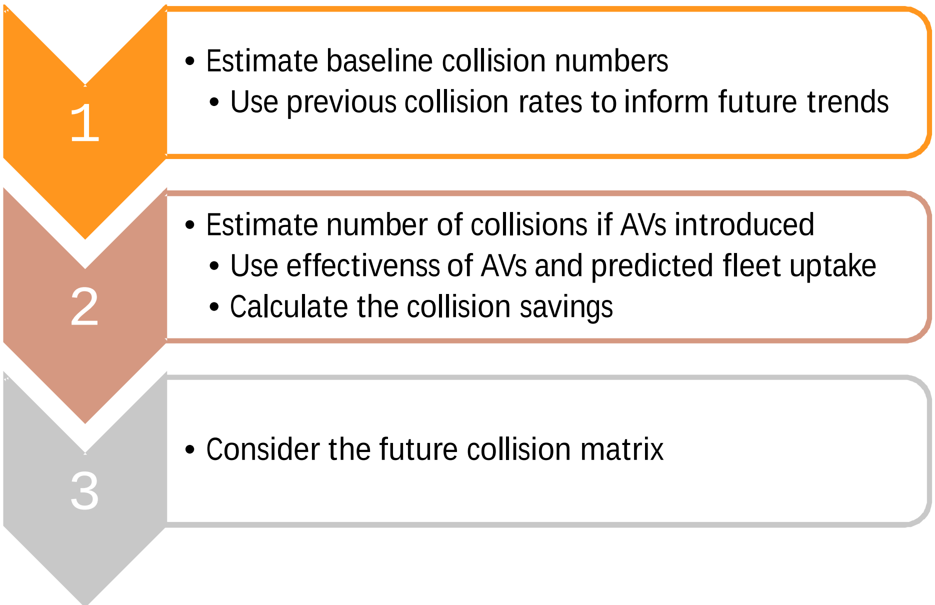


Figure 18: Overview of methodology for future collision modelling

## 8.1 Baseline collisions

Figure 19 shows how the number of fatal and serious collisions in GB has changed over the period 2005 to 2015. Generally, there has been a declining trend the collision numbers which appears to have slowed in recent years. The reduction can be attributed to a number of improvements in road safety including improvements to the road infrastructure, improvements to vehicles, better driver education and compliance.

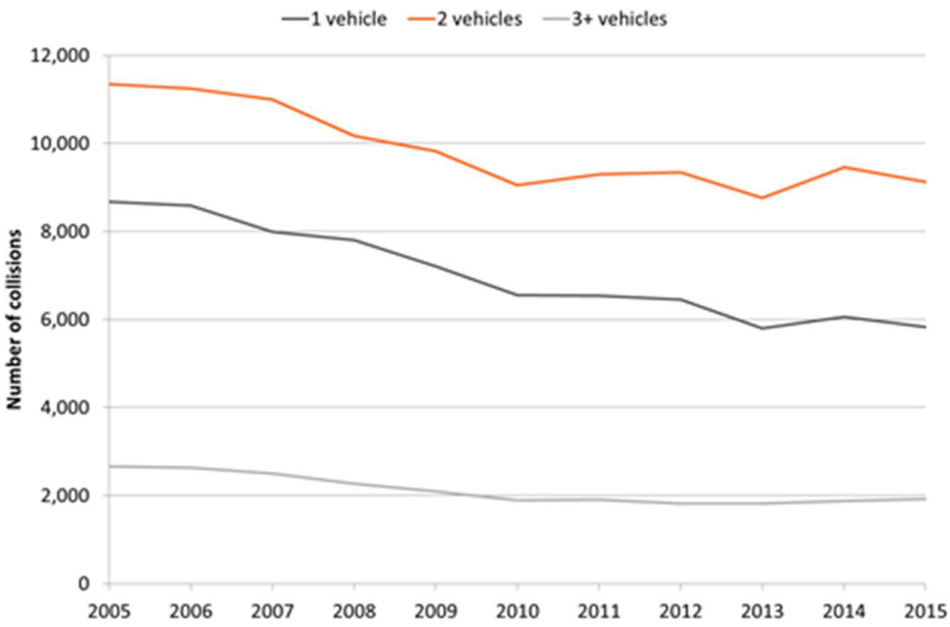


Figure 19: Number of fatal and serious collisions by number of vehicles involved (2005-2015)

In any forecasting task it is important to account for the background trend when estimating future values. This trend will be influenced by the amount of exposure to risk, in this case, exposure to the road environment i.e. the amount of driving.

Whilst the best measure of exposure for collisions is typically traffic data (i.e. the number of miles driven by all vehicles on the road), the number of registered cars has been used here. This was chosen because traffic estimates are not available split by age of the vehicle, and this was necessary to know in order to predict the number of AVs as part of Task 4. By using registered vehicles and incorporating the age of the vehicle and turnover of the fleet it was possible to estimate how quickly AVs might enter the passenger car fleet. Figure 20 shows the collision rate per thousand registered vehicles for the collisions of interest.

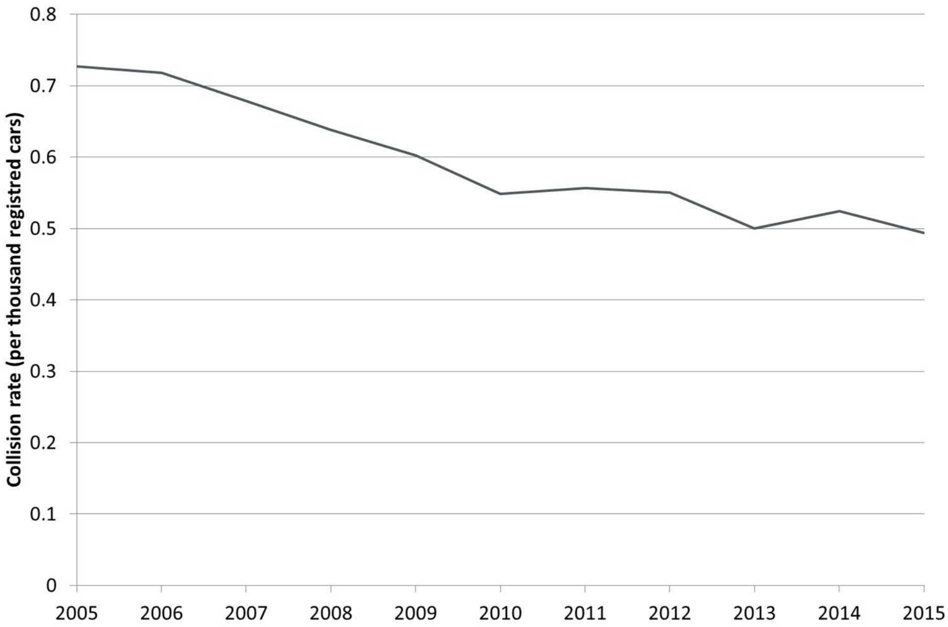


Figure 20: One and two vehicle fatal and serious collision rate (2005-2015)

This shows that despite the fact that the number of registered cars is increasing, the number of collisions per registered vehicles has still been reducing over this period.

In order to account for uncertainty, a range of predictions will be made in this analysis. At the first stage, the future collision rate has been estimated using two scenarios (see Figure 21):

1. Assume the collision rate declines linearly at the rate it was declining between 2013 and 2015
2. Assume the collision rate decrease exponentially (with the same trend as between 2005 and 2015)

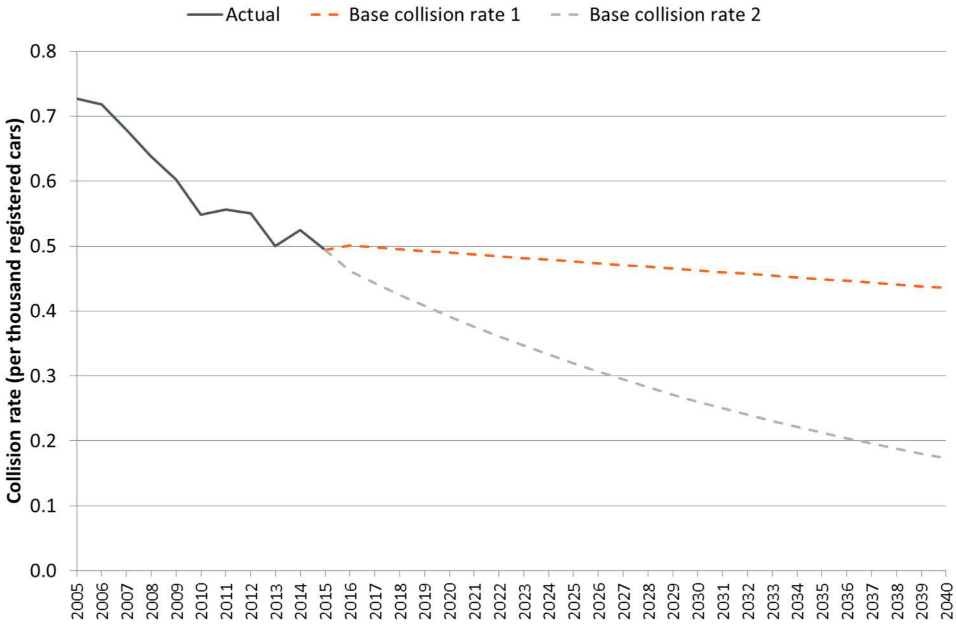


Figure 21: Actual and predicted one and two vehicle fatal and serious collision rate (2005-2040)

The collision rate figures are then converted to estimates of the number of collisions using the predicted number of cars registered (from Figure 14). The estimated number of baseline collisions under the two different scenarios is shown in Figure 22.

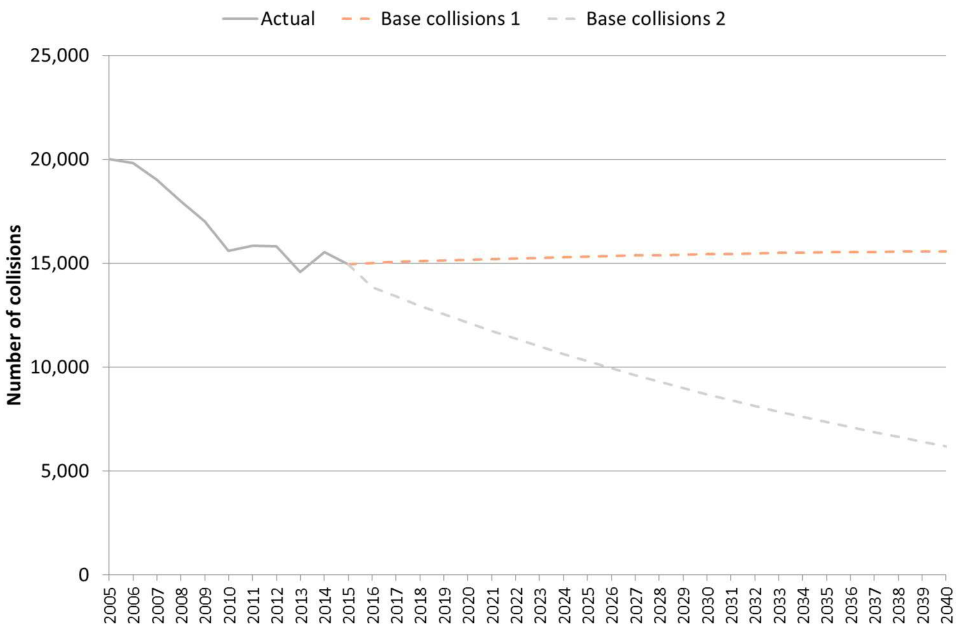


Figure 22: Actual and predicted one and two vehicle fatal and serious collisions (2005-2040)

These scenarios suggest that if AVs were not introduced into the fleet, the number of fatal or serious collisions involving one or two vehicles (at least one of which is a car) will be somewhere between 6,000 and 15,000 a year. The difference in these estimates reflects the relatively large uncertainty in how collisions and travel will develop in the future, particularly when forecasting 25 years ahead.

## 8.2 Collision savings

From the previous tasks it has been estimated that:

- Level 4 AVs will result in around 22% of collisions being avoided (see Section 6.4)
- By 2040, the proportion of car fleet which is AVs will be around 8% to 19% (see Section 7.2)

By combining these estimates with the baseline collision figures estimated above, it is possible to estimate how many collisions there will be in each year between 2020 and 2040 following the introduction and uptake of level 4 AVs. These figures can then be subtracted from the baseline collision numbers to estimate the savings achieved by the introduction of AVs (Figure 23).

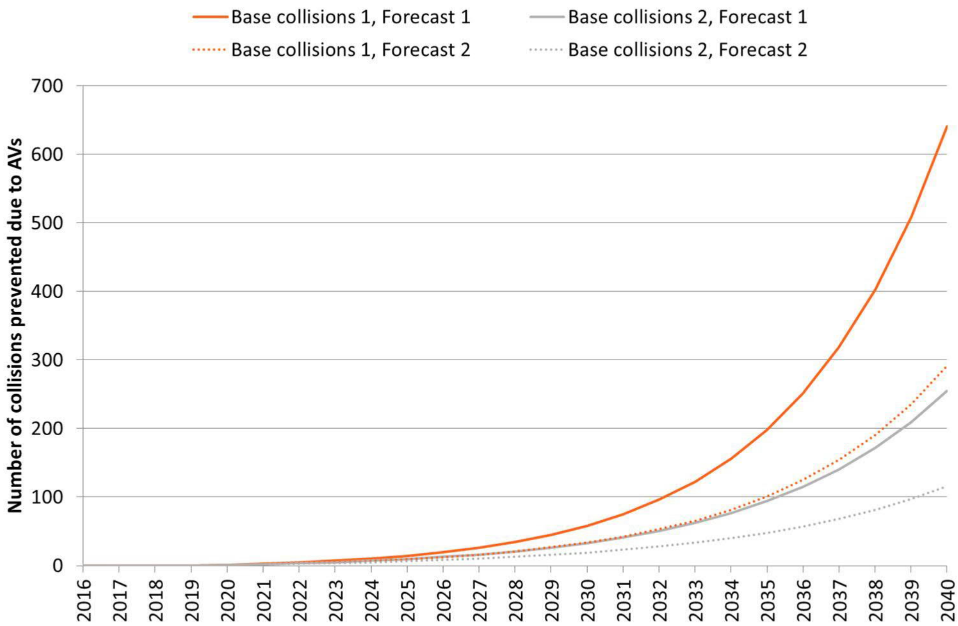


Figure 23: Number of collisions prevented due to introduction of AVs (2016-2040)

The models estimate that there will be around 100-650 collisions prevented due to the introduction of AVs. These figures seem quite low; however these are based on a relatively low uptake of AVs (8-19% by 2040), so savings could be higher if AVs are quicker to be adopted into the fleet, or if the vehicles are more effective at reducing collisions than predicted.

In addition to these collision savings:

- There are likely to be reductions in the severity of collisions which have not been considered in this analysis.
- Three or more vehicle collisions, and collisions involving slight injury, have not been considered and therefore the total collision savings are likely to be substantially higher.
- This analysis only considers the impact of AVs in the passenger car fleet. Much of the current thinking points to goods vehicle users being the first likely adopters of AVs;

these will likely result in higher collision reductions, although these cannot be quantified from this study.

- The study only considers the implications of level 4 AVs where the driver is still required to take control of the vehicle in certain use cases. Level 5 AVs, where the driver is no longer required at all, should be more effective at reducing collisions, although it is anticipated that some will still occur, particularly whilst the fleet is a mixture of AVs and conventional cars.

## 8.3 Future collision matrix

Due to the limited number and distribution of the case studies used in the RAIDS analysis, it was not considered appropriate to accurately estimate the number of collisions of each type following the introduction of AVs in the car fleet. Therefore, the high risk collision scenarios for AVs could not be identified. Further work could incorporate the assessment of more case studies to improve the representativeness of the sample and better predict the reduction in each collision type, rather than just the overall reduction in collision numbers applied here. Individual collision type models could then be developed to estimate how the distribution of casualties would differ in the future. For example, would AVs reduce the number of VRU casualties faster than the number of occupant casualties, or would both reduce in parallel?

This additional work could also consider in more detail whether the severity of collisions is likely to reduce (or increase) following the introduction of AVs, and consider whether new collision types might be created.

# 9 Discussion

## 9.1 Quality of the methodology

The methodology applied to this study demonstrates proof-of-concept that, given the right data, information could be combined to estimate the number of collisions predicted if automated cars were introduced into the vehicle fleet.

The selection of a level 4 automated vehicle added complexity to the analysis because the system could only be engaged in certain operating conditions. This resulted in a large number of cases in the RAIDS analysis where the automated driving system could not be engaged, and the analysis then considered the effect of the individual ADAS on the vehicle. Selection of a level 5 automated vehicle would be likely to simplify the analysis.

The use of a larger more representative sample for the in-depth case analysis would have allowed more robust modelling to have been completed. A larger sample would have enabled the modelling to have considered the trends within each of the collision types defined in the collision matrix. It should be noted that the sample size for this study was restricted by the scale of the project.

The in-depth analysis of the RAIDS cases considered whether the ADS/ADAS would have reduced the severity of a collision in general terms. More detailed analysis of the injuries sustained in the original collision and the change to impact kinematics could be completed to improve the estimated benefit for severity reduction (or possibly increase in severity). However, this type of analysis could potentially be limited by the availability of sufficient cases with the required level of detail.

The case analysis resulted in 20% of the collisions analysed being re-classified as an unknown type of collision. The inclusion of a hierarchy of alternative collision types to help determine the outcomes from an ADS/ADAS intervention during the case review process could help to reduce the number of collisions assigned to the “unknown” category.

This study has focused on the effect of introducing automated vehicles of one specific level of automation. The methodology could be extended to allow the consideration of a mixed vehicle fleet with varied levels of automation. However, the additional effort required for this kind of analysis may not be proportional to the additional knowledge gained.

Information about the uptake of automated vehicles identified in the literature review was limited. Many studies considered the vehicle fleet in the US and there were contradictory findings. Having an improved understanding of the uptake of AVs within the vehicle fleet for the specific market (e.g. GB), including ownership models.

With a more robust estimate of the benefit of the AVs (from a larger more representative sample of case studies), predictions for each group within the collision matrix could be made.

## 9.2 Limitations of the data sources

The estimates produced by this study are based on a substantial number of assumptions and the literature findings were inconclusive around many of the questions posed:

- What collision types will occur when AVs interact with conventional cars?
- What impact will AVs have on traffic?
- How will these vehicles penetrate the fleet?

For example, the impact of AVs on how people will travel in future is unknown. If ride sharing increases then the amount of traffic or levels of car ownership might decrease. Alternatively, AVs might increase travel for those individuals who cannot currently access cars. It is acknowledged that this study has made a substantial assumption that cars will continue to be owned by individuals and used in a similar manner to the way they are now.

The analysis has also demonstrated that unless government promote the purchase of AVs, or they prove to be more popular in terms of uptake than electric vehicles, it could take a long time for these vehicles to penetrate the GB car fleet. This will result in a long period of time during which conventional cars and AVs will interact.

However, whilst the timespan for penetration of AVs into the fleet is not clear, it is predicted that the dispersion times of new technologies will reduce in future. There was traditionally an approximate 10-year timespan between initial market offering of a technology and availability on 95% of new vehicles. Fleet dispersion requires another 15 years before fitment rates across the fleet reach 95%. These timespans will likely reduce in the future:

- As innovation in vehicle systems is becoming increasingly software-driven, OEMs face innovation pressure from other industry sectors, primarily IT.
- New vehicle functions can be added as over-the-air upgrades and thus also reach parts of the legacy fleets.
- Over-the-air software updates after deployment allow cheaper modifications and improvements to existing systems compared to vehicle recalls.
- The European legislator becomes more willing to more quickly mandate successful systems such as ISA and AEB, thereby boosting market uptake.
- Euro NCAP has proven to react more dynamically to technological developments and is fast to encourage technologies such as pedestrian AEB or ISA.

Many of the studies with information on collision rates of self-driving vehicles are based on data from the USA. The vehicle types, driving conditions and subsequently the collision types in the USA are very different from those experienced in Great Britain so it is not clear how transferrable these findings will be.

This research aimed to will define a single level of autonomy based on the findings of the literature review. In reality, a range of vehicles with differing levels of autonomy will be present within the vehicle fleet.

For all levels of autonomy except level 5, it is assumed that seating positions remain as they are in a conventional car, with all drivers and passengers required to be restrained. Only level 5 autonomy, where the driver is not required to intervene at any time, would permit the driver to be seated in an unconventional position, which could lead to new occupant protection concepts being required.

Analysis has been restricted to the most serious collision types because RAIDS has a focus on these severities of collision. There are issues with under-reporting of slight collisions (and no reporting of damage only) in national accident databases. In contrast, there is a requirement to report all incidents involving AVs (at least in California) so there may be some bias in this dataset compared to the national accident database.

## 9.3 Future of occupant and VRU protection

Although individual technology companies are collecting data relating to the performance of their technology in collisions and near misses, there are no aggregate studies and the data is mostly based on US collisions. It is therefore important to understand how AV technology is performing in different road environments, especially those which are geographic in nature (i.e.UK/European based data).

The RAIDS in-depth case analysis suggested that the introduction of AVs is likely to result in a reduction in collisions at junctions and collisions involving vulnerable road users. There is also likely to be a reduction in single vehicle run off road collisions. In order to identify if these reductions in the number of collisions should influence vehicle design, further investigation regarding collision energy and configuration would be required.

There was a less clear trend for other types of collision such as head-on collisions and shunts. However, the number of cases reviewed within these categories was some of the smallest in the analysis and so a clear trend may not have been expected.

# 10 Conclusions and recommendations

This study has developed and applied a methodology to investigate the potential effect of the introduction of automated vehicles on the future collision scene.

The methodology was applied to a limited scope of collisions (one and two vehicle collisions involving at least one car that resulted in fatal or serious injury) to demonstrate proof of concept. The output from the analysis included an estimate of the number of collisions that may be avoided by the introduction of level 4 automated vehicles. However, the methodology could be improved in the following ways:

- The use of a larger more representative sample for the in-depth case analysis;
- Greater consideration of injury mitigation during the case studies;
- Including a hierarchy of alternative collision types to help determine the outcomes from an AV intervention during the case review process. This would help to reduce the number of collisions classified as unknown following the analysis;
- Consideration of a mixed vehicle fleet with varied levels of automation;
- Having an improved understanding of the uptake of AVs within the vehicle fleet for the specific market (e.g. GB), including ownership models.
- With a more robust estimate of the benefit of the AVs (from a larger more representative sample of case studies), predictions for each group within the collision matrix could be made.

There was minimal information available regarding collisions involving AVs. To understand the potential consequences of introducing AVs into a mixed fleet, data collection is critical. This should help to understand how collision patterns will change, and identify any “new” collision types.

The RAIDS in-depth case analysis suggested that a reduction in collisions at junctions and those involving vulnerable road users would be reduced, accompanied by a reduction in single vehicle run off road collisions. However, 20% of the collisions were assigned to an “unknown” collision category. Depending on how these collisions could be re-assigned has the potential to change any conclusions drawn from the changes to the collision matrix. Therefore it was not possible to identify the high risk collision scenarios for AVs.

It has not been possible to identify from this study how requirements for vehicle occupant restraint design or vulnerable road user protection may change with the introduction of level 4 automated vehicles.

Based on the number of unknowns in this study, it may be beneficial to repeat this analysis once the capabilities of AVs and future uptake/use of these vehicles becomes clearer.

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# Automated Driving Systems: Understanding Future Collision Patterns

## Development of Methodology and Proof of Concept

Automation of the driving task is becoming more common and automated or self-driving vehicles are increasingly becoming a reality. The development of these vehicles is widely reported in the media. Previous research by KPMG estimated that by 2040 80% of collisions will be avoided through the introduction of automated vehicles. Before the full adoption of automated vehicles, there will be an interim period where traditional and automated vehicles will need to co-exist. During this period, are there likely to be different types of collision? What are the potential risks of a vehicle fleet with a mix of automated and non-automated vehicles?

This document describes the proof of concept of a methodology for assessing the potential effect of introducing automated vehicles on the frequency and types of collision that may occur. The methodology uses in-depth case analysis from the UK Road Accident In-Depth Studies (RAIDS) and vehicle fleet data to estimate the effect on collisions of introducing automated vehicles into the vehicle fleet. Improvements to the methodology and additional resources to provide more robust analysis have been identified.

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