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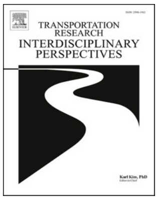

On the road safety benefits of advanced driver assistance systems in different driving contexts

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ABSTRACT

Advanced Driver Assistance Systems (ADAS) have introduced several benefits in the vehicular industry, and their proliferation presents potential opportunities to decrease road accidents. The reasons are mainly attributed to the enhanced perception of the driving environment and reduced human errors. However, as environmental and infrastructural conditions influence the performance of ADAS, the estimation of accident reductions varies across geographical regions. This study presents an interdisciplinary methodology that integrates the literature on advanced driving technologies and road safety to quantify the expected impact of ADAS on accident reduction across combinations of road types, lighting, and weather conditions. The paper investigates the safety effectiveness of ADAS and the distribution of frequency and severity of road accidents across 18 driving contexts and eight accident types. Using road safety reports from the United Kingdom (UK), it is found that a high concentration of accidents (77%) occurs within a small subset of contextual conditions (4 out of 18) and that the most severe accidents happen in dark conditions on rural roads or motorways. The results of the safety effectiveness analysis show that a full deployment of the six most common ADAS would reduce the road accident frequency in the UK by 23.8%, representing an annual decrease of 18,925 accidents. The results also show that the most frequent accident contexts, urban-clear-daylight and rural-clear-daylight, can be reduced by 29%, avoiding 7,020 and 3,472 accidents, respectively. Automatic Emergency Braking (AEB) is the most impactful technology, reducing three out of the four most frequent accident categories – intersection (by 28%), rear-end (by 27.7%), and pedestrian accidents (by 28.4%). This study helps prioritise resources in ADAS research and development focusing on the most relevant contexts to reduce the frequency and severity of road accidents. Furthermore, the identified contextual accident hotspots can assist road safety stakeholders in risk mitigation programs.

Introduction

Connected and automated vehicles (CAV) are expected to introduce a substantial improvement in road safety, with many researchers forecasting a significant reduction in accident frequency and severity (Scanlon et al., 2021; Shannon et al., 2021; Sheehan et al., 2017). The potential safety benefits are mainly attributed to reducing human error and the capability of new technologies to sense the environment and anticipate hazards with better accuracy and speed than the human eye (Fagnant and Kockelman, 2015). Advanced driver assistance systems (ADAS) are a set of such technologies that introduce an augmented layer of safety through cooperation between the driver and the vehicle (Burridge et al., 2020; Piao and McDonald, 2008). ADAS reduces exposure to hazardous situations and enhances driving comfort by providing

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Abbreviations: ACC, Adaptive Cruise Control; ADAS, Advanced Driver Assistance Systems; AEB, Automatic Emergency Braking; AHP, Analytic Hierarchy Process; BSW, Blind-spot Warning; CAV, Connected and Automated Vehicles; ESC, Electronic Stability Control; FCW, Forward Collision Warning; IMA, Intersection Movement Assist; LCW, Lane Change Warning; LDW, Lane Departure Warning; LKA, Lane Keeping Assistance; PCAM, Pedestrian Crash Avoidance Mitigation; SAE, Society of Automotive Engineers; UK, United Kingdom; V2V, Vehicle to Vehicle; V2I, Vehicle to Infrastructure.

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Table 1
ADAS safety effectiveness estimates by previous works that aggregate the state-of-the-art of ADAS safety benefits (Wang et al., 2020; Yue et al., 2018).

Technology	Safety effectiveness estimates	
	Yue et al. (2018) (conservative) [%]	Wang et al. (2020) (95% Confidence Interval) [%]
ACC (Adaptive Cruise Control)	–	[5, 14]
AEB (Automatic Emergency Braking)	43	[20, 31]
BSW (Blind-spot Warning)	14	[10, 20]
ESC (Electronic Stability Control)	41	[38, 48]
FCW (Forward Collision Warning)	–	[17, 25]
IMA (Intersection Movement Assist)	40	[40, 57]
LCW (Lane Change Warning)	28	[10, 33]
LDW (Lane Departure Warning)	–	[21, 30]
PCAM (Pedestrian Crash Avoidance Mitigation)	59	[36, 42]
FCW + ACC	10	–
FCW + AEB	50	–
FCW (fog)	35	–
LDW + Curve Speed Warning (CSW)	11	–

warnings or automating dynamic driving tasks. In general, these technologies can be grouped into five categories: collision warning, collision intervention, driving control assistance, parking assistance, and other driver assistance systems (Brannon et al., 2019).

The proven enhancements to road safety and driving comfort associated with ADAS have motivated policymakers to promote their installation in most modern vehicles and accelerate the deployment of vehicular technologies with proven safety benefits (European Parliament, 2010; McDonnell et al., 2021; US Department of Transportation, 2016). As of May 2018, in the United States, 92.7% of new vehicles have at least one ADAS (American Automobile Association, 2019). In Europe, all vehicles produced by 2022 must have a predefined set of safety features such as safety warnings and, for light vehicles, Lane-keeping Assistance (LKA), Automatic Emergency Braking (AEB), and improved safety belts (European Commission, 2019). Although these systems provide considerable societal benefits, there is absent comprehensive literature on the potential accident reductions across various driving contexts.

Several factors may influence the performance of ADAS, including vehicle integration, driver behaviour, and environmental conditions (Yue et al., 2018). In particular, the driving environment affects vehicle dynamics and sensor capabilities. A system that executes sudden braking when it detects an imminent collision is likely to perform better in clear weather conditions with a dry road surface than in adverse weather conditions that diminish the surface's friction coefficient. Adverse conditions might also impair the sensors' ability to perceive the environment accurately (e.g., a snowstorm could obstruct the camera vision system or cover lane boundaries). Hence, the driving environment constrains the ADAS likelihood of avoiding accidents, also known as the safety effectiveness (Tian et al., 2018). Although previous studies have investigated the overall efficacy of ADAS, there is a lack of research focusing on how different driving contexts affect ADAS benefits on road safety (Yue et al., 2018). This paper overcomes this challenge by proposing an interdisciplinary methodology based on the state-of-the-art in transportation accident analysis and advanced driving technologies to determine the impact of ADAS on the decrease of eight accident types across 18 diverse driving contexts.

The first objective of this paper is to determine the influence of the driving context on the performance of ADAS to modulate the estimations of safety effectiveness posited by previous studies. The state-of-the-art of each technology is examined to analyse the principal environmental conditions (i.e., driving contexts) that affect their functionality. The paper proposes the application of the Analytical Hierarchy Process (AHP) to rank different driving context combinations according to their influence on maximising the effectiveness of ADAS. AHP is a decision-making tool to technically analyse and rank performance evaluations (Saaty, 1988). This technique structures the decision-making criteria using relative weights through pairwise comparisons. Therefore, the result is a rational representation of the knowledge used to determine the importance of each criterion. The AHP has been used in a wide range of areas, including engineering, transportation, and road safety (Barić et al., 2016; Jun et al., 2021; Vaidya and Kumar, 2006). For instance, Agarwal et al. (2013) used the AHP to rank hazardous road conditions in terms of importance for road safety. By providing a methodology that incorporates qualitative and quantitative notions of performance, the AHP framework allows for technically quantifying the relative importance of each driving context combination. This paper combines such a methodology with estimates of safety effectiveness, resulting in a detailed disaggregation of ADAS effectiveness by driving context.

The second objective of this research consists of quantifying the safety benefits of ADAS in a geographical region by driving contexts. The disaggregation of ADAS effectiveness is linked with road safety reports to estimate accident reductions across different contexts and accident types. Road safety reports are a fundamental source of information for the continuous development of the automotive sector as they help study the distribution of the accidents' environmental conditions. They provide information about the vehicles and casualties involved and the accident circumstances (e.g., geographical, temporal, and road information). This paper leverages such data to estimate the potential reductions in accidents that ADAS can mitigate.

The results provide automotive stakeholders such as regulators, manufacturers, and insurers, with guidance on ADAS research and development towards safer roads, in a market that forecasts a compound annual growth rate of 19% between 2020 and 2025 (More, 2021). Furthermore, the identified contextual accident hotspots using accident frequency, severity, and type can assist organisations focused on road safety risk mitigation.

The remainder of the paper is organised as follows; Section 2 discusses the ADAS safety effectiveness research posited by previous studies and extends upon them using the performance across different driving contexts. Section 3 introduces the road safety reports used to estimate accident reductions and applies the modulated safety effectiveness to them. Section 4 provides estimates about the potential of ADAS technologies on road safety, analysing reductions in accident frequency and identifying critical driving contexts in terms of accidents severity. The paper concludes in Section 5 with a proposal for future research.

Safety effectiveness of ADAS

Different assessment methods and experimental conditions have led to differences in ADAS safety efficacy estimates in the literature. This has motivated researchers to aggregate past studies to provide a more robust estimation. This section analyses the literature on ADAS safety efficacy estimates. First, it examines the overall safety estimations presented by previous works. Second, it presents empirical studies analysing the likelihood of ADAS to avoid an accident (i.e., the safety effectiveness) in driving contexts that challenge their performance. Then, the overall estimates of safety effectiveness presented are modularised according to the ADAS performance by driving context.

Overall safety effectiveness

To quantify the potential accident reductions due to several ADAS, authors Li and Kockelman (2016), Yue et al. (2018), and Wang et al.

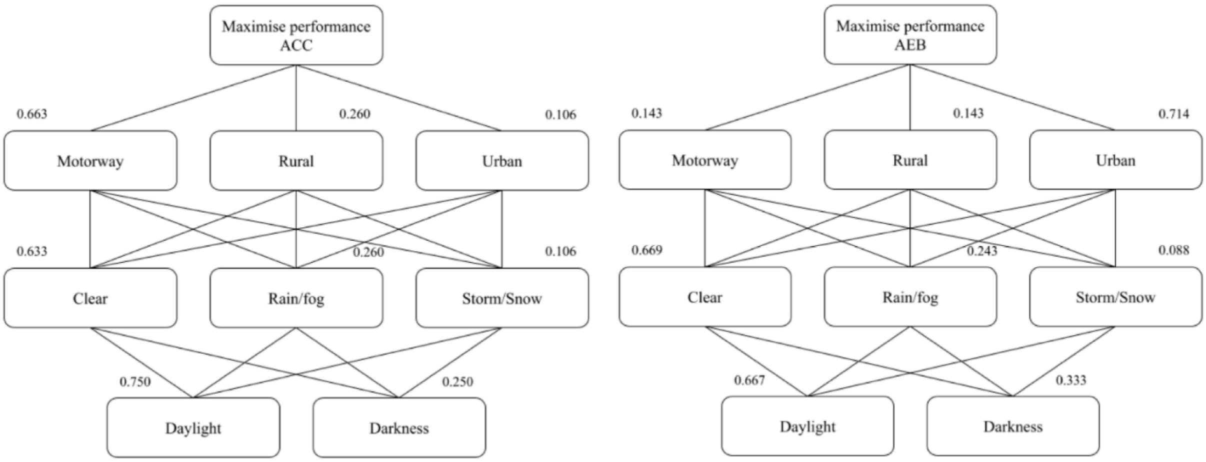
Table 2
Assessment of performance of ADAS across different driving contexts – road types (motorways, rural, and urban), weather conditions (clear, rain/fog, storm/snow), lighting conditions (daylight, darkness).

ADAS	Road type	Weather conditions	Lighting conditions
ACC	Best performance on motorways (Li et al., 2017; Mahdinia et al., 2020; Winter et al., 2017). Limitations in rural roads due to curves and roundabouts (National Safety Council, 2020a; Strand et al., 2011). Limitations in urban roads due to traffic conditions and road layout (Najm et al., 2006; Seppelt and Lee, 2007; Volvo Car Corporation, 2018a; de Winter et al., 2017).	Best performance in clear weather (Cafiso and Di Graziano, 2012; Najm et al., 2006). Limitations with inclement weather leading to higher lost detection rates or false positives (Seppelt and Lee, 2007; Strand et al., 2011; Vidhya et al., 2016).	Potential limitations in dark environments leading to a higher lost detection rates than in daylight conditions (Najm et al., 2006)
AEB	Limitations in high-speed roads since the system performs only partial braking at moderate-to-high speeds (Consumer Reports, 2019; Guo and Zhang, 2021; Ivanov et al., 2018; Seacrist et al., 2020). Best performance in urban roads due to the low-speed range (Cicchino, 2017; Doyle et al., 2015; Rizzi et al., 2014).	Best performance in clear weather due to good road friction coefficient and visibility (Bärgman et al., 2017; Ivanov et al., 2018). Limitations with inclement weather due to braking constraints and impaired camera system (Anderson et al., 2013; Haus et al., 2019; Kusano and Gabler, 2012; Seacrist et al., 2020; Yanagisawa et al., 2017).	Potential limitations in camera-based systems in dark environments (Anderson et al., 2013; Yanagisawa et al., 2017)
BSW	Best performance on motorways due to standardised lane width and traffic flow, and followed by urban roads (AAA, 2014; Liu et al., 2017; National Safety Council, 2020b; Nodine et al., 2011; Ra et al., 2018; Wu et al., 2012). Worst performance in rural roads (Yue et al., 2020).	Best performance in clear weather and limitations with inclement weather due to sensor impairment (Chen and Chen, 2009; Schaudt et al., 2014; Volvo Car Corporation, 2018b; Wu et al., 2012).	Potential limitations in camera-based systems in darkness (Ra et al., 2018).
ESC	Best performance on high-speed roads. Motorways reported better effectiveness than rural (Scully and Newstead, 2008; Thomas, 2006).	Best performance as conditions worsens and decrease the road friction coefficient (Chouinard and Lécuyer, 2011; Green, 2006; Lie et al., 2006; LIE et al., 2004; Thomas, 2006).	No differences due to system design (Kreiss et al., 2005)
FCW	No significant differences in performance across road types. Motorways reported slightly better performance than urban roads, and urban better than rural ones (Lyu et al., 2019; Yue et al., 2020).	Best performance in clear weather and limitations with inclement weather due to sensor impairment and braking constraints (Chen et al., 2013; Jermakian, 2011; National Safety Council, 2020c).	Potential limitations in camera-based systems in darkness (National Safety Council, 2020c)
LDW	Best performance in motorways due to standardised lane markings (Lyu et al., 2019; Scanlon et al., 2016; Son et al., 2015). Limitations in rural areas due to curves and lower quality of lanes (National Safety Council, 2020d; Nodine et al., 2011). Urban roads have the lowest effectiveness due to low-speed system restrictions (Cicchino, 2018; Sternlund et al., 2017).	Best performance in clear weather and limitations with inclement weather due to sensor impairment and obstructed lane markings (Cicchino, 2018; Gordon et al., 2010; Hickman et al., 2013; Nodine et al., 2011; Sternlund et al., 2017; Wilson et al., 2007).	Potential limitations due to obscured lane markings (Hickman et al., 2013; Scanlon et al., 2016)

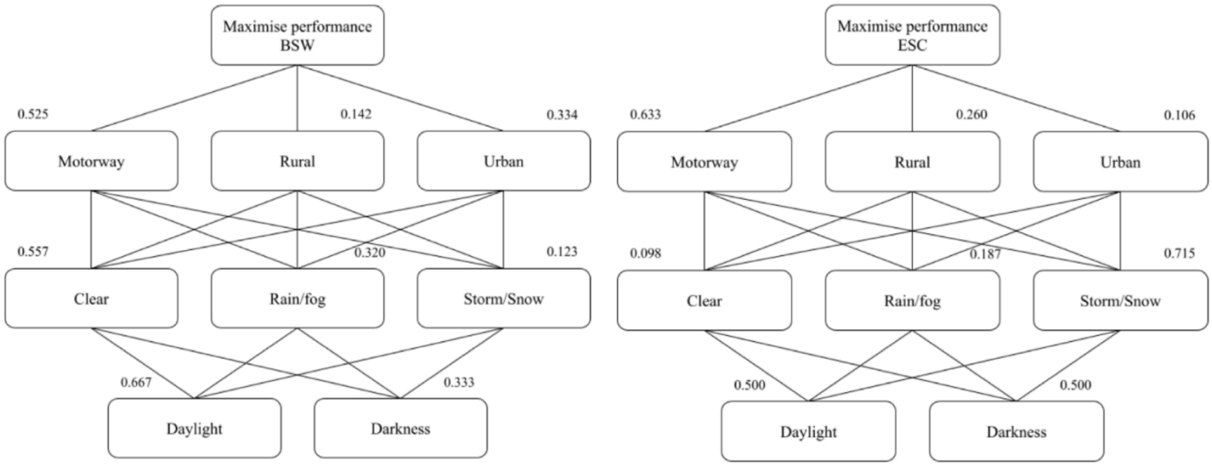
(2020) have investigated each technology's safety effectiveness and linked them to accident records. In contrast to Li and Kockelman (2016) that used assumptions for the effectiveness values, Yue et al. (2018) and Wang et al. (2020) have reviewed the state-of-the-art of ADAS and aggregated their safety benefits. The authors have identified the accident types that ADAS could mitigate and then estimated the reduction in accident frequency by applying the ADAS benefits to their respective accident records. Even though these works present important insights about the potential of ADAS on road safety, a significant limitation is that they do not consider the accident circumstances in which the safety reductions are applied.

Table 1 presents a comparison of the safety estimates of the studies mentioned above. While Yue et al. (2018) measure effectiveness as the average of previous research, Wang et al. (2020) follow a robust measurement methodology to avoid possible biases (e.g., publication bias). The estimations of Yue et al. (2018) shown in the table correspond to light vehicles only and are the average of the lower bound estimate (i.e., conservative estimate) across studies of each technology. A drawback of this study is the limited number of previous works considered, leading to some technologies relying on a single study. Contrastingly, Wang et al. (2020) considered 73 papers containing safety-related information and, for every ADAS technology, the effectiveness is computed through a weighted average. Each paper's weight is inversely proportional to the variance experimented in the research and across studies, thus avoiding systematic differences. Finally, the results are expressed with a 95% confidence interval, representing the weighted mean effectiveness of each technology for light and heavy vehicles.

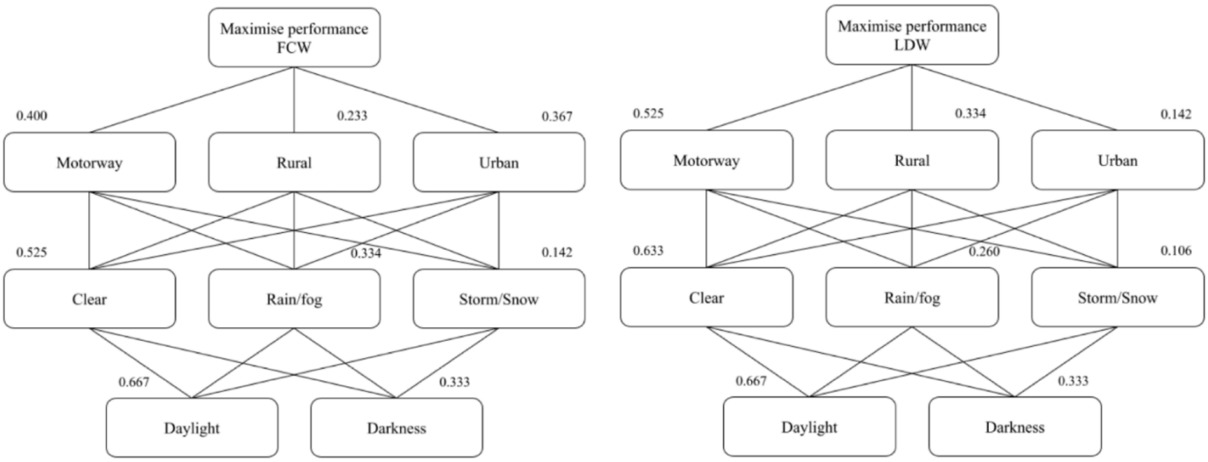
One limitation of Wang et al. (2020) is that it contemplates each technology's effectiveness separately, assuming independence between them. The reason is that existing studies seldom analyse the effectiveness of combined technologies. Therefore, to estimate the proportion of yearly crashes that can be reduced using ADAS technologies, the authors multiply the effectiveness of all the technologies that may mitigate a given accident type. However, this assumption overestimates the potential safety benefits as the effectiveness of some of these technologies are mutually dependent, as shown by Yue et al. (2018). For instance,



(a) Weights for Adaptive Cruise Control (ACC) (b) Weights for Automatic Emergency Braking (AEB)



(c) Weights for Blind Spot Warning (BSW) (d) Weights for Electronic Stability Control (ESC)



(e) Weights for Forward Collision Warning (FCW) (f) Weights for Lane Departure Warning (LDW)

Fig. 1. Analytical Hierarchy Process diagrams for the studied ADAS technologies. Each criterion corresponds to the principal driving contexts observed in the systematic review introduced in Section 2.2.1. The weights are given by the evidence of the criterion in affecting the performance of ADAS, according to the literature (Table 2).

Forward Collision Warning (FCW) with Automatic Emergency Braking (AEB) have more effectiveness together than the components alone (50% vs 35% and 43%, respectively).

This paper extends the effectiveness posited by Wang et al. (2020) due to their comprehensive aggregation of previous studies that avoid potential biases. ADAS combinations are not included since the number of studies about the effectiveness of multiple technologies together is not yet statistically relevant (the values of combined ADAS posited by Yue et al. (2018) are based on single studies). Moreover, each technology is evaluated separately to avoid the overestimation problem mentioned

Table 3
Effectiveness ranking matrix. The driving contexts are the 18 possible combinations of road types (motorway, rural and urban roads), weather conditions (clear, rain/fog, and snow/storm), and lighting conditions (daylight and darkness). The effectiveness ranking represents the level of performance of a given technology by driving contexts and goes from 1 (low performance) to 5 (high performance).

Driving context			Effectiveness ranking (1: worst, 5: best)					
Road type	Weather conditions	Lighting conditions	ACC	AEB	BSW	ESC	FCW	LDW
motorway	clear	daylight	5	4	5	3	5	5
motorway	clear	darkness	4	3	4	3	4	5
motorway	rain/fog	daylight	5	3	5	4	5	4
motorway	rain/fog	darkness	3	2	4	4	3	3
motorway	storm/snow	daylight	4	2	3	5	2	3
motorway	storm/snow	darkness	2	1	2	5	1	2
rural	clear	daylight	5	4	3	2	4	5
rural	clear	darkness	3	3	2	2	3	4
rural	rain/fog	daylight	4	3	3	3	3	4
rural	rain/fog	darkness	2	2	2	3	2	3
rural	storm/snow	daylight	3	2	1	5	2	2
rural	storm/snow	darkness	1	1	1	5	1	1
urban	clear	daylight	4	5	5	1	5	4
urban	clear	darkness	2	5	4	1	4	3
urban	rain/fog	daylight	3	5	4	2	4	2
urban	rain/fog	darkness	1	4	3	2	3	2
urban	storm/snow	daylight	2	4	2	4	2	1
urban	storm/snow	darkness	1	2	1	4	1	1

Table 4
Safety effectiveness intervals of ADAS. The safety effectiveness intervals posited by Wang et al. (2020), described in Table 1, are divided into five sub-intervals corresponding to the effectiveness ranking detailed in Section 2.2.2.

ADAS	Wang et al. (2020) [%]	Safety effectiveness intervals associated with the effectiveness ranking [%]				
		Low (1)	Moderate-to-low (2)	Moderate (3)	Moderate-to-high (4)	High (5)
ACC	[05, 14]	[05, 07)	[07, 09)	[09, 10)	[10, 12)	[12, 14]
AEB	[20, 31]	[20, 22)	[22, 24)	[24, 27)	[27, 29)	[29, 31]
BSW	[10, 20]	[10, 12)	[12, 14)	[14, 16)	[16, 18)	[18, 20]
ESC	[38, 48]	[38, 40)	[40, 42)	[42, 44)	[44, 46)	[46, 48]
FCW	[17, 25]	[17, 19)	[19, 20)	[20, 22)	[22, 23)	[23, 25]
LDW	[21, 30]	[21, 23)	[23, 25)	[25, 26)	[26, 28)	[28, 30]

Table 6
Example of variables included in the road safety reports of the UK Department for Transport (UK Department for Transport, 2021a).

Accident circumstances	Vehicles involved	Casualties involved
Accident Severity	Vehicle Type	Casualty Class
Number of Vehicles	Vehicle Manoeuvre	Sex of Casualty
Number of Casualties	Junction Location	Age of Casualty
Datetime	Skidding and Overturning	Casualty Severity
Coordinates	Hit Object in Carriageway	Casualty Type
Road type	Vehicle Leaving Carriageway	
Speed limit	Hit Object off Carriageway	
Junction Detail	1st Point of Impact	
Junction Control	Journey Purpose of Driver	
Light Conditions	Sex of Driver	
Weather Conditions	Age of Driver	
Road Surface Conditions	Engine Capacity	
Special Conditions at Site	Age of Vehicle (manufacture)	
Carriageway Hazards		

Table 5
ADAS safety effectiveness by driving context. The safety effectiveness of Table 4 is linked to the ranking detailed in Table 3. Technologies with a ranking of 1 (low performance) in a given driving context are assigned the lower-end interval of their respective safety effectiveness range. Similarly, high-performance rankings are matched with higher-end intervals.

Driving context			Estimated safety effectiveness of ADAS by driving context [%]					
Road type	Weather conditions	Lighting conditions	ACC	AEB	BSW	ESC	FCW	LDW
motorway	clear	daylight	[12, 14]	[27, 29)	[18, 20]	[42, 44)	[23, 25]	[28, 30]
motorway	clear	darkness	[10, 12)	[24, 27)	[16, 18)	[42, 44)	[22, 23)	[28, 30]
motorway	rain/fog	daylight	[12, 14]	[24, 27)	[18, 20]	[44, 46)	[23, 25]	[26, 28)
motorway	rain/fog	darkness	[09, 10)	[22, 24)	[16, 18)	[44, 46)	[20, 22)	[25, 26)
motorway	storm/snow	daylight	[10, 12)	[22, 24)	[14, 16)	[46, 48]	[19, 20)	[25, 26)
motorway	storm/snow	darkness	[07, 09)	[20, 22)	[12, 14)	[46, 48]	[17, 19)	[23, 25)
rural	clear	daylight	[12, 14]	[27, 29)	[14, 16)	[40, 42)	[22, 23)	[28, 30]
rural	clear	darkness	[09, 10)	[24, 27)	[12, 14)	[40, 42)	[20, 22)	[26, 28)
rural	rain/fog	daylight	[10, 12)	[24, 27)	[14, 16)	[42, 44)	[20, 22)	[26, 28)
rural	rain/fog	darkness	[07, 09)	[22, 24)	[12, 14)	[42, 44)	[19, 20)	[25, 26)
rural	storm/snow	daylight	[09, 10)	[22, 24)	[10, 12)	[46, 48]	[19, 20)	[23, 25)
rural	storm/snow	darkness	[05, 07)	[20, 22)	[10, 12)	[46, 48]	[17, 19)	[21, 23)
urban	clear	daylight	[10, 12)	[29, 31]	[18, 20]	[38, 40)	[23, 25]	[26, 28)
urban	clear	darkness	[07, 09)	[29, 31]	[16, 18)	[38, 40)	[22, 23)	[25, 26)
urban	rain/fog	daylight	[09, 10)	[29, 31]	[16, 18)	[40, 42)	[22, 23)	[23, 25)
urban	rain/fog	darkness	[05, 07)	[27, 29)	[14, 16)	[40, 42)	[20, 22)	[23, 25)
urban	storm/snow	daylight	[07, 09)	[27, 29)	[12, 14)	[44, 46)	[19, 20)	[21, 23)
urban	storm/snow	darkness	[05, 07)	[22, 24)	[10, 12)	[44, 46)	[17, 19)	[21, 23)

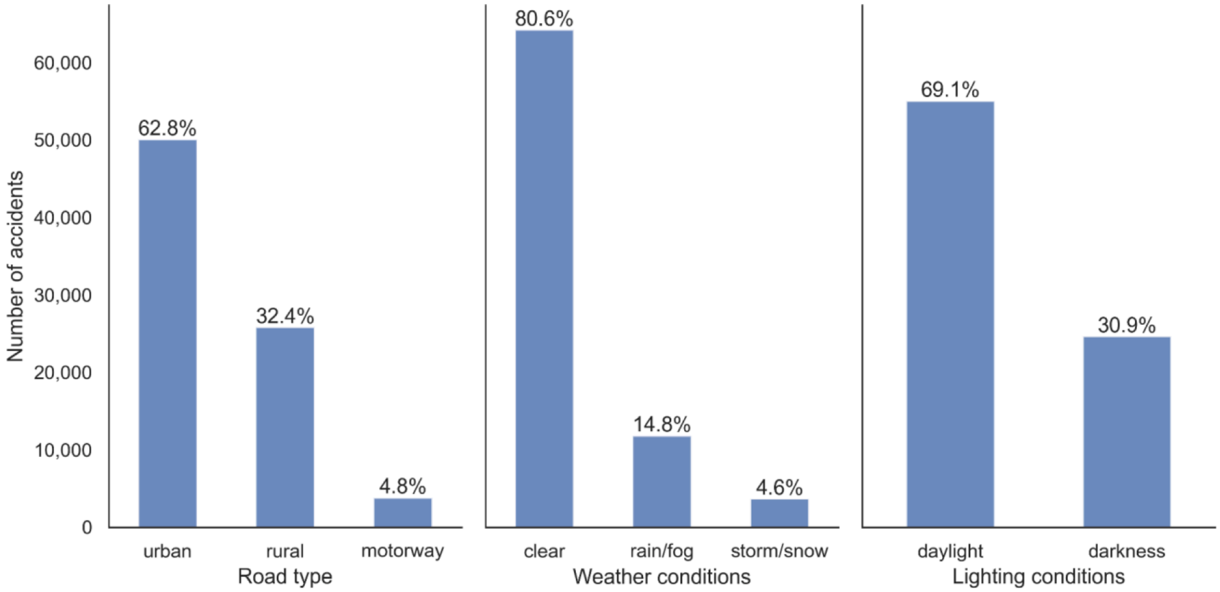


Fig. 2. Proportion of contextual variables in the UK's road safety reports for the year 2019 in collisions involving only light and heavy vehicles (UK Department for Transport, 2021a). Left: proportion of road types; centre: proportion of weather conditions; right: proportion of lighting conditions. Total number of accidents: 79,656.

Table 7
Average cost per reported casualty according to the RAS60001 report (UK Department for Transport, 2020).

Casualty type	Cost per casualty (£, 2019)
Fatal	2,029,237
Serious	228,029
Slight	17,579

above. Thus, for an accident type that multiple technologies may mitigate, the maximum accident reduction corresponds to the technology that presents the highest effectiveness. Furthermore, manufacturers' wide variety of terminologies has motivated the Society of Automotive Engineers (SAE) to release recommendations for common ADAS terminology (Brannon et al., 2019). This paper follows such recommendations and investigates the following technologies: ACC, AEB, BSW, ESC, FCW, and LDW.

Safety effectiveness by driving context

Understanding the influence of the driving context on ADAS performance becomes paramount for a comprehensive analysis of the safety benefits. The effectiveness of each ADAS varies depending on the context, such as wet or dry road surface conditions. For instance, a driver equipped with AEB who drives under dry conditions is more likely to benefit from AEB safety enhancements than someone equipped with AEB who drives under wet conditions (Scanlon et al., 2017; Seacrist et al., 2020). Therefore, there is a need to disaggregate the effectiveness values to enhance the effectiveness estimation by conducting a literature review. This section analyses the performance of each technology across different contexts according to the literature and modulates the effectiveness values of Wang et al. (2020) presented in Table 1.

Assessment of ADAS performance by driving context

The selection of the main factors influencing the performance of ADAS has been performed using a systematic review that consisted of looking for challenges, strengths, and overall performance of the studied technologies. For each study, the process reviewed the contextual factors that influence the performance of ADAS quantitatively or qualitatively. In total, 51 studies have been reviewed, and three principal contextual variables emerged as research focal points – road type, weather conditions, and lighting conditions. The surveyed studies analysed one or many of these contextual variables, with different levels of disaggregation: (i) for road types: motorway, rural, and urban, or freeway and non-freeway; (ii) for weather conditions: clear, rain or fog, heavy rain, snow or ice, or adverse conditions; (iii) for lighting conditions: daylight and darkness. While traffic conditions have also been found to affect ACC, this factor has been excluded due to absent research across the remaining ADAS technologies.

Table 2 summarises the performance of the six studied ADAS across the contextual conditions analysed in previous studies. It can be observed that, in general, clear weather and lighting conditions relate to good performance in most technologies. The most significant variability is observed across road type categories — motorway, rural, or urban roads. In particular, as motorways mainly feature standardised and well-maintained lane markings, it leads to a good performance in technologies that rely on lane boundary detection. On the other hand, their high-speed ranges imply a constraint on technologies that depend on the braking system, like AEB.

Most of the reviewed publications analyse the contextual factors independently, and there exists an absence of research investigating the safety benefits of ADAS across contexts in a joint manner (i.e., how the triad composed of road type, weather and lighting conditions impact the functionality). The following section proposes an approach to incorporate expert knowledge from previous studies in order to technically rank driving context combinations based on their influence on the performance of ADAS technologies.

Performance ranking

The assessment of Table 2 shows how particular driving contexts lead to superior, moderate or limited functionality of ADAS. However, there is an absence of research that examines the influence of combinations of these contexts on ADAS performance. This undermines individual estimations as it is not clear how the performance of driving contexts compound between one another. This section proposes an approach to modulate the safety effectiveness estimates posited by previous research, based on the literature of ADAS performance by driving context.

The main objective is to propose a ranking of driving context

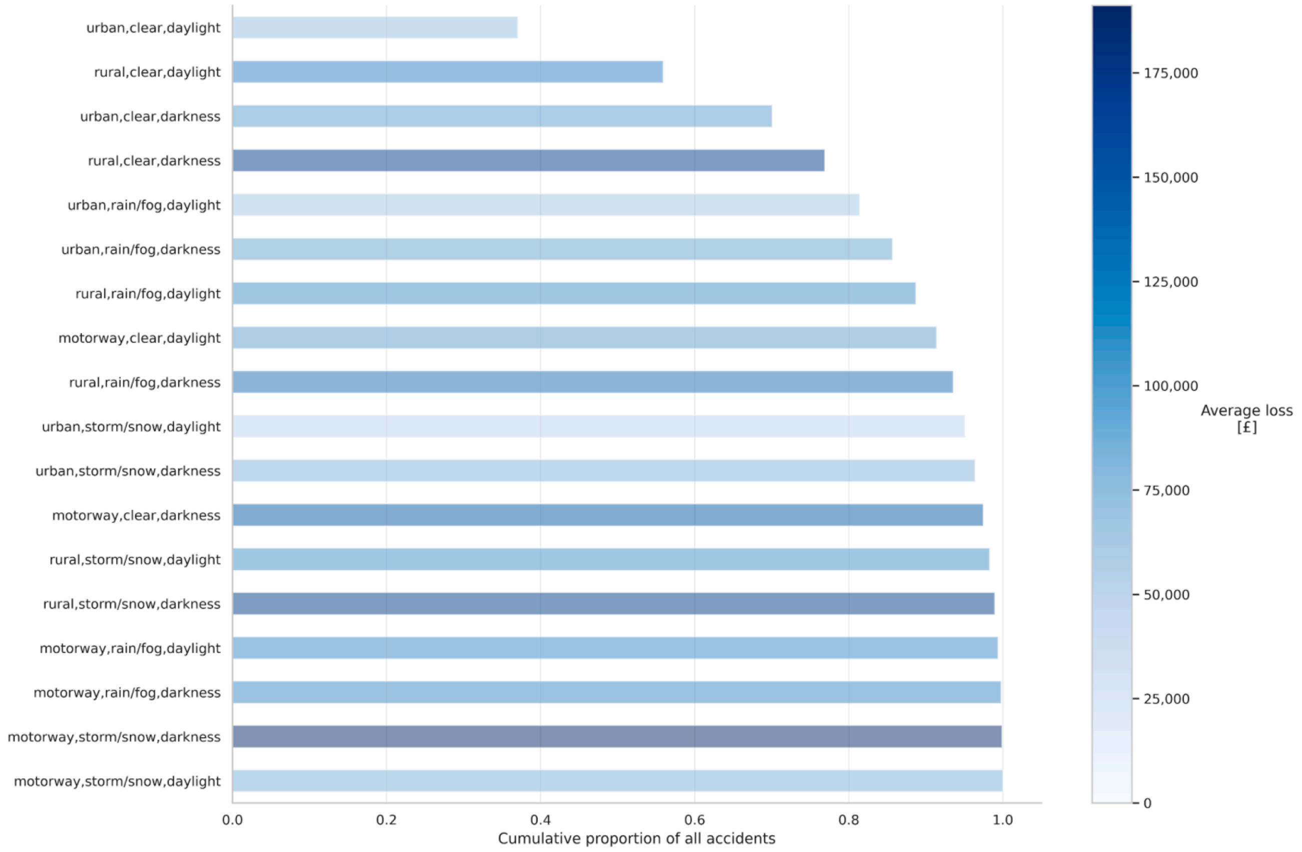


Fig. 3. Cumulative proportion of accidents by driving context. The y-axis contains the 18 possible combinations of the studied driving contexts (i.e., road types, weather and lighting conditions), sorted by the most frequent accident types in descending order. Each bar shows the cumulative proportion of the group accidents out of all accidents. In particular, four groups encompass 77% of all accidents. The colour scale represents the severity of the accidents in each group, given by the average loss incurred in those crashes (Equation 1). The five most severe contexts are: *motorway-storm/snow-darkness* (£191,172), *rural-clear-darkness* (£175,921), *rural-storm/snow-darkness* (£174,829), *motorway-clear-darkness* (£151,521), and *rural-rain/fog-darkness* (£136,974).

Table 8
Relationship between accident types and ADAS that might mitigate them.

Accident type	Description	ADAS
Against a pedestrian	Accidents with only one vehicle hitting a pedestrian in the carriageway.	AEB
Against an animal	Presence of an animal on the road.	AEB, ESC
Against an object	Presence of an object or vehicle load on the road.	AEB, ESC
Intersection	Accidents happening at junctions which were not included in the other accident types.	AEB
Lane change	Vehicles performing a lane change manoeuvre to the left or right.	BSW
Lane departure	Vehicles leaving the carriageway that did not impact other vehicles or pedestrians.	LDW
Skidding and overturning	Vehicles skidding or overturning.	ESC
Rear-end	Vehicles colliding in a front-to-rear manner.	ACC, AEB, FCW

combinations according to their influence on maximising ADAS performance. The paper applies the AHP to obtain such a ranking since it provides a structured and analytical approach to quantify the relative importance of driving context combinations based on the literature.

The AHP organises the problem with hierarchical criteria layers, where the first level represents the goal. In each layer, all criteria are compared in pairs using a fundamental scale from 1 to 9. The values of such a scale indicate the importance of one criterion over another. Saaty (1988) defines these values as 1 (equal importance), 3 (moderate importance), 5 (strong importance), 7 (very strong importance), 9 (extreme importance), and suggests using even numbers for intermediate values when a compromise is needed. The pairwise comparison serves to obtain the eigenvector representation of each layer, which is then used to rank alternatives for the desired goal. Thus, alternatives having higher weights are preferred over those with lower weights.

As most reviewed studies analyse each driving context independently, the AHP model presented in this paper uses three criteria layers corresponding to the three principal variables observed in Table 2 (i.e., road type, weather conditions, lighting condition). Thus, the categories of a layer are compared by pairs, and then the resulting eigenvector is aggregated with the other layers. This results in 18 alternatives of context combinations — the permutation of three road type variables (motorway, rural, urban), three weather variables (clear, rain/fog, snow/storm), and two lighting conditions (daylight, darkness).

Fig. 1 shows the resulting AHP for the six studied ADAS technologies. The goal, represented in the first layer, is to maximise the safety effectiveness of each technology. Pairwise comparisons within each layer have been performed using the performance assessment of Table 2 and detailed in Appendix A. Each importance value is determined by the amount of evidence showing that a given criterion (e.g., road type: urban) has better safety effectiveness than another (e.g., road type: rural). Then, the normalised representation of such values is computed and presented above each criterion (i.e., the weights observed in the figure). Finally, these values are used to obtain a ranking of context combinations determined by the multiplication of each criterion's weight. Context combinations composed of conditions where the ADAS technology has the best performance are associated with the best ranking. Conversely, combinations that strongly limit the effectiveness have the worst ranking.

Table 9
Accident types distribution in the UK accidents report of 2019 (UK Department for Transport, 2021) compared to Wang et al. (2020) and contributory factors found in UK road safety reports "RAS 10012: Reported accidents involving pedestrians and one vehicle by severity and vehicle type" and "RAS 50001: Contributory factors: Reported accidents by severity" (UK Department for Transport, 2020). Abbreviations: N/A: Not applicable.

Accident type	Proportion of accidents [%]		
	Wang et al. (2020)	UK accidents report of 2019	RAS 10,012 and RAS 50,001 (contributory factors)
Against an animal	0.01%	0.34%	1% Animal crossing
Against an object	2.74%	1.12%	1% Deposit on road
Against a pedestrian	0.13%	10.95%	12% pedestrian-only
Lane departure	N/A	12.29%	11% Loss of control, 1% Poor or defective road surface
Skidding and overturning	N/A	7.39%	7% Slippery road
Lane change	1.13%	1.99%	2% Failed to signal, 3% Swerved
Rear-end	31.6%	21.62%	20% Driver failed to judge other person's path or speed, 5% Following too close, 16% Driver careless, reckless or in a hurry
Intersection	38.4%	26.88%	37% Driver failed to look properly, 2% Disobeyed automatic traffic signal, 2% Disobeyed 'Give Way' or 'Stop' sign or markings, 2% Junction overshoot
Other accidents	25.99%	17.42%	N/A

Since the ultimate objective is to modulate the effectiveness range posited by previous works, the resulting ranking of 18 driving context combinations is organised into five ranking groups. The assignment to groups is determined in decreasing order following the ranking. Thus, the higher the group number, the better the context ranking. Applying such a process to each technology gives the effectiveness ranking presented in Table 3. For example, in LDW, the triad composed of *motorway-clear-daylight* has the best ranking and is assigned to group 5, and *urban-storm/snow-darkness* has the worst and is assigned to group 1.

Safety effectiveness by driving context

The effectiveness ranking of Table 3 allows the modularisation of the safety effectiveness values posited by Wang et al. (2020), introduced in Table 1. As there are five possible rankings, the range of effectiveness of Table 1 is broken down into five intervals. The main goal is that contexts that negatively affect a given ADAS performance use the lowest segment of the effectiveness from Wang et al. (2020), and conversely, favourable contexts use the highest interval. Table 4 details such a modularisation into safety effectiveness intervals.

In Table 5, the effectiveness ranking of Table 3 is combined with the effectiveness intervals (Table 4). Consequently, the range of effectiveness of each ADAS becomes dependent on the driving contexts. For example, the former effectiveness range of LDW, [21%, 30%], is adjusted to [28%, 30%] in favourable conditions such as *motorway-clear-daylight* and to [21%, 23%) in adverse contexts, like *urban-storm/snow-darkness*.

This section has analysed the ADAS performance across different driving contexts, studying their functionalities under favourable and adverse conditions through a literature assessment. Such an analysis has led to the modularisation of previous effectiveness estimates into five intervals according to the context, enabling comprehensive studies of ADAS and road safety. The following section investigates the relationship between ADAS–context and road safety reports to estimate accident frequency reductions.

Estimating accident frequency reductions due to ADAS

Understanding the safety implications of ADAS becomes a fundamental factor in developing policies and fostering future research for safer roads. This section analyses the distribution of accidents frequency and severity across contextual variables in road safety reports. Then, it presents a methodology to estimate the potential accident reductions due to ADAS by linking road safety reports with ADAS effectiveness by driving context.

Road safety reports

The United Kingdom's (UK) Department for Transport provides comprehensive annual reports about accidents on public roads reported to the police (UK Department for Transport, 2021a). They allow the quantification of accident types and monetary costs in different accident contexts and contain information about the accident circumstances and the involved vehicles and casualties. An example of such information is presented in Table 6. This level of comprehensiveness has provided research teams with useful information to study accidents and improve road safety. For instance, Fountas et al. (2020) used these reports to investigate the effect of weather and lighting conditions on the severity of accidents in Scotland.

Fig. 2 illustrates the distribution of UK accidents of 2019, according to the variables identified in Section 2 – road type, weather conditions, and lighting conditions. Following previous studies of ADAS effectiveness, this work analyses the collisions involving only light and heavy vehicles, discarding other vehicle types such as motorcycles. This represents 70% (N = 79,656) of all accidents on the UK's roads in 2019.

Accident severity

The relevance of each context is measured using the accident severity, determined by the average number of casualties. Casualty data are often classified according to the degree of the injury – *slight*, *serious* and *fatal*. A casualty is considered *fatal* if the injuries caused the person's death in less than 30 days after the accident, *seriously injured* if the person was hospitalised or suffered a severe injury, and *slightly injured* if there was a minor injury or an injury that did not require medical treatment (UK Department for Transport, 2013a).

To provide a scalar value that objectively represents the relevance of each context, the casualty's injury data are combined with their associated costs, which are also published annually (UK Department for Transport, 2020). Table 7 shows the figures associated with the RAS60001 report of the year 2019. The cost per casualty can be interpreted as the loss to society. It includes the loss of output due to injury (e.g., expected loss of earnings), medical costs and the human cost of casualties (UK Department for Transport, 2013b).

The estimated loss of each context is computed using the dot product between the average number of casualty's injuries and their associated cost, as shown in Equation 1. $\#Accidents_i$ refers to the number of accidents happening in context i. Similarly, $\#Fatal_i$, $\#Serious_i$, and $\#Slight_i$ refer to the number of *fatal*, *serious*, and *slight* accidents, respectively. The result represents the expected loss of having an accident in context i.

$$Averageloss_i = \frac{1}{\#Accidents_i} \cdot (\#Fatal_i \cdot Cost_{fatal} + \#Serious_i \cdot Cost_{serious} + \#Slight_i \cdot Cost_{slight})$$

Equation 1: Average loss of accident context i. $\#Fatal$, $\#Serious$, and $\#Slight$ represent the number of casualty injuries observed in a given context i. $Cost_{fatal}$, $Cost_{serious}$, and $Cost_{slight}$ correspond to the cost per casualty described in Table 7.

Accident frequency by driving context

The wide granularity of the aforementioned reports allows the analysis of accident frequency in each of the 18 possible combinations of

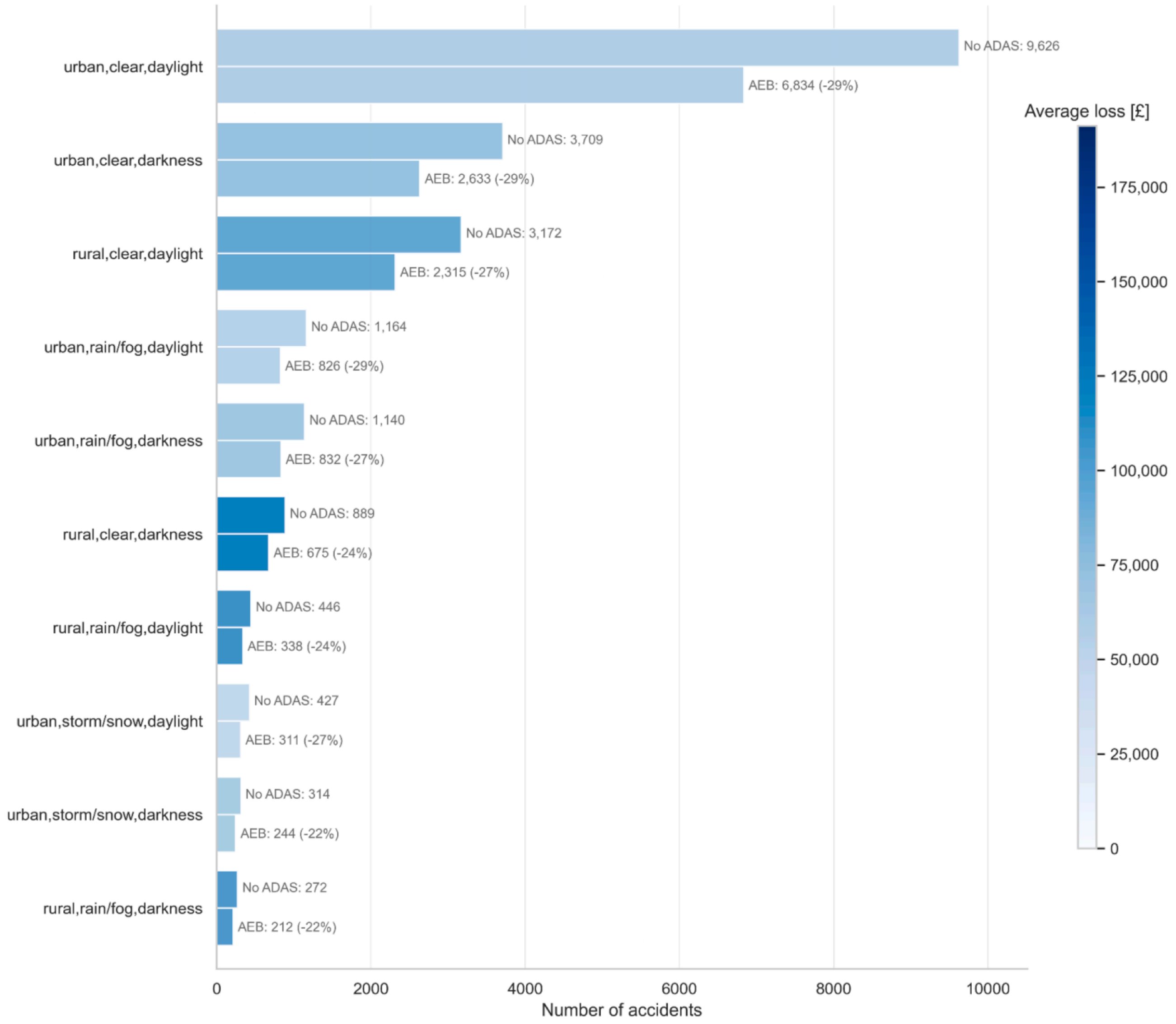


Fig. 4. Intersection accident reductions in the top 10 most frequent intersection accident contexts. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bar applies the potential reduction in accident frequency due to Automatic Emergency Braking (AEB), expressed in the resulting accident count, followed by the percentual reduction of the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). Four of these accident contexts correspond to average losses higher than 100 thousand pounds – *rural-clear-darkness* (£131,999)*; rural-rain/fog-daylight* (£118,347)*; rural-rain/fog-darkness* (£112,310); rural-clear-daylight (£102,288).

the contextual variables defined in Section 2 and examined in Fig. 2. Fig. 3 shows the cumulative proportion of accidents explained by these contexts. The colour variable represents the average loss detailed in Equation 1. Around 20% of the combinations (i.e., four contexts) explain 77% of the accidents. According to Tables 2 and 3, the top four contexts consist of situations prone to moderate to high ADAS performance. Hence, it is expected that considerable market penetration of ADAS might consequently reduce the most frequent accidents.

In terms of average loss, the five most severe contexts happen in dark conditions, out of which three occur in rural areas, and one belongs to the most frequent accidents mentioned earlier—*rural-clear-darkness*. These findings align with the results posited by Alogaili and Mannering (2022), who analysed the severity of vehicle-pedestrian accidents. Even though many accidents in these conditions might be unavoidable road traffic accidents (Cunneen et al., 2019), this paper promotes further research and development of ADAS in adverse lighting conditions to help reduce the frequency and severity of these critical accidents. As Alogaili and Mannering (2022) suggested, these might involve policies and technologies that minimise the perception differences between daylight and dark environments.

Linking ADAS with accident types

Wang et al. (2020) combined road safety data of different countries with the effectiveness of ADAS shown in Table 1 to estimate the potential reductions of road accidents. This involved a mapping between six accident types and the ADAS technologies that might mitigate them. The authors have considered the following accident types: (i) *against an animal*, (ii) *against a pedestrian*, (iii) *intersection*, (iv) *lane change*, (v) *off-road or hitting an object*, and (vi) *rear end*. Nevertheless, the inference of these accident types from the accident reports has been undisclosed.

This research leverages the wide granularity of the UK road safety reports to arrive at the accident types mentioned above. For replication purposes, Table 8 details the inference applied for each accident type with the link to ADAS, according to Wang et al. (2020). Furthermore, this research separates the *off-road or hitting an object* category into

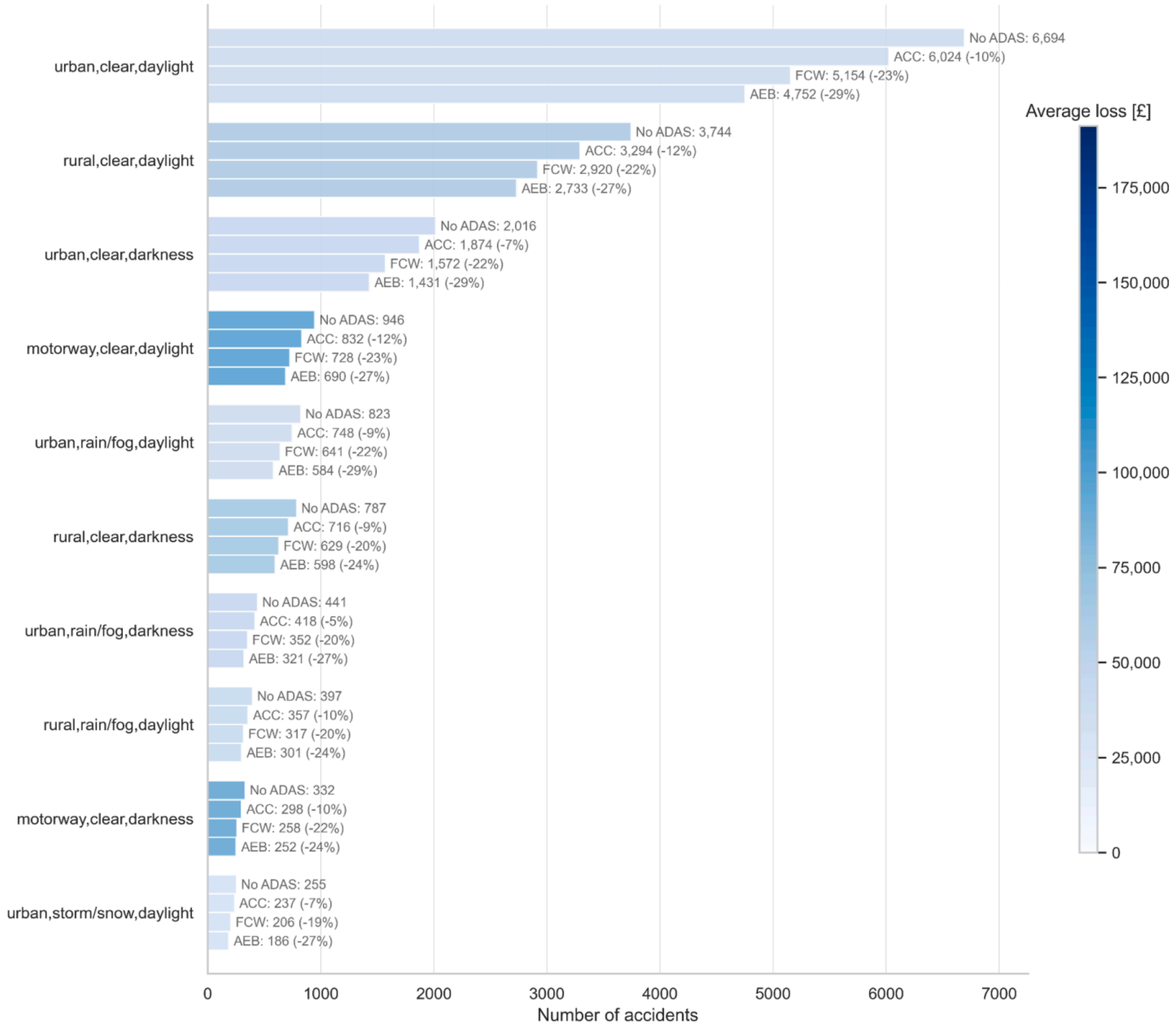


Fig. 5. Rear-end accident reductions in the top 10 most frequent rear-end accident contexts. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bars apply the potential reduction in accident frequency due to Adaptive Cruise Control (ACC), Forward Collision Warning (FCW), and Automatic Emergency Braking (AEB). Each accident reduction is expressed in the resulting accident count, followed by the percentual reduction of the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). The top three most severe contexts are: *motorway-clear-daylight* (£98,092); *motorway-clear-darkness* (£93,968); *rural-clear-darkness* (£65,589).

against an object, lane departure and *skidding and overturning*. The reason is to provide a more explicit mapping to ADAS than the previous work where *off-road or hitting an object* has been associated with LDW, ESC and AEB. As mentioned in Section 2.1, this paper only analyses the technologies mentioned in the standardisation document from the SAE, and therefore IMA, LCW, PCAM are not included in the table.

Table 9 presents the accident types distribution using the road accidents report of 2019 (UK Department for Transport, 2021a). The table allows for the comparison with the work of Wang et al. (2020). In both cases, the definition of accident types is mutually exclusive. In the event of intersection between types (i.e., an accident belonging to more than one category), this paper gives preference to type with a lower percentage to minimise the variance across types.

Wang et al. (2020) have underestimated some accident types (e.g., hitting a pedestrian) and overestimated others (e.g., rear-end). Therefore, the percentages obtained using the accident report of 2019 have been validated with other UK road safety reports – the "RAS 10012: Reported accidents involving pedestrians and one vehicle by severity and vehicle type" and "RAS 50001: Contributory factors: Reported accidents by severity" (UK Department for Transport, 2020). As these reports do not contain the exact definition of accident types, the percentages of the leading causes of accidents in the UK, known as contributory factors, have been considered for comparison. These percentages correspond to the exposure of the contributory factor over all accidents. However, since there may be more than one factor per accident, the sum of these numbers is higher than 100%. Moreover, these numbers comprise all accidents regardless of the vehicle type, unlike this paper which includes only light and heavy vehicles. Hence, the percentages do not match exactly, although they represent similar magnitudes.

Applying ADAS effectiveness to road accidents

The classification by accident types introduces another level of

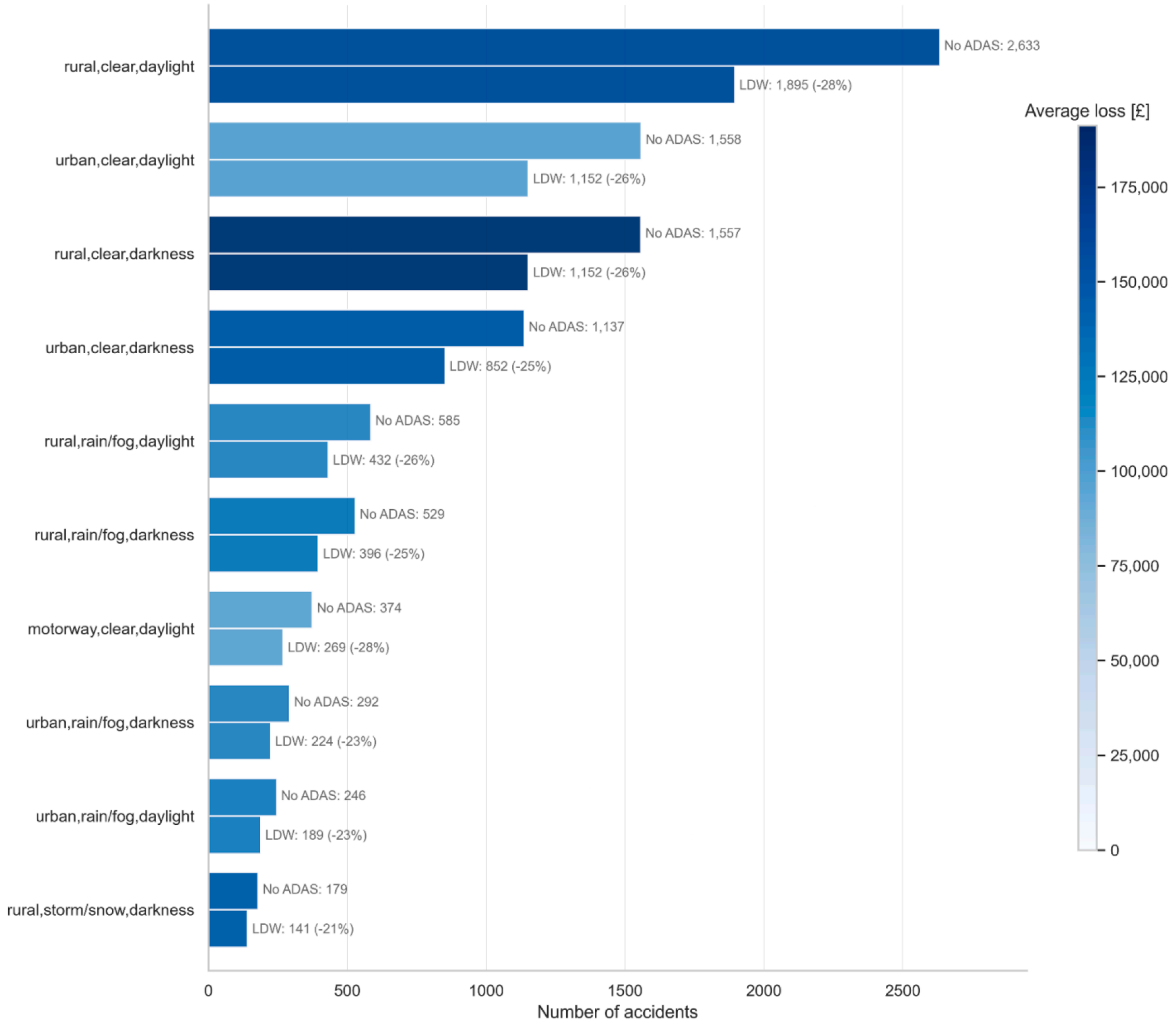


Fig. 6. Lane departure accident reductions in the top 10 most frequent lane departure accident contexts. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bar applies the potential reduction in accident frequency due to Lane Departure Warning (LDW), expressed in the resulting accident count, followed by the percentual reduction of the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). All these accident contexts correspond to average losses higher than 100 thousand pounds, with the top three most severe ones being: *rural-clear-darkness* (£194,302); *rural-clear-daylight* (£169,486); *urban-clear-darkness* (£158,596).

disaggregation in analysing accident frequency and severity – the study of accident types across contextual variables. Consequently, the impact of ADAS on reducing the frequency of a given accident type depends on the distribution of driving contexts within it. That is, the context distribution influences the safety effectiveness of ADAS in each accident type. Thus, the same ADAS might vary its safety benefits according to the kind of accident. This represents one of the main contributions of this paper as previous works have taken unique effectiveness for all accident types.

The estimation of accidents reduction is expressed in mathematical terms in Equation 2. The first part, $|A_i \cap X_j|$, represents the number of type i accidents (A_i) happening in a specific context $X_j : \{RT_k, WC_l, LC_m\}$, which is composed of a combination of road types (RT), weather conditions (WC), and lighting conditions (LC). Then, the number of accidents in context j is combined with the effectiveness of the respective ADAS, determined by Table 8. For example, intersection accidents use the safety effectiveness values of AEB for context j. This value represents the lower bound of each effectiveness range detailed previously in Table 5, providing a conservative estimation.

$$AccidentReduction_{ijy} = \left|A_i \cap X_j\right| \cdot Effectiveness_{ADASyj}, \forall i \in Accidenttypes, \forall j \in Accidentcontexts, \forall y \in ADASlinkedtoAccidenttype_i$$

Equation 2: Estimation of the reduction of accident types happening in a given context due to ADAS. The term $|A_i \cap X_j|$ represents the number of a given accident type (A_i) occurring in a specific driving context (X_j). The ADAS considered for each accident type is determined by Table 8, and the effectiveness of the pair ADAS–context is given by Table 5.

In situations where more than one technology can mitigate the accident type, as in rear-end accidents, the term $Effectiveness_{ADASyj}$ points to the technology with the highest effectiveness among them. Hence, the study avoids the overestimation problem of Wang et al. (2020) that assumes independence between technologies.

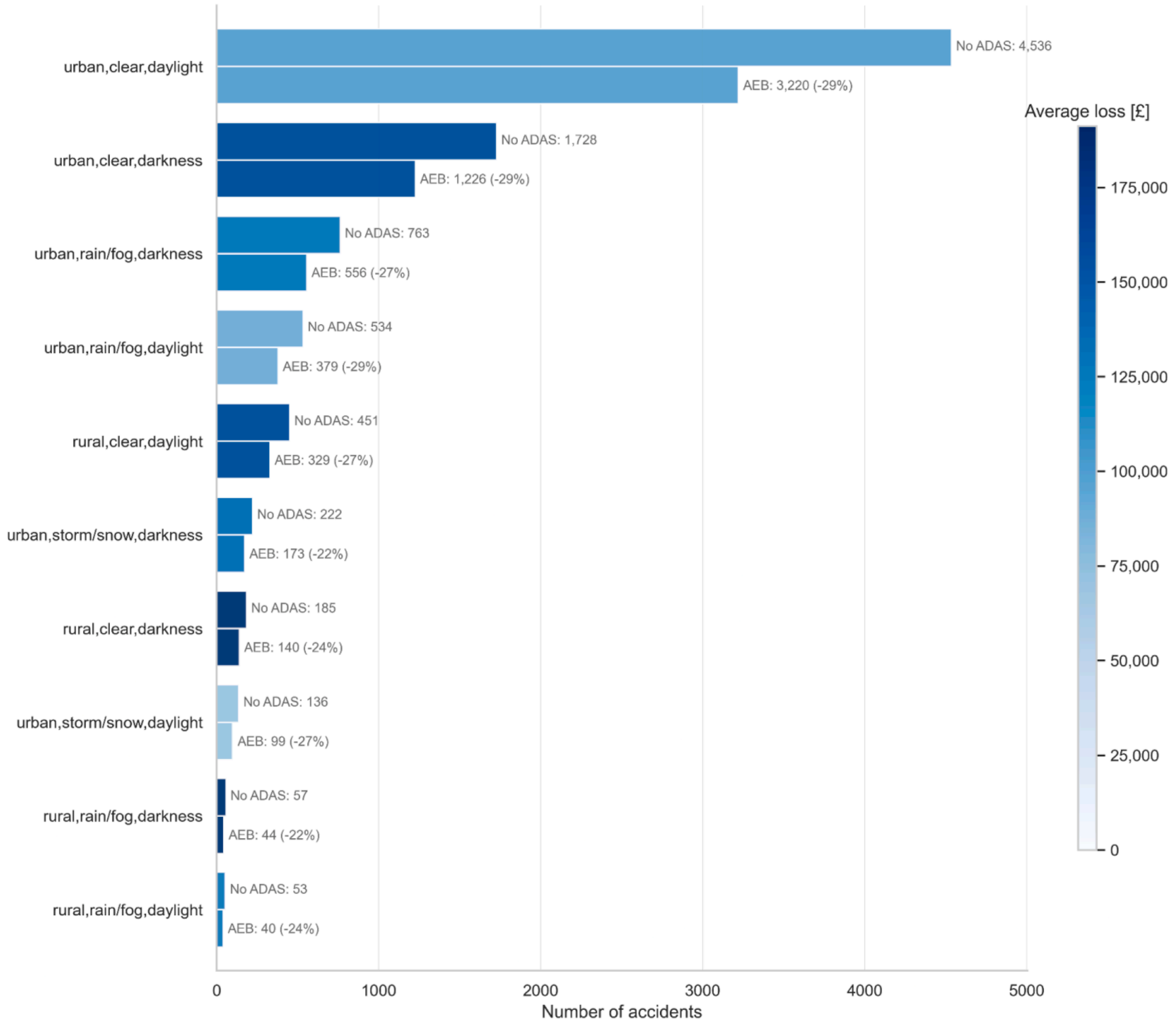


Fig. 7. Against pedestrian accident reductions in the top 10 most frequent against pedestrian accident contexts. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bar applies the potential reduction in accident frequency due to Automatic Emergency Braking (AEB), expressed in the resulting accident count, followed by the percentage decrease in the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). Eight of these accident contexts correspond to average losses higher than 100 thousand pounds, with the top three most severe ones being: *rural-clear-darkness* (£464,388); *rural-rain/fog-darkness* (£251,667); *urban-clear-darkness* (£168,766).

Results

This section presents the results of the estimated reduction in accident frequency due to ADAS across different driving contexts and accident types. The estimates, given by Equation 2, are obtained using the UK's road safety reports presented in the previous section and the safety effectiveness by driving context presented in Table 5. To provide conservative estimates, the effectiveness value of each technology represents the lower bound of the respective effectiveness interval, as done in Yue et al. (2018). Then, the resulting estimations of each technology are aggregated to provide an overall conservative estimate of the ADAS safety benefits.

Figs. 4–9 show the accident frequency reductions in the most frequent accident types – intersection, rear-end, lane departure, against a pedestrian, skidding and overturning, and lane change accidents, respectively. The estimations use the safety effectiveness of the technology designed to mitigate each respective accident type (Table 8). For instance, the intersection accident category only includes AEB, while the rear-end accident category includes AEB, ACC, and FCW. In the latter, AEB outperforms the other two technologies, reaching a reduction of 29% of the most frequent rear-ends accident context. The figures show how the effectiveness of each technology varies with the context. For example, AEB goes from 22% to 29% reduction in Fig. 4, and LDW goes from 21% to 28% in Fig. 6.

The contexts that encompass most road accidents in the studied accident categories are *urban-clear-daylight* and *rural-clear-daylight*. This was expected since it aligns with the busiest road traffic conditions (UK Department for Transport, 2021b). With a full deployment of ADAS, this research estimates a 29% decrease in accident frequency of these contexts (i.e., a reduction of 7,020 and 3,472 accidents, respectively) considering the eight accident categories of Table 8.

Enhancing the safety effectiveness of ADAS in fundamental driving

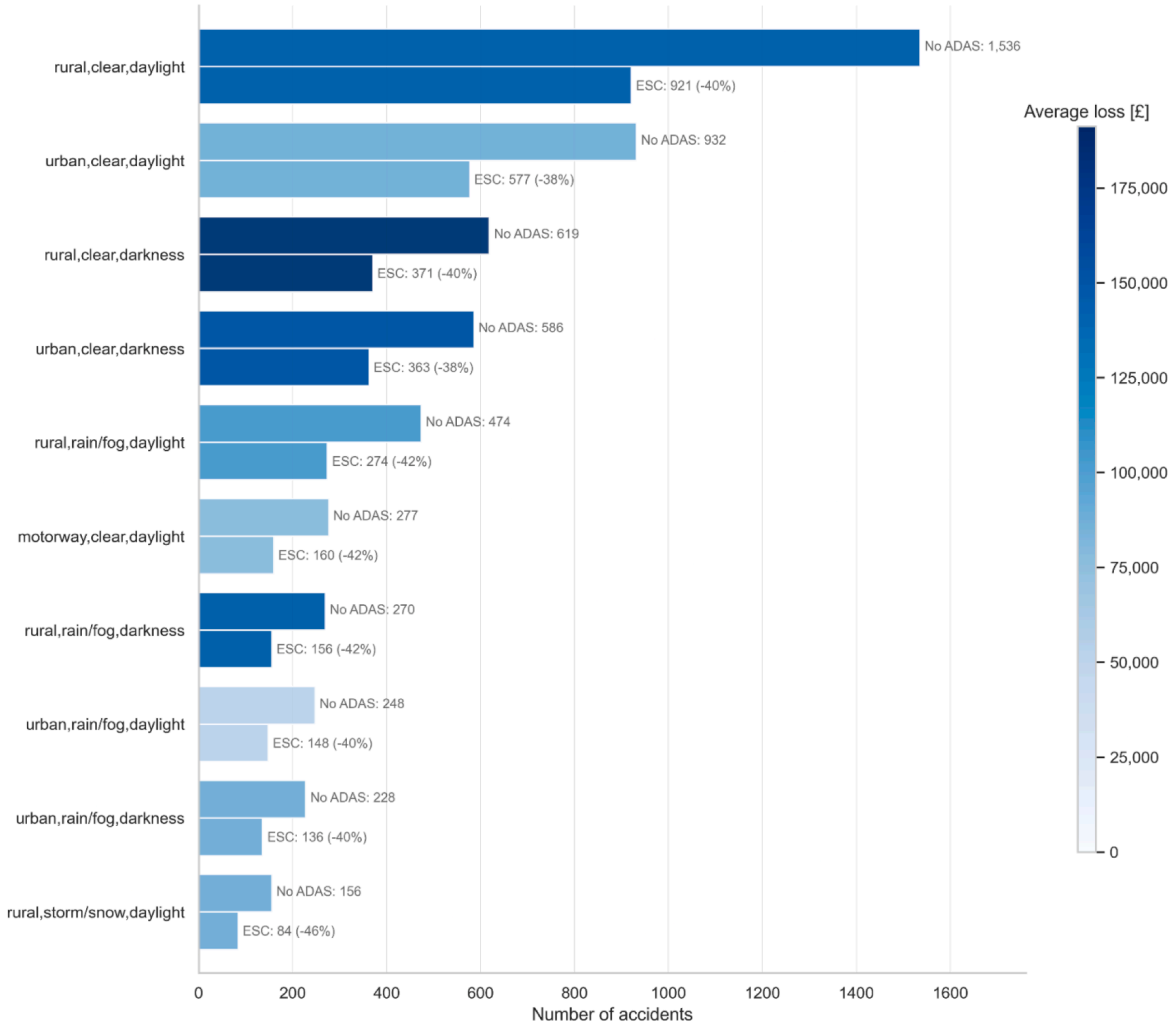


Fig. 8. Skidding and overturning accident reductions in the top 10 most frequent accident contexts of this accident type. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bar applies the potential reduction in accident frequency due to Electronic Stability Control (ESC), expressed in the resulting accident count, followed by the percentage decrease in the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). Five of these accident contexts correspond to average losses higher than 100 thousand pounds, with the top three most severe ones being: *rural-clear-darkness* (£199,257); *urban-clear-darkness* (£162,599); *rural-rain/fog-darkness* (£156,445).

contexts, in terms of frequency and average loss, might help reach the goal of preventing at least 50% of road traffic deaths by 2030 (United Nations, 2020). Hence, analyses by context enable the prioritisation of resources in risk mitigation programs and ADAS research and development. For instance, the study of intersection accidents shows that rural environments are more severe than urban ones, albeit less frequent (Fig. 4). The figures also show that high-speed limits are generally associated with more severe accidents, which aligns with the results of Alnawmasi and Mannering (2022).

This paper promotes further research to enhance the ADAS performance ranking under challenging contexts and extend beyond their maximum effectiveness in favourable contexts (e.g., strengthening AEB in urban environments to reduce more accidents against pedestrians and rear-end accidents). We suggest that road safety organisations and research teams follow a systematic approach to optimising road safety with ADAS. Road safety reports of the target region might be used to prioritise resources according to the current accident loss tied to accident types and contexts. Thus, stakeholders might focus on accident contexts above a specific average loss, and put forward road safety policies, incentivising ADAS development to mitigate particular accident types. For example, accidents on rural roads and in dark conditions are associated with a high expected loss. Then, road safety policies can promote further usage of intelligent systems to increase safety in those contexts, such as a higher deployment of infrared cameras.

Aggregating the accident reductions by driving context enables the estimation of the decrease in frequency for each category. Fig. 10 presents the overall estimates in accident frequency decline over the six most frequent accident types. The values are aligned with recent studies of the safety benefits of collision avoidance technologies performed in the United States (Insurance Institute for Highway Safety, Highway Loss Data Institute, 2022). Accidents against an animal or an object are omitted since they represent less than one thousand accidents. AEB is the component that has the most significant impact on several accident types, with overall effectiveness ranging from 27.7% to 28.4%. The promising benefits of AEB go conjointly with the agreement between the vehicle manufacturers that represent 99% of the United States

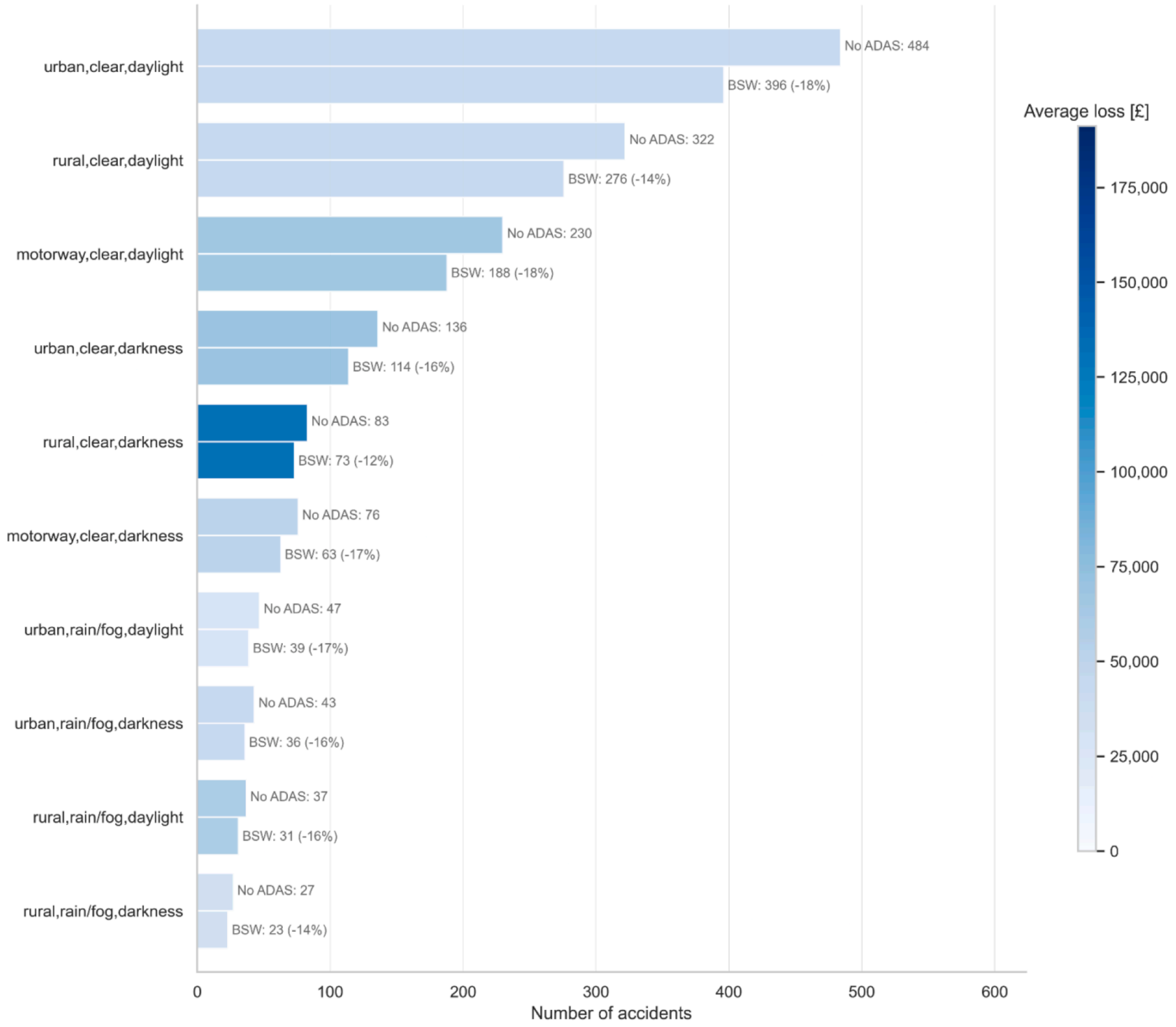


Fig. 9. Lane change accident reductions in the top 10 most frequent accident contexts of this accident type. Each group bar represents the number of accidents happening in a given driving context. The top bar refers to the accidents count found in the UK road safety reports of 2019. Its subsequent bar applies the potential reduction in accident frequency due to Blind-spot Warning (BSW), expressed in the resulting accident count, followed by the percentage decrease in the top bar. The colour scale illustrates the severity of the accidents in the group, given by the average loss incurred in those crashes (Equation 1). The top three most severe contexts are: *rural-clear-darkness* (£142,506); *urban-clear-darkness* (£74,682); *motorway-clear-daylight* (£71,616).

automotive market to equip all new light vehicles with low-speed AEB by 2022 (NHTSA, 2017). LDW and ESC also present promising benefits in accidents in which the vehicle loses control. In contrast to ESC, where the system acts once the vehicle is involved in a hazardous manoeuvre, LDW may prevent such a situation a-priori. Complementary technologies to LDW, like Lane-Keeping Assist (LKA), may enhance the reduction of lane departure accidents. As observed in Fig. 6, this category has a significant average loss over contexts. Thus, it is encouraged to focus on enhancing the performance of such systems in two of the most frequent and costly contexts, *rural-clear-daylight* and *rural-clear-darkness*, which represent an average loss of £169,486 and £194,302, respectively.

Combining all accident types, this paper estimates an overall annual accident reduction of 23.8% of UK road accidents (i.e., a decrease in 18,925 crashes) if all vehicles incorporate the ADAS studied in this paper. Fig. 11 illustrates the accumulated reductions by accident types and the total estimate. This estimate is approximately half of the UK's posited by Wang et al. (2020). A principal reason for such considerable difference lies in the former study overestimating the safety effectiveness in accident types mitigated with multiple technologies. For those cases, the authors assumed independence between the technologies and compounded their effectiveness; however, these values are mutually dependent, as mentioned in Section 2.1. This research only considered the technology with the highest estimate to overcome this problem in such scenarios, resulting in a more conservative estimate. Furthermore, this study included only six technologies instead of nine, following the nomenclature recommendations of the SAE presented in Section 2.1. Other reasons for this difference include the variance in the proportion of accident types shown in Table 9 and the disaggregation by driving context.

There are limitations with the estimations presented within this section, similar to those found in previous studies. It assumes that the level of vehicles equipped with ADAS involved in the studied accident reports is negligible. However, some technologies have been in the market for some years as an option or standard feature. For instance, ESC has been mandatory for all new vehicles from 2012 in the United States (NHTSA, 2007) and 2014 in the European Union (European

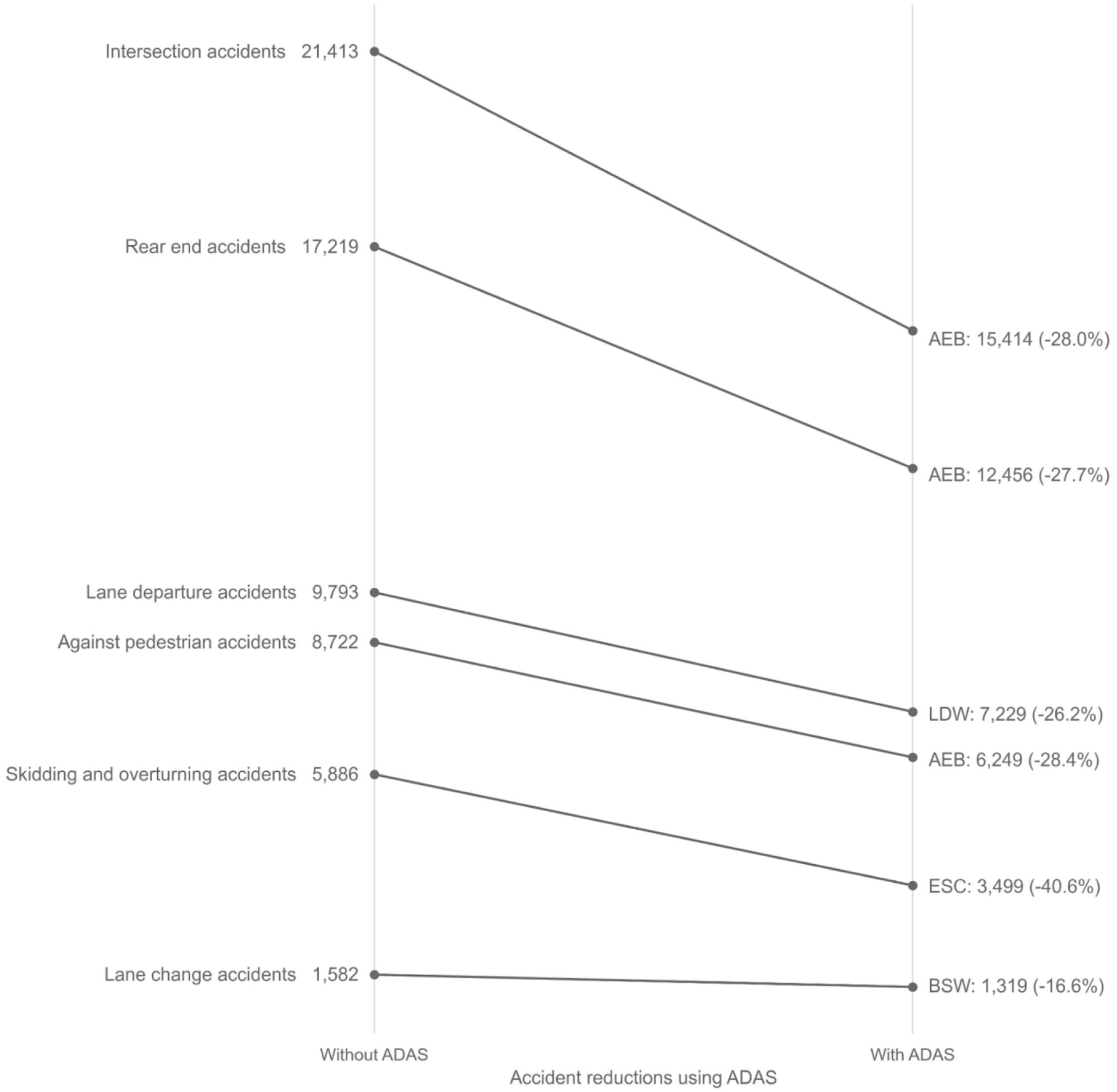


Fig. 10. Accident reductions using ADAS for the six most frequent accident types. The left-hand values represent the accidents count for the accident types according to the UK road safety reports of 2019. The right-hand values show the potential number of crashes if all vehicles are equipped with the ADAS technology designed to mitigate each respective accident type, as described in Table 8. These values are also expressed as the percentage decrease of the left-hand value. The estimates are obtained aggregating the effectiveness of the corresponding ADAS applied to the driving contexts distribution of each accident type. Abbreviations: Automatic Emergency Braking (AEB), Blind-spot Warning (BSW), Electronic Stability Control (ESC), and Lane Departure Warning (LDW).

Parliament, Council of the European Union, 2009). It is encouraged that future road safety campaigns include the vehicle's level of autonomy or ADAS equipment to allow for a more accurate estimation. Additionally, the level of reductions achieved in this paper assumes a full market penetration of ADAS in which all vehicles involved in the accident reports have the studied technologies. Furthermore, in cases where multiple technologies can mitigate an accident type, this paper has used the technology with the highest effectiveness since there is a lack of significant research studying the efficacy of multiple technologies together.

Even though the safety benefits of ADAS are notable, a potential limitation is that their functionality and proper application depend on human drivers and their trust in these systems. The limitations of ADAS presented in Section 2 might cause drivers to disregard warnings triggered by ADAS or turn them off. For instance, Lyu et al. (2019) found that driver acceptance for FCW is higher than LDW and that the driving context is a principal factor influencing this behaviour. Similarly, Orlovska et al. (2020a) showed that the driving context influences ADAS performance and, consequently, driver attitude towards these systems. The authors posited that ADAS limitations affect drivers' perception and trust in the system. As discussed in Orlovska et al. (2020b), importance should be attached to the level of communication support between ADAS and the driver to improve driver acceptance. The lack of a straightforward human–machine interface makes the driver overlook the reasons for ADAS behaviour. Such a drawback influences the user's trust in the system and the willingness to use it. Having a system that communicates through proper information about ADAS performance, including its limitations and the reasons for its behaviour, might increase the driver's understanding and exploit the safety benefits of this technology.

Conclusions

Vehicles enabled with Advanced Driver Assistance Systems (ADAS) provide significant societal benefits, but there is a lack of comprehensive literature on their potential accident reductions across various driving contexts. This paper addresses that gap by estimating the decrease in accident frequency of eight accident types due to ADAS across 18 combinations of relevant contextual variables influencing ADAS

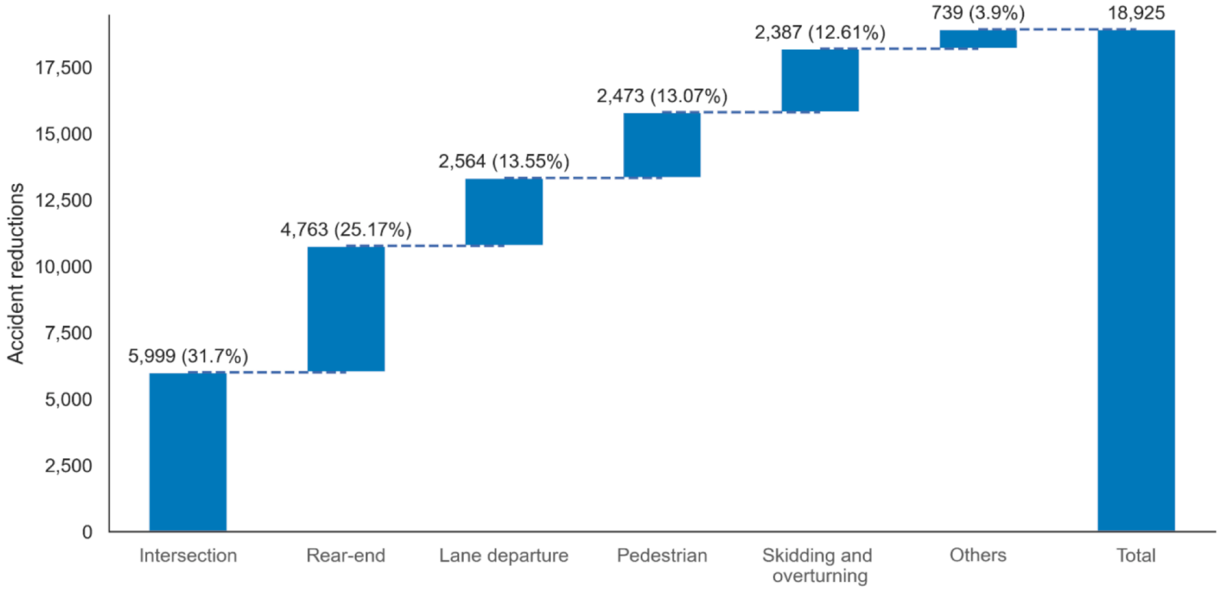


Fig. 11. Overall accident reductions using ADAS by accident types. Each bar represents the conservative estimated accident reductions for the studied accident types, and the values are accumulated until reaching the total accident reduction of 18,925 (right-hand bar). Above each bar, the figure shows the decrease in accidents, followed by its percentage of the total decline. The category Others encompass the accident types lane change, against animals and objects.

performance. Using the disaggregation by accident context, the paper provides a methodology to quantify the potential safety benefits of ADAS technologies on annual road accidents of a given region.

Through assessing the systems' literature, the paper identifies the primary environmental and road conditions influencing their performance and safety effectiveness. These contextual variables consist of road types (motorway, urban, and rural), weather conditions (clear, rain/fog, and snow/storm), and lighting conditions (daylight and darkness). Eighteen combinations of these contextual variables are used to investigate the UK's Road accidents distribution for 2019. The results show that four combinations represent 77% of road accidents. In particular, these are contextual variables that favour the performance of ADAS, and therefore considerable effects on accident reductions are expected with a significant market penetration of these systems. Moreover, the five most severe accident contexts involve dark conditions on rural roads or motorways. By providing information about the frequency and severity of the accidents occurring across driving contexts, this research might help road safety and automotive stakeholders prioritise policies, research, and development to make transportation safer and mitigate critical accidents.

The paper also analyses the accident reduction by driving contexts within the most frequent accident types. It leverages the relationship between eight accident types and the systems designed to mitigate them to estimate potential road safety benefits. For each accident type, the distribution of collisions by driving context is analysed, and then, the reductions due to their respective ADAS are measured. Following a conservative approach, the results estimate an overall decrease of 23.8% of all UK's accidents, representing a reduction of 18,925 collisions out of which 31.7% are intersections accidents, 25.2% rear-endings, 13.5% lane departures, 13.1% against pedestrians, 12.6% skidding and overturning, and 3.9% lane changes, and against animals and objects. The results also show a decrease of 29% in the frequency of the most frequent accident contexts – *urban-clear-daylight* and *rural-clear-daylight* – representing a reduction of 7,020 and 3,472 accidents, respectively. Among the six studied technologies, Automatic Emergency Braking is the most impactful for road safety, providing effective accident reduction in three out of the four most frequent accident types. Such findings align with transportation policies to equip new vehicles with ADAS. This research encourages further advancements to enhance ADAS performance in challenging and favourable contexts, extending beyond the current levels of safety effectiveness, to reach more significant decreases in essential accidents contexts (e.g., severe lane departure accidents).

The estimations of this research can be improved by future work involving other CAV technologies. It is expected that vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications introduce safety benefits to two of the most frequent accident types – intersection and rear-end accidents. For example, intersection movement assist (IMA) warns the driver when approaching a dangerous intersection (Maile et al., 2015). The proliferation of vehicles with intermediate levels of autonomy (i.e., SAE level 2–4) is another factor expected to contribute to road safety, supplementing this research.

Other lines of thought for future work include a field study rather than an Analytic Hierarchy Process to obtain rankings and effectiveness of ADAS across the studied contexts. To the best of the authors' knowledge, there is also a lack of research comprehensively investigating ADAS performance with the interaction between the contextual variables used in this study (road types, weather conditions, and lighting conditions) and more detailed variables such as road infrastructure, traffic density, and different intensities of weather conditions. Thus, it is recommended that future research includes these interactions to gain more understanding on the safety benefits of ADAS. Since road infrastructure, driving patterns, and environmental conditions vary from region to region, extending this study to other geographical areas is also envisioned. Analysing ADAS benefits by driving contexts using specific road safety reports for several geographical regions might help promote automotive development and policies in different parts of the world and achieve a collective decrease of road injuries.

CRediT authorship contribution statement

Leandro Masello: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Visualization. **German Castignani:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision. **Barry Sheehan:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision. **Finbarr Murphy:** Writing – review & editing, Supervision. **Kevin McDonnell:** Writing – review & editing.

Table A1
Pairwise comparisons for the Analytic Hierarchy Process (AHP) presented in Section 2. The comparisons are based on the importance of maximising the performance of each ADAS, according to the literature review shown in Table 2. All criteria are compared in pairs using the AHP's scale from 1 to 9, where the values indicate the importance of one criterion over another, as 1 (equal importance), 3 (moderate importance), 5 (strong importance), 7 (very strong importance), 9 (extreme importance). Even numbers are suggested for intermediate values when a compromise is needed and it is the case where only partial evidence was found.

Technology	Criterion 1 (C1)	Criterion 2 (C2)	Ratio C1/C2	Notes
ACC	Motorway	Rural	3	ACC is predominately used on motorways and rural roads. While motorways present the best performance, there are limitations in rural roads due to roundabouts and curves. Road layout and traffic conditions negatively impact the ACC usage on urban roads.
	Motorway	Urban	5	
	Rural	Urban	3	
	Clear	Rain	3	The best performance is observed in clear weather. As the weather conditions worsen, the signal continuity of the ACC sensors degrades, leading to higher lost detection rates or false positives.
	Clear	Snow	5	
	Rain	Snow	3	
	Daylight	Darkness	3	Previous studies reported a higher rate of false negatives at night.
AEB	Motorway	Rural	1	There are limitations in high-speed roads for AEB, both in motorways and rural roads, since the system performs partial braking at those speeds instead of full braking. The best performance is achieved in urban roads due to the low-speed range.
	Motorway	Urban	0.2	
	Rural	Urban	0.2	
	Clear	Rain	3	Clear weather favours the performance of AEB due to the friction coefficient and visibility. Inclement weather reduces progressively the performance for the same reasons.
	Clear	Snow	7	
	Rain	Snow	3	
	Daylight	Darkness	2	Dark environments might impair camera-based systems, reducing the performance.
BSW	Motorway	Rural	3	The performance by road types is mainly determined by the quality and standardisation of lane markings. Motorways present the best performance as they feature standardised and well-maintained lane markings.
	Motorway	Urban	2	
	Rural	Urban	0.33	
	Clear	Rain	2	Similar to other technologies, inclement weather reduces progressively the sensor capabilities of camera-based or radar-based BSW.
	Clear	Snow	4	
	Rain	Snow	3	
	Daylight	Darkness	2	There exists potential performance limitations in dark environments for camera-based systems.
ESC	Motorway	Rural	3	ESC focuses on dangerous situations involving high-speed roads and adverse conditions. While motorways and rural roads present high-speed limits, motorways reported better performance.
	Motorway	Urban	5	
	Rural	Urban	3	
	Clear	Rain	0.5	Adverse weather conditions represent a main target of ESC. These situations involve inclement weather and, thus, a reduction in the road's friction coefficient.
	Clear	Snow	0.14	
	Rain	Snow	0.25	
	Daylight	Darkness	1	There are no differences in performance with different lighting conditions due to the ESC system design.
FCW	Motorway	Rural	1	There exists no significant performance differences across road types. Motorways reported slightly better performance than urban roads, while urban facilities had better effectiveness than rural ones.
	Motorway	Urban	2	
	Rural	Urban	0.33	
	Clear	Rain	2	Similar to AEB, inclement weather increases the likelihood of sensor impairment and braking constraints due to the friction coefficient.
	Clear	Snow	3	
	Rain	Snow	3	
	Daylight	Darkness	2	There exists potential performance limitations in dark environments for camera-based systems.
LDW	Motorway	Rural	2	The well-maintained and standardised lane markings make motorways the preferable road type for LDW. It is followed by rural areas, which present a lower performance due to lower lane quality and higher exposure to curves. Urban roads come after due to low-speed system restrictions.
	Motorway	Urban	3	
	Rural	Urban	3	
	Clear	Rain	3	The best performance is achieved in clear weather conditions, since inclement weather increases the likelihood of impairing sensors and obstructing lane markings.
	Clear	Snow	5	
	Rain	Snow	3	
	Daylight	Darkness	2	Dark environments increase the likelihood of obscuring lane markings, and thus, reducing the performance of LDW.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

This study presents a methodology that integrates the academic literature on ADAS and publicly available road safety reports from the United Kingdom, appropriately referenced in the bibliography.

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Appendix A

This appendix is complementary to the Analytic Hierarchy Process (AHP) presented in Section 2 to rank different driving context combinations in terms of their likelihood of maximising the performance of the ADAS studied in this research: Adaptive Cruise Control (ACC), Automatic Emergency Braking (AEB), Blind-spot Warning (BSW), Electronic Stability Control (ESC), Forward Collision Warning (FCW), and Lane Departure Warning (LDW). The respective weights for each criterion are based on the evidence found in the literature review presented in Table 2 and described in the *Notes* column of Table A1. Such values follow the standard AHP's scale from 1 (equal importance) to 9 (extreme importance). Therefore, ratios above one mean that the first criterion favours maximising ADAS performance. Similarly, ratios below one indicate that the second criterion takes more relevance.

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