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The current paper proposes a data analysis method to evaluate the impact of vehicle-technology evolution on road safety based on a recent and extensive accident dataset (1.3 million vehicles in 2017 and 1.7 million in 2018, Italy). Seventeen models of vehicles equipped with an event data recorder were selected for acquiring data, including the distances travelled by the vehicles during the year, and were aggregated by their year of initial registration and model. This unique information in conjunction with the accident datasets enabled a consistent estimation of risk exposure and accident rates for various subsets of vehicles. Thereafter, the comparative analysis of accident rates revealed an improvement in the road safety along with a significant variation between various vehicle models that approximately ranged from 5–10 accidents per million kilometres. Moreover, the accident rate reduced after the electronic stability control system was mandated for vehicles in the market, exhibiting variations in the range of 15–30% for serious accidents that were dependent on the vehicle model. Further safety improvements were identified for the latest generation of vehicles equipped with more advanced technologies such as the autonomous emergency braking that can reduce the accident rate up to 38%.

Keywords: road safety; accident rate; autonomous emergency braking; electronic stability control; advanced driver-assistance systems; black box

1 Introduction

Globally, around 1.35 million people perish in road accidents every year, accounting as the first cause of death of young people between 5 and 29 years of age (World Health Organization, (European Commission, 2020)). Although the road safety levels in developed nations have improved with a 50% reduction in deaths in 2017 as compared to 2001 and 20% as compared to 2010, the European Commission underlines that the progress has slowed, and the human and social costs resulting from the road accidents have increased over the last five years.

In past decades, several initiatives have been proposed at the European and global political levels. For instance, the United Nations General Assembly in 2010 proposed a "Global Plan for the Decade of Action for Road Safety 2011–2020" to reduce the number of road accident victims (UN Road Safety Collaboration, 2010); in 2015, the commitments were confirmed with the approval of "The 2030 Agenda for Sustainable Development" (United Nations, 2015). Recently, the UN and WHO promoted the "Partnership for Safer Journeys", a project that is aimed at ensuring road safety of personnel and vehicles working for the United Nations (United Nations & World Health Organization, 2019).

In May 2019, the EU institutions promulgated a provisional political agreement on the revised General Safety Regulation: new safety technologies[1] will be mandated in European vehicles by 2022, in addition to the *anti-lock braking system* (ABS) and *electronic stability control* (ESC) that were mandated from 2004 and 2011, respectively. The General Safety Regulation, which will be enforceable on new vehicles from July 2022, has been officially reviewed and implemented in a European Regulation in November 2019 (European Parliament, 2019).

In context, *advanced driver-assistance systems* (ADAS) can be defined as vehicle-based intelligent safety systems that improve road safety in terms of crash avoidance, crash severity mitigation, protection, and post-crash phases (European Commission, 2018). However, certain studies reported that the adoption of these vehicle safety solutions may reduce the attention of the driver towards primary driving tasks,

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[1] Proposed list of new mandatory safety features in May 2019: https://ec.europa.eu/docsroom/documents/34588. See Article 7 of the Regulation (EU) 2019/2144 for the revised safety equipment for passenger cars and light commercial vehicles.

thus increasing the potential risk level (Dunn, Dingus, & Soccolich, 2019). In contrast, other studies (Hojjati-Emami, Dhillon, & Jenab, 2014) reported that ADAS can especially help young drivers compensate their less experience in driving tasks and additional age-related developmental factors. Moreover, as safety improvements derive from a complex mix of causes related to driver behaviour, vehicle performance, and environment conditions, they are pursued by warning actions as well as direct intervention in collision situations.

Therefore, the focus of this study is to investigate the global impact of these technology improvements on road safety, which was measured using observations of accidents for a wide set of monitored vehicles categorised based on their generation.

The safety impact of various ADAS solutions cannot be easily isolated owing to their conjoint installations or optional presence in different versions of vehicles. Thus, the age of each vehicle model can be used as a proxy to identify its generation based on two relevant milestones in the evolution of vehicle technology, as described herein.

Moreover, a radical change has been recognised in vehicle features since ESC[2] was first implemented in 2014 for all new vehicles sold in EU (ERTICO, 2014). In addition, a further vehicle-technology innovation was detected with the introduction of the more recent *autonomous emergency braking (*AEB[3]) system as a standard in new vehicles.

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[2] The ESC system is an active safety system that prevents vehicle skidding when the driver takes a wrong turn or loses control of the vehicle. It is an extension of the ABS technology that includes speed sensors and independent braking for each wheel. The ECS system provides a consolidated solution and has been mandated since November 2011 for all new vehicle types and has been made standard since November 2014 for all new vehicles sold.

[3] The AEB systems detect approaching vehicles or other road users by usually measuring their position and speed, and these systems apply braking to either prevent a forthcoming

Therefore, the relevance of these two ADAS and their distribution in the market can be considered for the following vehicle classification:

- NO ESC vehicles generation consider vehicles introduced in the market before ESC was mandatory, identified as “no ESC”,
- ESC vehicles generation comprise vehicles registered after the ESC became mandatory, identified as “ESC”; however, this generation excludes vehicles equipped with AEB, and
- AEB vehicles generation include models equipped with both ESC and AEB, identified as “AEB”.

The analysed data source comprised an accident dataset of vehicles that were registered in Italy and equipped with event data recorders (EDR), also known as “black boxes”, for insurance purposes. In addition, this specific data collection method provided relevant information acquired by the vehicles regarding their average annual distance travelled. This information is not generally available in the national statistics on accidents, which poses as a limitation for comparing accidents of vehicles pertaining to various sets. In certain studies such as Beck, Dellinger, & O’Neil (2007), only the estimated values of global annual distance travelled were used. Thus, the current study fulfilled this research gap by measuring the travelled distance data of each vehicle with the EDR instead of using the national statistics. The reliability of this kind of

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collision or reduce the impact severity. There are two major types of AEB: the “city-AEB” or “low-speed AEB” that can apply brakes to sufficiently avoid a collision for speeds up to 30 km/h or 50 km/h by analysing information from the camera or LIDAR sensors; in addition, the “AEB” can operate at faster speeds to support a driver who tends to apply inadequate pressure on the brakes in an emergency situation.

measurement ensured an effective estimation of the risk exposure of the observed models based on other estimations such as Williams, Chigoy, Borowiec, & Glover (2016). As a proxy of this information in case of unavailability, the number of observed vehicles or their insured days over the year were assumed to be the risk exposure (Cicchino, 2017).

The accident rate, defined as the number of accidents in relation to traffic exposure and determined from the average annual daily traffic, is commonly used (Van Raemdonck & Macharis, 2014) to identify black spots and assess the risk of road sections based on safety levels. The accident rate estimates the probability of an accident occurring per million kilometres travelled. Nonetheless, the current study refers to the accident rate based on various selected subsets of vehicles, excluding specific road infrastructures.

Therefore, the accident rates can be computed for wide sets of vehicles throughout the year for comparing the safety levels of various vehicle generations. Although the current level of data aggregation could not be represented for a single vehicle, the number of accidents for each examined vehicle model was known by the year of its initial registration. After an initial data cleaning process, 1.3 million vehicles in 2017 and 1.7 million in 2018 were included in the observation dataset. Notably, the extent and volume of the observed dataset was similar to that used in the national statistics on accidents, which ensured the random consideration of various factors in the sampling, for instance, heterogeneous drivers, different driving context (urban, rural, motorway), and the types of accidents. Therefore, the potential polarisation problems associated with selection of small sample sizes were mitigated.

The literature on the impact of vehicle-technology evolution on road safety has been analysed by investigating the main methods used for evaluations and reported in

Section 2. The methodology proposed in this work is presented in Section 3, with the description of the dataset, the classification of vehicle sets into generations and the definition of the indicators used. Finally, the results are discussed in Section 4.

2 Literature review

The impact of vehicle-technology evolution on road safety is highly complex for evaluation. In general, a cause–effect methodology cannot be applied for identifying the principal functions to support driving tasks and the related risk mitigation, because a behavioural adaptation can influence the risks and introduce over-reliance on system capabilities (Spyropoulou, Penttinen, Karlaftis, Vaa, & Golias, 2008). Thus, certain research approaches attempted to evaluate the global contribution of these systems towards reducing the observed road accidents. Nevertheless, the risk reduction can be estimated using various methodologies in case a direct observation is not possible. For instance, Bekiaris and Stevens (2005) presented a wide and general framework describing a risk assessment process. In addition, extensive scientific literature evaluating the safety benefits of ADAS has been reported by the European project SafetyCube[4] as well. In general, the methodologies proposed for evaluating the effect on road safety follow different approaches and are often applied on a specific driving-assistant system.

A *backwards-looking approach* represents analysing accidents data selected according to scenarios in which the ADAS could have a direct influence (Rizzi, Kullgren, & Tingvall, 2014) (Cicchino, 2017). In certain studies, the focus is only on a set of vehicle models that are equipped with known technology (Doyle, Edwards, &

[4] https://www.safetycube-project.eu/publications/

Avery, 2015). In addition, the data collected by insurance companies were used by Anderson et al. (2011) to assess ADAS solutions: the probability or the severity reduction of the event was estimated based on injuries or deaths data. Thereafter, the benefits were inferred on the population considering the share of the accident type examined as compared to the total. Moreover, Benson et al. (2018) proposed an *aggregate projection* to represent the impacts on road safety. They assumed the effectiveness of the selected ADAS in mitigating the risk of a specific accident and related them to the number of accident cases associated with the identified scenarios.

One of the most commonly adopted estimation techniques for assessing the reduction in number of accidents is based on the probability ratio between vehicles with and without ADAS (Thomas, 2006) (Chouinard & Lécuyer, 2011) (Lyckegaard, Hels, & Bernhoft, 2015). This ratio is termed as the *odds ratio*, and it measures the correlation between two factors by assessing the frequency of an event in a group and the frequency of the same event in a control group. The data required in this approach include the number of accidents involving a set of equipped vehicles for scenarios with or without the contribution of the selected system, as well as the number of accidents involving a set of vehicles not equipped for the same scenarios.

Moreover, the *meta-analyses* approach can be implemented to impart robustness to the estimations by merging data from independent research and integrating various evaluations. This method aims at compensating the gaps in data and results presented in certain studies with the availability offered by related research (Bayly, Fildes, Regan, & Young, 2007) (Fildes et al., 2015).

The impact of ADAS on road safety can be studied using *integrated approaches* (Wilmink, 2008) (Lai, Carsten, & Tate, 2012) including the economic benefits of estimating the percentage reductions in accidents, injuries, and deaths.

The *surrogate safety assessment model* (SSAM) is another estimation technique proposed in the literature that combines traffic microsimulation with conflict analysis tools. The level of road safety in a defined scenario is assessed by examining the frequency and characteristics of potential vehicle–vehicle and vehicle–pedestrian collisions in road traffic generated during the simulation (Kim & Autores, 2017) (Zoghi, Siamardi, & Tolouei, 2010). The advanced technologies on vehicles can be simulated by modifying their behavioural parameters, which however are required to be appropriately calibrated and validated in the simulation model. Common surrogate safety indices include the minimum time-to-collision, minimum post-encroachment, or the maximum speed of vehicles involved in the potential conflict (Johnsson, Laureshyn, & De Ceunynck, 2018).

Furthermore, several studies have tested the assistant driving solutions and the reaction of drivers through a *virtual laboratory* that simulates driving conditions. This method is advantageous because the experiments can be repeated in a controlled environment, which can be specifically modified to test the ADAS functions (Maag, Mühlbacher, Mark, & Krüger, 2011) (Butakov & Ioannou, 2015) (Saito, Itoh, Inagaki, & Member, 2016).

Finally, one of the most direct method for examining the safety performance of ADAS solutions is the *laboratory test* on real vehicles. The simulated road environment attempts to reproduce typical accident scenarios for evaluating the safety behaviour with codified procedures. The European New Car Assessment Programme (Euro NCAP), for instance, assesses the safety performance of a vehicle based on a standard scoring system. After years of testing vehicles for adult safety, child safety, protection of vulnerable road users (VRU), the operation of the Safety Assist program has been recently implemented, including ESC and AEB tests.

Table 1 summarises several results obtained from the literature review regarding the performance of the selected ADAS standards: ESC and AEB[5]. In particular, the percentage of accidents reduction is distinguished according to the total number of accidents and the accidents with injuries (serious accidents).

Thomas (2006) proposed an analysis regarding the ESC to estimate the reduction of accidents in Great Britain utilising the odds ratio based on data of 8685 vehicles equipped with the ESC system and 41318 control vehicles (without ESC) from the UK road accident database (STATS 19). Their results reported a reduction of 3% in all the accidents when the vehicle was equipped with the ESC, whereas a 19% and 15% reduction were reported for accidents with serious injuries and those that have proved fatal for at least one of the occupants, respectively. A similar approach has been proposed by Lyckegaard et al. (2015) using the Danish database of accidents considering at least one injured personnel, as recorded by the police between 2004 and 2011. In addition to the odd-ratio method, they also used a logistic regression model to evaluate other factors influencing the effectiveness of the system: age, gender, driving experience of the driver, year of initial registration and weight of the vehicle, and features related to accident scenario, such as visibility, light, speed limit, or road pavement conditions. For the vehicles equipped with ESC, their results indicated a reduction of 31% in the risk of an accident involving a single vehicle, and the percentage increased to 33% upon considering accidents with injuries. Furthermore, the effectiveness of the ESC in Canada was investigated by Chouinard and Lécuyer (2011) using the road accident data available in the National Road Accident Database (NCDB), the odd-ratio approach, and a logistic regression model. The reduction in the accident

[5] See footnote 3

risk for vehicles equipped with the ESC system was estimated at 41.1%, which increased to 49.3% upon considering accidents with injuries and to 51.1% for accidents occurring on the pavement covered by snow or ice. As remarked by Wilmink (2008), the ESC system reduces the frequency of accidents along with decreasing the collision speed of the vehicle. Consequently, the expected impact on the seriousness of the accident was determined to be positive. For instance, the project eIMPACT utilises an integrated approach to validate the potential impact in terms of safety for the ESC system: a reduction of 5.7% for deaths and 14% for injuries caused by road accidents. The project additionally investigated the impact of the AEB systems that are able to reduce the impact speed by increasing passive safety, and thus, diminish the consequences of the road accidents. They stated that a 100% diffusion of the AEB system on board of all vehicles in Europe can result in a drop of 7% for the number of deaths and 7.3% for the injured personnel.

In addition, the safety impact of AEB implementation was investigated by Cicchino (2017) with data analysis of accidents for selected vehicles involved in rear-end crashes. The total insured days of vehicles were used as the exposure data. However, the dataset included detailed information such as that on driver profile (e.g., age, gender, insurance risk level). The results depicted a 50% decrease in the crash rate for vehicles fitted with the AEB system, whereas the reduction was around 43% for low-speed AEB systems. Upon considering accidents with injuries, a 45% and 56% reduction could be estimated for low-speed AEBs and extra-urban AEBs, respectively. The meta-analysis study conducted by Fildes et al. (2015) confirmed a significant reduction in accidents (38%) for the vehicles equipped with AEB. Moreover, an accidents dataset obtained from 12 insurance agencies operating in Great Britain was analysed by Doyle et al. (2015). For two models equipped with the city-AEB, an overall reduction of 26.1% was estimated for accidents with injuries. In addition, Rizzi et al. (2014) used the Swedish Transport Accident Data Acquisition (STRADA) of the Swedish Transport Agency on accidents with at least one injured person to evaluate the effectiveness of the urban-AEB system (low-speed). The study considered 3922 accidents involving six models of vehicles equipped with the AEB system and 21 vehicle models not equipped with the AEB system. The study reports a 46% reduction in the number of rear-end collisions with AEB for low-speed accidents (less than 50 km/h) and an overall reduction of around 29–41%. According to Benson et al. (2018), the aggregate analyses based on rear-end collisions recorded in the USA in 2016 estimated an impact of AEB systems on almost 2 million accidents, which represent 29% of the total accidents.

3 Methodology

The principal aim of the current study is to estimate the impact of vehicular technology evolution on road safety, which was determined by analysing an accident dataset acquired from 17 vehicle models—all equipped with EDR for insurance purposes. As charted in Figure 1, the method follows a simple approach that can be easily replicated for other cases, if a similar dataset is available. In addition, the sets of vehicles could be compared using the aggregated values of accidents and travelled distances. The key fields of the database: damage threshold, vehicle models, and initial registration year are described in Section 3.1; the available models were classified in Section 3.2 as representative vehicle categories: market segments for each model and vehicle generation. Then their accident rates were calculated as aggregated values for the year of initial registration, which reveals if the vehicles were fitted with ESC and AEB systems and thereby their generation. The annual distances travelled by vehicles were aggregated according to the year of registration and model and was used to estimate the effective risk exposure and the accident rates related to specific subsets of vehicles in Section 3.3.

3.1 Dataset

The most popular car models on the market were identified based on the registration data published by Unione Nazionale Rappresentanti Autoveicoli Esteri[6] for 2018. In addition, 17 models of vehicles were selected for the accidents recorded in the years 2017 and 2018. Their initial registration year was used to deduce the three vehicle generations based on the fitted ADAS equipment (NO ESC, ESC, AEB). The commercial names of the models were not reported, because providing opinions on the safety level of specific models is beyond the scope of this study. Moreover, the current data aggregation level is inadequate for fulfilling this aim. Notably, the total distance travelled in the 2018 dataset was approximately 13 billion kilometres with 150,000 recorded accidents.

In 2017, the recordings of the total distance travelled was lower owing to the less number of vehicles installed with black boxes. The reduced number of recorded accidents (<100,000) was affected by their higher severity and assessed based on the reported damage. Thus, the method for selecting accident data was distinguished for the two datasets:

- the data in the 2018 dataset refer to all the accidents for the selected vehicle models,

[6] Association of foreign automobile manufacturers operating in Italy.

- an accident was included in the 2017 dataset only if it caused a total damage greater than € 10,000.

The two groups of data were used to estimate accident rates for two levels of accident severity. Therefore, the safety phenomena cannot be feasibly compared for two years, because the accident data included in the 2017 dataset were more serious than others.

The models observed with less than 30 vehicles for a particular year of registration or with an average annual travelled distance of less than 2000 km were discarded to clean the dataset for a robust estimation. Moreover, only vehicles with the years of first registration after 2000 were included. After the cleaning process, the dataset included around 1.3 million vehicles for relevant accidents and 1.7 million vehicles from the 2018 dataset (all accidents).

As reported in Figure 2, the average annual distance covered by vehicles was not uniform with their age. The average annual distance covered by the vehicles increased as the age of the vehicles decreased; the mileage of the last year was excluded as the vehicles could be registered on any month of the year. In general, new vehicles travelled much more than the older ones, and this was a common occurrence for both the serious (2017) and all accidents (2018) dataset. The evident trend of average annual distances verified the significance of introducing the risk exposure variable as the distance covered by the vehicle for estimating the accident rate. Moreover, this could be relevant if the comparisons included sets of vehicles with different age, where the number of vehicles may not represent a reliable risk exposure variable.

Research has demonstrated that the relation between the crash frequency and risk exposure may not be linear, especially at higher values. However, this phenomenon was mainly observed when the capacity constraints of the considered traffic flow produced a saturation effect on the given road section (Hakkert & Braimaister, 2002). A similar behaviour can be observed for risk estimation focused on vehicles, where the annual travelled distance was assumed as the risk exposure. Indeed, higher values of this parameter may indicate a greater driving experience of the driver, and therefore, a lower crash frequency for the observed vehicle. Nevertheless, the average annual distance used in this study is not indicative of single drivers but towards wide sets of vehicles, which yield far from extreme values. In general, the annual distance travelled by a vehicle in Italy is on average around 10,000 km/y, whereas that for the EU is 12,000 km/y (Enerdata, 2020). The values presented in Figure 2 are further lower for the various subsets of vehicles categorised by model and age, where the maximum annually travelled distance was less than 16,000 km/y. According to Pennisi (2005), the long annual distances observed for 10% of cars were greater than 23,000 km/y.

In context of these values and that reported in Figure 2, we can assume that the non-linearity between the crash frequency and risk exposure would be negligible for the average annual distances covered by the vehicles.

The number of serious (2017) and all accidents (2018) for the 17 selected models aggregated by the year of initial registration is depicted in Figure 3a and 3b, respectively. The total number of serious accidents ranged between 2500 and 7500, and up to more than 10,000 considering all accidents, depending on the age of the vehicle. Although the most popular cars were selected, the charts in Figure 3 display a great variability in the number of accidents for various models—less than 100 for certain vehicles, whereas more than 2000 for others.

3.2 Vehicles classification according to their generation

The vehicles can be equipped with various safety devices, which are optional in certain cases. Therefore, the knowledge of the ADAS configuration of a specific vehicle involved in an accident is vital for the safety analysis, because this information is not available in official statistics. Owing to this reason and considering the aggregation level of the current dataset, the year of initial registration was utilised to infer the various models of each vehicle generation. In addition, the three generations of vehicles were identified based on their equipment with or without the ESC and the AEB, which are considered as benchmark ADAS. This classification has been derived based on EU regulations (European Parliament, 2009) and information on safety systems fitted as standard and available on Euro NCAP[7].

In particular, the vehicles registered after 2014 were considered fitted with an ESC, whereas those with an initial registration year prior to 2011 were assumed to be not fitted with an ESC, as confirmed by the safety-assist information on Euro NCAP. Moreover, data referring to intermediate registration years were discarded for classifying information based on ESC owing to the unavailability of the model (Table 2).

The influence of technology equipment on the evolution of vehicle generations was determined by aggregating the models in four representative classes of market segments for similar models (Table 2), and thereby calculating the corresponding average accident rates. The models in AEB vehicles generation were further reclassified based on aggregation in two categories: *A-Mini + B-Small* and *C-Medium + D-SW/SUV*. Subsequently, the accident rates were averaged including only the models fitted in the specific year of registration (Table 2) with the AEB system. However, a disaggregated analysis could not be conducted for AEB and city-AEB as this level of

[7] https://www.euroncap.com/en/vehicle-safety

detail was not available in the data source. Furthermore, no information was present on the location of accidents, e.g., urban or extra-urban roads, to categorise low-speed AEBs.

3.3 Safety indicators and data analysis

The total distance travelled by the vehicles during each of the two years (2017 and 2018) were aggregated by registration year and model to calculate the average annual distance travelled by the selected models. The data structure comprised the following variables:

- Observation year (O)
- Vehicle model (M)
- Initial Registration year (R)
- Number of vehicles of a model for a year of registration (V [O, M, R])
- Average annual distance travelled (D [O, M, R])
- Number of recorded accidents (A [O, M, R])

As stated, the accident rate (AR) was used as an indicator for the comparative analysis, which represents the ratio between the number of accidents recorded for a set of vehicles and the total distances travelled by all the vehicles included in the same set. Moreover, the aggregation level reflects a specific model for each registration year as

$$AR\ [O,M,R] = A\ [O,M,R]/(V\ [O,M,R] * D\ [O,M,R])\ . \quad (1)$$

In case the distance travelled by vehicles—representing the risk exposure to accidents for the current level of data aggregation—is not available, the accident rate could be calculated using the number of vehicles. In such situations, a simplified formula describing the simplified accident rate (SAR) as a ratio between the number of accidents to the number of vehicles of a given dataset can be expressed as

$$SAR\ [O, M, R] = A\ [O, M, R]/V\ [O, M, R]\ . \tag{2}$$

As reported in Figure 4, the estimated values of AR and SAR indices, aggregated by the year of registration of the models, display an incomparable trend both for the accident data collected in 2017 and 2018. The data collected on the distance travelled by vehicles provided relevant comparison between the accident rates of various vehicle generations.

The SAR of older vehicles appeared to be lower in 2018 when calculated using the number of vehicles owing to their lower annual distances. On the contrary, the AR of new vehicles decreased with an evident trend, when calculated based on the observed annual distances travelled. Thus, an initial general safety evaluation can be obtained based on the age of the vehicles observed: a vehicle older than 15 years is approximately 30% more likely to be involved in a serious accident as compared to one registered for two years.

For the 2017 data, the vehicles registered after 2004 exhibited a distinct trend of these two indicators.

Note that the model–year information has been utilised as a proxy for its safety features and design standards, according to the information available on public databases (Euro NCAP). However, human elements may affect the results as well (Mannering et al., 2016). For instance, personnel who are more sensible toward safety may opt to drive newer cars fitted the latest safety systems. Thus, the model–year comparison can capture the driver's preferences along with the vehicle features, which can generate an unobserved heterogeneity across the observations that cannot be solved owing to the available dataset. Nevertheless, the large number of observed vehicles, as compared to that used in national statistics on crash reports, ensured an adequate random sampling of various factors. In addition, the polarisation problems that can arise from the selection of small sample sets were mitigated. Therefore, the current study can be considered as a prototypal study that can be further refined with a wider dataset containing more extensive data (e.g., on drivers' features) to ascertain the influence of other factors on the results.

Furthermore, the data of relevant accidents highlight an evident phenomenon, where the average accident rate decreases for vehicles registered in the year corresponding to which the accident data was collected. This occurrence was observed for both the accident indices (Figure 4a) and can be explained as a greater prudence adopted by the users when driving a newly purchased vehicle. In addition, the superior technical conditions of new vehicles can additionally affect the reduction of the rates. Surprisingly, this phenomenon was not observed for the AR index deduced from all the accidents (2018, Figure 4b). Nevertheless, this interesting aspect requires further investigation and was considered beyond the scope of this study.

4 Results and discussion

4.1 Safety evaluation of ESC vehicles generation

According to the classification proposed and explained in Section 3.2 ('Vehicles classification according to their generation'), the total number of vehicles under various categories is reported in Figure 5 for serious and all accidents. The two vehicle categories (C-Medium and D-SW/SUV) that include models of segments higher than others were expectedly represented by a small number of vehicles, whereas almost 900,000 vehicles were observed for the B-Small category.

The average accident rate was higher for each model selected from the NO ESC generation as depicted by the disaggregated values presented in Figure 6. In addition, the influence of the two primitive generations of vehicles—NO ESC and ESC—was more significant for serious accidents (Figure 6a). Moreover, the variation in the accident rates was determined for the most-used models according to the segments A, B, and C (Figure 7). The reduction of the AR was almost constant in the range 15–17% for the corresponding models of ESC vehicles generation in serious accidents. However, the estimation for the D-SW/SUV category could not be compared with others owing to the limited quantity of available data (Figure 5).

Furthermore, the reductions in ARs of ESC vehicles generation in all accidents were estimated to be 5% for the vehicles belonging to category A, 11% for those in category B, and 13% for category C.

4.2 Safety evaluation of AEB vehicles generation

The impact of technology improvements of recent vehicles (AEB vehicles generations) on road safety was analytically evaluated only on the models fitted with the AEB system as a standard from a specific year of registration. Consequently, the models with this system as optional (Table 2) were excluded. This consideration reduced the number of the selected models, and only the vehicles equipped with the standard ESC as well were compared to facilitate a prudential estimation and refined recognition of the safety contribution provided by the advanced generation of vehicles.

The vehicles of Model5, Model9, Model12, and Model15 could be directly compared using the serious accidents dataset; in addition, Model8 can be included for the all accidents dataset.

The four vehicle model categories used in the first analysis (Section 4.1 ‘Safety evaluation of ESC vehicles generation’) were merged into two categories, considering the less number of vehicles. As depicted in Figure 8, the number of vehicles in the new categories confirmed the greater sampling rate of the low-end vehicles (A+B) at 40,000 considering all the accidents, whereas that of the high-end vehicles (C+D) were less than 30,000. However, the number of vehicles equipped with AEB systems is similar in the two categories. Expectedly, the dataset size in the AEB vehicles analysis is smaller in comparison to the total dataset owing to the recent diffusion of this system as standard in new vehicles.

As presented in Figure 9a, the data for serious accidents confirmed that the average accident rates decreased for the AEB vehicles generation in all the selected models, except for Model5. In particular, the AR of Model5 has not been reportedly disaggregated for the generation with AEB owing to its low number of recorded accidents (<40), which is not comparable with the values of other sets of vehicles. Although the positive effect on safety was evident for newer vehicles of Model5, its probable combination with an induced safer driving behaviour was relatively less distinct for the all accidents dataset (2018, Figure 9b).

Note that the accident rate aggregated by the model categories were weight-averaged based on the total distances travelled by the model vehicles in the categories instead of computing their arithmetic average. In addition, the aggregate analysis increased the reliability of the estimates for facilitating beneficial comparisons between the vehicle generations. In particular, the category including both A and B segments (A+B) with ESC and AEB generations for serious accidents (2017) was globally observed for more than 213 million km and 37 million km, respectively. For this model category, an average improvement of 20% was estimated (Figure 10) as the relative difference between the corresponding ARs. The accident rate reduction was further significant at 38% for the vehicles in the category C + D, which were observed with ESC and AEB generations for more than 91 million km and 63 million km, respectively. Although these aggregated estimations rely on a large number of vehicles and travelled distances observed, the current availability of data along with the recent introduction of AEB in the market allow references to only four such vehicle models. Therefore, this comparison is relatively less general to that reported for the ESC vehicle generation, and the confirmation of this preliminary result would require further data acquisition in the following years.

The AR was computed for all accidents (2018) as well, and it decreased by 23% for AEB vehicle generations included in categories C and D.

In addition, a negative safety effect was detected with an AR increase of 11% for the new vehicles in category A+B including all accidents. The available data for this category were extensive for ESC and AEB generations with more than 229 million km and 111 million km, respectively. Although these AR estimations appear to be reliable, they highlight a potentially critical phenomenon. However, further analysis requires to be performed including specific information on the types of accidents to clearly understand and explain the causes to confirm this unexpected safety effect.

5 Conclusion

This study analysed an extensive dataset—containing information collected using black boxes or EDRs installed on vehicles for insurance purposes—to estimate accident rates of various vehicle generations based on their technology evolution. Considering the market distribution, 17 models were selected and approximately 1.3 million vehicles for 2017 and 1.7 million vehicles for 2018 were observed. In addition, the black box data was useful for determining the annual distance travelled for each set of vehicles as an effective aggregate risk exposure factor. Moreover, three vehicle generations were identified based on the two relevant ADAS solutions introduced in the market—ESC and AEB. The data from the two years (2017 and 2018) were used to replicate the analysis according to the severity of the accidents that can be related to the damage caused by the accidents in this period. In particular, the 2018 dataset included all the accidents recorded for the vehicles, whereas the 2017 dataset comprised only the serious accidents that were identified with a damage greater than € 10,000.

The annual distances travelled by the vehicles—recorded by the EDR and used as vehicle exposure to calculate the accident rates for different sets of vehicles—confirmed that the estimations significantly varied when the number of vehicles in the set was considered as the risk exposure, which is commonly available in official statistics as well.

The initial analysis results highlighted the significant variation in the average accident rate observed for different models, which ranged approximately from 5–10 accidents per million kilometres. Nevertheless, the vehicle models were aggregated based on their market segments to increase the sample size, and thereby the reliability of comparisons among the vehicle generations.

The variation in accident rates for the ESC vehicles generation was more distinct for serious accidents with an overall reduction for the categories A-Micro, B-Small, and C-Medium in the range of 15–17%. The estimates indicated fewer benefits for all the accidents, and the ESC vehicles generation exhibited a reduction between 5% and 13%.

The road safety improvements posed by the AEB vehicles generation were estimated with around 10,000 vehicles from the 2017 dataset and 25,000 vehicles from the 2018 dataset. As the sample size was reduced owing to the less adoption of AEB systems than ESC in 2017 and 2018, segments were aggregated in two classes for reliable comparisons. For the serious accidents, the estimated reduction of AR was 20% on average for vehicles of segments A and B. Moreover, the AEB vehicles generation from segments C and D displayed a higher reduction of AR at 38% and exhibited a positive effect (23%) for all types of accidents.

Nevertheless, the AR for segments A and B increased unexpectedly (11%) for the AEB vehicle generations, when observing minor accidents as well. In addition, the variability of benefits was also confirmed by other studies that estimated accident reductions for AEB vehicles in the range 26–50%. Although the "anomalous" case was observed for all the accidents in segment A and B, the negative impact on the last generations of vehicles was not found in the examined literature. Therefore, this result requires datasets on minor accidents from other nations for further investigation and remains an open field for the research community. In addition, possible explanations can be considered for unobserved factors, such as the quality level of the AEB technology implemented in different model segments, or possible reduction of the attention level during driving tasks, which may affect more drivers of segments A and B.

Note that the age of the vehicles could influence the accident rate as well. In particular, the frequency of accidents was observed as higher on average for older vehicles. Thus, the age factor was related to the technological innovation, efficiency of the vehicle, and more advanced equipment in general, which characterise the recent generations of vehicles. Therefore, the comparisons of accident rates for various models were aggregated with different registration years after identifying the common vehicle generations.

Furthermore, the proposed methodology can be easily applied in other contexts, given that the simple approach is adopted and a similar dataset is available. Moreover, only the aggregated values of crashes and travelled distances were required for the vehicle categories to compare their accident rates. Therefore, observing the global trend of safety as a result of vehicle-technology innovation is the main practical significance of the study.

The information available in the current dataset was analysed to obtain estimations and extract the utmost possible information related to risk. Unfortunately, no detailed information regarding the accident type or driver features could be obtained to further correlate these relevant features to the risk.

Thus, future research can focus on accident scenarios and merge data from similar and complementary databases for a comprehensive analysis. In such cases, the variation in accident rates would reflect the types of accidents, which can be more appropriately designated to the selected ADAS for mitigating the connected risk.

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Data availability statement:

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

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Declaration of competing interests:

No potential competing interest was reported by the authors.

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Tables:

Table 1. Studies on estimations of accident risk reduction for vehicles fitted with ESC and AEB systems.

Type of ADAS	Reductions in crash rate [%]		Source	Method
ESC	Total	3	(Thomas, 2006)	Analysis of accident cases
	With injuries	19		
	Total	31	(Lyckegaard et al., 2015)	Analysis of accident cases
	With injuries	33		
	Total	41	(Chouinard & Lécuyer, 2011)	Analysis of accident cases
	With injuries	49		
AEB	Total	50	(Cicchino, 2017)	Analysis of accident cases
	With injuries	56		
	With injuries	38	(Fildes et al., 2015)	Meta-analysis
City-AEB	Total	43	(Cicchino, 2017)	Analysis of accident cases
	With injuries	45		
	With injuries	38	(Fildes et al., 2015)	Meta-analysis
	With injuries	26	(Doyle et al., 2015)	Analysis of accident cases
	With injuries	46	(Rizzi et al., 2014)	Analysis of accident cases

Table 2. Vehicle model classification, years of introduction of the standard, and optional ESC and AEB systems in the selected models.

Model	**Vehicles categories**	**First-year with standard ESC**	**First-year with optional AEB**	**First-year with standard AEB**
1	A-Mini		NO	NO
2	C-Medium	2015	2015	
3	C-Medium	2009	2015	
4	B-Small	2012	NO	NO
5	D-SW/SUV	2012		2017
6	B-Small	2014	NO	NO
7	B-Small	2012	2017	
8	C-Medium	2012		2018
9	A-Mini	2010		2017
10	B-Small	2014	2014	
11	A-Mini		NO	NO
12	B-Small	2009		2017
13	B-Small		NO	NO
14	D-SW/SUV	2014	2014	
15	D-SW/SUV	2009		2016
16	B-Small			2017
17	A-Mini	2015	NO	NO

Figures:

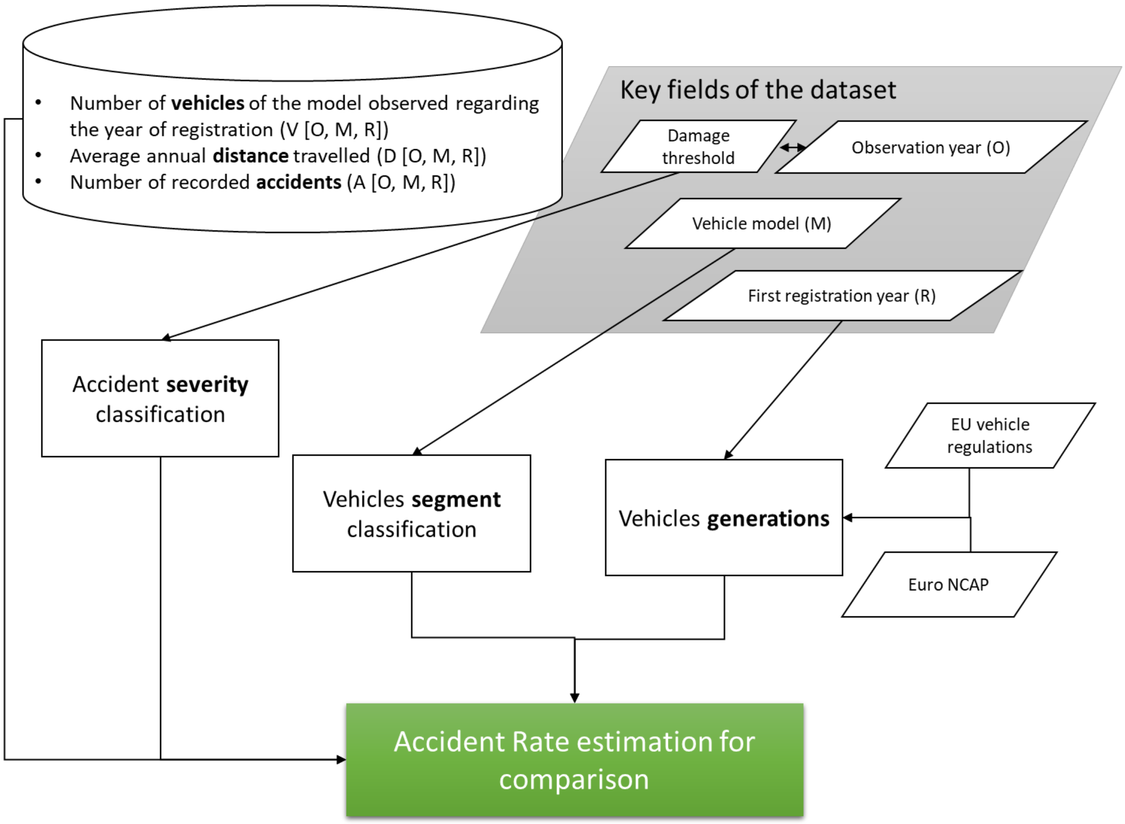
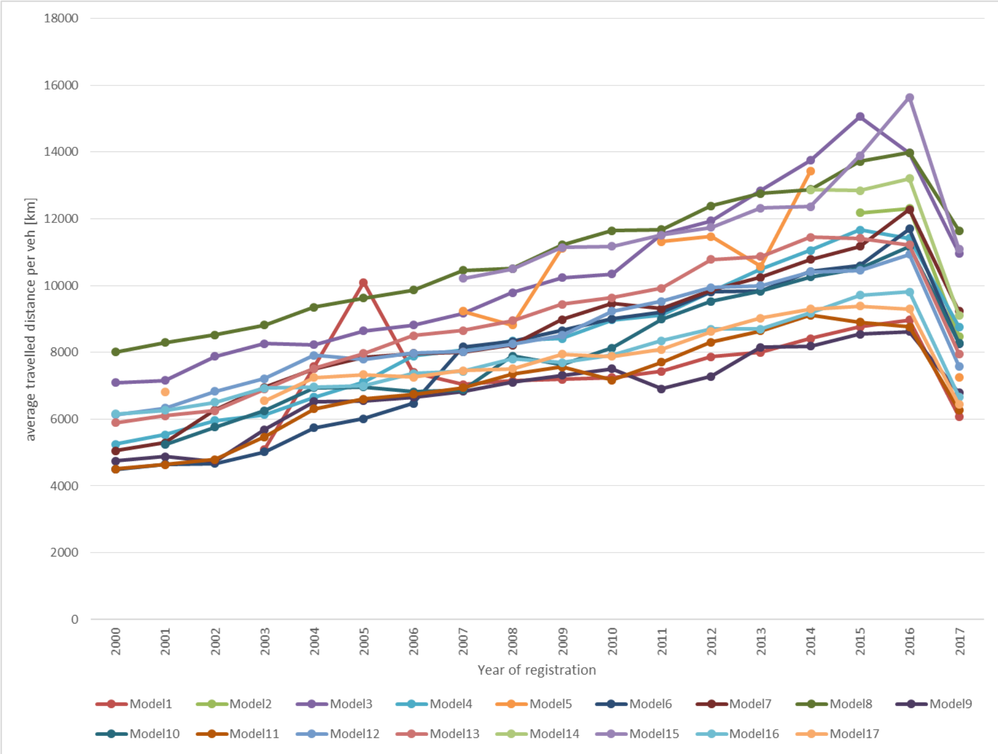
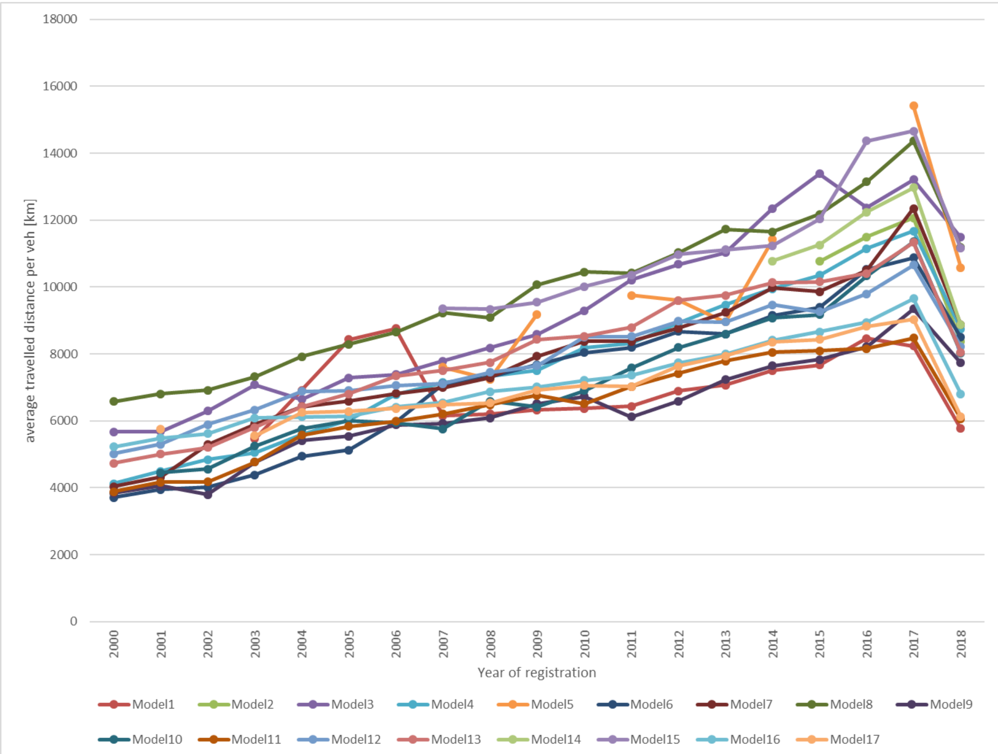


Figure 1



0
2000
4000
6000
8000
10000
12000
14000
16000
18000
average travelled distance per veh [km]
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year of registration
Model1
Model2
Model3
Model4
Model5
Model6
Model7
Model8
Model9
Model10
Model11
Model12
Model13
Model14
Model15
Model16
Model17

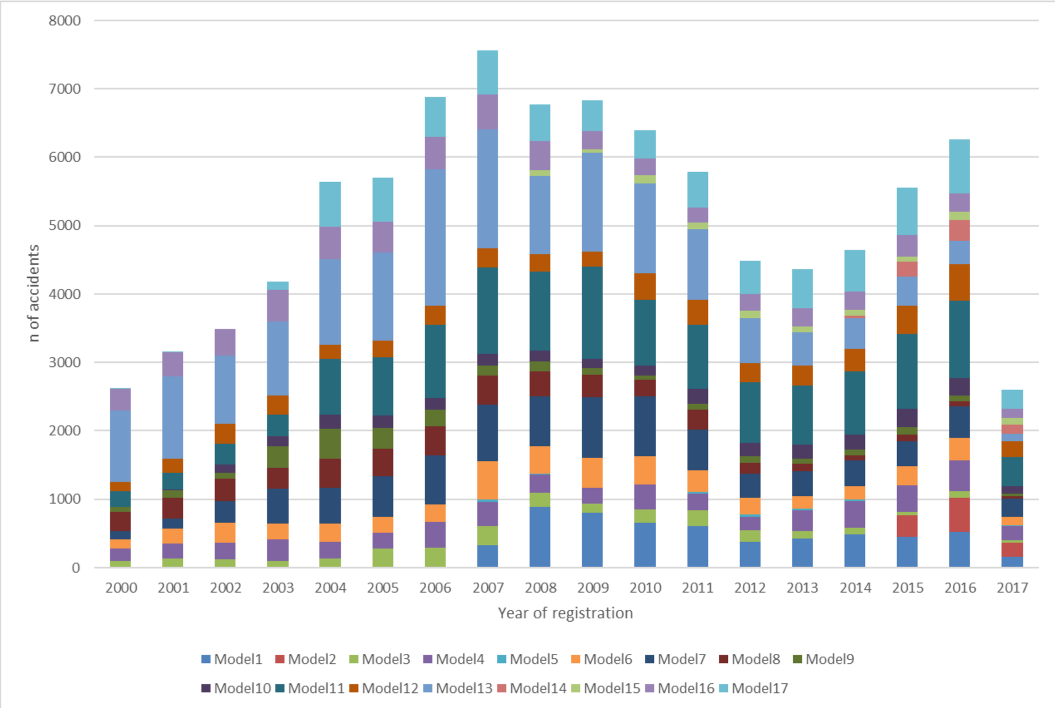
(a)



0
2000
4000
6000
8000
10000
12000
14000
16000
18000
average travelled distance per veh [km]
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year of registration
Model1
Model2
Model3
Model4
Model5
Model6
Model7
Model8
Model9
Model10
Model11
Model12
Model13
Model14
Model15
Model16
Model17

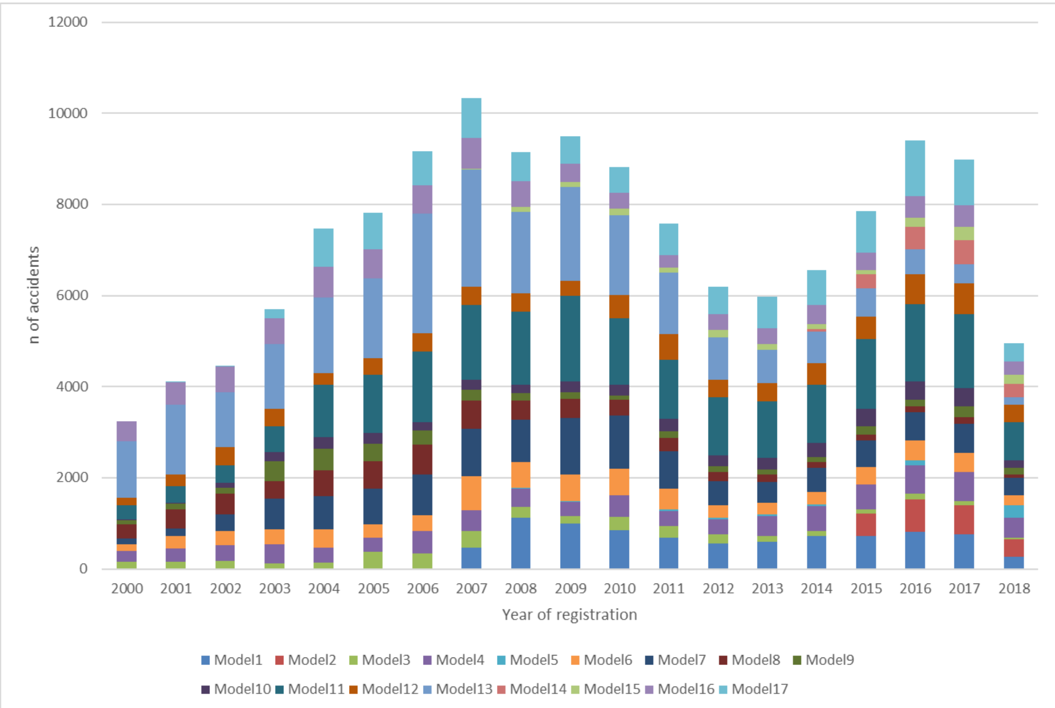
(b)

Figure 2



8000
7000
6000
5000
4000
3000
2000
1000
0
n of accidents
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year of registration
Model1 Model2 Model3 Model4 Model5 Model6 Model7 Model8 Model9
Model10 Model11 Model12 Model13 Model14 Model15 Model16 Model17

(a)



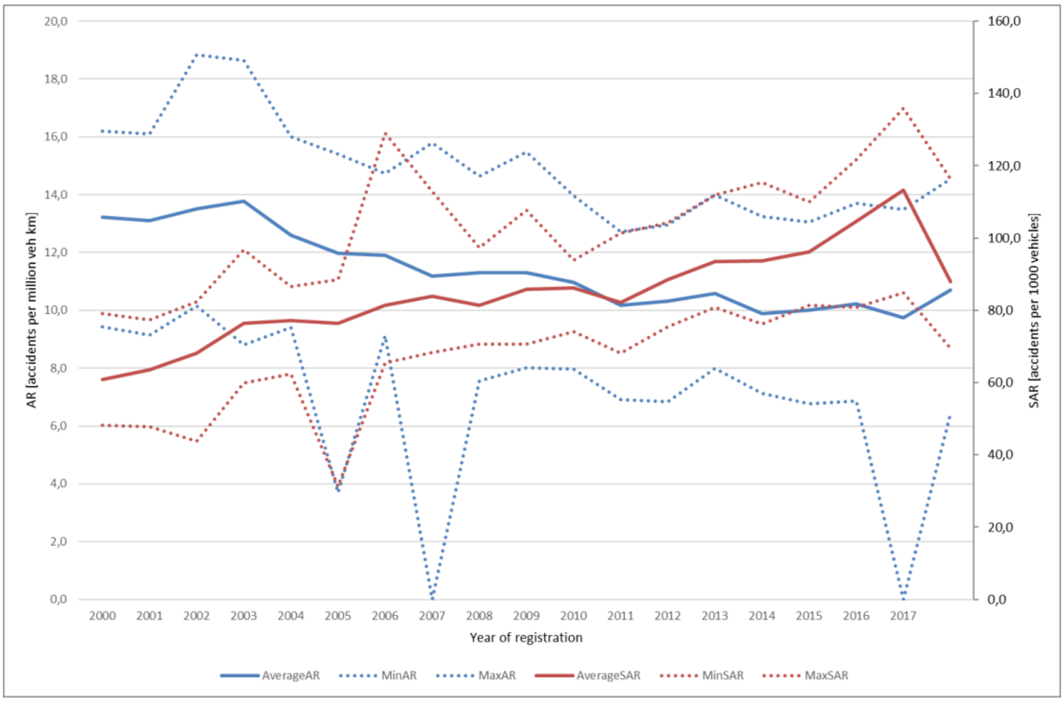
12000
10000
8000
6000
4000
2000
0
n of accidents
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Year of registration
Model1 Model2 Model3 Model4 Model5 Model6 Model7 Model8 Model9
Model10 Model11 Model12 Model13 Model14 Model15 Model16 Model17

(b)

Figure 3


20,0
18,0
16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
AR [accidents per million veh km]
120,0
100,0
80,0
60,0
40,0
20,0
0,0
SAR [accidents per 1000 vehicles]
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year of registration
AverageAR
MinAR
MaxAR
AverageSAR
MinSAR
MaxSAR

(a)


20,0
18,0
16,0
14,0
12,0
10,0
8,0
6,0
4,0
2,0
0,0
AR [accidents per million veh km]
160,0
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
SAR [accidents per 1000 vehicles]
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year of registration
AverageAR
MinAR
MaxAR
AverageSAR
MinSAR
MaxSAR

(b)

Figure 4

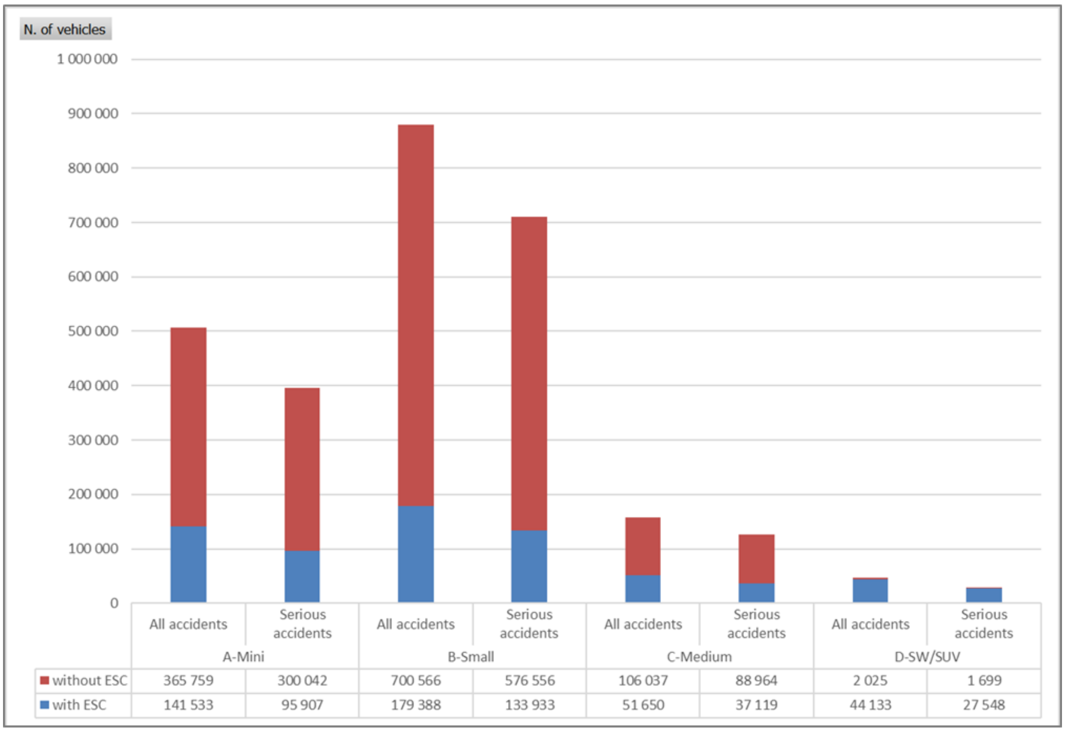
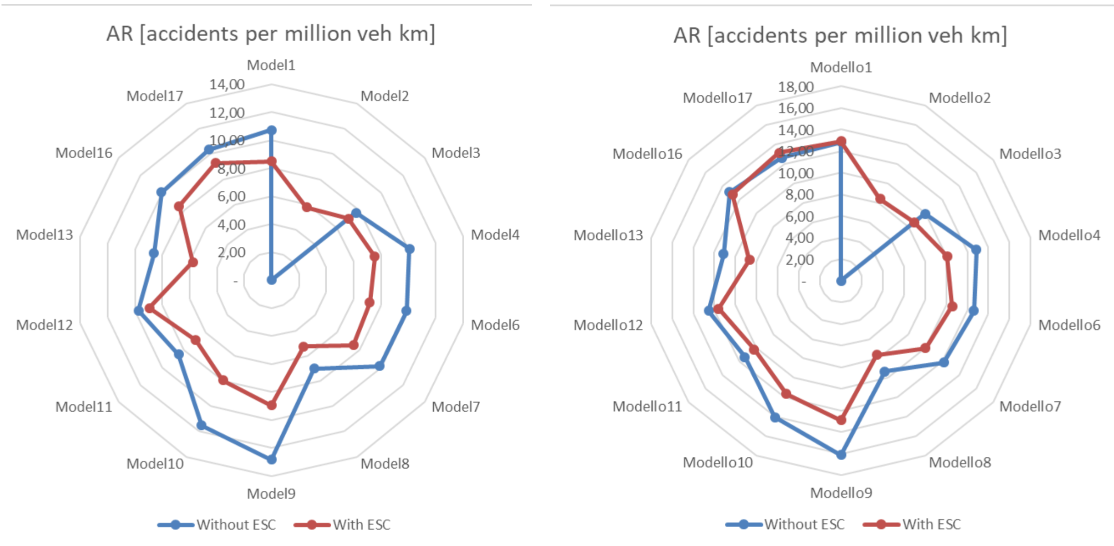


Figure 5



(a) (b)

Figure 6

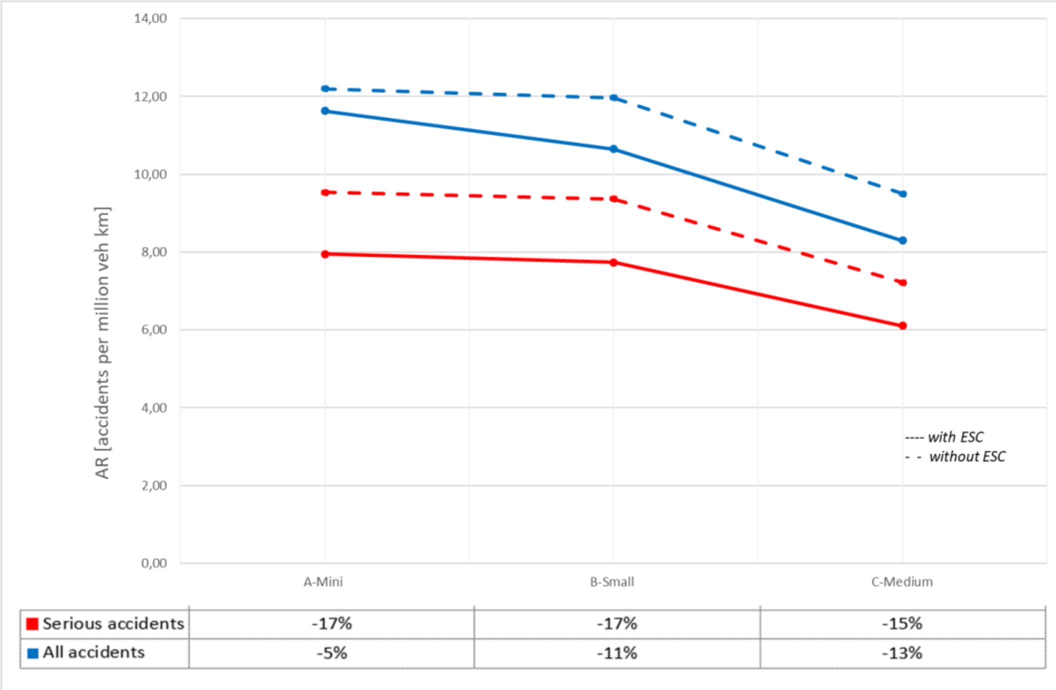


Figure 7

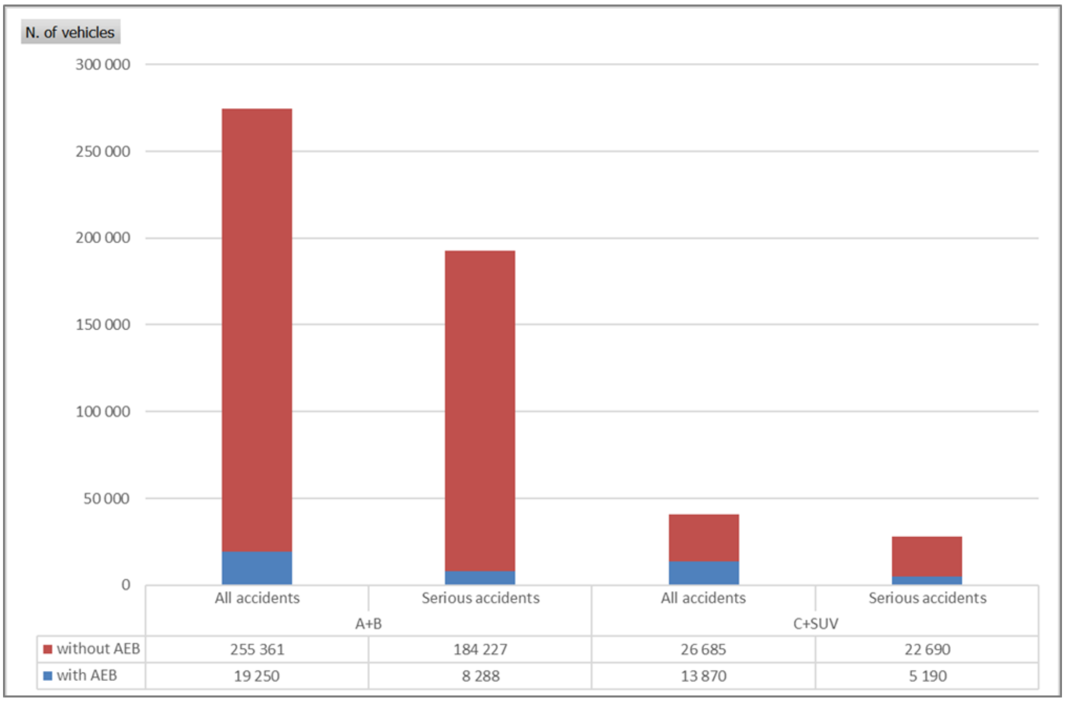


Figure 8

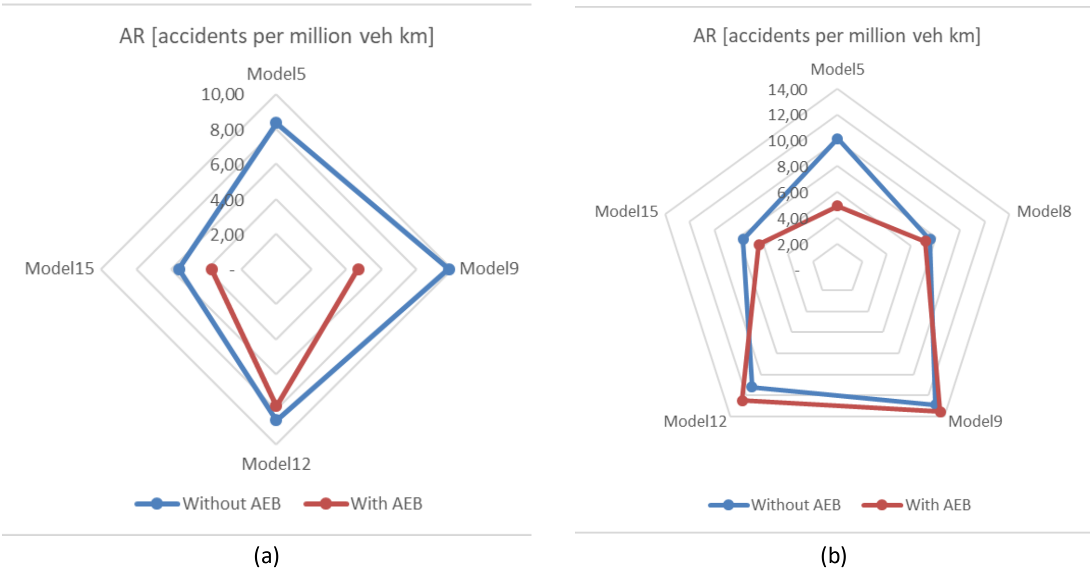


Figure 9

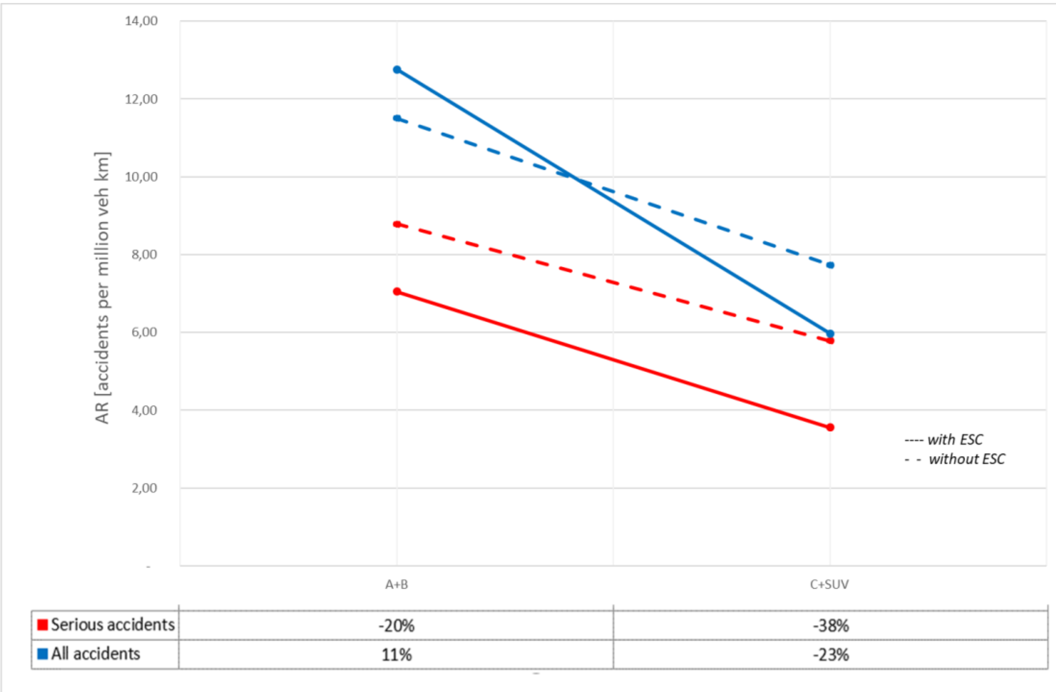


Figure 10

Figure Captions:

Figure 1. Schematic of methodology for accident rates estimation.

Figure 2. Average travelled distance of the 17 selected models aggregated by the year of registration for (a) serious and (b) all accidents.

Figure 3. Number of accidents of the 17 selected models aggregated by the year of initial registration for (a) serious and (b) all accidents.

Figure 4. Accident rates comparison (AR and SAR) from data of (a) serious and (b) all accidents.

Figure 5. Total number of vehicles in the two sets (NO ESC and ESC vehicles generations) for each model class.

Figure 6. Average accident rates for the selected models of NO ESC and ESC vehicles generations; data of (a) serious and (b) all accidents.

Figure 7. Average accident rates variation of NO ESC and ESC vehicles generations aggregated based on vehicle categories for serious and all accidents.

Figure 8. Number of vehicles compared for AEB (with AEB) and ESC (without AEB) vehicles generation.

Figure 9. Average accident rates for AEB (with AEB) and ESC (without AEB) vehicles generation; data of (a) serious and (b) all accidents.

Figure 10. Average accident rates variation between AEB and ESC vehicles generation aggregated based on vehicle categories for all and serious accidents.