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Driving to a future without accidents? Connected automated vehicles' impact on accident frequency and motor insurance risk

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Abstract

Road traffic accidents are largely driven by human error; therefore, the development of connected automated vehicles (CAV) is expected to significantly reduce accident risk. However, these changes are by no means proven and linear as different levels of automation show risk-related idiosyncrasies. A lack of empirical data aggravates the transparent evaluation of risk arising from CAVs with higher levels of automation capability. Nevertheless, it is likely that the risks associated with CAV will profoundly reshape the risk profile of the global motor insurance industry. This paper conducts a deep qualitative analysis of the impact of progressive vehicle automation and interconnectedness on the risks covered under motor third-party and comprehensive insurance policies. This analysis is enhanced by an assessment of potential emerging risks such as the risk of cyber-attacks. We find that, in particular, primary insurers focusing on private retail motor insurance face significant strategic risks to their business model. The results of this analysis are not only relevant for insurance but also from a regulatory perspective as we find a symbiotic relationship between an insurance-related assessment and a comprehensive evaluation of CAV's inherent societal costs.

Keywords Connected automated vehicles · Automated driving accident risk · Motor insurance

1 Introduction

Connected automated vehicles (CAV) offer both opportunities and threats to existing business models. Car manufacturers and automotive suppliers are under immediate pressure to innovate as the production of automobiles is their core business. However, direct and indirect downstream markets will also be affected by the ongoing automation and the interconnectedness of modern vehicles.

The insurance sector is acutely sensitive to the adoption of new technology as insurers cover risks resulting from the usage (motor insurance) and risks arising from the development and production of vehicles (e.g. product recall and product liability insurance). In this sense, the insurance sector assumes risks on individual and societal levels. The motor insurance business is worth €137.5 BN annually in Europe (Insurance Europe 2019), so technological changes will have major ramifications to that sector. In addition, a failure to adequately insure existing and emerging risks may slow the development and roll-out of the technology and inhibit societal acceptance.

If CAV does reduce the number of road accidents significantly, this would result in a material decrease in motor insurance premium volume. This path is by no means proven and straightforward but will herald profound changes and repercussions for the insurance sector. The combination of decreasing and emerging risks will reshape the volume and characteristics of motor insurance risk exposure. Different members of the insurance supply chain (insured, primary insurer and reinsurer) typically have different capabilities and appetite to take part of this risk exposure; therefore, the shift in the underlying risk landscape will likely also affect the risk allocation within the insurance supply chain.

There is an active and ongoing dialogue within academic literature on CAV from a technical, human-factor, ethical and legal perspective (Bertolini et al. 2016; Pütz et al. 2018; Duffy and Hopkins 2013; Lohmann 2016; Schroll 2015). In addition, initial accident research on the impact of advanced

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driving assistance systems (ADAS) on the frequency of accident losses exists, but, with the exception of relevant legal aspects, insurance-related assessment of CAV technology is largely limited to practice-related discussions (Morgan Stanley and Boston Consulting Group 2016; Swiss Re and HERE 2016; Munich Re 2016; Yeomans 2014). Therefore, this paper combines two separated research disciplines and contributes to an academic discussion of CAV's risk aspects focussing on the insurance sector as a key stakeholder of this technology. As motor insurance is a useful proxy of economic costs arising from motor traffic risk, this research also contributes to a risk understanding from a political and societal perspective (Claus et al. 2017). We enrich this analysis with an assessment of risks that are likely to emerge with CAV (i.e. risk of cyber-attacks (Sheehan et al. 2018)) with a special focus on their implication for the overall characteristics of motor insurance risk.

Even if this development takes decades due to the slow penetration pattern of CAV, this paper is a timely addition particularly for the early stages of strategic planning approaches undertaken by insurance companies, where relevant, the motor insurance market data used in this paper is taken from statistics available from the German Insurance Association (GDV) and the German Federal Financial Supervisory Authority (BaFin). Data on the German market is a good candidate to examine all (saturated) motor insurance markets as the scope of the single risks covered under German motor insurance policies is similar to the scope of insurance policies in other European countries.

2 Evaluation of CAV accident risk and literature review

This section explores existing literature on the impact of CAV on accident risk starting from lower levels of automation. The fact that 90% of all road accidents today are attributed to human error is often used to argue that taking the human driver out of the driving task would causally reduce the number of road accidents. However, in a rationale evaluation of this figure, the high contribution of human error to accident occurrences is just a logical consequence from the fact that, for the time being, it is the human driver, who almost exclusively fulfils the driving action without the intervention of active driving assistance systems. Thus, the figure might indicate the high potential of CAV to further increase overall road safety but is useless as a proxy to quantify CAV's potential decreasing impact on the overall number of accident occurrences. 769 billion kilometres were driven in Germany in 2016 resulting in only 5.6 accidents per million kilometres showing that humans are, in fact, very good drivers.[1]

A high potential of CAV to increase road safety results from generally favourable characteristics of robotic systems like the ability to permanently keep up attention (no distraction) or to react faster and with predetermined action patterns. In addition, the automated system is not exposed to accident risk due to physical and mental human deficiencies like drowsiness, alcohol consumption, distractions, emotional status that deteriorate the performance of the human driver. These factors are critical reasons[2] for about 22%[3] of all road accidents (NHTSA 2008). In contrast, it is questionable whether beneficial human cognitive abilities (e.g. anticipation, adaptability or empathy) can be adequately replicated in software-based driving systems. This is especially important as road traffic is dominated by high levels of complexity and flexibility of driving decisions. In addition to risk arising from inadequate driving software algorithms, an automated driving vehicle will also be exposed to the risk of malfunction of vehicle hardware (sensors and electronic control units). The fact that this risk cannot be neglected can be indicated by increasing numbers of product recalls resulting from defects of these components (Murphy et al. 2019). Hence, automated driving vehicles first have to prove that they (statistically) increase road safety by reducing the overall number and/or severity of road accidents ("positive risk balance").

Some empirical data for an indicative evaluation of CAVs' impact on the overall accident risk can be derived from two sources. First, early findings of accident research for single advanced driving assistance systems (e.g. for automated emergency braking (AEB), adaptive cruise control (ACC), forward collision warning (FCW) or lane keeping assistant (LKA)) can be used to evaluate the potential safety impact of these systems. However, these systems focus on separated driving tasks and only represent low levels of driving automation (level 1 automation) and this data cannot be simply transposed to CAV with higher automation capability. In this paper, we will describe findings of relevant

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[1] We use the number of collision-related insurance claims as a proxy for the total number of accidents including minor accidents. The number decreases to 3.36 accidents per million driven kilometres when selecting only police-recorded (Destatis 2017).

[2] The methodology defines the critical reason as the last failure in a causal chain. Therefore, it may not reflect the (only) cause of a crash and does not necessarily imply an assessment of fault. However, it does imply at least a contributory factor of human failure to an accident occurrence.

[3] This share of failure due to physical or mental shortcomings could be higher because the usage of smartphones has increasingly become a contributory reason for distraction within the last years and additional factors such as alcohol and drug abuse have not been considered in this source.

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accident research for single ADAS systems to indicate the risk-lowering impact of assisted driving vehicles (level 1 automation) only.

Second, findings from real-world testing of CAV with higher levels of automation can be used to indicate the current technical reliability of these vehicles. For instance, companies testing their CAV fleet in California have to publish reports on disengagements of the tested vehicles, if they conduct tests on public streets. However, the transferability of these results is limited due to the lack of transparency of testing conditions and an only limited statistical representativeness of data. We will detail these shortcomings when describing the empirical data and research findings in later sections.

In the following, we describe the specific effects of single levels of automation that are relevant to CAV accident risk in terms of probability. Equally important from an insurance point of view will be the development of average loss costs of vehicles equipped with CAV technology. Even if unit costs for the development and production of the implemented components (e.g. radar, Lidar, GPS, cameras, ultrasonic sensors, etc.) will decrease over time, these components will be implemented in addition to existing (mechanical) systems. This will promote technology-driven inflation of vehicle values. In addition, the implementation of sensors and on-board electronics, especially on surfaces exposed to damage in the event of an accident (e.g. bumpers in case of rear-end crashes), will lead to an increased extent and complexity of repair work that will further increase insured loss amounts (Liberty Mutual Insurance 2017).

2.1 CAV equipped with ADAS systems (level 1 automation)

In vehicles driving equipped with ADAS (level 1 automation), the human driver is supported by the automated system, which can control either the lateral (e.g. LKA) or longitudinal (e.g. AEB or ACC) steering function. Because the human driver still is continuously and actively engaged in all aspects of the dynamic driving task (motion control, tactical manoeuvre planning/display of action, monitoring of driving environment), the human driver and the assistance system collectively have redundancy and the risk resulting from the inadequate interaction of the driving automation system and the human driver is limited. The assistance system generally only intervenes in critical situations.[4] In doing so, the ADAS system performs a non-critical driving condition through decent countermeasures (e.g. ACC and LKA) or by fulfilling an automated safety manoeuvre if a time-critical intervention is required (e.g. AEB). Thus, the system is designed as a fall-back to the human driver. By contrast, in case of an error of the assistance system, the human driver generally has the situational awareness to conduct adequate countermeasures. Thus, the human driver and the driving automation system are related by a double-sided continuous redundancy.

Indeed, analyses of the efficiency of different ADAS systems have already shown significant safety benefits. For instance, Cicchino has found that forward collision warning (FCW) enhanced with AEB systems demonstrates significant reductions of rear-end striking crashes by up to 50%. In contrast, the rates of receiving a rear-end strike were seen to grow (Cicchino 2017). A possible reason for this phenomenon can be that the more sudden hard braking actions of automated systems have not been anticipated by the human vehicle's driver in the following car, thus exhibiting the potential conflicts arising from the interaction of non-automated and automated driving vehicles in the transition period of the single levels of automation. Besides the impact on accident frequency, the automated intervention of the CAV could also reduce the average severity of loss events within single accidents types (e.g. rear-end collisions) and lower the probability and severity of injuries in road accidents if the intervention of the AEB system proactively reduces impact speeds of crashes (Avery and Weekes 2019) (Kusano and Gabler 2012).

Jermakian (2011) investigates the potential safety benefits of FCW, LKA, side view assist and adaptive headlights concluding that all systems combined could potentially prevent about one third of crashes with FCW being the most effective and potentially preventing about 20%. Similarly, Harper et al. (2016) find that FCW, LKA and blind spot warning are relevant to 24% of overall accidents. However, they stress that the relevant share of accidents for the respective ADAS systems does not necessarily equal the share of accidents which are prevented. This would only be the case with full effectiveness and constant activation of the systems. With the same limitation, Kuehn et al. (2009) quantify a similar benefit to accident frequency of 25% for AEB and LKA systems. The discrepancy to the findings of Cicchino (2017) could result from technical progress between the two studies but also from the fact that the indicated safety benefits vary substantially by estimation methodology and by type of vehicle. This is demonstrated in a literature review conducted by Yue et al. (2018) and also by Blower (2014), who found that studies indicating the crash-decreasing impact of the combination of FCW, braking assist and AEB vary between 9 and 72%. Deviations in the used dataset, research methodology and specific technical design of the tested systems cause these high fluctuations.

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[4] Relevant critical situations for example could be driving too close to preceding vehicle (ACC), pedestrians/stationary object standing on the driving lane (AEB) and unintended departure from the driving lane (LKA).

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In another example, reversing accidents can be reduced significantly with the development and implementation of reverse AEB systems resulting in a reduction of the insurance claims in the near term (Grover et al. 2015; Highway Loss Data Institute 2017). This type of accident causes about 40% of all motor third-party liability and fully comprehensive losses (Allianz SE 2015). With passive parking assistance, which only warns the driver, insurance losses have not decreased (David et al. 2015; Keall et al. 2017) because any decrease in accident frequency was offset by an increase in average loss amounts.

Given the high potential of ADAS systems to increase road safety by active intervention in critical situations, the full risk-lowering impact will only materialise if the use of these systems does not impair human drivers' prudence. Otherwise, increased risk-taking of the human driver (e.g. omission to look over the shoulder, lowering distance to foregoing vehicle, etc.) would increase the number of critical situations to be solved by the ADAS system and at least partially offset the positive net impact of ADAS systems. This behaviour is already observed for passive safety systems such as airbags or mandatory seatbelts and led to significant rebound effects offsetting the overall increase in road safety. This offsetting effect is also especially relevant for non-occupants of the respective vehicle. This is because of an additional risk exposure if they or their vehicles are equipped with limited or only minor safety features (Chirinko et al. 1993). The risk that other travellers such as pedestrians or cyclists rely on a certain expected behaviour of the automated vehicle (e.g. automated emergency braking) may negate the risk of unexpected actions (Kockelman et al. 2016).

2.2 Partial and conditional automation (level 2 and 3 automation)

Vehicles with level 1 automation benefit from positive attributes and abilities of both the human driver and of the driving automation system. However, in vehicles with higher levels of automation, the positive attributes of the human driver have to be adequately reflected in the capability of the hardware and software system. In addition, level 1 automation functions generally work separately from each other, thus reducing the complexity of the vehicle infrastructure and data fusion process. Therefore, the findings on the risk exposure of vehicles equipped with ADAS only (level 1 automation) cannot be simply used as a proxy also for vehicles with partial and conditional automation. Indeed, redundancy between the human driver and the driving automation system also applies for vehicles equipped with partial driving automation (level 2 automation), but the human driver now acts as an immediate fall-back to the system which assumes the primary task of vehicle motion control during automated use-cases. Due to the fragmentation of the dynamic driving task between the driving automation system and the human driver, the level of partial driving automation in trend introduces an additional source of risk resulting from the human–machine interaction as humans are generally not adept at keeping up an adequate level of vigilance during longer periods of passive monitoring.

In vehicles with partial driving automation (level 2 automation), this risk is generally limited due to the limited scope of automated driving manoeuvres but is amplified for vehicles with conditional driving automation capability (level 3 automation). This is because the driver technically and legally even does not have to continuously monitor the driving scene but still has to be capable of taking control as a fall-back to the automated system (Merat et al. 2014). Here, the successive decoupling of the human driver from the driving task implies decreasing human driving skills and a decreasing ability to make decisions especially in potentially risky and urgent situations, where the automated system hands back driving responsibility to the human. The required duration for completion of this process depends on the complexity of the traffic scenario set, the level of distraction of the driver and the design of the takeover request (e.g. haptic, acoustic or visual signal). Depending on these variables, drivers on average need several seconds to take over the driving action from an automated system and even longer to recover full situational awareness (German Insurers Accident Research 2016). This risk is amplified by the fact that driver distraction (e.g. use of smartphones) is an increasingly important trigger of accidents (Choudhary and Velaga 2017; Kubitzki and Fastenmeier 2016). To limit this risk, the driving automation system not only has to perceive information from the external driving environment but also from inside the vehicle. The use of sensors (e.g. contact to steering wheel or physiological information such as heart rate, muscle activity, etc.) and cameras (e.g. tracking of eye blinking and head motion) can deduce the level of tiredness and distraction so that the automated system is able to evaluate the human driver's capacity to take over driving responsibility (Kircher and Ahlstrom 2017; Rezaei and Klette 2011).

Due to these potential risk-increasing effects of taking the driver only partially out of the loop, it is questionable whether highly automated vehicles (level 3) benefit in higher safety and comfort and also raises difficult legal questions and could hamper societal acceptance of automated vehicles. Recent announcements by some car manufacturers (e.g. Volvo (Volvo Car Group 2017) and Ford (Ross 2017)) have stated that they will skip the development of vehicles with conditional driving automation (level 3 automation) and target the design of vehicles with (at least) level 4 capability. For this level of automation, the risk exposure from handing over driving responsibility will abate, because the vehicle

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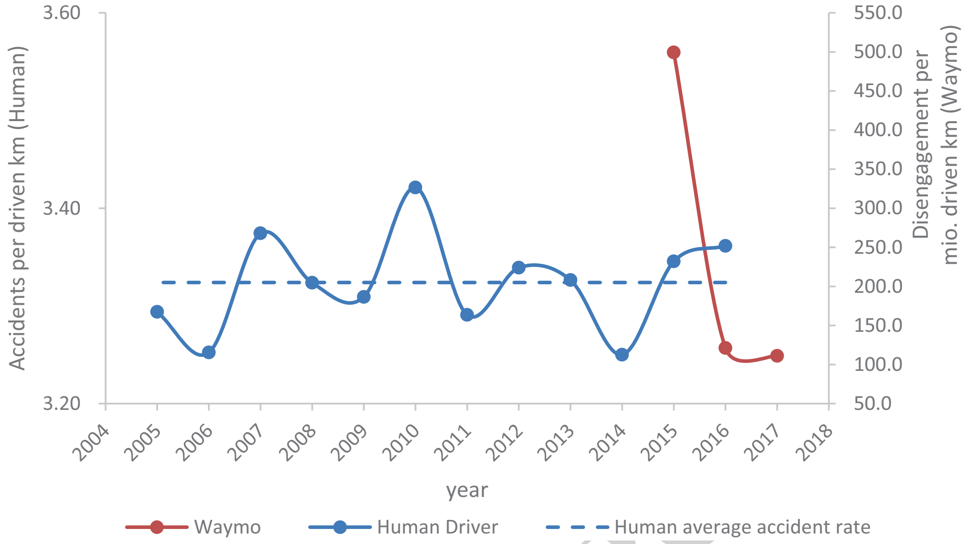

Fig. 1 Accident of human drivers versus disengagement rate of Waymo test fleet. The graph shows the development of accident rate per million driven kilometres of (manually) driven vehicles in Germany and the disengagement rate per million driven kilometres of Waymo's fully automated test fleet vehicles tested in California *Source* Illustration based on numbers provided by Destatis (2017) and Waymo (2017)

will be capable of fulfilling an adequate security manoeuvres allowing the human driver to take over driving responsibility from a safe status.

2.3 CAV with high and full automation (level 4 and 5 automation)

Vehicles with higher levels of automation are already driven on urban roads but limited to testing purposes. As the technology is still immature and largely used in test mode only, caution is required when using current statistics to predict the future impact of these vehicles on the number of accident occurrences. Manufacturers testing fully automated vehicles in California are legally obliged to publish yearly disengagement reports. Disengagements are defined as "a deactivation of the autonomous mode when a failure of the autonomous technology is detected or when the safe operation of the vehicle requires that the autonomous vehicle test driver disengages the autonomous mode and takes immediate manual control of the vehicle" (see California Code of Regulations Title 13, Article 3.7, § 227.46 (a)). For this, the vehicle manufacturers have to report the total number of disengagements, the total number of miles driven of each test vehicle and the circumstances of the disengagements including the location and reason for the disengagement (e.g. weather or road conditions, accidents etc.) (see California Code of Regulations Title 13, Article 3.7, § 227.46 (b)).

As the human drivers' accident risk can be measured by accident rate per driven kilometre, a statistically reliable equivalent indicator is missing for the comparison group. Even though the Waymo vehicle test fleet already completed over four million kilometres without any accident caused by the (sole) fault of the automated vehicles is often used as an argument to underline the superior performance of automated vehicles (Teoh and Kidd 2017). Also, Blanco et al. (2016) in their study (commissioned by Waymo) show that the Waymo test fleet only shows superior performance after (upper bound) scaling of accident rates.

That human drivers only cause about 3.3 (police-reported) accidents per million kilometres (see Figs. 1, 5) indicates that the mileage of the automated fleet is not yet sufficient to provide a statistically reliable comparison (Kalra and Paddock 2016). In addition, a comparison of accident rates has no scientific significance since information about testing conditions (e.g. road, traffic and weather condition) is not transparent enough to standardise and compare with representative traffic scenarios. Also, the fact that a specially trained safety driver is taking over driving responsibility if needed makes it impossible for third parties to assess how many accidents the vehicle would have caused if the human driver had not intervened. In addition to the comparison of accident rates, an analysis of the disengagement reports of Waymo can be used to analyse the reliability of highly/fully automated vehicles in their current state of development. As disengagements describe critical situations, which do not necessarily lead to an accident, a comparison of this risk indicator with human drivers' accident frequency rates (see Fig. 1) only allows for an indicative assessment.

Analysing the number of disengagements of automated vehicles, it can be argued that self-driving software will successively learn from each disengagement so that a high number of disengagements at the early stages of development are actually desirable from a testing perspective. However, given the proportion of 33[5] disengagements of Waymo's test fleet per (police-recorded) accident of a human-driven vehicles,

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[5] This factor is the result of the ratio of 111 reported disengagements of Waymo's test fleet per million driven kilometres and 3.36 accidents per million driven kilometres in Germany in 2016.

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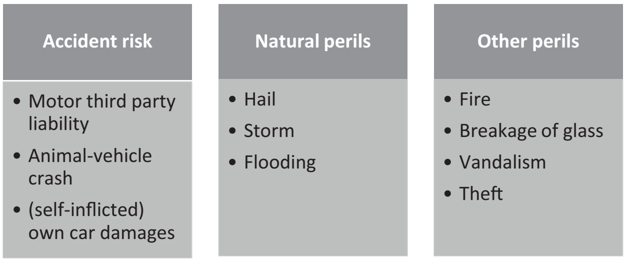
the comparison indicates that these systems (at least for the time being) are not yet capable of adequately replacing human driving capability (Favarò et al. 2017). Whilst the comparison is apt, the different driving conditions must be considered. For example, the snow and sleet conditions are more likely in Germany. However, it remains questionable and ambiguous whether a state of superior driving by automated vehicles can technically be achieved. This is not necessarily due to the bad performance of the technical system but due to the fact that the human driver shows very low failure rates measured by accidents per given mileage. Thus, the highly or fully automated driving vehicle first has to prove that it is capable of exceeding human performance. The technical system is exposed to other (partially new) risk sources like hardware and software failures or the risk of malicious cyber-attacks (Koopman and Wagner 2017; Kockelman et al. 2016). For instance, the analysis of relevant root causes for automotive product recalls also stresses that these risks cannot be simply neglected (Murphy et al. 2019). Thus, significant sources of accident risks will still persist so that ex-ante claims of significant decreases of road accidents remain largely unqualified and largely untested (International Transport Forum (ITF) 2018). It is not clear, how the frequency and even severity of accident events will actually develop in the future, especially given risk-relevant interdependencies to non-automated road users (Sivak and Schoettle 2015).



Accident risk	Natural perils	Other perils
• Motor third party liability • Animal-vehicle crash • (self-inflicted) own car damages	• Hail • Storm • Flooding	• Fire • Breakage of glass • Vandalism • Theft

Fig. 2 Risks covered under motor insurance policies. The figure shows the risks commonly covered under motor insurance policies (MTPL and fully comprehensive) in Germany

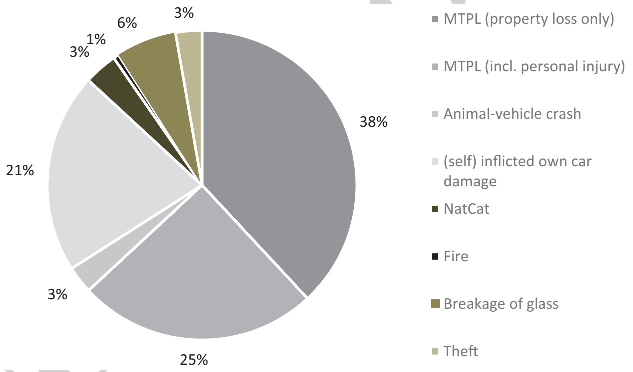


Fig. 3 Split of overall insured loss per single risks covered. The graph shows the average share of insured losses for the single risks covered by (MTPL and fully comprehensive) motor insurance in the German market between 2006 and 2015 *Source* Own calculation based on data published by German Insurance Association (GDV 2016)

3 Description of the current characteristics of motor insurance risk

Motor insurance is worth € 26.9 BN (2017) and accounts for about 40% of the total premium volume (non-life) in the German insurance market. Measured by premium volume, it is the most important line of (non-life) insurance business (GDV 2018). In the following, we will describe the relevance of single risks to the overall risk exposure and the characteristics of the single risks covered with regard to the frequency and severity of risk occurrences.

3.1 Composition of the overall motor insurance risk exposure

Motor insurance can be separated into three types of insurance coverage[6]:

- Motor third-party liability (MTPL): Compensates for property and bodily injury claims of damaged third parties against the owner, keeper and driver of a car and accounts for € 16 BN premium income (59.5%).
- Partially comprehensive insurance coverage: Compensates for property losses to the insured vehicle due to fire, breakage of glass, animal–vehicle crash, theft, hail, storm and flooding. It accounts for about € 1.7 BN premium income (6.6%).
- Fully comprehensive insurance coverage: Compensates for all losses covered by partially comprehensive insurance and in addition for property losses due to vandalism and (self-inflicted) own car damages. It accounts for about € 9.2 BN premium income (33.5%).

Given the scope of the different types of coverages, we separate these single insured risks into the subordinate categories of accident risk, natural perils and other perils as shown in Fig. 2.

Simplistically assuming that the net risk premium for the single covered risks corresponds with the (expected) average insured loss amount incurred for each risk, Fig. 3 indicates the relevance of each risk for the overall (net risk) premium income of motor insurance. It shows that accident risk is

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6FL01 6FL02 [6] Premium figures are based on figures for year 2017 provided by GDV (2018).

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the most prevalent driver of overall motor insurance net risk premium contributing to about 87% of all loss payments. Following from this, material changes to the number of road accidents induced by CAV would have significant impacts on the overall motor insurance premium volume.

3.2 Characteristics of motor insurance risk exposure

Overall, motor insurance risk exposure is characterised by a stable loss pattern. However, in a more granular assessment, the single risks covered show different characteristics regarding the frequency and severity of loss events. This can be illustrated by the mean annual amount, the standard deviation and the variation coefficient of annual insured losses per type of risk as shown in Table 1.

Using the variation coefficient as the indicator of the volatility of the annual loss amount of the single risks covered, the value of 3.4% shows that overall motor insurance risks exposure is characterised by quite high stability.

This is mainly due to the stability of annual loss amounts due to accident risk, which is characterised by high frequency and low severity of single loss events. The only exception of the only limited severity of insured accident losses is MTPL insurance, where losses can indeed be exposed to financial tail-risks. This is because MTPL insurance not only covers liability claims for a damaged third-party vehicle (property damage) but also further liability claims of third parties (i.e. bodily injury claims). This amount, especially in case of death or (severe) bodily injuries, can exceed property damages several times. Thus, MTPL coverage is exposed to financial tail-risks, due to potentially high loss amounts of single accidents (e.g. in case of permanent disability of claimants). As a result, MTPL insurance's overall insured loss expenditure is indeed affected by a higher financial tail risk than the other insured accident risk categories as illustrated in Fig. 4.

However, even in case of a higher financial tail risk of MTPL insurance, the still relatively low variation coefficient of this risk shows that the general independency of single insured MTPL loss events leads to a risk balancing effect in a homogenous and sufficiently large risk portfolio. Accumulation events are largely only limited to those instances where the probability of losses for (a part of) the portfolio is increased by external effects (e.g. black ice on the streets).

In contrast, losses due to natural perils (NatCat risks) are characterised by low frequency but potentially high severity of loss events leading to a high variation coefficient of the annual insured loss amounts of 49.5% (storm and hail) and 46.7% (flooding). The high severity results from the correlation of single insured objects affected in one loss event. Even if the loss amount to a single insured vehicle is regularly limited to (a fraction of) its property value, natural perils typically affect multiple insured objects in their sphere of activity. Hence, natural perils regularly lead to events with high accumulated loss amounts. Because of this, it is more difficult to balance NatCat risk throughout a year, especially within a regionally limited risk portfolio. Therefore, NatCat risks have to be balanced within the own portfolio through time or by a (partial) risk-transfer to an external party (e.g. reinsurer).

4 Potential impacts on accident risk characteristics

The low volatility of annual insured losses is mainly due to the fact that accident risk is only exposed to a limited risk exposure from accumulation or series loss events. However, with CAV on the roads, this could change due to series loss events arising from the correlation of software-based driving decisions and due to accumulation loss events arising from cyber-attacks.

4.1 Correlation of accident risk losses of CAV

When a fleet of CAV (e.g. from the same manufacturer) is fulfilling the automated driving task based on the same deterministic algorithm, the driving behaviour of these vehicles is directly correlated with each other. This means that CAVs are programmed in the way that every vehicle will decide uniformly on how to fulfil a driving action within a given scenario set.

Driving algorithms that can unilaterally adopt themselves to input from the dynamic environment could potentially introduce severe legal risks for vehicle manufacturers, as the obligation to monitor (unknown risks of) the products after bringing the vehicles into the market could be inadequate, complex and costly. This is because the duty to monitor should increase, as the potential risk resulting from the system carrying out safety-crucial driving actions autonomously will increase. Therefore, a centralised adjustment of the algorithms by the vehicle manufacturer based on the input data of the CAV fleet is a realistic solution and fulfils legal requirements to ensure adequate safety monitoring processes.

With this assumption, series accident losses become manifest, if single vehicles of the affected fleet face the same risk scenario set. The extent of series loss exposure depends on the period of time the car manufacturer needs to discover and fix algorithmic errors by applying patches via (over-the-air) software updates.

In addition, the risk of accumulated accident loss events could arise from several vehicles jointly travelling in

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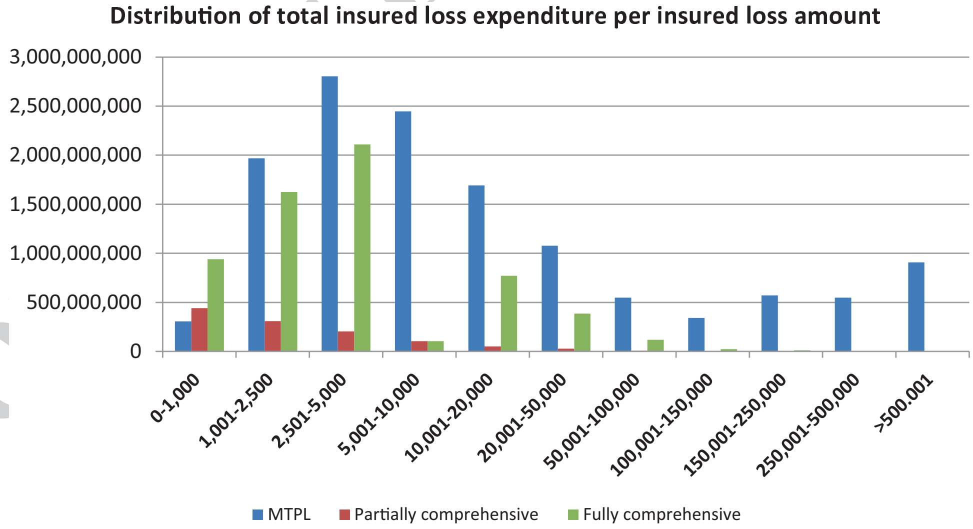
Table 1 Mean value, standard deviation and variation coefficient of total insured losses of single risks

Type of risk covered	Mean (in € 1000)	Standard deviation (in € 1000)	Variation coefficient (%)
Accident risk			
MTPL (property loss only)	6,903,143	289,054	4.19
MTPL (incl. personal injury)	4,536,305	333,397	7.35
Animal–vehicle crash	517,761	46,993	9.08
(Self-inflicted) own car damage	3,792,456	220,320	5.81
Nat cat			
Storm, hail	618,243	306,011	49.50
Flooding	12,061	5638	46.74
Other risks			
Fire	104,922	18,165	17.31
Breakage of glass	1,147,331	89,794	7.83
Theft	498,454	52,518	10.54
Other	10,585	1930	18.23
Total			
Overall motor insurance risk	18,143,273	611,942	3.37

The table shows the mean value, standard deviation and variation coefficient of annual insured losses per type of risk covered under (MTPL and comprehensive) motor insurance in the German market between 2006 and 2015. Source: Own calculation based on data published by German Insurance Association (GDV 2016)

Fig. 4 Distribution of total insured losses per insured loss amount. The graph shows the distribution of overall loss expenditure per insured loss amount for MTPL, partially comprehensive and fully comprehensive motor insurance in the German market for the year 2015 *Source* calculations based on data published by German Insurance Association (GDV 2016)



platoons, where accident risks might turn from crashes of single or two vehicles to more severe multi-vehicle crashes. This is because a cohort of vehicles is driving close to each other, at high speed and dependent on information received by the foregoing vehicle increases correlation risk.

4.2 Cyber risk

The automation of the vehicles' driving action technically does not need to be accompanied by an (over-the-air) communication interface (local navigation through on-board sensors), but the interconnection enables parts of the expected benefits of comfort and safety features brought by automated vehicles (global navigation of the vehicle fleet). In this way, the automation and interconnection of CAV are complementary and interrelated technologies.

Cyber-attacks against road vehicles are not yet common, but modern vehicles already possess several communication interfaces that can be used as access points for cyber-attackers. In general, these communication interfaces can

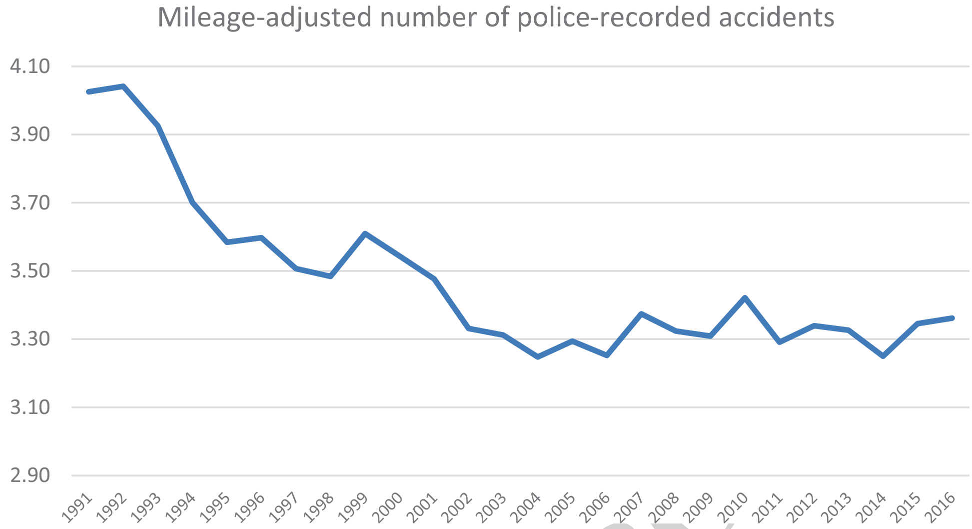


Fig. 5 Mileage-adjusted number of police-recorded accidents. The graph shows the development of the overall number of police-recorded accidents events per million driven kilometres in Germany between 1991 and 2016 *Source* Own illustration based on numbers provided by Destatis (2017), Radke (2014) and Bundesanstalt für Straßenwesen (2017)

be separated into (indirect) physical access and short-range or long-range wireless access channels (Checkoway et al. 2011). Short- and long-range wireless connections (e.g. Bluetooth, WiFi, broadcast connection) open access points for (external) remote cyber-attackers.

If it is possible for cyber-attackers to hack not only one, but a fleet of CAV or traffic infrastructure, losses to single vehicles would be directly correlated and exposed to accumulation risk. Depending on the probability of cyber-attacks and the financial losses due to each affected CAV, the loss pattern of the inherent risk could be both volatile and high in severity. As a result, cyber-attacks on a fleet of CAV could induce a second source of accumulation loss events (in addition to NatCat risk) and shift the characteristics of overall accident risk to higher volatility and severity of loss occurrences. In addition, cyber-attacks to digital infrastructure show the phenomenon that they are not only limited to one specific line of business (e.g. motor insurance) but could also affect several lines of the insurance business (e.g. business interruption). This characteristic even presents special challenges to enterprise risk-management of a vehicle manufacturers but also accumulation risk control of insurance entities. Due to the NatCat-like characteristics of cyber-risks, again the need for risk-transfer of motor insurers (e.g. via reinsurance coverage) is relevance and not limited to smaller and mid-size motor insurers with a regional focused portfolio but also insurance companies with a portfolio that is regionally diversified. This is because of the described phenomenon of cyber-risks that are neither limited to single regions nor to single lines of insurance business.

5 Effects from a shift to service-based mobility solutions

The increasing penetration of CAV technology is generally expected to accelerate a change in societal mobility approach shifting away from the ownership of vehicles to the use of shared on-demand mobility services (Krueger et al. 2016). This shift would strongly affect customer interfaces because a (commercial) entity providing the mobility service assumes the role of the vehicle owner and is obliged to maintain adequate insurance coverage. This produces a shift in customer interfaces from a business-to-customer (b2c) relationship between the insurer and the individual vehicle owner to a business-to-business (b2b) relationship between the insurer and the (commercial) mobility service provider.

The progressive usage of shared-mobility services could also facilitate the penetration of CAV technology into the overall vehicle fleet because of a potential decline of the required fleet size (Morency et al. 2015) and because the relatively high acquisition costs of CAV[7] could be balanced by more efficient use of the vehicles. In turn, this would shorten the traditionally slow-moving penetration patterns[8] of driving assistance systems and would catalyse the impacts of CAV technology on the overall road safety and insurance-specific risk exposure.

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[7] It is assumed that vehicles equipped with CAV technology especially in the beginning of market penetration will be relatively expensive due to required hardware (e.g. cameras and sensors) and software components.

[8] For instance, the anti-lock braking system (ABS) and electronic stability control (ESC) took about 20 and 15 years until more than 80% of all newly registered vehicles were equipped based on figures of the Deutsche Automobil Treuhand GmbH (DAT 2018). DAT 2018. DAT Report 2018.

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In a potentially shrinking vehicle fleet, the extent of (insured) loss events due to natural perils such as storm, hail or flooding events declines in line with the reduction in the number of vehicles affected in the spatial sphere of activity of the respective natural peril. This potentially risk-lowering impact is especially relevant as the adoption of shared-mobility higher in urban areas where the concentration of exposed vehicles in a relatively small area is especially high. Resulting from this, the absolute risk exposure resulting from NatCat events would decrease due to the indirect effects of CAV on societal mobility patterns, which would (partially) counterbalance or even overcompensate expected increases of average loss amounts to single affected vehicles due to technical inflation.

By contrast, the impact of the shift to a service-based mobility approach to the overall accident risk exposure strongly depends on the future amount of overall driven vehicle kilometres (Ahangari et al. 2017). This is because of the strong correlation between the total mileage driven and the overall number of road accidents which can be indicated by a Pearson correlation coefficient $r = 94\%$. The following graph shows that the number of accidents per mileage remains stable and on already very low levels with currently the human driver taking over driving responsibility.

Indeed, there are different reasons why the wider adoption of shared service-based mobility solutions could lead to an increase in the overall vehicle mileage and thus increase risk exposure (Wadud et al. 2016; Litman 2018). First, an increase in mobility participation for impaired or elderly people could stimulate additional mobility demand by these user groups. Assuming, that these groups today have to use public transport services, higher individualisation of mobility solutions for this cohort could increase the total mileage driven. In addition, increasing use of individual mobility services instead of centralised public mass transport could also be applicable for broader user groups that today satisfy their individual mobility demand with public transport services (e.g. commuters) if shared-mobility solutions reduce mobility costs. Second, assuming that the trip planning of two independent individuals is unaffected by a shift in societal mobility approach, the total mileage driven increases because of empty journeys of the shared automated vehicle between two successive users. Depending on different assumptions and scenarios, for instance (Trommer et al. 2016) expects increases in total mileage between 2.5 and 8.5% by 2035. This would mean that increased mileage would likely offset parts of potential safety gains in absolute terms, even if automated vehicles would turn out to be safer per mile than the average human driver today (Groves and Kalra 2017).

6 Conclusion

A lack of empirical data and suitable proxies to assess the CAV impact on accident risk makes decisions by policymakers, society and businesses very difficult. As a result, public and political debates of CAV's future implications on society and risk tend to be based on simplified and biased assumptions, which are (not yet) based on scientific evidence. From an insurance point of view, this presents a fundamental challenge, as the business model of motor insurance is directly dependent on accident risk.

Given these challenges, we have described current motor insurance risk exposure and risk characteristics and have used findings from accident research as well as available data on Waymo's CAV fleet to qualitatively assess the (insurance-relevant) risk implications of this technology. In doing so, our research shows important findings for insurers and regulators.

Empirical data indicates that vehicles equipped with ADAS systems of level 1 automation indeed contribute to road safety. However, from an insurance perspective, the decreasing impact on accident frequency will likely be (partially) balanced as the average loss amounts will increase due to technologically driven inflation and the higher complexity of repair work as well as risk compensation resulting from more intensive driving. We describe why those findings for lower levels of automation cannot just be applied analogously to vehicles with higher levels of automation capability and we use a comparison of disengagements (automated Waymo vehicle fleet) and accidents (human-driven fleet) per million driven kilometres to illustrate that (at least the current) performance of automated driving vehicles does not seem to be superior to human drivers.

From a regulatory point of view, this comparison is not able to precisely quantify the future risk exposure of vehicles with high and full automation but indicates that the promise of accident-free traffic is based on fragile grounds. We propose that CAV vehicles should be subject to close monitoring of their actual risk impacts. This monitoring should be conducted by independent and interdisciplinary institutions. Here, the insurance industry is one of the key stakeholders and bridging the gap between accident research and insurance industry knowledge can ground considerations of the inherent societal costs of CAV technology (Casualty Actuarial Society 2018; Finkel and Gray 2018). Stating this, the current approach of disengagement reporting does not allow for a transparent assessment of possible risk implications and opens the risk that regulatory and economic decisions to introduce CAV technology are based on illusive assumptions. This could turn out to be negligent if potential faulty assumptions lead to a reallocation of investment budgets for conventional road traffic safety strategies also taking into

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account vulnerable manual road users (e.g. pedestrians, bicyclists, motorcyclists, etc.) in more realistic scenario which is highly exposed to mixed-traffic scenes.

Due to the surrounding uncertainty related to CAV insurance risk analysis, further actuarial analysis and research are needed to prepare the insurance sector for a possibly changing risk landscape in the future. To proactively prepare for these changes, a more short-term measure of motor insurance companies is to explore accident data sets of different ADAS systems (level 1 and level 2 automation) already covered insured fleets. That said, a major challenge for this is the granularity of data gathered for traditional motor insurance pricing, which does not always allow identification of the technology's presence in vehicles (Casualty Actuarial Society 2018). With a long-term focus on vehicles with higher levels of automation, the adjustment of pricing models that currently focus on proxies to account for human driver's individual risk has to be replaced with a pricing model to reflect the reliability of the automated driving system. As transparent and longstanding loss data for this is missing, insurers have to build up interdisciplinary know-how to expand today's actuarial driven pricing knowledge with deep technical know-how about CAV hard- and software vulnerability. Furthermore, as driving capabilities of CAV could fluctuate with newly introduced software updates, pricing data could be exposed to higher variability.

With describing risk-relevant aspects, this paper provides a qualitative but more granular assessment of CAV's potential risk impact than existing quantitative forecasts of CAV's impact on the motor insurance premium. The results of the existing forecasts highly differ from each other contingent on the publisher (i.e. consulting firms or German Insurance Association), indicating that a lack of empirical data leaves space for a highly biased debate on the issue. This paper provides additional value to the insurance-related discussion by broadening the scope from a focus on absolute premium volume to crucial strategic questions such as the characteristics of risk exposure and customer interfaces. Here, our analysis shows that CAV will have a significant impact on the inherent risk characteristics of the motor insurance business. Beyond that, a shift in societal mobility approach with a changing customer interface will also have a strong impact on the risk exposure of the motor insurance market.

Referring to the possible changes of motor insurance risk characteristics, we emphasise the current smoothing impact of accident risk to the overall volatility of annual motor loss insurance loss expenses. The relevance of this risk could decrease with CAVs on the road, but this is still uncertain and accompanied by significant adverse side effects. In addition, the volatility could further increase due to possible correlated accident events and the emerging risk of cyber-attacks as well as accumulation loss events resulting from platooning. A declining relevance of regular accident occurrences would just enhance this volatility-increasing effect. This means the required risk-capital for a given volume of written motor insurance premium will also increase.

The increasing volatility of losses and the potential correlation of emerging (automotive) cyber-risks with other insurance lines of business present challenges for the management of loss accumulation risk of insurance companies. It is important that the changing loss pattern of the future motor insurance business adequately matches the risk-appetite and capacity of the risk-taking insurance company. For (smaller) insurance groups with a focus on retail property and casualty insurance risks and limited risk-taking capacity, risk-transfer to reinsurers will likely be more relevant to smooth the unbalancing impact on the net risk portfolio.

Given the already competitive environment of the motor insurance market in saturated markets together with the low profitability[9] and the expected increasing volatility of losses, we expect the return on risk adjusted capital (RORAC) to decline and lead to a higher consolidation within the motor insurance market. This is even fostered by the described potential shifts in societal mobility leading to changing customer interfaces towards commercial customers. As a result, we find that primary insurers focusing on private retail motor insurance face strategic risks to their business model. However, the development and penetration of market-ready CAV especially of these with higher levels of automation required for fully service-based mobility approaches (level 4 and 5 automation) take several years or even decades so that the significant changes described in this analysis will proceed on an evolutionary rather than a disruptive basis.

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[9] The average gross combined ratio of the motor insurance business between 2010 and 2016 in the German market is 102.2%. The combined ratio is the ratio of expenses for insurance operations and insurance claims to premiums.

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