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Research Article

Characterizing future crashes on Indian roads using counterfactual simulations of pre-crash vehicle safety technologies

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ABSTRACT

India's national road crash statistics indicate a continuing increase in casualties. Pre-crash safety technologies are effective in high-income countries, but it is unclear how these will perform in India and which crash types will remain after their implementation. The study objective was to predict and characterize the crashes resulting in moderate or more-severe injuries (Maximum Abbreviated Injury Scale 2 or above: MAIS2+) that remain on Indian roads after 22 pre-crash safety technologies have been implemented in all cars, heavy vehicles (buses and trucks), and Powered Two-Wheelers (PTW). Two deterministic rulesets (one optimistic and one conservative) were modeled for each of the pre-crash safety technologies. Each rule was designed and tuned to the functionality of one technology. The data were obtained from the Road Accident Sampling System India (RASSI) database. In addition to the effectiveness of each technology alone, the combined effectiveness of all technologies was estimated. Further, the characteristics of those crashes that none of the technologies would have avoided were determined. Rear-end-specific Autonomous Emergency Braking (AEB REAR-END) and Electronic Stability Control (ESC) installed in cars and heavy vehicles reduced MAIS2+ crashes the most. Crashes between PTWs and cars were significantly reduced by a rear-end-specific AEB installed in the cars. A pedestrian-specific AEB (AEB-PED) in cars and heavy vehicles was also shown to be effective. The only pre-crash safety technology in PTWs that was included, Antilock Braking Systems (ABS), reduced overall PTW crash involvement, but only reduced PTW-to-pedestrian crashes marginally. The largest proportion of remaining crashes were those that involved PTWs, indicating that PTW safety will remain a concern in future.

1. Introduction

Road traffic crashes are a burden to public health, particularly in low- and middle-income countries. India's statistics on road traffic crashes nationwide indicate a steady increase in casualties over the years; the most recent data indicate that these crashes resulted in 151,113 fatalities and 451,361 injuries in 2019 [1]. If the current rate of increase continues, approximately 241,751 (95% CI, 194,102-289,399) road traffic crash-related fatalities can be expected by 2030 [2].

In 2019, the government of India amended the Central Motor Vehicle Rule (1989), which regulates the production, registration, and maintenance of motor vehicles; the certification of auto components; and driver licensing. It is expected that the amendment and the current level of enforcement will help to reduce the number of fatalities. However, alternative strategies to prevent or mitigate road traffic crashes should also be investigated, since additional, drastic steps are required to reach the goal of at least halving fatalities from 2020 to 2030 [3].

One such step would be to mandate pre-crash safety technologies, e.g., Electronic Stability Control (ESC) and Autonomous Emergency Braking (AEB), in motor vehicles in India. While pre-crash safety technologies have proven to reduce fatalities and severe injuries [4–10], these technologies were not mandated in the recent amendment. The effectiveness of pre-crash safety technologies has been primarily estimated for high-income countries [11,12]; not many studies have been conducted in low- and middle-income countries such as India. The few studies that have estimated the effectiveness of pre-crash systems in India [13–17] are listed in Table 1, together with articles published from 2005 to date on pre-crash safety technologies in other countries. Notably, the Intelligent Speed Adaptation (ISA) installed in cars in Great Britain was estimated to be highly effective, as were cyclist-

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Table 1
Effectiveness estimates of identified pre-crash safety technologies. Italics indicate effectiveness percentages and references for India. The seven pre-crash safety technologies for heavy vehicles are the same as for passenger cars, so they are presented in the same row.

Pre-crash safety technologies	Vehicle type(s)	Country	Reduction in addressed[1] crashes (%)	Reference
Advanced Front Lighting System (AFS)	Passenger car	USA	2 (cars)	[18]
Blind Spot Detection (BSD)	Passenger car	USA, Germany	1–7, 2–3(cars)	[20–21]
Break Assist System (BAS)	Passenger car	Germany	8 (cars)	[21]
Evasive Steering Assist (ESA)	Passenger car	*India*, USA	*2*, 4–14 (cars)	[16,19]
Intelligent Speed Adaptation (ISA)	Passenger car, heavy vehicles (trucks and buses)	*India*, Great Britain	*3*, 25 (cars)	[16,22]
Intersection Movement Assist (IMA)	Passenger car	USA, *India*	2–9, *2* (cars)	[16,20,23]
Cyclist specific AEB (AEB-CYCL)	Passenger car, heavy vehicles	Sweden, *India*	34–86 (cars) *0* (cars)	[16,24]
Pedestrian specific AEB (AEB-PED)	Passenger car, heavy vehicles	USA, *India*	7 (cars) *0* (cars)	[16,25]
Alcohol Interlock (ALCI)	Passenger car, heavy vehicles	USA	25 (cars)	[26]
Rear-end specific AEB (AEB REAR-END)	Passenger car, heavy vehicles	USA, *India*	16–21 (cars) 8 (trucks) *19–48* (cars)	[4,17,18,27]
Electronic Stability Control (ESC)	Passenger car, heavy vehicles	EU, USA, *India*	12–38 (cars) 11–20 (trucks) *15* (cars)	[27–29]
Lane Change Assist (LCA)	Passenger car	Germany, *India*	1–4, *1* (cars)	[16,30]
Lane Keep Assist (LKA)	Passenger car	USA, Germany, *India*	1–3, 7–27, *5* (cars)	[16,18,19,31,32]
Driver Distraction Alert (DDA)	Passenger car, heavy vehicles	Germany	3–10 (cars)	[30]
Antilock Braking System (ABS)	PTW	*India*, Italy, and Sweden	*33*, 24–34 (PTW)	[14,33]

[1] Addressed crashes may differ from study to study.

specific AEB in the USA and ESC in cars and trucks in the EU, USA, and India. In addition, Antilock Braking Systems (ABS) installed on Powered Two-Wheelers (PTWs) are effective, according to studies carried out on data from India, Italy, and Sweden.

It is evident that pre-crash safety technologies reduce crashes in high-income countries. Since only a few studies have been carried out on road accident data from India it is unclear how state-of-the-art pre-crash safety technologies will perform in India, as India's road traffic has a unique composition, with a high proportion of trucks, PTWs, and pedestrians. Its road infrastructure differs from that of high-income countries as well. Therefore, pre-crash safety technologies that are effective in high-income countries cannot simply be assumed to be effective in India.

Furthermore, even highly effective pre-crash technologies are unlikely to prevent all crashes [19,20,34]. Hence, the crashes remaining after the interventions should be estimated, to facilitate studies into additional safety solutions and ensure the interventions' relevance [35,36].

The aim of this study was to estimate the number, and more importantly, the types of remaining road crashes resulting in MAIS2+ (moderate or more severe) injuries when 22 state-of-the art pre-crash safety technologies have been adopted in all passenger cars, heavy vehicles (buses and trucks), and PTWs. Characterizing remaining crashes in India can help ensure that future countermeasures and policies will prioritize the prevention of the remaining crash types, reducing road crashes and fatalities even further.

2. Method

2.1. Crash data

We used data from the Road Accident Sampling System - India (RASSI), an in-depth database of Indian road traffic crashes, to calculate the expected effectiveness of pre-crash safety technologies. The database includes crashes that occurred on public roads in five different regions, in both urban and rural areas. Between 2014 and 2019, 3721 crashes were recorded. We initially selected all crashes in which at least one participant suffered at least one moderate or more severe injury, defined as 2 or higher on the Abbreviated Injury Scale (AIS2+) ($n = 2212$). In order to make the sample representative of crashes in all of India, we used the weights provided for each crash within the database [37]. Three crashes were excluded because the weight factors (132,875; 62,353; 43,716) exorbitantly exceeded the average (637), and might inordinately influence the results [38]. The final sample totaled 2209 crashes, which translates to 1,170,003 crashes in India over a six-year period (2014–2019). The percentages of each crash participant were: PTWs 30.6%, passenger cars 21.3%, trucks 21%, pedestrians 16.1%, buses 8.4%, bicycles 0.5%, and other 2.1%. To understand crash types in more detail, the weighted distribution of collision partners in the first event from RASSI data (2014–2019) is shown in Table 2. In the RASSI database, most first events are crashes between passenger cars and PTWs followed crashes between two trucks. Only few crashes observed between bicyclist and passenger cars in the first event.

2.2. Modeling pre-crash safety technologies

Twenty-two pre-crash safety technologies, commercially available in passenger cars, heavy vehicles, and PTWs, were modeled following the approach from Östling et al. [19]. For each technology, we developed two rulesets by limiting several crash parameter values to filter out typical crashes which that technology is expected to avoid. The two different rulesets (optimistic and conservative) account for model uncertainty, which originates from necessary simplifications of the rulesets and the resolution of the crash data. The optimistic ruleset assumes the system will work in all possible conditions, modeling the pre-crash safety technology when road/weather conditions are ideal. In contrast, the conservative ruleset reflects the functional constraints when conditions are poor (such as harsh weather or lack of infrastructure support), providing a more conservative estimate of the system's effectiveness. As an example, the conservative ruleset for the in-car AEB-PED prevents the following type of crash: Passenger car front impacting a pedestrian with a maximum travel speed of 60 km/h; no visual obstructions and clear weather conditions. The system's optimistic ruleset prevents the same type of crash, regardless of visual obstructions or weather conditions. Similar rulesets were modeled and applied to the accident data for all the pre-crash safety technologies (Appendix A).

2.3. Effectiveness estimation

The effectiveness of each technology was estimated by calculating the percentage of original MAIS2+ crashes that were avoided by its implementation. The effectiveness of a safety technology is defined as the percent reduction of injury severity (fatality reduction in this study)

Table 2
Distribution of collision partners in the first event of crashes in RASSI for the period of six years (2014–2019).

Second collision partner	First collision partner							
	Passenger car	Truck	Bus	PTW	Bicycle	M3W	Others*	Total
Passenger car	534,201	741,057	243,338	856,223	7380	132,694	11,500	2,526,393
Truck		763,940	205,018	448,511	3120	22,264	3650	1,446,503
Bus			52,552	190,545	632	4218	5104	253,051
PTW				325,386	7675	23,618	9608	366,287
Bicycle					0	290	0	290
Motorized three-wheeler (M3W)						221	1694	1915
Others							0	0
Pedestrian	237,999	91,145	61,270	250,963	60	9268	1420	652,125
Animal	591	0	0	2873	0	640	0	4104
Object	701,018	286,031	37,721	74,919	0	31,954	0	1,131,643
Non-collision	120,883	304,454	120,102	128,312	123	13,416	0	687,290
Total	1,594,692	2,186,627	720,001	2,277,732	18,990	238,583	32,976	7,069,601

* Others include special vehicles like farm tractor, cranes, and earth movers.

that would result if a population went from nobody using the technology to everyone using it, provided that other factors remained unchanged [39]. The overview of the workflow is depicted in Fig. 1. The following example of ESC demonstrates the individual effectiveness estimation calculation. ESC optimistic and conservative rulesets were applied to all the MAIS2+ crashes. Crashes satisfying all conditions in a ruleset were marked as prevented. Individual effectiveness was calculated (Eq. (1)). With the optimistic ruleset, ESC installed in passenger cars was estimated to prevent 11.5% of crashes (134,224 out of 1,170,003); with the conservative ruleset, 11.2% of crashes (131,359 out of 1,170,003).

$$\text{Weighted Effectiveness}_{Technology} = \frac{\text{Weighted number of AIS2} + \text{crashes avoided by Technology}}{\text{Weighted number of all AIS2} + \text{crashes}(1,170,003)} \quad (1)$$

We calculated the combined effectiveness by counting the crashes prevented by the individual pre-crash safety technologies for passenger cars, heavy vehicles, and PTWs. If multiple technologies prevent a specific crash, that crash is counted as avoided only once, thereby allowing us to estimate the combined effectiveness accurately without counting the same crash as avoided more than once [39]. More detailed coding logic for estimating individual and combined effectiveness is given in Appendix C.

2.4. Data uncertainty

In addition to the performance uncertainty of each pre-crash safety technology (model uncertainty) addressed with the two deterministic rulesets, there is also uncertainty about the accuracy of the in-depth crash data (data uncertainty). There was variability in the data collection, but the sample is of limited size and may not accurately represent the population of interest.

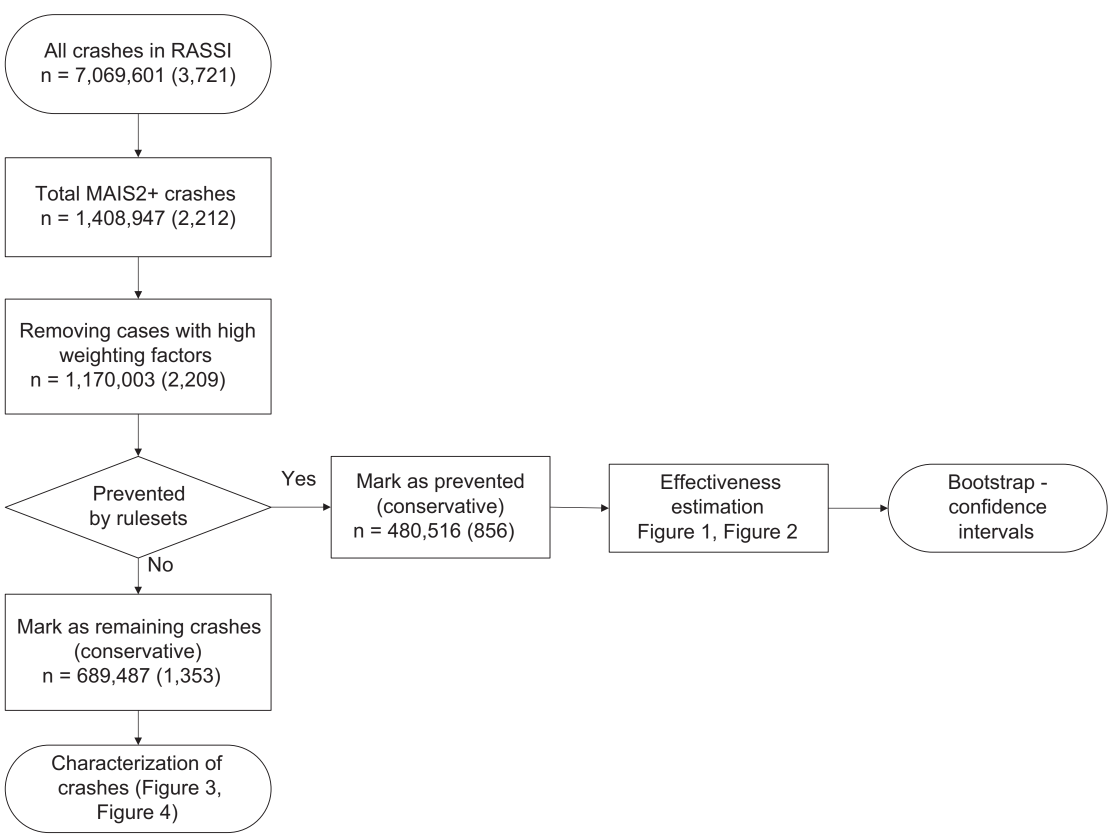

Fig. 1. Flowchart for conservative effectiveness and remaining crash estimates. Numbers are weighted to national level, unweighted data (raw counts) in parenthesis.

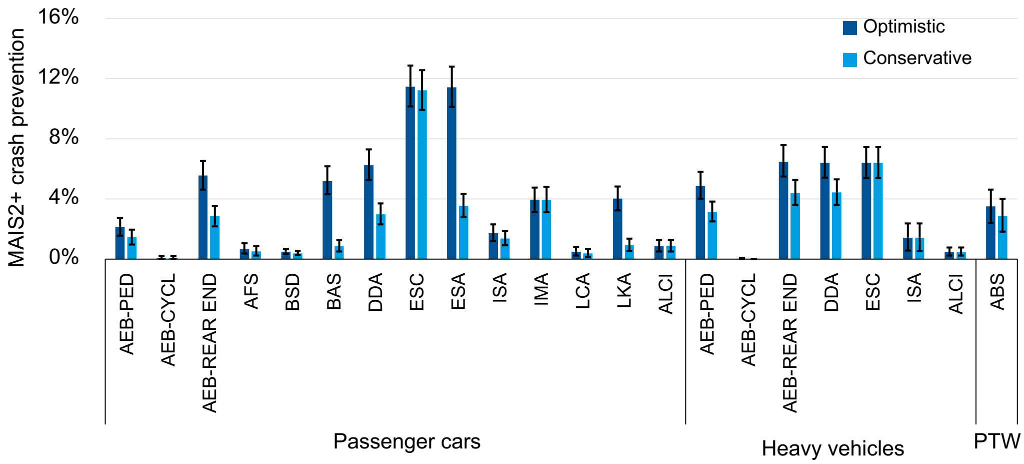

Fig. 2. Estimated effectiveness of individual pre-crash safety technologies in India. Error bars indicate data uncertainty. Refer to Table 1 for expansion of acronyms.

We employed bootstrapping to quantify the uncertainty of our estimations, using statistical computing software R (version 3.5.1). The uncertainty is expressed as confidence intervals or variance in the randomly drawn sample estimates [40]. The dataset along with individual effectiveness was bootstrapped (10,000 samples), and bootstrap means of effectiveness were used to calculate the confidence intervals (95%). The variations of the resulting bootstrap means from the respective point estimates of each technology's effectiveness were treated as reasonable approximations of variance in the effectiveness estimations.

2.5. Remaining crash analysis

The crashes that were not avoided by any of the safety technologies modeled using the conservative rulesets were considered remaining crashes. (Refer to Appendix C for workflow.) The remaining crashes were characterized by pre-crash event types (based on accident scenario classifications proposed by Sander [41]), collision partners, and impact types. Descriptions of all 30 pre-crash event types are given in Appendix B. The impact types were defined by their contact planes at first impact, with a frontal damage priority for heavy vehicles, passenger cars, and PTWs. The characteristics of the remaining crashes were compared to those of the original crashes.

3. Results

The individual effectiveness of each modeled pre-crash safety technology in avoiding MAIS2+ crashes in India when all vehicles are equipped with these technologies was assessed using conservative and optimistic rulesets for cars, heavy vehicles and PTWs. The results are presented in two sections: the effectiveness of the technologies and the analysis of the remaining crashes.

3.1. Pre-crash safety technology effectiveness

The most effective technology for reducing MAIS2+ crashes was ESC (10%–13% of crashes when installed in passenger cars and 5%–7% of crashes when installed in heavy vehicles), followed by rear-end-specific AEB for passenger cars and heavy vehicles (Fig. 2). When only system-relevant crashes were considered, the estimates for ESC were 97%–100% in passenger cars and 100% in heavy vehicles. For AEB REAR-END, system-relevant effectiveness was 47–92% when installed in passenger cars and 67–100% when installed in heavy vehicles. Cyclist-specific AEB was the least effective technology for passenger cars and trucks; there are few cyclists in India. A system that warns drivers when they are distracted was found to be slightly more effective in heavy vehicles than in passenger cars.

The technologies' combined effectiveness was higher for passenger cars than for heavy vehicles (Fig. 3). This difference is a consequence of two factors: individual technologies are more effective in passenger cars than in heavy vehicles (Fig. 2), and more technologies are available for passenger cars. Overall, these 22 technologies combined have the potential to prevent 80,086–99,339 crashes per year in India.

The estimated overall crash reduction for each technology is given in Table 3. Weighted RASSI data for six years (2014–2019) were analyzed for the estimate.

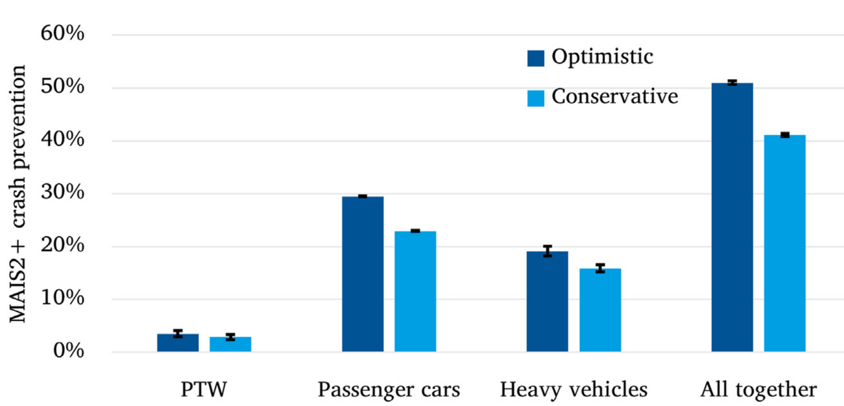

Fig. 3. Effectiveness of all technologies combined, grouped by type of vehicle with the technology installed. Error bars indicate data uncertainty. For PTWs, only ABS was modeled; for heavy vehicles, only seven technologies were modeled.

Table 3
Estimated total number of MAIS2+ crashes avoided (assuming 100% fleet penetration) for a six-year period.

Body types	Technology	Crashes avoided during six years	
		Optimistic	Conservative
Passenger car	AEB-PED	25,000	17,043
	AEB-CYCL	972	972
	AEB-REAR END	65,085	33,373
	AFS	7904	6089
	BSD	5859	4454
	BAS	60,795	10,097
	DDA	73,016	34,784
	ESC	134,224	131,359
	ESA	133,790	41,354
	ISA	20,164	16,014
	IMA	46,109	46,004
	LCA	5859	4454
	LKA	47,086	11,007
	ALCI	10,228	10,228
Heavy vehicle	AEB-PED	51,348	36,699
	AEB-CYCL	217	0
	AEB-REAR END	75,835	51,348
	DDA	74,057	51,778
	ESC	74,786	74,786
	ISA	16,731	16,679
	ALCI	5,525	5525
PTW	ABS	41,011	33,588
	All passenger car technologies	344,731	268,200
	All heavy vehicle technologies	223,689	185,602
	All combined	596,032	480,516

3.2. Remaining crashes

Fig. 4 illustrates the ten most prevalent pre-crash event types in the original MAIS2+ crashes split in the fractions of prevented and remaining crashes (using conservative rulesets). A significant reduction in crashes that were due to loss of control of the vehicle can be attributed to the effectiveness of ESC (Fig. 4). Crashes related to driver incapacity were substantially removed by DDA. The most frequent crash type, Straight On-Path – VRU Crossing, was also the most frequent remaining crash type—even though its incidence was reduced by 8.9% (from 20.3 to 11.4%), mainly due to the AEB-PED.

Crash participants and impact types of the original crashes were also compared to those of the remaining crashes (Fig. 5). Overall, passenger car-to-PTW and heavy vehicle-to-PTW crashes were reduced, mostly due to fewer front-rear crashes; AEB REAR-END was effective. The numbers of car-to-pedestrian and car-to-heavy vehicle crashes were also reduced, mainly due to AEB-PED effectiveness. Notably, the proportion of crashes involving PTWs is higher in the remaining crashes.

Car-to-car crashes are not in the top ten MAIS2+ crashes in India (Fig. 5). Also, cars were not the predominant crash participant even when other crash partners were considered. Together, heavy vehicle-to-VRU crashes and crashes involving a PTW account for as much as 31% of the estimated remaining MAIS2+ crashes in India (if all 22 technologies implemented).

4. Discussion

This study used an in-depth database of Indian road traffic crashes and counterfactual simulations to model the implementation of pre-crash safety technologies in cars, heavy vehicles, and PTWs. The simulations allowed us to estimate the expected effectiveness of these technologies in order to define the probable characteristics of the remaining crashes in India.

4.1. Most effective technologies

Both AEB and ESC, targeting crashes with other vehicles or pedestrians, prevented the majority of MAIS2+ crashes—whether installed in cars, trucks, or buses. The ESC was about as effective as it is in Europe [42]. AEB REAR-END was estimated to prevent 47–92% of rear-end crashes in India in our analysis. This range encompasses the 48% reported by Penumaka et al. [17] based on the simulation of a hypothetical rear-end-specific AEB (using a set of Indian crashes not in RASSI). A similar effectiveness for rear-end-specific AEB was observed in the USA (50%) with slightly lower effectiveness in Europe (38%) [4,6]. The lower effectiveness in one of these latter studies (Fildes et al. [6]) is likely a consequence of their analyzing low-speed AEB (up to 50 km/h) only.

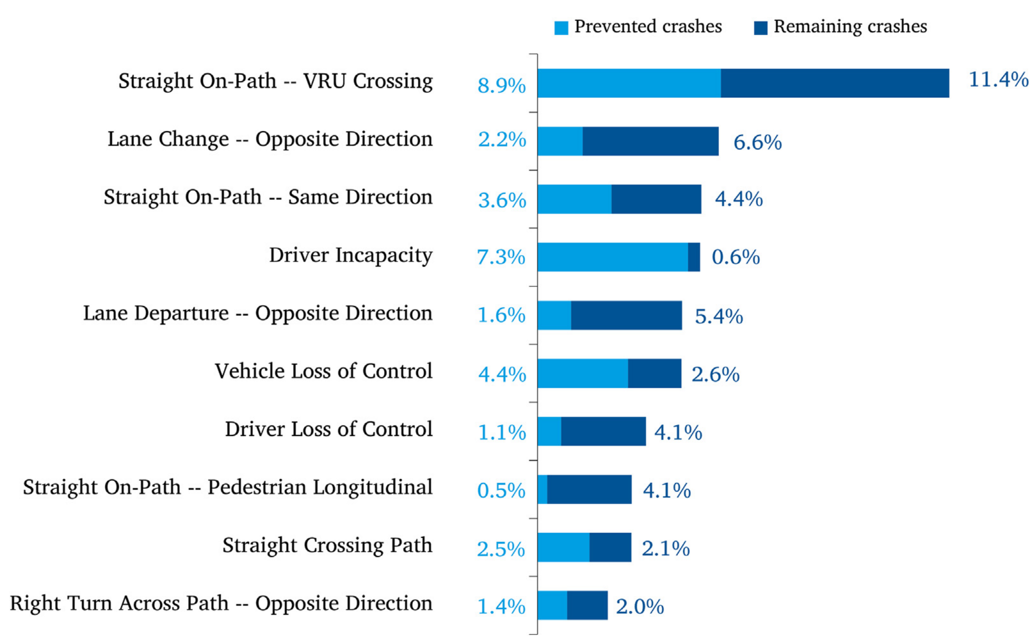

Fig. 4. Distributions of the ten most frequently occurring pre-crash events, for the prevented MAIS2+ crashes (light blue) and the remaining crashes (dark blue). Results shown for conservative rulesets. Pre-crash events are defined in Appendix B.

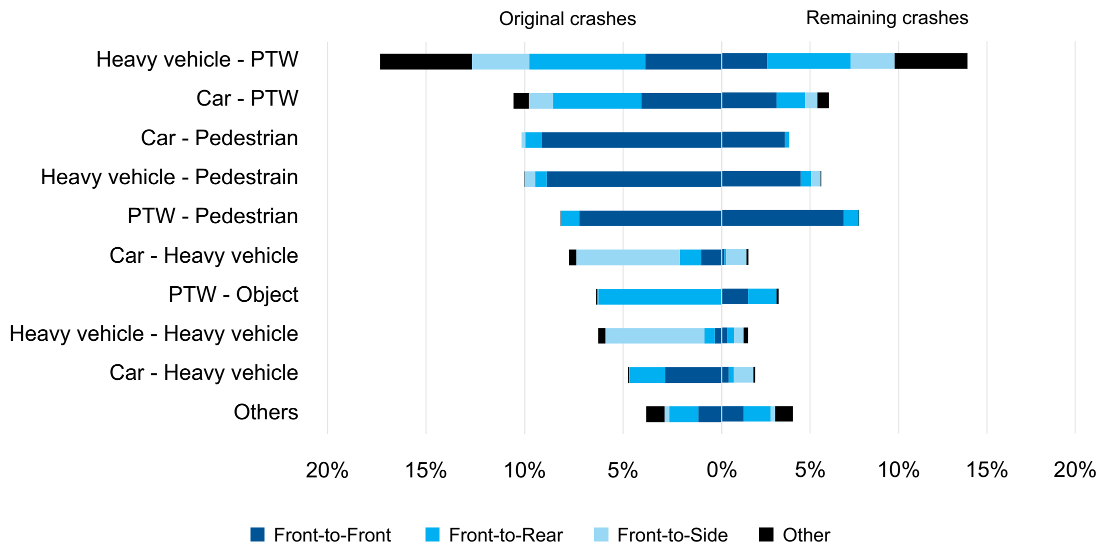

Fig. 5. Distribution of the ten most frequent crash participants with impact types (frontal damage priority to cars, heavy vehicles, and PTWs).

When ISA was installed in passenger cars, Lai et al. [22] found that ISA reduced serious crashes in Great Britain by as much as 25%, but we estimated only a 1–2% reduction of MAIS2+ crashes in India when installed in passenger cars and 4–6% when installed in heavy vehicles. However, our estimation of the effectiveness of ISA in passenger cars in India was similar to a previous estimation of 3% using a different set of unweighted RASSI data [16]. Lai et al. [22] used field trial data extrapolated to the national levels of Great Britain. However, our effectiveness estimates were based on a variable (critical pre-crash event) which allows “traveling too fast for the conditions” to be coded. This variable may well be rather subjective and additional investigations should be performed. Another reason for the difference could be the variety of speed limits in India. Further, the effectiveness of ISA depends on infrastructure design and user acceptance.

The estimated effectiveness of ABS (3.5%) is substantially lower than previous estimates for India. Lich et al. [14] estimated 33% effectiveness from a much smaller sample of crashes, and the percentage was calculated against ABS-relevant crashes using unweighted data. One of the reasons for the higher effectiveness in their study is their assumption that all riders in relevant crashes would be braking; however, their data suggests that 48% of riders did not apply the brakes [14]. In this study, our ruleset checks for braking as an avoidance maneuver in order to identify the crashes where the rider applied brakes before the crash; as a result, 3.5% effectiveness is likely to be a more realistic estimate. Removing “braking as an avoidance maneuver” from the ruleset results in an increase of 7.7% from 3.5% (optimistic) in ABS effectiveness in India. This increase demonstrates that riders often do not brake or do not brake hard enough to activate ABS. Mohan et al. [14] report ABS effectiveness at 13%, based on other references from Latin America and Germany. However, our effectiveness estimates implies that ABS is not equally effective in India.

Fig. 6 provides a comparison of our effectiveness estimates with other estimates for India found in the literature. The greatest differences were observed in AEB-REAR END and ABS. In contrast, comparable effectiveness was observed for ESA, ISA, IMA, LCA, AEB- CYCL, and LKA. Similarity was found for AEB-REAR END even though the sample sizes were smaller and data were unweighted in [16] [17]. A previous study estimated near-zero effectiveness for AEB-PED and AEB-CYCLE [16]. No prior studies were found assessing the effectiveness of DDA or ALCI in India.

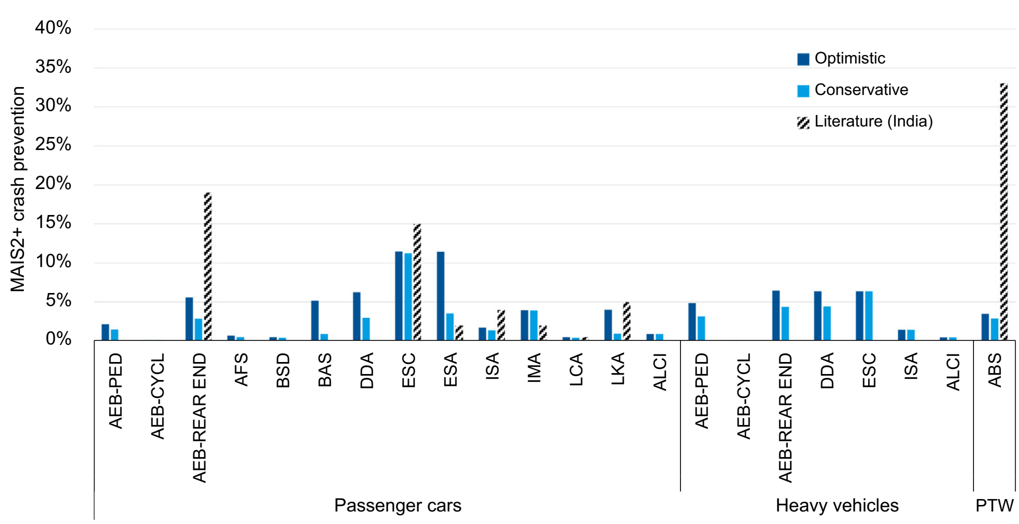

Fig. 6. Comparison of estimates with India-specific estimates from relevant literature.

4.2. Remaining crashes

The remaining crashes (if all cars and heavy vehicles had been fitted with pre-crash safety technologies at the time the crashes occurred) were characterized by pre-crash events (Fig. 4) and crash participation (Fig. 5) to guide future traffic safety priorities in India. With these pre-crash technologies implemented, the most frequent pre-crash event in India will be vehicles traveling straight on-path while crashing into a VRU crossing the road. Therefore, VRU protection needs to be awarded more attention; the technology is already available. On the other hand, the predominant crash type will be PTWs crashing into pedestrians, and there is currently no pre-crash safety technology addressing it. Moreover, front-to-front crashes due to sudden lane changes into opposing traffic will not be reduced by the technologies available today.

The modeled technologies prevented many serious and fatal crashes involving PTWs, especially those with heavy vehicles and cars. However, PTW collisions with pedestrians, cyclists, or other PTWs remain, as no technology currently addresses them. The number of PTW-user fatalities in India is already high and requires additional efforts [1]. These efforts could include improving the infrastructure. In fact, PTWs have been separated from main traffic in Malaysia, with a reduction in crashes involving PTWs [43]. Furthermore, changes to road infrastructure increasing visibility could help reduce crashes involving PTWs [44].

In addition, promoting heavy-vehicle designs that are VRU-friendly could reduce injurious corner crashes. The Advanced Rider Assistance System (ARAS) for PTWs is in an early stage of development, but it may address PTW-to-other-vehicle crashes in the near future. Encouraging the use of helmets and other wearable protective systems by PTW riders could also reduce serious injuries and fatalities.

Some of the pre-crash safety technologies modeled in this study only warn the driver, without taking control of the vehicle. As such, they rely on the driver's actions to avoid a crash. These warnings may be ignored or missed, due to a low level of trust in pre-crash safety technologies or simply to a lack of attention. This study did not account for scenarios in which drivers ignore or miss a warning. Although this oversimplification is a limitation, its influence on the presented effectiveness estimations is minimal since the systems with the highest effectiveness (like AEB and ESC) did not rely on driver action.

While this study considered only crashes with moderate or greater injury severity crashes, the modeled technologies can address crashes with minor or no injuries as well. Therefore, further benefits beyond those reported in this study can be expected.

4.3. Limitations and future work

Future studies should estimate the cost effectiveness of pre-crash safety technologies by considering the costs of crashes, including injury treatment, cost for long-term consequences, property damage, and other economic losses. Reliable data for these costs are sparse. A recent study estimated that India's socio-economic loss due to road traffic crashes was about 0.55–1.35% of India's GDP [45]. Extending these results by performing detailed cost benefit analyses for each of the safety technologies will help facilitate informed decisions about the prioritization of technologies.

Future effectiveness estimations of pre-crash safety systems could incorporate more detailed data, such as traffic volume, improvements in road infrastructure, user attitudes, transport mode shares, and system market penetration. Although these data are neither available nor easy to obtain at present, future studies could use such data to study future crashes in India in greater detail. Scenario techniques and sensitivity analyses could be adopted to estimate crash reductions with a more complete description of the traffic system in India.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A

Table A1 provides the variables and text description for the conservative rulesets of the 22 pre-crash safety technologies. Table A2 provides the variables and text description for their optimistic rulesets. These rulesets were used to identify system-relevant crashes. Since seven technologies (AEB-PED, AEB-CYCL, AEB REAR-END, ESC, ISA, DDA, and ALCI) apply to heavy vehicles as well as passenger cars, these rules are combined in the table; the only difference is the body type of the vehicle.

Table A1
Conservative Rulesets (Refer to Table A3 for description of variables).

Pre-crash safety technologies	Ruleset using RASSI variables	Ruleset description
LKA, Lane Keep Assist	BODYTYPE = (1:9) CRITPRE = (12,13) LANES ≠ 99,999 WEATHER = 18 TRAVELSP ≥60	Passenger car Original critical pre-crash event: Vehicle traveling on edge of the road towards left or right No unknown lanes No adverse weather conditions Speed ≥60 km/h
LCA, Lane Change Assist	BODYTYPE = (1:9) PREVEH = 15 LANES ≠ 99,999 WEATHER = 18 120 ≤ TRAVELSP ≥40	Passenger car Pre-event movement: Changing lane No unknown lanes No adverse weather conditions 120 ≤ Speed ≥40 km/h
BSD, Blind Spot Detection	BODYTYPE = (1:9) PREVEH = (15,16) WEATHER = 18 TRAVELSP ≥40	Passenger car Pre-event movement: Changing lane or merging accident No adverse weather conditions Speed ≥40 km/h
AFS, Advanced Front Lighting System	BODYTYPE = (1:9) LGTCOND = 2 PREVEH = (10,11,14)	Passenger car Light condition equal to dark Pre-event movement:

(continued on next page)

Table A1 (*continued*)

Pre-crash safety technologies	Ruleset using RASSI variables	Ruleset description
	Travel speed ≤70 km/h	Curve or turning to right or left prior to accident Speed ≤70 km/h
ESC, Electronic Stability Control	BODYTYPE = (1:9) / BODYTYPE = (11:29) PRESTAB = (2,3,4) SURCOND = (1,2) SURTYPE = (1,2) ESC = 0	Passenger car /Heavy vehicle Skidding prior to accident Dry or wet road Concrete or asphalt surface ESC not present in vehicle
AEB REAR-END, Autonomous Emergency Braking to avoid rear-end crashes	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front" GADEV2 = "Rear" Collision Partner = Any vehicle Relative speed ≤70 WEATHER = 18	Passenger car /Heavy vehicle General areas of damage: front of installed vehicle impacting rear of another vehicle Relative speed between vehicles ≤70 km/h No adverse weather conditions
AEB-PED, Autonomous Emergency Braking to prevent crashes with pedestrian	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front" Collision Partner = Pedestrian TRAVELSP ≤60 WEATHER = 18	Passenger car /Heavy vehicle Speed ≤60 km/h Front impacting pedestrian No adverse weather conditions
AEB-CYCL, Autonomous Emergency Braking to prevent crashes with cyclist	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front" Collision Partner = Cyclist TRAVELSP ≤60 WEATHER = 18	Passenger car /Heavy vehicle Speed ≤60 km/h Front impacting cyclist No adverse weather conditions
DDA, Driver drowsiness/distraction Alert	BODYTYPE = (1:9) / BODYTYPE = (11:29) DISTRACT = 11/12	Passenger car /Heavy vehicle Driver is drowsy or sleepy
ISA, Intelligent Speed Adaptation	BODYTYPE = (1:9) / BODYTYPE = (11:29) CRITPRE = 6 WEATHER =18	Passenger car /Heavy vehicle Traveling too fast for the conditions and loss of control No adverse weather conditions
IMA, Intersection Movement Assist	BODYTYPE = (1:9) CRITPRE = (15:17,65:68) WEATHER = 18	Passenger car Critical pre-crash event: Installed vehicle turning or moving into intersection or other vehicle turning in same/opposite direction or turning across path No adverse weather conditions
ESA, Evasive Steering Assist	BODYTYPE = (1:9) GADEV1 = "Front" AVOIDMAN = (6:9,11,12) 100 ≤ TRAVELSP ≥50	Passenger car General a rea of damage: Front Avoidance maneuver by steering to right or left 100 ≤ Speed ≥50 km/h
ALCI, Alcohol Interlock	BODYTYPE = (1:9) / BODYTYPE = (11:29) ALCINV = 1	Passenger car /Heavy vehicle Driver under influence of alcohol/Driver incapacity
BAS, Brake Assist System	BODYTYPE = (1:9) AVOIDMAN = 2 PREVEH = (1,2) WEATHER = 18	Passenger car Braking crash avoidance maneuver in longitudinal direction (no lockup) Vehicle movement prior to crash: Straight or decelerating No adverse weather conditions
ABS, Antilock Braking System	BODYTYPE = (31:34) PRESTAB = 2 AVOIDMAN = (3,4,8,9) ANTILOCK = 0	Motorcycle/Scooter Skidding longitudinally Braking with lockup or braking with steering as avoidance maneuver ABS not present

Table A2
Optimistic Rulesets.

Pre-crash safety technologies	Ruleset using RASSI variables	Ruleset description
LKA, Lane Keep Assist	BODYTYPE = (1:9) CRITPRE = (10,11,12,13) TRAVELSP ≥60	Passenger car Original critical pre-crash event: Vehicle traveling on lane line or edge of the road towards left or right Speed ≥60 km/h
LCA, Lane Change Assist	BODYTYPE = (1:9) PREVEH = 15 120 ≤ TRAVELSP ≥40	Passenger car Pre-event movement: Changing lanes No skidding prior to accident No speeding 120 ≤ Speed ≥40 km/h
BSD, Blind Spot Detection	BODYTYPE = (1:9) PREVEH = (15,16) TRAVELSP ≥40	Passenger car Pre-event movement: Changing lanes or merging accident Speed ≥40 km/h
AFS, Advanced Front Lighting System	BODYTYPE = (1:9) LGTCOND = 2 PREVEH = (10,11,14)	Passenger car Lighting condition equal to dark Pre-event movement: Curve or turning right or left prior to accident
ESC, Electronic Stability Control	BODYTYPE = (1:9) / BODYTYPE = (11:29) PRESTAB = (2,3,4) ESC = (0,999,999)	Passenger car /Heavy vehicle Skidding longitudinally or laterally prior to accident ESC not present in vehicle or ESC availability unknown
AEB REAR-END, Autonomous	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front"	Passenger car /Heavy vehicle General area of damage: Front of installed vehicle impacting rear of another

Table A2 (*continued*)

Pre-crash safety technologies	Ruleset using RASSI variables	Ruleset description
Emergency Braking To avoid Rear-end crashes	GADEV2 = "Rear" Collision Partner = Any vehicle Relative speed ≤100	vehicle Relative speed between vehicles ≤100 km/h
AEB-PED, Autonomous Emergency Braking To avoid crashes with pedestrian	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front" Collision Partner = Pedestrian TRAVELSP ≤60	Passenger car /Heavy vehicle Speed ≤60 km/h Front impacting pedestrian
AEB-CYCL, Autonomous Emergency Braking to prevent crashes with cyclist	BODYTYPE = (1:9) / BODYTYPE = (11:29) GADEV1 = "Front" Collision Partner = Cyclist TRAVELSP ≤60	Passenger car /Heavy vehicle Speed ≤60 km/h Front impacting cyclist
DDA, Driver drowsiness/distraction Alert	BODYTYPE = (1:9) / BODYTYPE = (11:29) DISTRACT = (3:13,97)	Passenger car /Heavy vehicle Driver is drowsy or sleepy or any/unknown distraction
ISA, Intelligent Speed Adaptation	BODYTYPE = (1:9) / BODYTYPE = (11:29) CRITPRE = 6	Passenger car /Heavy vehicle Traveling too fast for conditions, loss of control
IMA, Intersection Movement Assist	BODYTYPE = (1:9) CRITPRE = (15:17,65:68)	Passenger car Critical pre-crash event: Installed vehicle turning or moving in intersection or other vehicle turning in same/opposite direction or turning across path
ESA, Evasive Steering Assist	BODYTYPE = (1:9) GADEV1 = "Front" AVOIDMAN = (6:9,11,12) 100 ≤ TRAVELSP ≥20	Passenger car General area of damage: Front Avoidance maneuver by steering to right or left 100 ≤ Speed ≥20 km/h
ALCI, Alcohol Interlock	BODYTYPE = (1:9) / BODYTYPE = (11:29) ALCINV = 1	Passenger car /Heavy vehicle Driver under influence of alcohol /Driver incapacity
BAS, Brake Assist System	BODYTYPE = (1:9) AVOIDMAN = (2,4,5,8,9) PREVEH = (1,2)	Passenger car Braking or braking and steering crash-avoidance maneuver in longitudinal or lateral direction (no lockup or unknown lockup) Vehicle movement prior to crash: Going straight or decelerating
ABS, Antilock Braking System	BODYTYPE = (31:34) PRESTAB = (2,3,4) AVOIDMAN = (2,3,4,8,9) ANTILOCK = (0,999999)	Motorcycle/Scooter Skidding longitudinally or laterally Braking or braking with steering as avoidance maneuver ABS not present or ABS availability unknown

Table A3
Description of variables in Table A1 and A2 [46].

Variable Name	Description
BODYTYPE	Body type of the vehicle
PRESTAB	Pre-impact stability of the vehicle
AVOIDMAN	Attempted avoidance maneuver
ANTILOCK	Availability of Antilock Braking System
PREVEH	Vehicle movement prior to recognition of critical event
ALCINV	Driver is under the influence of alcohol or drugs at the time of the crash or not
TRAVELSP	The probable traveling speed of the vehicle at the time of crash
LGTCOND	The light condition at the time of the crash near the crash spot
ESC	Availability of the Electronic Stability Control
GADEV1	General area of damage of the striking vehicle as per the third character of the "Collision Deformation Classification" - SAE Standard J224 or the "Truck Deformation Classification" - SAE Standard J1301
GADEV2	General area of damage of the entity which is struck by the referred unit as per the third character of the "Collision Deformation Classification" - SAE Standard J224 or the "Truck Deformation Classification" - SAE Standard J1301
CRITPRE	Critical event that led to the crash
LANES	Total number of lanes in the vehicle's direction of travel
WEATHER	Atmospheric condition at the time of the crash at the crash location
DISTRACT	Reasons for driver distraction prior to the critical pre-crash event

Appendix B

Table B1 provides the pre-crash event classifications for left-hand traffic based on RASSI variables. The classifications were based on the scenario classifications proposed by Sander (2018) for right-hand side traffic, utilizing GIDAS variables and the German "Unfalltypen-Katalog" [47]. Variables from RASSI equivalent to those of GIDAS were used to replicate pre-crash event definitions.

Table B1
Scenario classification scheme for left-hand traffic (adapted from Sander (2018)). (Refer Table B2 for description of variables).

ID	Classification	Description	RASSI variables
1	Technical Failure	Vehicle sustains a technical failure with the consequence of a conflict situation.	PRECREV = (771:775) and VDEFECT = (1:14); Exclusive for all following scenarios
2	Vehicle Loss of	Vehicle loses stability and skids with the consequence of	PRECREV = (101, 102, 109, 111, 112, 119, 121, 122, 123, 129, 131, 132, 139, 141, 151, 152, 153,

(continued on next page)

Table B1 (*continued*)

ID	Classification	Description	RASSI variables
	Control	a conflict situation.	159, 161, 162, 163, 169, 171, 172, 173, 179, 181, 182, 183, 189, 199) and PRESTAB in (2, 3, 4)
3	Driver Loss of Control	Driver loses control over the vehicle and creates a conflict situation.	PRECREV = (101, 102, 109, 111, 112, 119, 121, 122, 123, 129, 131, 132, 139, 141, 151, 152, 153, 159, 161, 162, 163, 169, 171, 172, 173, 179, 181, 182, 183, 189, 199) and PRESTAB not in (2, 3, 4, 888,888)
4	Driver Incapacity	Driver is in drowsy or physically impaired and creates a conflict situation.	PRECREV = (761:763)
5	Straight On-Path – Same direction	Vehicle heads straight on-path and creates a conflict with a vehicle ahead.	PRECREV = (201, 231, 541, 542, 549, 583, 584, 601, 602, 603, 604, 609, 611, 612, 613, 614, 619, 621, 622, 623, 624, 629)
6	Straight On-Path – Pedestrian Longitudi-nal	Vehicle heads straight on-path and creates a conflict with a pedestrian moving in same or opposite direction.	PRECREV = (671:675)
7	Straight On-Path – VRU[1] Crossing	Vehicle heads straight on-path and creates a conflict with a pedestrian crossing the roadway.	PRECREV = (272, 274, 341, 342, 343, 344, 349, 361, 362, 363, 364, 369, 371, 372, 379, 401, 402, 403, 404, 405, 409, 411, 412, 413, 414, 419, 421, 422, 423, 424, 429, 431, 432, 433, 434, 435, 436, 439, 441, 442, 443, 444, 449, 451, 452, 453, 454, 455, 459, 461, 462, 463, 464, 465, 469, 471, 472, 473, 479, 491, 492, 493, 494, 499)
8	Straight On-Path – Parked Vehicle	Vehicle heads straight on-path and creates a conflict with a parked vehicle.	PRECREV = (501, 502, 509, 581, 582, 589, 741, 742, 749)
9	Turn Across Path – Same Direction	Vehicle turns across path and creates a conflict with another vehicle moving in same direction.	PRECREV = (202, 203, 232, 307, 327)
10	Turn Off-Path – Same Direction	Vehicle turns off-path and creates a conflict with another vehicle moving in same direction.	PRECREV = (202,203,232)
11	Left Turn Across Path – Opposite Direction	Vehicle turns left across path and creates a conflict with another vehicle moving in opposite direction.	PRECREV = (211, 212, 281, 328, 351, 354, 543)
12	Turn On-Path – VRU Crossing	Vehicle turns on-path and creates a conflict with a VRU crossing a roadway.	PRECREV = (221, 222, 223, 224, 225, 226, 227, 229, 241, 242, 243, 244, 245, 246, 247, 248, 249, 282, 283, 284, 285, 273, 275, 481, 482, 483, 484, 489)
13	Turn On-Path – Parked Vehicle	Vehicle turning on-path and creates a conflict with another parked vehicle.	PRECREV = (591, 592, 593, 594)
14	Straight Crossing Path	Vehicle crosses intersection and creates a conflict with another straight crossing vehicle.	PRECREV = (271, 301, 311, 321, 331, 353, 355)
15	Left Turn Across Path – Lateral Direction	Vehicle turning left across path and creates a conflict with another vehicle approaching laterally.	PRECREV = (215, 261, 302, 312)
16	Left Turn Into Path – Lateral Direction	Vehicle turning left into path and creates a conflict with another vehicle approaching laterally.	PRECREV = (322, 332, 352)
17	Right Turn Into Path – Lateral Direction	Vehicle turns right into path and creates a conflict with another vehicle approaching laterally.	PRECREV = (303, 304, 213, 214)
18	Turn Off-Path – Lat-eral Direction	Vehicle turns off-path and creates a conflict with another vehicle due to lateral approach.	PRECREV = (262, 286, 306, 323, 324, 326, 333, 334)
19	Lane Change – Same Direction	Vehicle changes lanes and creates a conflict with another vehicle moving in same direction.	PRECREV = (204, 233, 305, 313, 314, 315, 373, 374, 551, 552, 555, 559, 631, 632, 633, 634, 635, 636, 639, 641, 642, 643, 644, 645, 646, 647, 649, 663)
20	Lane Change – Oppo-site Direction	Vehicle changes lanes and creates a conflict with another vehicle moving in opposite direction.	PRECREV = (325, 335, 661, 662, 664, 684, 685, 686, 553, 554)
21	Lane Departure – Same Direction	Vehicle departures from lane and creates conflict with another vehicle moving in same direction.	PRECREV = (651, 652, 659)
22	Lane Departure – Opposite direction	Vehicle departures from lane and creates a conflict with another vehicle moving in same direction.	PRECREV = (681, 682, 683, 687, 689)
23	Backing-Up – Oppo-site Direction	Vehicle reverses and creates a conflict with another vehicle moving in opposite direction.	PRECREV = (711, 712)
24	Backing-Up – Lateral Direction	Vehicle reverses and creates a conflict with another vehicle moving in lateral direction.	PRECREV = (571, 572, 579, 713, 714, 715, 716)
25	Evasive Maneuver	Vehicle makes an evasive maneuver and creates a conflict with another vehicle.	PRECREV = (511, 512, 519, 521, 531, 532, 533, 534, 539)
26	Object On Road	Vehicle is in conflict with an object on road.	PRECREV = (731, 732, 637, 648)
27	Animal On Road	Vehicle is in conflict with an animal standing on or crossing roadway.	PRECREV = (751, 752, 753, 759)
28	U-Turn	Vehicle makes a U-turn and creates a conflict with another vehicle.	PRECREV = (721, 722, 723, 724, 725, 729)
29	Parking	Vehicles is in conflict at a parking area.	PRECREV = (561, 562, 569, 701, 702, 703, 709)
30	Other	Vehicle is involved in other kind of conflict.	PRECREV = (209, 219, 239, 279, 289, 299, 308, 309, 319, 329, 339, 359, 399, 599, 669, 679, 699, 719, 799, 999,999)

[1] VRU consists of pedestrians, cyclists, and powered two-wheelers.

Table B2
Description of variables in Table B1 [46].

Variable Name	Description
PRECREV	Pre-crash event type (the conflict situation) that led to the crash
PRESTAB	Pre-impact stability of the vehicle
VDEFECT	Presence of any defect in the vehicle

Appendix C

The effectiveness calculation is described in three steps. An overview of the effectiveness calculation is described in Fig. C1. The flow chart shows the stepwise process for conservative estimates. This estimation was carried out for all the technologies and for all the crashes. The characterization was carried out for conservative remaining crashes only. After the flow chart, the coding is presented in pseudo-code; Table C1 gives the sample output of the code.

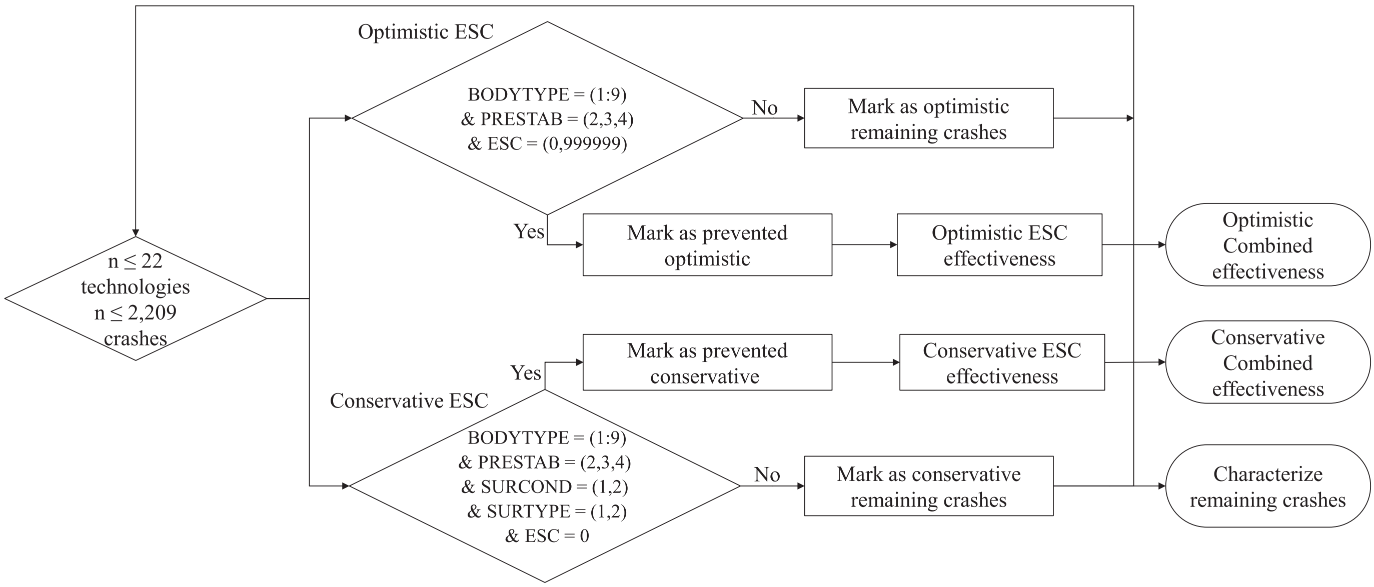

Fig. C1. Flowchart of the steps followed in coding.

The following pseudo-code describes the general logic.

The following pseudo-code describes the general logic.

T1 - Technology 1, T2 - Technology 2, TN - Technology N
O-Optimistic, C-Conservative

For each of the identified 2209 crashes:

If *optimistic* ruleset of T1 satisfied, write T1O = 1,
else
write T1O = 0
If *conservative* ruleset of T1 satisfied, write T1C = 1,
else
write T1C = 0
If *optimistic* ruleset of T2 satisfied, write T2O = 1,
else
write T2O = 0
If *conservative* ruleset of T2 satisfied, write T2C = 1,
else
write T2C= 0
If *optimistic* ruleset of TN satisfied, write TNO = 1,
else
write TNO = 0
If *conservative* ruleset of TN satisfied, write TNC = 1,
else
write TNC = 0

Generalized code for estimating combined effectiveness.

For each of identified 2209 crashes:

If T1O = 1 or T2O = 1 or TNO = 1, then write Combined Optimistic =1,
else write Combined Optimistic =0
If T1C = 1 or T2C = 1 or TNC = 1, then write Combined Conservative =1,
else write Combined Conservative = 0

Table C1
Generalized output of the code for effectiveness estimations.

Crash	Weight	Technology 1		Technology 2		Tech. N		All Tech. combined	
		O	C	O	C	O	C	O	C
1	w1	1	0	0	0	1	1	1	1
2	w2	1	1	0	0	0	1	1	1
3	w3	0	0	1	0	0	0	1	0
n	wn	1	1	1	1	1	1	1	1
Sum	wT	x11	x12	x21	x22	xN1	xN2	xA1	xA2
Effectiveness		x11/wT	x12/wT	x21/wT	x21/wT	xN1/wT	xN2/wT	xA1/wT	xA2/wT

Note: O - Optimistic, C - Conservative.
Sum is the weighted sum of the crashes with values equal to one. Calculation for x11 is given below as an example.

$$x11 = \sum_{i=1}^{n} T1Optimistc_i \times w_i.$$

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