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Authors	Shannon, Darren;Jannusch, Tim;Spickermann, Florian;Mullins, Martin;Cunneen, Martin;Murphy, Finbarr
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Connected and Autonomous Vehicle Injury Loss Events: Potential Risk and Actuarial Considerations for Primary Insurers

Darren Shannon[1*]
Tim Jannusch[2]
Florian David-Spickermann[1]
Martin Mullins[1]
Martin Cunneen[1]
Finbarr Murphy[1]

[1] University of Limerick, Ireland
[2] TH Köln, Germany
[*] Corresponding author: Darren.Shannon@ul.ie

Abstract

The introduction of connected and autonomous vehicles (CAVs) to the road transport ecosystem will change the manner of collisions. CAVs are expected to optimise the safety of road users and the wider environment, while alleviating traffic congestion and maximising occupant comfort. The net result is a reduction in the frequency of motor vehicle collisions, and a reduction in the number of injuries currently seen as 'preventable'. A changing risk ecosystem will introduce new challenges and opportunities for primary insurers. Prior studies have highlighted the economic benefit provided by reductions in the frequency of hazardous events. This economic benefit, however, will be offset by the economic detriment incurred by emerging risks and the increased scrutiny placed on existing risks. We posit four plausible scenarios detailing how an introduction of these technologies could result in a larger relative rate of injury claims currently characterised as tail-risk events. In such a scenario, the culmination of these losses will present as a second 'hump' in actuarial loss models. We discuss how CAV risk factors and traffic dynamics may combine to make a second 'hump' a plausible reality, and discuss a number of opportunities that may arise for primary insurers from a changing road environment.

Keywords: Autonomous Vehicles, Actuarial Models, Injury Claims, Liability Risk, Insurance Risk, Anticipatory Regulation.

1 Introduction

The introduction of connected and autonomous vehicles (CAVs)[1] is expected to have a profound impact on the landscape of road transport risk. These vehicles are expected to introduce tiered reductions in the frequency and severity of motor vehicle collisions. Each tiered reduction represents the additional safety benefits provided by increased levels of vehicle automation (Table 1). A set of projections for expected availability of CAVs, according to the vehicles' own manufacturers, detail that highly-automated vehicles are expected to be available by 2030 (Grace and Ping 2018). Current literature[2] on CAV safety detail how tiered reductions will occur through risk-mitigating advanced driver assistance systems (ADASs)[3] and wireless communication software. The latter is otherwise known as V2X[4] communication. In contrast to conventional vehicles, which require full navigational input from human drivers, vehicles equipped with ADAS technologies can improve driving efficiencies and avoid oncoming safety hazards (Scanlon *et al.* 2015).

With the availability of a suite of ADAS technologies, navigation software, and V2X communication software, CAVs are expected to reduce collision rates. More importantly, CAVs are expected to the reduce the frequency of injuries stemming from motor vehicle collisions (Bareiss *et al.* 2019). This expectation is due to their ability to predict and react to oncoming hazards at a level that human drivers cannot attain, while remaining free of human fallibilities such as distracted or impaired driving behaviour (Fagnant and Kockelman 2015). Furthermore, in the event that collisions do transpire, safety-optimised vehicle design and ADAS technologies will largely mitigate the severity of the incident and reduce the severity of injuries that occur (Bareiss and Gabler 2020). These safety advancements will have implications for motor insurers.

As a key stakeholder in the area of road transport, primary insurers must adapt to the shifting risk landscape that faces vehicle occupants. Motor insurance providers capitalise on accurate representations of risk using actuarial modelling techniques (Denuit *et al.* 2007). These techniques provide a relatively accurate generalisation of the number and extent of realised single-loss events. This study argues that ADAS and eventual CAV rollouts will require a more nuanced analysis beyond the expected changes in collision frequency and

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[1] CAVs can be defined as the set of vehicles that can facilitate the connection to, and communication with, other vehicles and the surrounding infrastructure, as well as maintaining the ability to perform autonomous functions.

[2] A detailed overview is provided in Litman, T., 2020. Autonomous vehicle implementation predictions: Implications for transport planning.

[3] ADASs are vehicle technologies that can monitor and assist driving tasks in order to ensure the safety of the driver and improve operational efficiency. Examples include Cruise Control, Automatic Emergency Braking (AEB) and Lane-Keeping Assistance (LKA).

[4] V2X ('vehicle-to-everything') software describes wireless communication software in which vehicles communicate with surrounding vehicles and other appropriately-equipped surrounding infrastructure (traffic lights, cellular towers, etc.), and use this information to navigate the road environment.

severity. Reduced loss frequencies, along with changing risk patterns, will change the distribution of loss events. We demonstrate how this, along with access to in-vehicle data and technical expertise, could pose challenges and opportunities to current business models.

We detail in this study the effect that changes in road traffic and vehicle ownership may have on single-loss actuarial models as they pertain to third-party injuries. We do so through the use of targeted scenario analyses that assess the safety capabilities and market penetration of CAVs. Third-party injuries, in this context, refer to injuries sustained by vehicle occupants as a result of a negligent or reckless third party's actions. Single-loss events[5], meanwhile, describe the expected distribution of losses stemming from events that occur in a localised area. We envision that high-frequency, low cost single-loss events that currently dominate actuarial considerations (Figure 1, left) may change to a loss-distribution profile driven by an increased ratio of high-severity single-loss events (Figure 1, right). Assuming an 'extreme value' threshold of €100,000, high-severity loss events currently account for 5% of all injury loss events[6] (Central Bank of Ireland 2019). High-severity loss events that occur with a low frequency are known as 'tail-risk events'. They are so-called as they occur in the 'tail' of the distribution, i.e. away from the main body of claims. However, we reason that this rate may reach higher levels in years to come. We present four scenarios in which actuarial models may divert from their current representation. These four scenarios assume a 20%, 40%, 60%, and 80% reduction in collision frequencies, respectively. Our objective is not to pinpoint the likelihood of these scenarios occurring. Rather, the objective of this study is to explore how these plausible scenarios may occur, and the associated implications for primary insurers.

Insert Table 1 here

The scenarios presented in this study subsist on ADAS-enabled and autonomous vehicles that are adept at avoiding hazardous events. Many minor-injury or 'preventable' collision events are expected to be avoided (Cicchino 2017), and a larger proportion of collision events that remain are expected to be of a higher severity. Given the encroaching costs of the advanced technology within these vehicles, and the level of liability placed upon the vehicle to ensure occupant safety, it is plausible that these collision events will incur high losses for primary insurers. Assuming a drop in hazard events and minor collision frequencies, these scenarios suggest that a higher relative frequency of large-loss events

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[5] Single-loss events, such as motor vehicle collisions, are distinct from multiple loss events, such as adverse weather leading to multiple hailstorm damage claims.

[6] This ratio represents the proportion of claimants who settled injury claims in Ireland between 2015-2018.

will generate an elongated ‘tail’ or a second ‘hump’ in the general distribution of single-loss actuarial models.

An increase in large cost events has significant implications for insurers. The objective of this study is to detail the temporality of this ‘hump’ – how this hump may prevail as road infrastructures and vehicle ownership patterns evolve. Moreover, the study explains how this second peak will emerge alongside increasing levels of vehicle automation. We also consider the optimised safety introduced by CAVs, the market penetration of these vehicles, traffic patterns, and a shifting liability landscape.

Current attempts by the motor insurance market to capitalise on updated risk metrics do so by utilising usage-based insurance (UBI). In a UBI rate-making system, the insurance rates are tied to the use of the insured vehicle. UBI differs from traditional policies in that premiums are based on driving behaviour and vehicle usage, rather than premiums based on the expected risk profile of the driver. The premium level in UBI is determined based on either the policyholder’s frequency of driving (Pay-As-You-Drive, or PAYD), or the policyholder’s quality of driving (Pay-How-You-Drive, or PHYD) (Desyllas and Sako 2013, Baecke and Bocca 2017, Tselentis *et al.* 2017). PAYD designates a system that charges the policyholder based on miles driven (Husnjak *et al.* 2015). In contrast, PHYD systems calculate premiums based on individual driving behaviour, using parameters that indicate driving speed, harsh acceleration, abnormal braking and excessively sharp or wide cornering (Tselentis *et al.* 2017).

Driving within normal or expected limits of acceleration, speed, braking, or cornering is typically rewarded with discounted insurance rates. In contrast, unusual acceleration, speeding, deceleration, or cornering behaviours suggest a poor pattern of driving behaviour or distracted driving. The driver is subsequently penalised with a loss of discount benefits or increased baseline rates. Smartphones or telematics devices are used to track these parameters (Handel *et al.* 2014), which can be used to assign risk scores to policyholders based on their driving performance (Ryan *et al.* 2020). Both policyholders and insurers benefit from this arrangement. In return for allowing the insurer to monitor their driving behaviour, policyholders receive discounts. Insurers, meanwhile, attain a more accurate risk profile of the policyholder, leading to lower underwriting and loss expenses. These savings are compounded on both sides by positive self-selection bias – safer drivers move to these policies to secure further discounts, while insurers incur fewer losses by covering safer drivers (Desyllas and Sako 2013). In addition, the use of risk-scoring has allowed for the most at-risk drivers to be identified, as the lowest quintile of performance scores account for 30-40% of all accidents (Neininger 2019). Flat discounts are also available in certain regions if the insured vehicle is equipped with the latest safety-optimised technology (Baumann *et al.* 2019). However, some insurers have been reluctant to offer discounts due to a lack of observable safety benefits and higher repair costs (Bellon 2019).

Despite these updated methods of determining premiums, the underlying assumptions regarding the expected distribution of third-party injury losses largely goes unquestioned. Relatively few anticipatory insurance schemes or actuarial model adaptations have been proposed that deviate from conventional loss frequency[7] and loss severity[8] models (Denuit *et al.* 2007). It can be argued that actuarial models need not be updated until autonomous vehicles, and therefore hazard events involving autonomous vehicles, are commonplace. For example, Bayesian inferencing can be used to update actuarial models in line with gradual changes in collision frequencies and severities (Sheehan *et al.* 2017). However, reactive assessments rather than proactive assessments introduce the risk of underestimating the level of exposure, as recently evidenced by large losses in the natural catastrophe insurance-linked securities market (Schultz 2019).

This article is organised as follows. First we outline plausible scenarios in which a second ‘hump’ may present in loss distributions, as well as outlining the extent of the ‘hump’ in each scenario. Thereafter, we argue how these scenarios may present by assessing current expectations on the future of transportation and insurance. We begin by examining the state-of-the-art proactive risk assessments and policies that are available from insurers. We then detail the future of CAVs and the additional costs associated with increased vehicle complexity. Higher vehicle purchase and repair costs will impact insurance premiums as the underwritten liability limits will increase (Ryan *et al.* 2019). Thereafter, based on extant industry and academic research, we explore the likely changes that will occur in accident claims due to ownership rates and vehicle usage characteristics (Gatzert and Osterrieder 2020). Finally, we use this background research to highlight a number of challenges that may face primary motor insurers under these assumed scenarios. These challenges may present in terms of their role as actuaries and underwriters, and in terms of their role as a key stakeholder of the motor vehicle industry.

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[7] For example, Poisson or Negative Binomial models

[8] For example, lognormal or Gamma models

2 The Anticipated ‘hump’

We explore scenarios where the underlying distribution of single-loss events deviates from conventional right-skewed distributions with a single cluster of events close to zero (Figure 1, solid line). The loss distributions that are presented in Figure 1 (dashed line) are scenarios in which we assume a 20%, 40%, 60%, and 80% reduction in collision frequencies causing injury, respectively.

Insert Figure 1 here

Insert Table 2 here

As noted previously, tail-risk injury loss events currently make up 5% of total bodily-injury losses (Central Bank of Ireland 2019). However, the scenarios presented here posit that the proportion of tail-risk injury losses could plausibly reach 10%-40% by the time that fully-autonomous vehicles become commonplace. Advances in vehicle safety will significantly reduce collision frequencies and severities due to sophisticated technological equipment that can navigate through oncoming hazards. Vehicle ownership rates, upgraded road infrastructures, and adapted driving behaviours will change the nature of collisions. At the same time, public liability paradigms will likely generate high pay-outs for vehicle at-fault claims. Initial vehicle-at-fault claims, in particular, may be subject to the ‘Social Amplification of Risk’ phenomenon, where relatively minor risk events can elicit strong public concerns and have a substantial impact on policy (Kasperson *et al.* 1988). Furthermore, latent costs will be introduced by increased vehicle repair and replacement costs. We also incorporate our expectations on how loss distribution may transform due to the changing mix of vehicles on the road. We detail how this coincides with increases in the aforementioned repair and replacement costs, and liability penalties for ‘vehicle-at-fault’ claims.

The scenarios in Figure 1 are based on specific reductions in collision and hazard event frequencies, ranging from 20% to 80%, with the introduction of CAVs. Further details on the formation of the loss distributions that make up the scenarios in Figure 1 are provided in Appendix 1. Table 2 also indicates the cumulative losses that are expected from the distributions in Figure 1, as a percentage of current losses.

2.1 20%–40% Reduction in Collision Rates Causing Injury:

We largely attribute the changing dynamic of claim distributions in our scenarios to the market share of vehicles that are equipped with a suite of ADAS technologies and capable of autonomous functions and wireless communication (V2X). Vehicles that are equipped with these technologies are referred to as connected or autonomous vehicles, or CAVs. Presently, it is expected that a vehicle equipped with ADAS functions can reduce bodily injuries by up to 60-80% when given appropriate take-over control (Bareiss *et al.* 2019). The same study found that bodily injuries can be reduced by up to 90% when both vehicles in a ‘would-be’ incident are equipped with ADAS technology. However, current automated navigational functionality is minimal, ADAS market penetration is emergent, and the wireless communication of vehicles with other vehicles is minimal. Using current rates (a 0% reduction in injuries) as a baseline, we anticipate that a road environment consisting entirely of connected and autonomous vehicles will lead to an 80% reduction in injuries.

Based on these expectations, it can be suggested that a 20%-40% realised reduction in collisions would suggest incremental advancements in road safety rather than a sufficiently-high market share of CAVs. A sizeable but minority share of CAVs equipped with ADAS technologies and automated navigational software have the potential to prevent or mitigate a high number of minor-moderate collisions that would incur injuries. However, conventional vehicles will still represent the majority of vehicles in the road ecosystem, ensuring that loss event models will remain similar to current loss distributions in some capacity.

Furthermore, a large number of minor-moderate loss events that are mitigated will be replaced by claims for damage repairs on costly safety and navigational equipment (Liberty Mutual Insurance 2017, Williams 2018). Incidents in which CAVs are found to be at-fault in a collision while in ‘automated mode’ may incur excessive claim penalties owing to their increased level of liability (Deutscher Bundesrat 2017, Automated and Electric Vehicles Act 2018). Therefore, costs saved by preventing injuries may be supplemented both by higher repair costs (Liberty Mutual Insurance 2017, Williams 2018) and higher liability costs (Casualty Actuarial Society 2018). This is reflected in the costs outlined in Table 2, which indicates the expected cumulative losses for insurers for each of these scenarios. Relative to current values, scenarios in which collisions reduce by 20% and 40% will maintain or increase on current levels of losses (110.4% and 111.4%, respectively). Despite a reduction in overall collisions, higher repair and liability costs will result in a higher average pay out. This aligns with the views put forth by the Casualty Actuarial Society (2018), who suggest that a 75% reduction in incident rates is required to maintain current premium levels.

As such, we anticipate that incremental advancements on road safety will not significantly impact on current actuarial models, and injury-claim changes that do manifest may present as elongated ‘tails’ rather than distinct humps due to higher liability pay outs. Based on these assumptions, both the ‘20% Reduction’ and ‘40% Reduction’ loss distributions in Figure 1 (right) may remain largely similar to the current loss distribution (Figure 1, left). Instead, we only expect CAVs to have a significant impact on actuarial models when they reach a majority market-share of newly-bought vehicles, such that their full safety capabilities can be realised.

2.2 60%–80% Reduction in Collision Rates Causing Injury:

CAVs have the potential to reduce collision and injury rates by greater than 20%-40%, based on the findings of Bareiss *et al.* (2019). However, we expect that 60%-80% reductions in collision and injury rates will only arrive if there are systematic changes made to the road environment. We anticipate that these reductions will only be observed in an environment where CAVs represent a significant majority of vehicles on the road. At this stage, CAVs will come equipped with a suite of ADAS technologies, automated navigational software, and vehicle-to-everything wireless communication (V2X). Additionally, it is expected that a majority of CAVs operating in the road environment will do so as part of a ride-sharing service rather than through private ownership (Litman 2020). This will have the effect of contracting the number of insured vehicles (Henao and Marshall 2019) and increasing occupancy rates (Lokhandwala and Cai 2018), which in turn increases the number of passengers exposed to a single insurance loss event.

Since conventional vehicles will represent a minority share of the on-road traffic mix, current loss-distribution dynamics will no longer hold. Instead, loss-distribution dynamics will largely be driven by incidents involving CAVs, whose risks differ from those faced by conventional vehicles. The vast majority of claims currently realised by insurers are of low severity and are clustered relatively close to zero (Denuit *et al.* 2007, Central Bank of Ireland 2019). However, the sophisticated technological capabilities of CAVs will ensure that a majority of minor-moderate injury claim events are avoided. The scenarios underlying the '60% Reduction' and '80% Reduction' loss distributions (Figure 1, right) assume that collisions that currently incur minor (superficial) injuries will largely be prevented, and moderate-severity collisions (causing non-superficial injuries) will be mitigated to minor injury events. Table 2 indicates that the expected total loss faced by insurers will fall by up to 40% with an 80% reduction in collisions. However, there will a relative increase in the number of events that are 'unavoidable' and likely to commit great personal harm – i.e. those that can incur a significant risk to life. Given that occupancy rates are expected to increase over time (Lokhandwala and Cai 2018), this may have the effect of concentrating a higher number of serious-injury events into fewer collisions.

The implications this has for insurers is that the average size of realised claims may become larger and costlier, even though the overall cost of liabilities will decrease relative to current values (Table 2). Although conventional vehicles will remain subject to current claim loss dynamics, a higher percentage of bodily injury claims resulting from collisions involving CAVs will stem from 'unavoidable' collisions involving a higher number of passengers, on average. 'Unavoidable' collisions, such as vehicles that are traveling at high speeds, or 'blind-spot' collisions that occur while cornering, will incur significant losses for insurers.

Given the nature of these incidents, it stands to reason that serious injuries may still be suffered in these incidents. The losses stemming from the injuries will be compounded by extensive repair and replacement costs, particularly if safety-critical equipment is damaged. Furthermore, incidents in which CAVs are found to be at-fault in a collision while in ‘automated mode’ may also incur excessive liability penalties owing to their increased level of liability (Deutscher Bundesrat 2017, Automated and Electric Vehicles Act 2018).

Assuming these situations become evident, there is a latent possibility that an increase in the relative percentage of these ‘unavoidable’ events, given a significant reduction in less severe events, have the ability to introduce a second ‘hump’ to loss distributions (Figure 1 right). Hence the elongated tail that is expected to appear with a 20%-40% reduction in collisions may progress in to a second ‘hump’ as the overall rate of collisions continue to decrease, while the relative percentage of high-severity collisions continues to increase.

Given that traditional loss models do not account for a second 'hump', the remainder of this study explores the factors that may influence its occurrence, and investigate the opportunities that may arise as a result. The uptake in CAV ownership is expected to be gradual, with industry experts proposing widely-varying assessments on public acceptance and market penetration rates (Claus *et al.* 2017). The path to CAV ubiquity remains uncertain due to a myriad of regulatory, liability and infrastructure roadblocks, despite the feasibility of a rapid introduction of advanced safety technology (Martínez-Díaz and Soriguera 2018).

The remainder of this study focuses on the feasibility of the scenarios above, based on current developments in ADAS and V2X. We first detail how non-life insurers are reacting to a road environment that contains ADAS-equipped vehicles. We further expand on how these vehicles, and future iterations toward full autonomy, may impact motor insurance costs. We also detail the potential impact of anticipatory and reactive regulations and governance, the future landscape in terms of vehicle ownership and occupancy rates, and the dynamic effects of public perception. The latter factors play a particularly influential role in the formation of the second ‘hump’, given that we expect sizeable changes to actuarial models only if CAVs achieve a significant market share.

3 Current Insurance Adaptations to ADAS and Telematics

The traditional paradigm of motor insurance has evolved over many decades. Risks can be represented through cost distribution models that combine the frequency of incidents (Negative Binomial or Poisson distribution) with the severity of those incidents (Log-normal or Gamma distribution). The price of insurance premiums reflects the average expected loss per policy, plus a profit margin. Therefore, insurers operate on the basis of the Law of Large Numbers, i.e. given an increasingly large number of loss events, the average loss amount of realised events will tend toward the average loss amount that was initially expected. Risk pricing for conventional vehicles has been optimised over time to adequately pool insurers' risk exposure to both frequent small losses and infrequent large losses. The optimisation of risk pricing means that gains made from the frequent occurrence of small loss events more than offset the large losses garnered from 'tail-risk' events. Therefore, insurers remain relatively insulated from threats of capital reserve risks because of a well-diversified portfolio of policy losses. From a prudential regulatory perspective, the motor insurance business is seen as offering a degree of financial stability to insurers.

The risk-pooling regime has previously updated to changing risk values. This includes accounting for new risks such as changes in driving behaviour (distracted driving caused by mobile phone use) (McEvoy *et al.* 2005), and changes to vehicle safety (the standardisation of seatbelts and airbags) (Campbell 1986). The introduction of autonomous vehicle capabilities is expected to disrupt traditional insurance premium pricing due to the wealth of data that CAVs generate (Weidner *et al.* 2017, Casualty Actuarial Society 2018). Motor telematics is viewed as promising way forward in understanding the dynamics of motor vehicle collisions (Weidner *et al.* 2017). Telematics records vehicle data including location, acceleration, time of day, and so on. They therefore provide a window in to the overall health of the vehicle and a policyholder's driving behaviour (Goyal 2014). As previously outlined, motor insurance companies have used telematics data to introduce Usage-Based-Insurance (UBI) policies such as Pay-As-You-Drive (PAYD) and Pay-How-You-Drive (PHYD). Smartphones or vehicle monitoring devices are used to track individual driving behaviour (Handel *et al.* 2014), which can be used to assign risk scores to policyholders based on their driving performance (Ryan *et al.* 2020).

In addition to tracking the driving behaviour of policyholders, smartphones have proven to be effective feedback loops to drivers, significantly improving their driving performance (Birrell *et al.* 2014, Jiang *et al.* 2018). UBI has therefore become increasingly popular within the last decade, partially driven by the scalability, affordability and high penetration rate of smartphones (Ptolomeus Consulting Group 2018), and has resulted in improved profitability for insurers (Vaia *et al.* 2012). Monitoring driving behaviour allows for fairer premiums as traditional homogenised insurance overcharges safer drivers in order subsidise the higher insurance costs for riskier drivers (Tselentis *et al.* 2017). As vehicles evolve from level 0 automation to level 5 automation (Table 1), they will be increasingly equipped with advanced driver assistance systems (ADASs) as standard. Some insurance providers seem willing to provide discounts on insurance premiums for vehicles with ADASs (Allianz SE 2016), and already make extensive use of the passive ‘eCall’ assistance system. The ‘eCall’ assistance system places calls to the emergency services when crash sensors within the vehicle are activated, and have played a role in saving a number of drivers’ lives (Ponte *et al.* 2016). The proliferation of these discounts have been slow however, as insurers have struggled to accurately assess the reduction in risk provided by ADAS technologies (Bellon 2019).

4 Expected Shift in Risk Landscape

4.1 Progression of Technology & Insurer Losses

The introduction of the retractable seatbelt in the 1950s and vented airbag restraints in the 1960s sparked a movement toward improving occupant safety. Measures have prioritised the development of practical safety mechanisms, and encouraged a broader evolutionary movement toward vehicle automation, particularly since the 1990s (Griffin *et al.* 2018).

Using a suite of sensors (cameras, radar, lasers) that monitor the dynamic driving environment, ADAS technology can assess a consistent feed of external information regarding the vehicle's surroundings (Figure 1). These safety systems are designed to mitigate the leading causes of collisions, such as distracted driving (Hirayama *et al.* 2012, George *et al.* 2018, Jannusch *et al.* 2021) and driver fatigue (Lee and Chung 2012, Jung *et al.* 2014). If an imminent danger is detected, the assistance system alerts the driver through tactile, audible or visual stimuli (Level 0 automation using SAE International (2016) guidelines). However, if no response from the driver is received, or if the driver's reaction time exceeds established limits, a fall-back exists wherein the system activates autonomously (Levels 1 automation) and acts to avoid the potentially hazardous event (Hajek *et al.* 2013).

Simulation studies have highlighted the effectiveness of Level 2 ADAS technologies (where two systems act concurrently to avoid or mitigate an oncoming hazard) in reducing collision and injury rates relative to vehicles with no intervention systems (Scanlon *et al.* 2017). A number of studies have also used collision data to retroactively assess the extent to which Level 1 and 2 ADAS mechanisms would have prevented collisions (Spicer *et al.* 2018, Bareiss *et al.* 2019, Östling *et al.* 2019). These studies find that Electronic Stability Control (ESC), Automatic Emergency Braking (AEB) and Lane Departure Prevention (LDP) systems are particularly adept at reducing collision rates (by up to 90%) and preventing potentially serious injuries.

The increased proliferation of ADAS technology will impact insurer's liabilities with many minor incidents eliminated (Scanlon *et al.* 2015, Bareiss *et al.* 2019). At the same time, there will be fewer than expected moderate bodily injury loss events. AEB, for example, has been shown to substantially lower the extent of Third Party Injury claims in the UK (Doyle *et al.* 2015), while blind-spot ADAS technology reduced claim costs by up to 30% in Sweden (Isaksson-Hellman and Lindman 2018). However, a decrease in bodily injuries as a result of ADAS (Doyle *et al.* 2015, Isaksson-Hellman and Lindman 2018) will be offset by the increased cost associated with vehicle repair and part replacement (Pütz *et al.* 2019). According to Liberty Mutual, the cost of repairing vehicles equipped with the latest technology will almost double (Liberty

Mutual Insurance 2017) because of the cost of the damaged parts and additional labour costs. This higher repair cost has also been confirmed by AXA UK (Williams 2018).

ADAS technology typically begins providing warnings when a potential hazard is within 5 seconds to collision. As automation levels increase, the suite of advanced safety technologies will incorporate elements of on-board navigation and Vehicle-to-Vehicle (V2V) communication that will eventually progress to Vehicle-to-Everything (V2X) communication. Level 3 Connected Autonomous Vehicles (CAVs) have already been shown to perform on par with human drivers (Pütz *et al.* 2019), with latest reports suggesting that CAVs encounter fewer hazard events than humans (State of California DMV 2019). This indicates that advanced technological vehicles rapidly adapt to the nuanced driving behaviour of other road users, and can quickly lower the expected frequency of incidents. The addition of autonomous navigational and communication elements will allow the vehicle to detect and proactively assess potential hazards rather than reacting to oncoming dangers, even when the hazard is out of the line-of-sight (Ali *et al.* 2018).

These advancements all contribute to a shift in loss distributions. While conventional vehicles continue to dominate the make-up of vehicles in the road environment and ADAS-enabled vehicles remain a minority, we expect few changes to occur in traditional actuarial models. However, over time, vehicles equipped with V2X communication, collision avoidance technologies, and navigational software will become a growing percentage of vehicles in the road environment. Once CAVs become the majority, we would expect the proportion of minor-moderate bodily injury collisions to significantly reduce and the proportion of serious bodily injury collisions to increase, increasing the likelihood of a second ‘hump’ in loss distributions.

4.2 Liability Landscape

Motor insurance consists of Motor Third-Party Liability (MTPL) and Motor Own Damage (MOD) (Insurance Europe 2018). MTPL policies generally reimburse third-party claims for bodily injury, property damage and subsequent economic losses within a predetermined compensation limit. MOD policies insure the vehicle (and therefore the owner) up to its property value. MOD policies also insure the vehicle for fire, theft or accidental damage. The liability in this sense is therefore placed on the insured driver, and the risks to which they are exposed through no fault of their own (e.g. theft).

Table 3 demonstrates the stability of MTPL and MOD loss patterns, indicating how insurers operate because of the Law of Large Numbers. While variation coefficients in Germany are high for natural catastrophe events (over 50%), the long-run volatility of claim estimates for the accident risks are 15% or lower. Both vehicle damage and bodily injury claims are even more stable with overall industry costs typically varying by 6.9% and 7.5%, respectively. The highest incidence of tail-risk events occurs for theft-coverage and accidents resulting in bodily injuries. These events have the highest average cost-per-policy (€15,603 and €14,305, respectively). However, in the scenario of a 'second hump' presenting in loss curves, the higher relative frequency[9] of tail-risk events will increase these volatility estimates. Insurers in this scenario may have to retain higher capital reserves to meet claim losses that reach higher levels of volatility, a cost that may be passed on to policyholders.

INSERT TABLE 3 HERE

The current liability landscape will shift to one that incorporates a product liability element (Casualty Actuarial Society 2018). Product liability refers to the onus placed on original equipment manufacturers (OEMs) to ensure a safe product reaches the consumer. Product defects that cause injuries to consumers can result in significant liability being placed on the manufacturer. Given the increasing level of sophisticated technology in vehicles, and their associated vulnerabilities, the resulting probability of a defective piece of equipment making its way into a vehicle and leading to a safety-critical error is greater than zero (Bhavsar *et al.* 2017). This means that vehicle and equipment manufacturers will be exposed to elevated levels of risk from insurers reclaiming losses.

The German Road Traffic Act was updated in 2017 to clarify the liable party when a CAV collision occurs while the automated mode is activated (Deutscher Bundesrat 2017). In this case, the statutory compensation limits in Germany will double from €5 million to €10 million for bodily injury claims and from €1 million to €2 million for property damages (Deutscher Bundesrat 2017). In theory, doubling the statutory compensation limits would increase the maximum possible loss burden for the insurer, which should be reflected in the insurance pricing. The expected shift to a focus on product liability will bring with it greater coverage — but that greater coverage would be accompanied by higher frictional costs. In the context of actuarial modelling, further liability regulations may increase the level of compensation that is owed to injured claimants, further contributing to the eventual 'hump' appearing in loss distributions.

This German Act is supplemented by the 'single insurer' model that introduced as part of the 'Automated and Electric Vehicles Act 2018' in the United Kingdom (Automated and Electric Vehicles Act 2018). This act stated that both driver and vehicle are covered under the driver's insurance policy while the vehicle is in 'automated mode', so that in the event of defective or faulty vehicle equipment causing an accident while the vehicle is in control of the

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[9] i.e. as a % of claim frequency, given that overall claim frequencies will decrease

driving tasks, the driver would still be able to secure a claim for damage incurred in the accident.

Previously, it could have been argued that since there was no ‘negligent party’ involved in such an accident, the insurer could withhold compensation on the premise that the event was a product liability litigation issue to be directly addressed between the claimant and at-fault original equipment manufacturer (OEM), rather than through the insurer. However, the Automated and Electric Vehicles Act (2018) clarified that in these situations, the policyholder could still claim from their insurance (and so the event would still add to their loss distribution), while the insurer could thereafter recover their losses from the defective equipment’s manufacturers. As such, while still remaining present in their expected loss distributions, the extent of their compensation pay outs may increase given the increased liability burden that will be placed on primary insurers. This further adds to the plausibility of an elongated tail and eventual second ‘hump’.

As it stands, the expected outcome for this change is that extra costs will be introduced in the value chain in order to adequately cover the high penalties caused by product liability issues. Combining coverage and costs, the shift will plausibly result in one of two scenarios. The current view is that increased product liability will indirectly affect consumers through increased insurance premiums. A study by the Casualty Actuarial Society (2018) found that CAVs would need to reduce incident rates by 75% to maintain the level of insurance premiums that are currently available in the market. This view is based on the additional costs that will be placed on vehicle repairs, bodily injury estimates, and reserves to cover product liability loss. An alternative view is that product liability will directly impact consumers by increasing the costs of vehicles. The burden of product liability placed on OEMs will guarantee that the quality of the equipment in these vehicles are not comprised, the cost of which is passed on to the consumers.

In sum, the introduction of CAVs to the road environment are expected to significantly reduce the number of collisions, and mitigate the extent of collisions that do occur. While this is highly beneficial for those within the vehicle, insurers may not benefit to the same extent. The complexity of the technologies within these vehicles will increase the repair costs associated with injury claims in addition to the costs associated with the injuries themselves. Furthermore, in the event of a defective part within these vehicles causing a collision, primary insurers would be exposed to higher liability costs. These expectations are outlined in Table 4.

INSERT TABLE 4 HERE

5 Temporality of Risk Landscape

5.1 Anticipatory Regulations and Governance

The introduction of safety technology will require amendments to national and international legislation worldwide. ADAS and CAV technologies will present challenges for regulators in terms of legal and civil liberty commitments particularly regarding privacy, data use, profiling and social access to insurance. Insurance and regulation face a similar task in anticipating a supportive governance and regulatory environment that will realise the safety benefits of autonomous vehicle technologies, while maintaining recourse to compensation through mandatory insurance.

The governance response must factor in the need for supportive regulation and standardisation to avail of the potential risk mitigation benefits of autonomous vehicle technologies, whilst also being cognisant of changes in accident rates and injuries (Mittelstadt *et al.* 2015). The speed with which the 'second hump' may present in actuarial curves is dependent on the increased proliferation of CAVs. Historical attempts at introducing regulation for vehicle safety optimisation have been slow. Three-point seatbelts were first required to be fitted for all seats as standard in 1969 (Japan), 10 years after their introduction. Airbags were first introduced for front-seat passengers in 1973, and were made mandatory 25 years later in the United States. Similarly, anti-lock braking system (ABS) and electronic stability control (ESC) were equipped on 80% of newly registered vehicles in Germany after 20 and 15 years, respectively (Pütz *et al.* 2019). That said, the pace of technological advancements may be changing with mobile phones and data-interconnectivity (IoT) being adopted at an accelerating rate (Davidson and Spinoulas 2015).

Regulatory bodies have a safety and economic duty to ensure the timely introduction of ADAS-enabled vehicles and CAVs. A free market approach to CAV governance could be suboptimal and fail to realise the safety potential of these technologies, and would result in fractured transport legislations from lagging municipalities (Cohen *et al.* 2018). A 'laissez-faire' governance approach would also result in significantly lower market penetrations of safety- and technologically optimised vehicles for non-affluent road users. Transport route efficiency will suffer and traffic congestion will increase (Cohen and Cavoli 2019), which may result in an increased frequency of property-damage loss events.

Initial indicators point to encouraging signs of active anticipatory governance. The United States Department of Transport have committed to ensure that 20 of the leading manufacturers[10] will employ at least Level 1 Automation capabilities by 2022 (Insurance Institute for Highway Safety 2016). All vehicles manufactured from this point must have at

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[10] representing more than 99% of the automotive market

least one ADAS system that can autonomously stop or correct the vehicle if required[11]. Furthermore, the European Commission (2019) have committed to ensure that every vehicle produced in the European Union from 2022 must have Level 2 automation capabilities. This states that each vehicle must have at least two ADAS systems that can work simultaneously to prevent a hazardous event or correct a vehicle approaching a hazardous event. However, road infrastructure will require upgrading and the economic cost of these developments are significant (Kaltenhäuser *et al.* 2020). Nevertheless, anticipatory regulations that recognise the safety benefits of CAVs and encourage their introduction, may further speed up the process by which primary insurers are exposed to shifting loss distributions.

5.2 Public Perception & Acceptance

5.2.1 Ownership Rates & Occupancy Rates

An increasing rate of ADAS and higher-level AVs in the road environment will be a catalyst for change in terms of vehicle ownership and vehicle occupancy rates, particularly in urban areas. Highly-automated vehicles (Level 4) or fully-automated vehicles (Level 5) are expected to be available by a majority of vehicle manufacturers by 2030 (Grace and Ping 2018). These vehicles will have higher purchase costs and will be costly to maintain, and their introduction to the traffic mix is expected to be gradual (Kaltenhäuser *et al.* 2020). However, the cost-per-mile-travelled is expected to decrease due to longer-lasting vehicles, their use as a shared vehicle, and cheaper fuel (through electric charging stations) over time (Walker and Johnson 2016, Airbib and Seba 2017). These high purchase and maintenance costs, combined with the possibility of lower costs per-mile-travelled, will significantly widen the disparity between the utility of owning a CAV and the utility of mobility services operated by CAVs (Chen *et al.* 2016, Claus *et al.* 2017, Lokhandwala and Cai 2018, Litman 2020). Based on this disparity, it is envisioned that ‘Autonomous Taxis’ will become the predominant transport mode of choice by the time that CAVs are widespread (Kaltenhäuser *et al.* 2020, Litman 2020). Ultimately, there will transition to shared-mobility services, and a decline in demand for private-use CAVs.

This shift may have an appreciable impact on occupancy rates. Average occupancy rates have been found to be low for shared-mobility services (Lokhandwala and Cai 2018, Henao and Marshall 2019) as current road infrastructure do not provide efficient travel routes for CAVs (Papa and Ferreira 2018, Litman 2020). The rate of deadheading[12] may therefore increase in the near- to medium-term as ‘empty’ vehicles travel to ride-share requests, increasing the relative frequency of policies that will be subject to Motor Own Damage

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[11] In this case, Automatic Emergency Braking (AEB) is required.

[12] ‘deadheading’ is otherwise known as ‘vehicle-miles travelled with no occupants’, as mentioned in Henao, A., Marshall, W.E., 2019. The impact of ride-hailing on vehicle miles traveled. Transportation 46 (6), 2173-2194.

(MOD) claims and ensuring that insurance loss distributions will not deviate much from their current state.

As CAVs become more commonplace, however, road environments will become optimised for shared-mobility services, possibly through optimal charging-point placements (Chen *et al.* 2016) or designated lanes for CAVs (Litman 2020). This will have the effect of decreasing deadheading over time, meaning that the average number of occupants per vehicle may rise (from 1.3 to 3, on average) in tandem with increased travel efficiency and decreased fleet size (Chen *et al.* 2016, Lokhandwala and Cai 2018, Henao and Marshall 2019, Litman 2020). A reduction from a heterogeneous mix of CAV and conventional vehicle traffic to a road environment primarily containing higher levels of autonomous vehicles acting as mobility providers may also have ramifications for primary insurers. They face business model risks given that the number of policies they underwrite will contract and the risk dynamics of the policies they do underwrite will change.

Currently, loss-distributions and premium calculation models assume the predominant coverage of private vehicles, where each covered vehicle is assumed to be owned by a single driver. However, an expected drop in privately-owned vehicles and an increase in shared 'autonomous taxis' will reduce the pool of insured vehicles, and contract the profitability of insurers, *ceteris paribus*. Furthermore, a greater concentration of occupants within a small pool of vehicles has the potential to significantly increase claim sizes in the event of injuries being suffered and critical safety equipment being damaged. Given that shared-mobility services may become the primary mode of transportation, it is a distinct possibility that these events may become a higher relative percentage of overall claim frequencies, and therefore contribute further to the 'second hump' (Figure 1, right). There is a likelihood of this scenario presenting as a result of advances in vehicle safety that will reduce collision frequencies and severities.

5.2.2 Market Penetration

The primary driver behind the introduction of CAVs is the public's willingness to buy highly-automated vehicles. This will require achieving and maintaining public trust in CAVs (Xu and Fan 2019). The path to full ubiquity of CAVs remains unclear. Initial opinions suggested that 75% of new-vehicle-purchases will be self-driving by 2040 (Claus *et al.* 2017), and that 75%-95% of all vehicles on the road would be self-driving by 2060 (Bierstedt *et al.* 2014). These predictions have since tapered to 'optimistic' scenarios describing a 50% adoption rate and 35% market share by 2040 (Forsgren 2018), while research studies have suggested highly-automated vehicles to have a market share between 24%-87% by 2045 (Bansal and Kockelman 2017). A higher market share of CAVs will result in higher collision reductions and fewer collisions being realised (Scanlon *et al.* 2017, Bareiss *et al.* 2019), which we expect in turn to change to the shifted loss distributions outlined in Section 2. Regardless, a rapid introduction of these vehicles requires a significant buy-in from low- and middle-income motorists, who would need to spend significantly beyond their typical vehicle purchase in order to secure a vehicle with self-driving capabilities (Litman 2015).

Current market expectations indicate an eagerness to adapt to or use new technologies, particularly when presented with personal benefits (i.e. enhanced safety, fuel consumption, liability shift, low-cost mobility-as-a-service) (Bansal and Kockelman 2017, Daziano *et al.* 2017, Shabanpour *et al.* 2018, Kaltenhäuser *et al.* 2020). Bansal and Kockelman (2017) find that consumers in the US would be willing to pay a significant amount for full automation capabilities. Shabanpour *et al.* (2018) find that motorists have an increased willingness to purchase CAVs if they remain covered in the event of a vehicle-at-fault incident, similar to the acts introduced in Germany and the United Kingdom (Deutscher Bundesrat 2017, Automated and Electric Vehicles Act 2018). Regulators may take these sentiments in to account if they are reflected in vehicle sale patterns. The market penetration rate of CAVs is directly related to realised safety benefits for road users. From this, we can infer that a higher market penetration rate of CAVs will lead to greater changes to conventional loss distributions, to the extent that a second ‘hump’ may present in loss distributions in the event that CAVs reach a dominant market share.

Therefore, current expectations dictate that regulatory bodies look favourably upon the eventual introduction of CAVs to improve safety, given their willingness to exploit opportunities to guide their introduction (Insurance Institute for Highway Safety 2016, European Commission 2019). Ownership rates of privately-owned vehicles are expected to decrease (Litman 2020), due to a shift in using these vehicles for ride-sharing purposes through ‘autonomous taxis’ (Henao and Marshall 2019, Kaltenhäuser *et al.* 2020). The net result of the expected change in ownership/usage rates is a higher occupancy rate, which is expected to rise from 1.3 to 3 (Lokhandwala and Cai 2018). Combined with the safety capabilities of CAVs (Bareiss *et al.* 2019), it can be suggested that a greater concentration of passengers in to fewer vehicles will lead to a higher proportion of large injury losses payable by primary insurers in the event of a collision occurring. This has the effect of reducing the number of minor events that currently exist in loss distributions, and increasing the proportion of ‘tail-risk’ events, lending further credibility to the likelihood of a second ‘hump’ presenting in loss distributions.

INSERT TABLE 5 HERE

6 Implications for Insurer Pricing and Underwriting

Insurance pricing models derive safety from the Law of Large Numbers. Considering this theorem, insurers can implement a risk-pooling strategy to remain insulated from claim losses that deviate significantly from the average loss. This strategy is effective as long as average claim sizes, on an ongoing basis, eventually tend toward the initially-expected average. In Section 2, we detailed four scenarios in which total claim losses are expected to be dynamic, rather than static, as a result of changing collision frequencies. When combined with changing collision severities and changing occupancy rates, these scenarios suggest that average loss dynamics may transform over time. As such, primary insurers may need to proactively assess their expectations regarding average claim losses. These scenarios, however, rely on an increased proliferation of CAVs, coinciding with knock-on effects on public perception, road safety dynamics, and the make-up of vehicles on road networks.

The scenarios we present in Section 2 do not envision that single-loss event models will drastically change with a gradual introduction of ADAS-enabled (Level 2) and partially-automated (Level 3) vehicles. Although it is difficult to determine the exact mixture of automated levels on the road, a greater level of safety afforded by ADAS-enabled vehicles will ensure that many incidents will be avoided or mitigated (Scanlon *et al.* 2015, Scanlon *et al.* 2017, Bareiss *et al.* 2019). In addition, initial forays in to CAV-sharing mobility services will increase the number of deadheading vehicles, decreasing occupancy rates on average. Minor collisions will largely be eliminated, while a large share of moderate-serious injuries will be reduced to minor injuries, or property-damage-only claims. The largest risk to insurers that are posed by limited fleets of CAVs, in a single-loss capacity, is the introduction of a liability shift. Increased capital allocations will be required to offset the change from a negligence-based liability system, to a strict product liability setting (Casualty Actuarial Society 2018). As such, the inevitable (few) incidents that occur amongst the initial fleet of automated vehicles will be increasingly scrutinised. Manifestations of the social amplification of risk phenomenon (Kasperson *et al.* 1988) has the potential to inflate the levels of compensation resulting from these incidents.

Furthermore, the reduction in compensation due to a decreased frequency of minor and moderate injuries will be offset by the large increase in the cost to replace or repair the sophisticated technology present in CAVs. This is due to the high manufacturing and specialised labour costs associated with these vehicles (Liberty Mutual Insurance 2017). Therefore, current actuarial loss models may remain static in the short-medium term. As outlined in §3 and above, insurers remain adequately hedged from these risks due to risk-pooling measures that ensure they are diversified and insulated from tail-risk events. A more pressing issue for primary insurers are the spread of Level 4 and Level 5 AVs.

Provided that they reach a sufficient market share, it is plausible that a higher relative percentage of compensation claims from Level 4 and Level 5 AVs (Table 1) will be loss events that are currently considered as tail-risk events. A disproportionate amount of single-loss events could therefore exceed 'extreme value' estimations that are used to allocate appropriate capital reserves for high losses. Motor insurance risk assessors and rate-makers may need to take proactive measures to ensure they are safeguarded from a shifting loss model and have priced their exposure to risk correctly.

With an increased dissemination of SAE Level 4 and Level 5 CAVs in the road environment, there is the potential to shift from the single-loss actuarial models as they currently present, to the loss distributions described in §2. If these vehicles make up the majority of vehicles in the road environment, as eventually anticipated, the number of collisions involving bodily injuries may fall by more than 80% (Bareiss *et al.* 2019). A high proportion of collisions that remain will be collisions that are 'unavoidable', such as high-speed or blind-spot collisions. These collisions would result in serious or worse injuries being incurred. As such, a road environment that is made up of Level 4 or Level 5 CAVs may result in more losses that are currently characterised as 'tail-risk' events. This has implications for primary motor insurers, which presents both challenges and opportunities for their business models.

7 Emerging Risks and Opportunities for Primary Insurers

Forecasts on future premium levels have been inconsistent. A report by KPMG (2015) has pointed to a sharp fall; other institutions have taken more cautious line. The Bank of England (Claus *et al.* 2017) predict a fall in premiums of 23% in the UK by 2040. However, the Casualty Actuarial Society (2018) predict a large increase in premiums, and the loss distributions we envision indicate a rise in the average premium level until a 60% fall in collision rates are realised (Table 2). The lack of a clear narrative puts the long term business prospects of primary insurers into question. We detail in this section alternative risks that may emerge for primary insurers with the introduction of CAVs, and possible opportunities this provides for primary insurers.

We envision that the transition across automation levels 1-5 (Table 1) will signal a profound change for the insurance sector. Changing liability terms, changing occupancy rates, changing vehicle sophistication, OEMs-as-insurers, cyber-security risk, and changing transport dynamics all have the potential to transform insurers' risk exposure. Paradoxically, insurance companies will be able to more-accurately price individual risk through the use of telematics and other data information sources gathered by vehicles. At the same time, the human driver will become progressively less important as a risk. This new dispensation will make it possible to assess more accurate risk metrics, however it will also prompt regulatory and legal responses around the concepts of insurability, consumer rights, privacy, and duties to ensure a safety-optimised transport environment.

7.1 Original Equipment Manufacturers (OEMs) as Insurers

Considering the roll-out of ADAS from an insurance value chain perspective raises a number of important issues pertaining to the future operation of the market. Current expectations are that an increasing emphasis will be placed on product liability. As a result, in terms of motor insurance sales, it is likely that much of the market will be mediated through OEMs, making joint ventures a more attractive business strategy going forward. This is recently evidenced by partnerships established between AXA and Tesla (2019), and Ford and Liberty Mutual Insurance (2020). This may eventually result in in-house insurance lines being directly offered by AV manufacturers, who double as OEMs. The utility of this strategy is that manufacturers are optimally-positioned to assess the risk of their vehicles, as they have direct knowledge on the vulnerabilities within the vehicle, direct access to highly-skilled engineers, and are equipped with immediate availability of replacement parts. The supply chain advantage of OEMs-as-insurers can therefore significantly reduce the cost of premiums, and the cost of vehicles, for consumers.

However, there are risks associated with this strategy that may result in higher premiums and longer waiting times in litigation cases for policyholders. As mentioned previously, the ‘single insurer’ model that has been drafted in the United Kingdom clarifies the relationship between insurer, policyholder, and vehicle equipment manufacturer. The Automated and Electric Vehicles Act (2018) states that in the event of defective equipment causing an accident, or the vehicle being at-fault in an accident while in ‘automated mode’, insurers are to first compensate policyholders, then seek recourse from OEMs. This ensures that policyholders are not left to engage in lengthy litigious cases wherein the exact manner of the fault or faulty equipment is determined. Rather, policyholders are expected to expeditiously receive payment from their primary insurer, who then seek compensation from the OEM of the faulty equipment. However, this process requires additional technical expertise and may lead to unexpected delays and financial management issues until the insurer’s claim for recourse is completed (Pütz *et al.* 2019).

A scenario in which OEMs become a sizeable market share of insurers may bring with it extra risks and costs for policyholders, as OEMs would be responsible for product liability losses as well as vehicle damage and third-party injury losses. This may result in higher premiums being passed on to policyholders. Furthermore, in contrast to the ‘pay now, seek recourse later’ regulations defining primary insurers in the United Kingdom, OEMs may dispute claims in which their equipment is named as ‘at-fault’, and withhold payment until the full circumstances in which the collision occurred are made clear. This can lead to protracted litigation cases, which are known to incur higher legal fees for policyholders and decrease their quality of life (Casey *et al.* 2015). As a result, we suggest that primary insurers may be well-advised to support and promote the terms outlined in the Automated and Electric Vehicles Act (2018), and lobbying other regulatory bodies to adopt similar directives. This support may be used as a strategic means of maintaining their role as a key stakeholder in the motor vehicle industry, despite the extra financial responsibility placed on them as a result of the terms laid out in the act.

7.2 Reinsurers

A matter that does not receive enough attention in the extant literature on insurance and ADAS technologies is the position of the reinsurance sector in this market. The ‘Law of Large Numbers’ argument may hold true given that the number of incidents is expected to decrease over time. However, there is a distinct possibility that current volatility levels within insurance markets (Table 3) will not remain. In a scenario containing an increasing number of large loss events, the volatility of claim loss sizes would spike and a number of smaller players may not have the capital requirements that will be needed to cover losses during concurrent adversarial events. Therefore, we expect that the introduction of CAVs will have a direct impact on the growth of reinsurers, as product liability and related responsibilities (cyber-security, product recall, etc.) make up larger portions of motor insurance risk. When we consider the pattern of claims costs posited in this study and an increase in the rate of high-severity losses, we anticipate that the market will react accordingly. Tail-risk insurance products such as policy tranches or syndicate-underwritten policies may become increasingly popular in business lines. As such, the reinsurance sector will play a key role in ‘smoothing out’ the ‘second hump’ that faces primary insurers. Primary insurers may be well-positioned to strengthen their relationships with reinsurers to solidify their market share as stakeholders of the motor vehicle industry, beyond that of the reinsurance cover mandated as part of Solvency II (European Commission 2014).

7.3 Cybersecurity

Cybersecurity risk is another concern for primary insurers and has been identified as the most prominent emerging issue for motor insurers with the introduction of CAVs (Claus *et al.* 2017). Cyber risk, wherein the vehicle is exposed to technological vulnerabilities that can be exploited using adversarial ‘hacking’ events, must be considered in two forms. Random, small-scale attacks on individual vehicles will require single-loss compensation considerations, since the attacks could lead to collisions incurring vehicle damage and bodily injuries. However, large-scale attacks could potentially hinder entire companies, localities or municipalities, creating significant business interruption risks.

This concern appears to be validated with an exponential growth in cybersecurity incidents since 2016 (Help Net Security 2020). These emerging cyber-vulnerabilities are within the current scope of insurers, indicating that increasingly-sophisticated CAVs and malign actors have the potential for large, single loss events. Faulty sensors or vulnerable software may result in the vehicle causing an injury to non-fault parties, or being recalled, which would also pose a greater risk for fleet insurers. While further adding to the liabilities they face, this provides an opportunity for primary insurers to incorporate these risks into further coverage plans for CAV owners (both privately-owned and commercially-owned), and offering further opportunities for profitability.

7.4 Potential Departure from ‘Bonus-Hunger’

The bonus-malus system[13] is well-established as an effective system for reducing the number of claims made against an insurance company. This is substantial evidence that a number of accidents go unreported in order for policyholders to maintain a high level of discount on their policy – a phenomenon known as bonus-hunger (Boucher *et al.* 2009, Charpentier *et al.* 2017). However, bonus-hunger in a non-viable approach for policyholders with CAVs. The level of technological complexity in CAVs indicates that owners must report all minor damages, lest the damage impede on safety-critical equipment.

This issue has been specifically addressed in both Germany’s (Deutscher Bundesrat 2017) and the United Kingdom’s (Automated and Electric Vehicles Act 2018) approach to the insurability of CAVs. These regulations state that given the level of sophisticated technology in these vehicles, all minor damages are required to be reported in the event that safety-critical functionalities no longer work. Failure to do so will nullify the policyholder’s contract with the primary insurer, and therefore relinquish any right to claim compensation in the event of an accident (Deutscher Bundesrat 2017, Automated and Electric Vehicles Act 2018). This may benefit primary insurers; a higher ratio of lower-cost bodily-damage claims means a lower ratio of policy ‘bonuses’ will remain active. If bonus-hunger remains and minor damages are not reported, primary insurers would be absolved from compensating subsequent high-cost bodily-injury incidents.

Insurers may leverage the perception on the safety of technologically-advanced vehicles, as well as their increased protection from ‘bonus-hunger’ policyholders, to offer an amplified bonus-malus system. This system would imply greater discounts for prolonged periods of safety, and greater penalisations for reported accidents. While safer drivers would benefit from greater discounts, those involved in collisions would be subject to higher penalties,

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[13] The bonus-malus system decision is a popular rate-making system where policyholders are rewarded with discounts for continued periods where no claim is made on their policy, and penalised with higher premiums when a claim is made.

offsetting the pay outs associated with the subsequent low-cost claims. Furthermore, given that unreported damages to the equipment contained within CAVs would absolve insurers from financial responsibility in the event of a collision, the amplified bonus-malus system may represent a further profitability opportunity for primary insurers.

8 Conclusion

Despite being a key stakeholder of the motor industry, primary insurers are seldom considered when discussing the changing dynamics of risks facing road users. This exploratory study considers the risk landscape facing primary insurers with the introduction of connected and autonomous vehicles (CAVs) from the perspective of third-party injury loss distributions. We examine approaches currently used by primary insurers to capture risk relating to safety-advanced vehicles, and investigate the changing dynamics of existing and emerging risks as CAVs become increasingly proliferated. These factors include advancements in safety technology, shifting terms of liability, the role of anticipatory governance and regulations, and the changing landscape of vehicle ownership, use, and occupancy rates. Ultimately, these factors will culminate in a shift away from private vehicle ownership and toward the use of CAVs as ride-sharing or ‘autonomous taxis’ that contain more passengers on average.

An increased presence of CAVs on the road may bring about a change in risk typology that will affect primary insurers and road users alike. We present four plausible scenarios whereby the introduction of CAVs can lead to decreased collision rates, and therefore injury rates. These scenarios outline that decreased collision frequencies, increased product liability, increased occupancy rates and increased vehicle repair costs could combine to increase the relative frequency of tail-risk events. This has the potential to create a second peak in loss curves. In this scenario, the volatility of insured single-loss events may spike, and primary insurers would no longer benefit from stable year-on-year insured losses.

We further outline how primary insurers may insulate themselves from a changing risk landscape, and profit from the introduction of CAVs. Original equipment manufacturers and reinsurers have the potential to disrupt the business models of primary insurers, but primary can seek to consolidate their position by proactively engaging with these parties and lobbying for ‘insurer-friendly’ regulations. Furthermore, the emerging risks posed by CAVs can be leveraged into profit-making opportunities, such as the proactive assessment of cybersecurity risk and the adoption of an amplified bonus-malus system.

There is a paucity of data on the implications that CAVs may have on secondary stakeholders, such as primary insurers. As such, there will be an increased reliance on expert judgement to discern the impact these technologies will have on the motor vehicle industry. In particular, the influence posed by new risks to which motor insurance providers are exposed. This study is therefore well-positioned to provide key insights to road safety practitioners and vehicle engineers, as well as to insurers in terms of the role that insurance providers will have as stakeholders of the motor vehicle industry over time.

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10 Figures

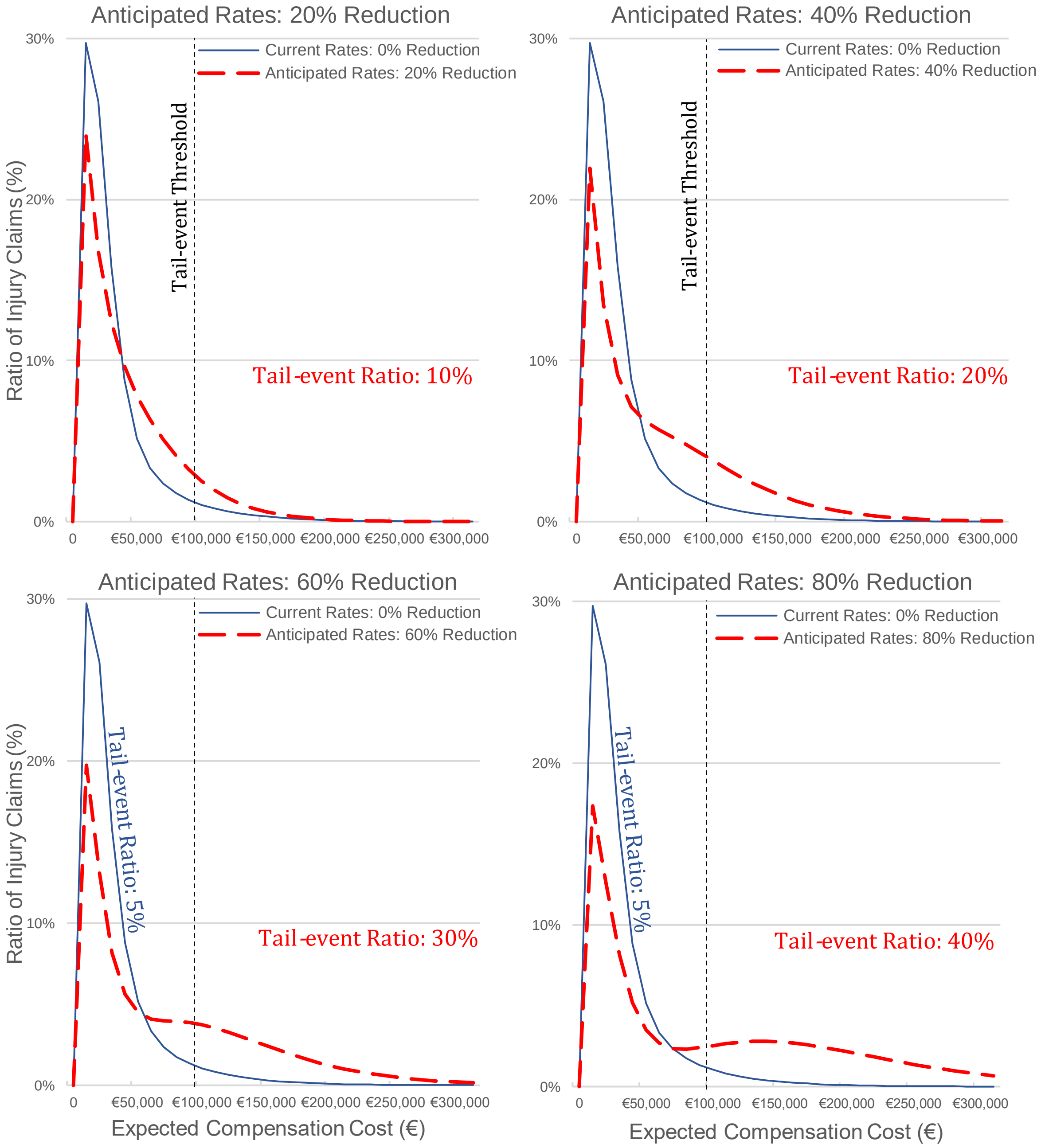

Figure 1 Loss distribution models (dashed line), as envisioned in four different scenarios where autonomous vehicles become increasingly prevalent. The scenarios represent a 20%, 40%, 60%, and 80% reduction in injury claims, respectively, and are overlaying a loss distribution model of current injury claim losses (solid line). The current loss distribution is of a similar shape to the Gamma Distribution commonly seen in actuarial literature (Denuit *et al.* 2007). The distributions in each of the four scenarios are formed using a mixture of two gamma distributions (detailed in Appendix 1). Currently, taking Ireland as an example, 5% of injury claims results in losses greater than €100,000, i.e. tail-risk events. However, a reduction in minor collisions, combined with shifting liability frameworks, may result in a claim distribution that features a higher relative rate of large-loss events. Source: data derived from National Highway Traffic Safety Administration (NHTSA) applied to the methodology of Shannon *et al.* (2020), using figures provided by the Central Bank of Ireland (2019).

11 Tables

Table 1 Levels of Driving Automation according to SAE International (2016), along with the likely impact they may have on primary motor insurers

SAE International (2016) Levels of Driving Automation						
Level	Name	Execution of Driving Functions *(Steering, Braking, Acceleration / Deceleration, etc.)*	Monitoring of Driving Environment	Human Interaction with Driving Tasks	Likely Impact on Primary Insurers	Key Primary Insurer Risks
Human driver maintains full control of the driving tasks						
0	No Automation	Manual navigation	Human	Full control at all times	None	• Driver as major hazard • Reduced frequency and severity of collisions • Emerging risks include increasing vehicle costs
1	Basic Driver Assistance	One advanced driver assistance system (adaptive cruise control, automatic emergency braking, etc.) working independently	Human	Full control at all times	Low	
2	Advanced Driver Assistance	Two or more advanced driver assistance systems (adaptive cruise control, automatic emergency braking, etc.) working concurrently	Human	Full control at all times, except momentarily	Medium	
Varying degrees of automated driving becomes available at this point						
3	Conditional Automation	Some automated driving in appropriate environments	Vehicle	Full control most periods, high alert during automated mode	High	• Vehicle as major hazard • Mitigates or avoids minor-moderate collisions; tail-risk remains. • Emerging risks include product liability and cybersecurity, changing occupancy rates • Rate of change reliant on market penetration rate.
4	High Automation	Fully-automated driving except in adversarial environments	Vehicle	Full control some periods, high alert during automated mode	High	
5	Full Automation	Fully-automated driving in all environments	Vehicle	No control or alert required	High	

Table 2 Expected cumulative cost of claims in each of the four scenarios outlined in Figure 1 (dashed line), relative to current values (Figure 1, solid line).

Scenario	**Cumulative Losses (as % of current values)**
0% Reduction in Collisions Causing Injury (current losses)	100%
20% Reduction in Collisions Causing Injury	110.4%
40% Reduction in Collisions Causing Injury	111.4%
60% Reduction in Collisions Causing Injury	92.8%
80% Reduction in Collisions Causing Injury	59.9%

Table 3 Summary statistics of insured losses for passenger cars in Germany (own calculations based on insured single-loss amounts between 2005 and 2018); Source: data derived from German Insurance Association (GDV)

	Type of Risk Covered	**Average Claim Frequency**	**Average Claim Severity € (,000s)**	**Standard Deviation € (,000s)**	**Variation Coefficient (Volatility)**	**Average Claim per Policy**
Accident Risk	Motor Third Party Liability (Bodily Injury)	261,496	€3,740,636	€282,997	7.57%	€14,305
	Motor Third Party Liability (Property Loss/Damage)	2,455,520	€5,500,077	€377,924	6.87%	€2,240
	Animal-Vehicle Crash	243,478	€516,837	€75,698	14.65%	€2,123
	Self-inflicted Vehicle Damage	760,515	€1,731,977	€204,771	11.82%	€2,277
Nat Cat	Storm, Hail	287,751	€531,283	€278,474	52.42%	€1,846
	Flooding	3,370	€11,932	€6,594	55.26%	€3,541
Other Risks	Fire	14,588	€54,210	€5,031	9.28%	€3,716
	Breakage of Glass	2,334,675	€1,018,846	€71,451	7.01%	€436
	Theft	172,640	€420,002	€63,691	15.16%	€15,603
	Other	11,064	€8,747	€1,792	20.49%	€791

Table 4 Summation of the shift in risk for primary insurers as automated vehicles become an increasingly-likely feasibility, as it relates to the damages associated with these vehicles.

Anticipated Shift in Risk Landscape (Insurer's Perspective)				
Factors to Consider	Frequency Effects		Severity Effects	
	Automation Levels 0-2	Automation Levels 3-5	Automation Levels 0-2	Automation Levels 3-5
Progression of Technology (Safety)	↓	↓↓	↓	↓↓
Progression of Technology (Repair Costs)	No Effect	No Effect	↑	↑↑
Liability Shift	No Effect	No Effect	↑	↑↑

Table 5 Summation of the shift in risk for primary insurers as automated vehicles become an increasingly-likely feasibility, as it relates to the temporal changes in the market-share and use of these vehicles.

	Anticipated Shift in Risk Landscape (Insurer's Perspective)				
	Factors to Consider	Frequency Effects		Severity Effects	
		Automation Levels 0-2	Automation Levels 3-5	Automation Levels 0-2	Automation Levels 3-5
From Table 4	Progression of Technology (Safety)	↓	↓↓	↓	↓↓
	Progression of Technology (Repair Costs)	No Effect	No Effect	↑	↑↑
	Liability Shift	No Effect	No Effect	↑	↑↑
	Regulations	↓	↓↓	No Effect	No Effect
	Occupancy Rates	No Effect	↓ [14]	No Effect	↑↑
	Ownership Rates	No Effect	↓	No Effect	No Effect
	Market Penetration	↓	↓↓ [15]	↑	↑↑ [16]

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[14] Indirectly, through ownership

[15] Indirectly, through increased safety

[16] Indirectly, through increased repair costs and liability

12 Appendix 1: Forming Loss-Distribution Scenarios

Loss-modelling using Gamma Distribution:

The expected injury loss distribution models in Figure 1 (§2) are formed using a mixture of Gamma probability density functions. We detail here how these scenarios are generated. The Gamma distribution is often used in non-life insurance pricing to anticipate the severity of expected claim losses (Denuit *et al.* 2007, Bahnemann 2015). The probability density function of the Gamma distribution is:

$$f_{\Theta}(\theta) = \frac{1}{\Gamma(k)\theta^{k}} x^{k-1} e^{-\frac{x}{\theta}}, \theta > 0, k > 0$$

where θ describes the shape of the distribution, while k describes the scale of the distribution. $\Gamma(k)$ is the Gamma function, where $\Gamma(k) = (k-1)!$. Further details are provided in Denuit *et al.* (2007). However, this distribution fails to capture the observed 5% of injury claim losses that occur above €100,000 (Central Bank of Ireland 2019). Hence, a mixture of Gamma distributions, where one distribution captures low-severity events, and the other captures high-severity events, is required.

Loss-modelling using a Mixed Gamma Distribution:

Given the proposition that a second 'hump' may become a reality, we extend the Gamma distribution to form a flexible, heavy-tailed distribution. To incorporate extra flexibility in to our loss distribution, we combine two Gamma distributions and scale the resulting equally-weighted mixture to one ('1'). The first Gamma distribution is intended to capture the extent of low-severity claims ('Low-Severity Gamma'), while the second Gamma distribution is intended to capture the extra risk posed by high-severity claims ('High-Severity Gamma'). These distributions are summated to form the 'Gamma Mixture'. This Gamma-distribution mixture is represented as:

$$f_{\Theta}(\theta) = \frac{1}{2\Gamma(k_1)\theta_1^{k_1}} x^{k_1-1} e^{-\frac{x}{\theta_1}} + \frac{1}{2\Gamma(k_2)\theta_2^{k_2}} x^{k_2-1} e^{-\frac{x}{\theta_2}}, \theta_1, \theta_2 > 0, k_1, k_2 > 0,$$

where θ_1 and θ_2 describes the shape of the low-severity and high-severity distribution, respectively, while k_1 and k_2 describes the scale of each distribution. These are represented in Figure A1 as dotted and dashed lines, respectively. The summation of these distributions, the 'Gamma Mixture' distribution, is represented in Figure A1 as a solid line ('Anticipated Rates'). Setting the shape parameters θ_1 and θ_2 to be 0.70 and 4.25 respectively, and the scale parameters k_1 and k_2 to be 3 and 0.9 results in the baselines scenario; the 'Current Rates: 0% Reduction' distribution in Figure A1. Although the 'Gamma Mixture' distribution largely tracks the conventional 'Gamma' distribution, the mixture allows for the consistently high minor loss-events (<€30,000) to be captured as well as the 5% of claims that exceed €100,000.

How loss-events may change:

The ‘20% Reduction’ scenario is formed by setting the shape parameters to be $\theta_1 = 1.25$, $\theta_2 = 2.5$ and the scale parameter to be $k_1 = 1.25$, $k_2 = 2.5$. The fall in collisions in this scenario is primarily due to the assumed effectiveness of CAVs. These vehicles are expected to be equipped with ADAS technologies, have the ability function autonomously, and have the ability to wirelessly communicate with their surrounding environment (V2X). These vehicles are therefore effective at reducing or mitigating the frequency of ‘would-be’ collisions (Bareiss *et al.* 2019). However, the ‘20% Reduction’ scenario assumes that these vehicles have not achieved a high market penetration rate. In this scenario, conventional vehicles represent the majority of vehicles in the road environment, and as such, the current loss distribution remains a largely in place ‘Low-Severity Gamma’. The ‘High-Severity Gamma’ captures the high number of moderate loss-events and few severe loss-events due to the increased vehicle repair costs and liability costs associated with these vehicles.

The ‘40% Reduction’ scenario is formed by setting the shape parameters to be $\theta_1 = 1.25$, $\theta_2 = 3$ and the scale parameter to be $k_1 = 1.25$, $k_2 = 3$. Much like the ‘20% Reduction’ scenario, the ‘40% Reduction’ scenario subsists on the expectation that CAVs are effective and commonplace, but do not represent the majority of on-road vehicles. Despite not reaching a majority, higher-liability injury claims will increase as a proportion of total claims. This will lead to an increased rate of claims currently classed as ‘tail-risk’ events, in tandem with the increased repair costs associated these technologically-sophisticated vehicles.

A 60% reduction in collisions suggests a scenario in which CAVs have achieved a high market penetration rate and make up the majority of vehicles on the road. The loss distribution is formed by setting the shape parameters to be $\theta_1 = 1.25$, $\theta_2 = 3.5$ and the scale parameter to be $k_1 = 1.5$, $k_2 = 3.5$. Low-cost bodily injury claims are expected to decrease as a proportion of total bodily injury claim frequencies. However, they still represent a sizeable majority of claims given the likelihood that a number of collisions will be ‘mitigated’ rather than avoided. An increased proportion of bodily injury claims will be events currently classified as ‘tail-risk’ events, leading to initial indications of a second ‘hump’. This is as a result of a higher relative proportion of collisions that result in serious injuries, given that the majority of low-severity injuries can be avoided.

An 80% reduction in collisions suggests a scenario in which ADAS-enabled vehicles, that are capable of autonomous control and wireless communication, have achieved a dominant market share. The loss distribution is formed by setting the shape parameters to be $\theta_1 = 1.5$,

$\theta_2 = 4.25$ and the scale parameter to be $k_1 = 1.5$, $k_2 = 4.25$. In this latter scenario, a high proportion of minor-moderate severity loss events have been eliminated, and many loss events that remain are events that are ‘unavoidable’ and are likely to commit great personal harm. Hence, tail-risk events manifest as a second ‘hump’, as the overall rate of collisions decrease, while the relative percentage of high-severity collisions increase.

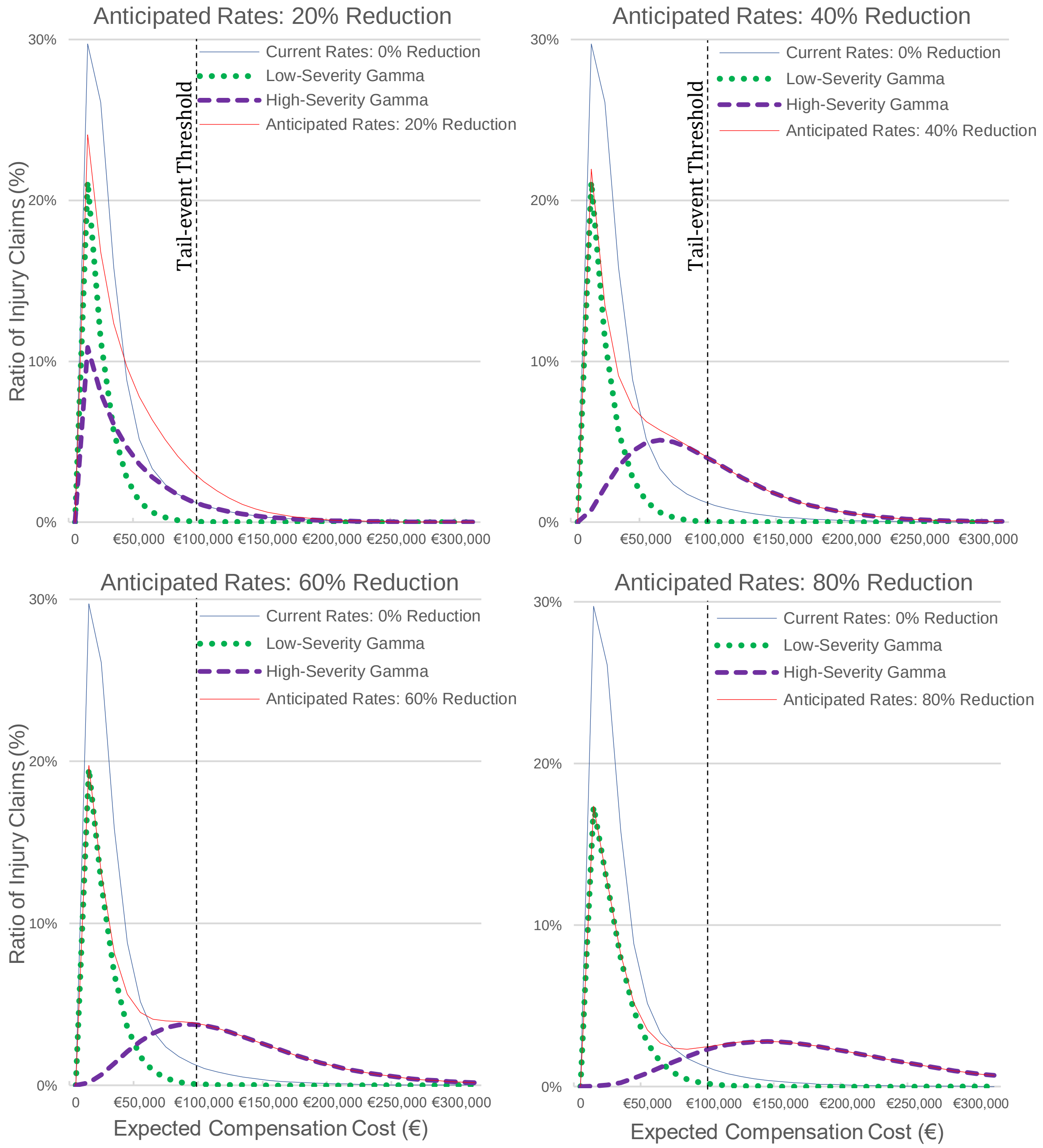

Figure A1 The formation of a current claim loss distribution, based on figures provided by Central Bank of Ireland (2019), overlaid with the formation of anticipated loss distributions as connected and autonomous vehicles (CAVs) attain an increasingly high market share of on-road vehicles.