Potential Crash Benefits of Motorcycle-Detecting Automatic Emergency Braking Systems

Morgan E. Dean, Samantha H. Haus, Rini Sherony, Hampton C. Gabler

Abstract In 2018 in the US, there were 4,985 motorcyclist fatalities and approximately 82,000 motorcyclists injured. One mitigation strategy is passenger vehicle (PV) mounted motorcycle-detecting automatic emergency braking (MD-AEB). The objective of this study was to characterise the MD-AEB target population and perform a safety benefits analysis for MD-AEB systems. To do this, two national databases, the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES), were used to identify the percentage of crashes which could be positively influenced by MD-AEB. These crashes were then characterised by crash and environmental factors. The HLDI 2015 market penetration curve for frontal crash prevention technology was then used to estimate MD-AEB prevalence in future US fleets. To predict crash and K+A+B (KABCO injury scale) injury reduction over 50 years we considered crash incidence rate as a function of vehicle miles travelled, MD-AEB prevalence in the fleet, and crash and injury-inducing crash reduction effectiveness. The target population for MD-AEB accounts for 8% and 9% of all fatal and police-reported motorcycle crashes, respectively. MD-AEB has the potential to mitigate or prevent 6,513 KAB injury crashes and 13,485 crashes by the year 2045 and even more upon reaching full market penetration (95%) in 2065.

Keywords Automatic Emergency Braking (AEB), Motorcycle Safety Benefits, US Crashes, Advanced Driver Assist Systems (ADAS)

I. INTRODUCTION

In 2018 in the US, there were 4,985 motorcyclist fatalities and approximately 82,000 motorcyclists injured. This was nearly a 5% decrease in motorcyclist fatalities from the previous year, yet motorcyclists are still largely overrepresented in fatal crashes. In the same year, motorcyclists made up 14% of traffic fatalities, yet comprised only 3% of the registered vehicle fleet [1]. Additionally, motorcyclist fatalities per vehicle-miles traveled (VMT) occurred nearly 27 times more frequently than passenger vehicle occupant fatalities [1]. One mitigation strategy for this problem may be passenger vehicle (PV) mounted motorcycle-detecting automatic emergency braking (MD-AEB) systems.

Motorcyclists are particularly challenging to protect during crashes due to the absence of an occupant compartment, which increases their direct interaction with the impact and the likelihood of ejection [2-3]. One way to protect motorcyclists on the road is to prevent passenger vehicles from colliding with motorcyclists. Previous AEB research has established AEB as an effective countermeasure to detect and avoid/mitigate both rear-end crashes and collisions with pedestrians [4-8]. Low-speed AEB has been estimated to reduce front-to-rear crash rates and injury crash rates by 43% and 45%, respectively [7]. Pedestrian detection AEB systems are expected to reduce fatality and injury risk in the target population by at least 83% [4]. Recent analyses also reveal AEB as a promising mitigation strategy for vehicle-to-animal and vehicle-to-bicycle crashes [9], [10]. Other research has been done to assess the applicability

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of motorcycle-mounted AEB (MAEB). One study found MAEB to be applicable to 23% of motorcycle crashes in Victoria, Australia [11]. In the same study, when used in combination with other motorcycle-mounted advanced driver assist systems (ADAS), MAEB was applicable to 58% of motorcycle crashes in Victoria, Australia. AEB is already equipped on many vehicles in the US fleet [12]. By increasing the detection capabilities of the AEB systems present in new vehicles, there is a potentially low-cost way to increase safety for motorcyclists, a particularly vulnerable population.

Despite previous work, there is still a need to understand the implications of a passenger vehicle mounted motorcycle detecting AEB system. The objective of this study was to characterise the MD-AEB target population and perform a safety benefits analysis for MD-AEB systems.

II. METHODS

Data Sources

This study used real-world crashes from 2011-2015 from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES). FARS is a census of all fatal crashes on public roads in the US [13]. GES is a probability sample of police-reported crashes in the US, collected from 60 locations across the US. GES cases are assigned sampling weights which, when applied to each case, can estimate the national incidence of various crash types [14]. Certain data elements, if unreported or marked unknown during data acquisition, are imputed by NHTSA after reviewing and interpreting information provided in the crash report [14]. Imputed variables minimise the amount of missing information in the database. Due to the sample populations of both databases, FARS represents the most severe crash outcomes, while GES better represents outcomes for all crash severities, including both property damage only crashes and fatal crashes. Table 1 summarises these datasets.

TABLE 1
OVERVIEW OF THE DATA SOURCES USED IN THIS STUDY

Dataset	FARS	GES
Injury Severity	Fatal	All Injury Levels
Years Considered for this Study	2011-2015	2011-2015
Total Cases (unweighted) from 2011-2015	153,669	261,665
Weighted	No	Yes
Nationally Representative	Yes	Yes
Sample Population	Census of Fatal Crashes	Sample of All Police Reported Crashes
Scene Diagrams	No	No
Imputed Variables	No	Yes

Determining the Target Population

The first aim of this study was to identify crashes which could be positively influenced by MD-AEB: two-vehicle crashes where the front of a passenger vehicle struck a motorcycle. Only cases where a passenger vehicle struck the motorcycle were considered because only passenger vehicles are likely to be equipped with initial MD-AEB systems. Sideswipe crashes were excluded because it was assumed these cases would be better detected and mitigated by blind-spot monitoring technology or lane departure warning systems. Loss of control cases were excluded because it was assumed that AEB would not be able to mitigate a crash if the driver was not in control of the vehicle. Figure 1 graphically demonstrates how inclusion criteria were applied to the motorcycle crash population to obtain the target population.

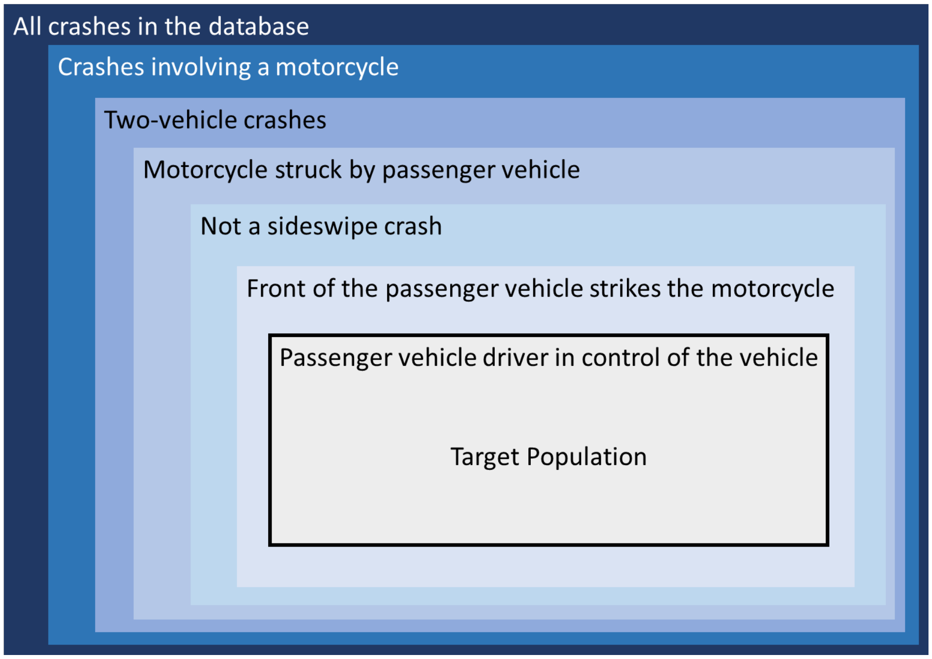

Figure 1. The order of the inclusion criteria applied to the motorcycle crash population to obtain the target population. The sizes of the boxes are not to scale. The numbers associated with each inclusion criteria appear in the Results section in Table 2.

Characterising the Target Population

Once the target population was identified, the cases were characterised by seven crash and environmental factors. Crash factors included collision type, speed limit at the crash scene, PV driver sightline obstructions, PV movement prior to impact, and PV avoidance maneuver. Environmental factors included the weather and lighting at the time and place of the crash. The FARS and GES target populations were characterised separately.

Benefits Prediction

The second aim of this study was to predict crash and KAB crash reduction after deployment of MD-AEB in the US fleet. KAB crashes refer to crashes where a motorcyclist involved in the crash suffered a K, A, or B injury on the KABCO scale. KABCO is a police-reported injury scale, where K, A, and B describe a fatal injury, incapacitating injury, and a non-incapacitating injury, respectively.

The Insurance Institute for Highway Safety Highway Loss Data Institute (IIHS-HLDI) releases annual reports that predict the market penetration of various vehicle safety features. At of the time of this study, HLDI had not yet released a report predicting the availability of MD-AEB. As a surrogate, we used the HLDI 2015 market penetration curve for frontal vehicle crash prevention technology to estimate MD-AEB prevalence in future US fleets. The newer 2016 HLDI AEB curves were not used as these curves used the 2022 voluntary AEB standardization commitment which does not explicitly apply to MD-AEB [15]. After tracing the HLDI 2015 curve for frontal crash prevention technology, the data points were interpolated to produce the curve in Figure 2. This curve's start point was shifted to the year 2022, the assumed year for when

MD-AEB technology would become commercially available. The dashed line represents the year 2065, which is when full deployment (95% market penetration) is predicted to occur.

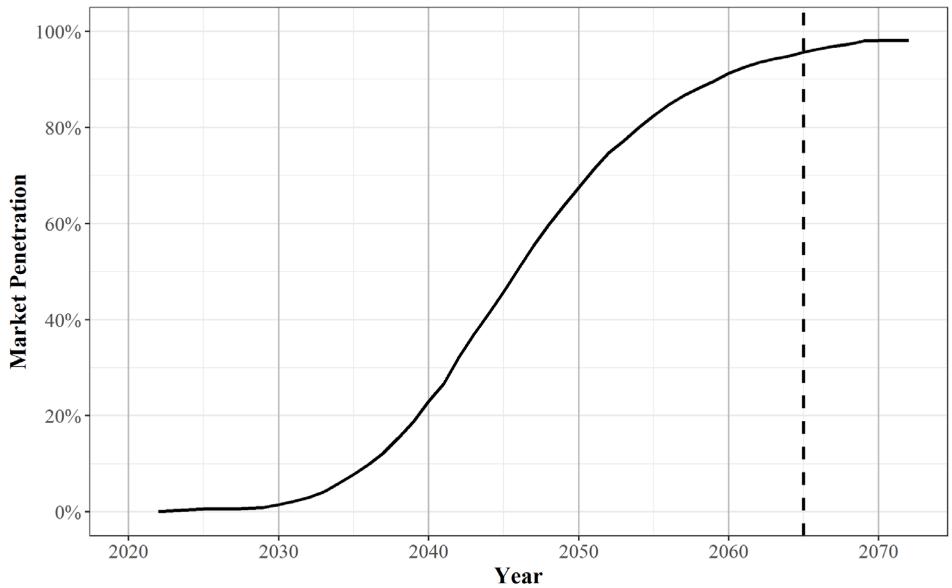

Figure 2. Predicted adoption of frontal collision prevention technology from 2022 to 2072 (IIHS-HLDI).

To predict crash and KAB crash reduction over the next 50 years, we considered crash incidence rate as a function of VMT, MD-AEB prevalence in the fleet (using the predicted adoption curve), and crash and KAB crash reduction effectiveness. It was assumed that VMT increases 1.01% annually and therefore the number of target population crashes increases 1.01% annually [16]. Simulations of motorcycle MD-AEB to estimate effectiveness were not conducted because motorcycle data is limited in the US and the data necessary for running simulations is often not available. As a surrogate, the effectiveness numbers from vehicle-vehicle collisions were used and they were weighted by the likelihood for that collision type to occur [7], [17], [18]. Four collision types were analyzed: rear-end, straight crossing paths (SCP), left turn across path opposite direction (LTAP/OD), and left turn across path lateral direction (LTAP/LD).

In order to appropriately use the vehicle-vehicle system benefit estimates, the number of applicable vehicle-motorcycle crashes was calculated in the same method the vehicle-vehicle numbers were calculated. For example, for SCP vehicle-vehicle crashes the effectiveness values apply to both struck and striking vehicles. SCP crashes and LTAP/OD crashes were assumed to have the same effectiveness value, as they are both intersection crash types. The number of relevant cases for each crash type was obtained from GES 2015. The weighted number of KAB crashes were divided by the weighted number of crashes to calculate the relative risk for each crash type.

The weighted effectiveness calculations for crashes and KAB crashes use the same vehicle-vehicle crash effectiveness numbers. This is because the injury calculation is for potential injury-inducing crashes, not the total number of injuries. We looked at injury-inducing crashes rather than the injuries because limited data prevented the development of a motorcyclist injury risk curve. A motorcyclist injury risk curve would have allowed for the calculation of KAB injury effectiveness values.

To determine the number of crashes and KAB crashes with no MD-AEB system for a given year, the number of crashes from the previous year was assumed to increase by 1.01%. To determine the number of crashes with the MD-AEB system, the percent market penetration was multiplied by the appropriate effectiveness value to calculate the number of preventable crashes.

III. RESULTS

Determining the Target Population

Table 2 tabulates how many cases were removed from the population as each inclusion criteria was applied. The final row shows the total annual FARS and GES cases included in the target population. It is important to note the small fraction of two-vehicle crashes wherein a motorcycle was struck. Most often, the motorcycle strikes the other vehicle involved. The motorcycle was the striking vehicle for 7,306 FARS cases and 164,131 weighted GES cases. The sum of motorcycle-striking and motorcycle-struck cases do not sum to the two-vehicle crash total because it was not always possible to determine which vehicle struck the other. In this study, the crash type variable in FARS and GES was used to determine vehicle roles. The target population for MD-AEB consists of about 358 fatal crashes and 9,659 police-reported crashes annually, which accounts for 8% and 9% of all fatal and police-reported motorcycle crashes, respectively. This target population represents the maximum potential benefit of a PV mounted system, as certain crash and environmental factors may reduce MD-AEB performance.

TABLE 2
TARGET POPULATION INCLUSION CRITERIA

	FARS Cases (2011-2015)	**GES Cases (2011-2015)**	**Weighted GES Cases (2011-2015)**	**Annual FARS Cases**	**Annual GES Cases**
All Motorcycle Crashes	23,533	13,711	511,262	4,706 (100%)	102,252 (100%)
Inclusion Criteria			**Cases remaining**		
Two-vehicle crash	11,650	6,504	257,992	2,330 (50%)	51,598 (50%)
Motorcycle is struck	2,266	1,258	60,103	453 (10%)	12,020 (12%)
Struck by car or LTV	1,930	1,154	56,021	386 (8%)	11,204 (11%)
Not a sideswipe crash	1,930	1,154	56,021	386 (8%)	11,204 (11%)
Frontal impacts	1,792	955	48,299	358 (8%)	9,659 (9%)
No loss of control	1,792	955	48,299	358 (8%)	9,659 (9%)
Target Population	**1,792**	**955**	**50,864**	**358 (8%)**	**9,659 (9%)**

Characterising the Target Population

Table 3 reports the two most common conditions for each of the crash and environmental factors for both the fatal and police-reported target populations. Certain conditions, such as low lighting, adverse weather, and non-ideal crash configurations are present in these populations and may reduce MD-AEB performance. For example, 20% of fatal crashes occurred in dark, unlighted conditions, and 25% of fatal crashes involved the PV negotiating a curve prior to impact.

TABLE 3
THE TWO MOST COMMON CONDITIONS FOR EACH CRASH AND ENVIRONMENTAL FACTOR

Factor	Fatal Crashes	Police-Reported Crashes
Collision Type	Head-on (45%) Rear-ended (25%)	Rear-end (53%) Straight crossing paths (18%)
Speed Limit (mph)	55 (28%) 45 (18%)	35 (23%) 45 (14%)
Sightline Obstructions	None (95%) Unknown (3%)	None (90%) Unknown (8%)
PV Movement Prior to Impact	Traveling a straight path (50%) Negotiating a curve (25%)	Traveling a straight path (63%) Starting in road (11%)
PV Avoidance Maneuver	None (64%) Unknown (28%)	Unknown (56%) None (29%)
Lighting	Daylight (60%) Dark – not lighted (20%)	Daylight (65%) Dark – lighted (23%)
Weather	Clear (83%) Cloudy (13%)	Clear (87%) Cloudy (11%)

Benefits Predictions

Table 4 tabulates the number of weighted crashes, the number of weighted injury-inducing crashes, the percent of total motorcycle crashes these populations comprise, and the relative injury risk for each crash type in GES. The percent of total motorcycle crash columns were found by dividing the 2015 weighted cases of each crash type by the total number of motorcycle crashes (62,445 KAB injury crashes and 98,137 crashes). Table 5 and Table 6 use the crash totals for each crash type to calculate the weighted crash effectiveness and weighted injury-inducing crash effectiveness, respectively. The portion of the MC target population column was found by dividing the 2015 weighted cases of each crash type by the total number of crashes (14,698 and 7,075). The population proportion was then multiplied by the vehicle-vehicle crash effectiveness number to get the weighted crash effectiveness. The overall crash effectiveness is the sum of the individual crash type effectiveness values. The total number of weighted crashes in Table 4 is different from the number of crashes in Table 2. This is because Table 2 is the average number of annual crashes, whereas Table 4 looks only at 2015. Additionally, Table 4 sometimes includes both vehicles involved, such as in SCP crashes. Table 2 only considers the motorcycle.

TABLE 4
RELATIVE RISK FOR EACH CRASH TYPE BASED ON THE TOTAL KAB INJURY CRASHES AND TOTAL CRASHES.

Crash Type	2015 Weighted Cases (KAB Injury Crashes)	% of Total MC KAB Injury Crashes	2015 Weighted Cases (Crashes)	% of Total MC Crashes	Relative Risk
Rear-End	1,307	2.1%	4,245	4.3%	0.308
SCP	1,510	2.4%	3,082	3.1%	0.490
LTAP/LD	1,200	1.9%	2,203	2.2%	0.545
LTAP/OD	3,058	4.9%	5,168	5.3%	0.592
Total	**7,075**	**11.3%**	**14,698**	**15.0%**	**-**

TABLE 5
WEIGHTED SYSTEM EFFECTIVENESS BASED ON CRASH TYPE AND ESTIMATED VEHICLE-VEHICLE EFFECTIVENESS FOR CRASHES

Crash Type	2015 Weighted Cases	Proportion of MC Target Population	Vehicle-Vehicle Crash Effectiveness	Weighted Crash Effectiveness
Rear-End	4,245	0.29	0.50 [7]	0.140
SCP	3,082	0.21	0.25 [17]	0.050
LTAP/LD	2,203	0.15	0.25	0.037
LTAP/OD	5,168	0.35	0.18 [18]	0.063
Total	**14,698**	**1.0**	**-**	**0.290**

TABLE 6
WEIGHTED SYSTEM EFFECTIVENESS BASED ON CRASH TYPE AND ESTIMATED VEHICLE-VEHICLE EFFECTIVENESS FOR KAB INJURY CRASHES

Crash Type	2015 Weighted Cases	Proportion of MC Target Population	Vehicle-Vehicle Crash Effectiveness	Weighted KAB Injury Crash Effectiveness
Rear-End	1,307	0.18	0.50	0.090
SCP	1,510	0.22	0.25	0.055
LTAP/LD	1,200	0.17	0.25	0.042
LTAP/OD	3,058	0.43	0.18	0.077
Total	**7,075**	**1.0**	**-**	**0.264**

Table 7 displays the predicted market penetration, percent crash reduction, and percent injury reduction in 2025, 2045, and 2065 (full deployment). Figure 3 and Figure 4 plot the predicted crash and KAB injury crash reduction effectiveness as functions of market penetration and the year, respectively. A reduction effectiveness of 100% would indicate that all target population motorcycle crashes could be mitigated or avoided. Full deployment was defined as the year in which motorcycle detecting AEB in PVs was estimated to reach 95% adoption. This corresponds to approximately a 25% KAB crash reduction effectiveness and a 28% crash reduction effectiveness, and is predicted to occur in 2065.

TABLE 7
PREDICTED MARKET PENETRATION AND CRASH REDUCTION IN 2025, 2045, AND AT FULL MARKET PENETRATION (2065)

Year	% Market Penetration	% Crash Reduction	% KAB Injury Crash Reduction
2025	0.64	0.19	0.17
2045	45.79	13.28	12.09
2065	95.65	27.74	25.25

In Figure 3 and Figure 4, the KAB injury reduction effectiveness is slightly lower than the crash reduction effectiveness. This is likely due to the differences in the proportions of each crash type between all crashes (Table 5) and KAB inducing crashes (Table 6). The different proportions result in different crash type effectiveness values, and therefore different total weighted effectiveness values. For example, the crash population had a larger proportion of rear-ends, the crash mode with the second highest estimated effectiveness, than the KAB crash population. The total weighted crash effectiveness value is higher than the total weighted KAB crash effectiveness value. Therefore, crashes are being prevented that, had they happened, would not have resulted in an injury.

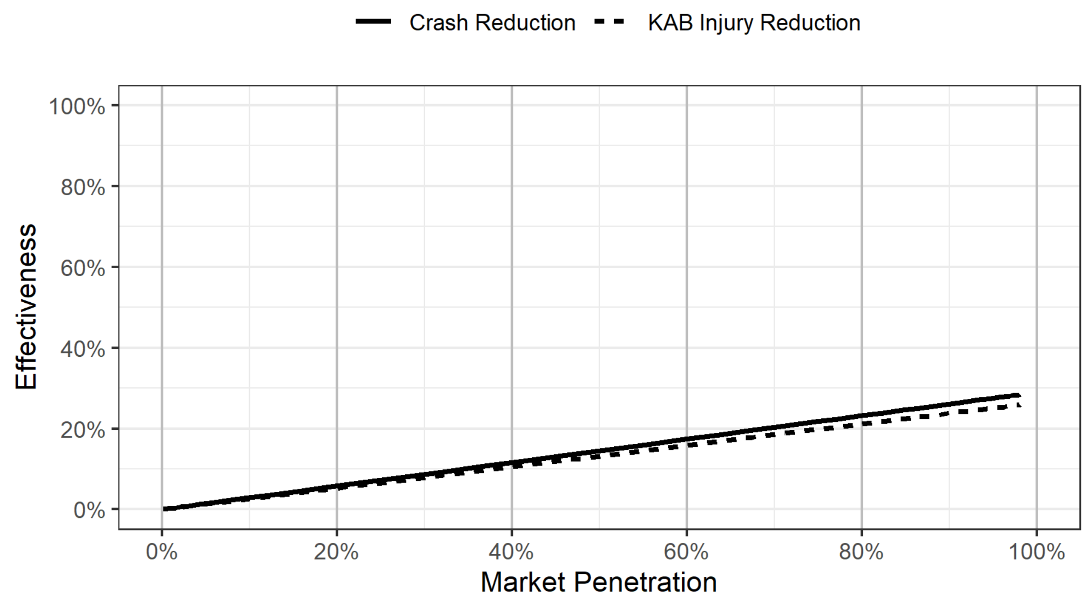

Figure 3. Predicted crash and KAB crash reduction effectiveness as a function of market penetration.

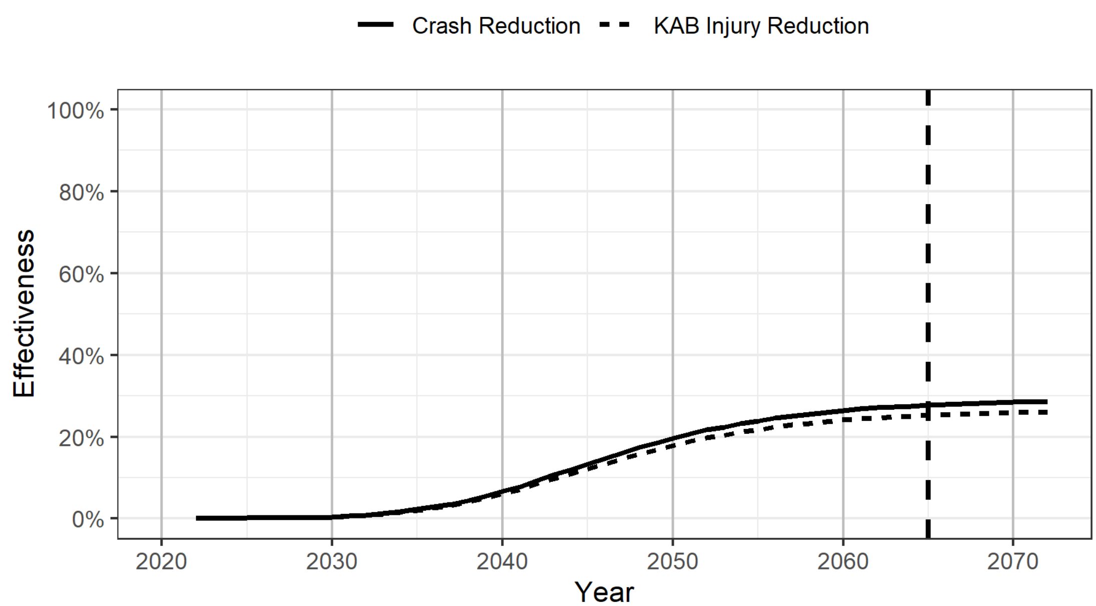

Figure 4. Predicted crash and KAB crash reduction effectiveness from 2022 to 2072. The dashed lines indicate the 2065 full deployment crash reduction. Full deployment was defined as the year in which motorcycle detecting AEB is estimated to reach 95% adoption.

Table 8 displays the predicted number of crashes and injuries in 2025, 2045, and 2065 (full deployment) both with and without an MD-AEB system. Figure 5 and Figure 6 display the number of crashes and injury-inducing crashes, respectively, with an MD-AEB system versus without an MD-AEB system. The vertical dashed line represents the year 2065, when MD-AEB is predicted to reach full deployment.

Assuming MD-AEB technology to be first available in the year 2022, the model predicts a 46% market penetration by the year 2045 which could result in a 13% crash reduction and a 12% KAB crash reduction (Table 7). Assuming constant growth of vehicle miles travelled by 1.01% annually, we predict 17,506 crashes in 2045 as opposed to the estimated 19,913 crashes without the deployment of MD-AEB technology. Between 2022 and 2045, MD-AEB has the potential to mitigate or prevent 6,488 KAB injury crashes and 13,434 crashes. These numbers were found by calculating the area between the with and without MD-AEB curves. It is important to note the relationship between the effectiveness values and number of predicted KAB injury crashes and crashes. A one percentage point (pp) decrease in the overall effectiveness value for either KAB injury crashes or crashes will result in a one pp increase in the number of predicted crashes for that crash type.

TABLE 8
PREDICTED CRASHES AND KAB CRASHES IN 2025, 2045, AND 2065 ASSUMING GROWING VMT

Model	Year	% Market Penetration of MD-AEB System	Crashes	KAB Injury Crashes
Without MD-AEB	2025	0	16,287	7,837
With MD-AEB	2025	0.64	16,260	7,824
Without MD-AEB	2045	0	19,913	9,582
With MD-AEB	2045	45.8	17,506	8,424
Without MD-AEB	2065	0	24,346	11,715
With MD-AEB	2065	95.7	18,198	8,757
			18,430	8,869

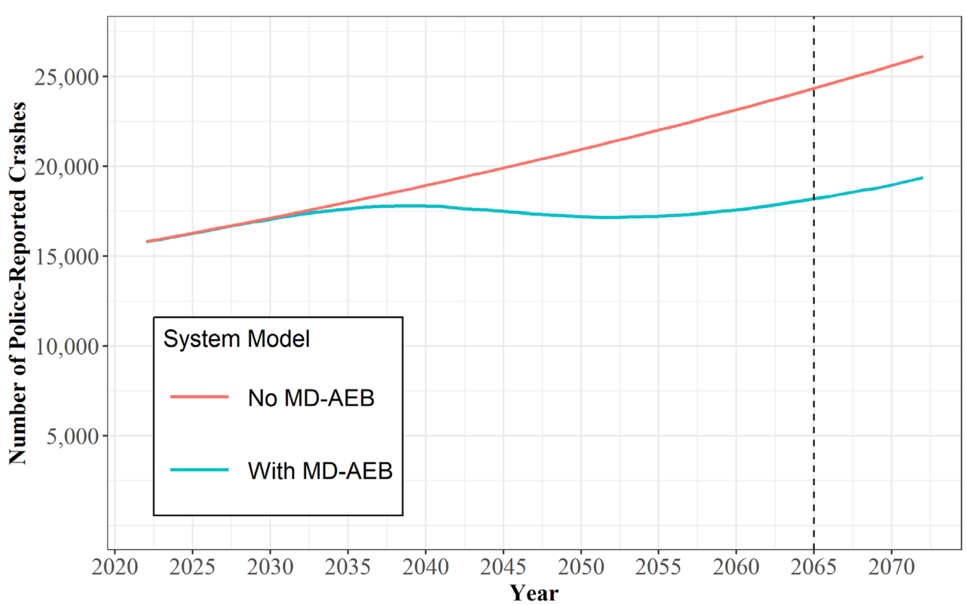

Figure 5. Predicted annual crashes with and without MD-AEB, assuming growing VMT.

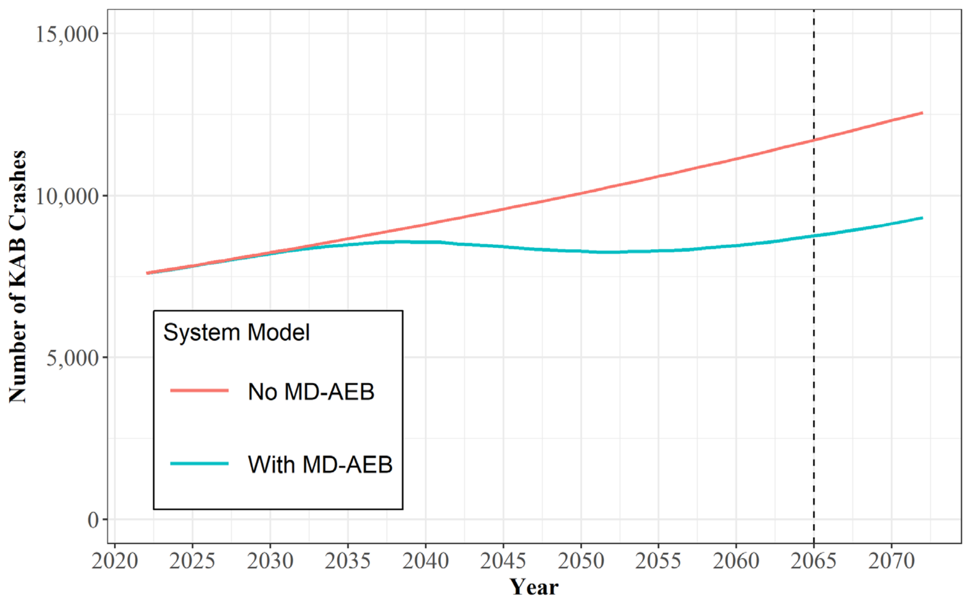

Figure 6. Predicted annual motorcyclist KAB crashes with and without MD-AEB, assuming growing VMT.

IV. DISCUSSION

The MD-AEB target population comprises 8% and 9% of all fatal and police-reported motorcycle crashes, respectively. These numbers are an upper bound on the target population, as certain crash and environmental factors may reduce the effectiveness of MD-AEB. For example, head-on collisions and high-speed crashes may present challenges to MD-AEB systems, as these conditions reduce the amount of time the system has to act, yet each of these characteristics was present in approximately one third of the fatal crash population. The passenger vehicle was negotiating a curve in 25% of fatal crashes, which may reduce MD-AEB effectiveness due to the potentially limited field of view of the MD-AEB sensor systems.

One limitation of this study is the large number of cases where it was unknown whether the motorcycle was the struck or the striking vehicle. A more robust method for determining who struck who could potentially reduce the number of these unknown cases, and may result in a larger target population. A more comprehensive method might include the use of additional variables to determine vehicle roles, or use of a database with scene diagrams available.

Additionally, this model assumes a 1.01% annual increase in VMT. In the past, external factors, such as the 2008 recession and the 2020 pandemic, have caused this assumption to not hold true. This model would not be able to accurately predict crash and KAB crash reduction under circumstances which disrupt the assumption of constant growth of VMT.

Another limitation is that GES uses the KABCO injury scale, a police-reported injury scale that does not reference motorcyclist medical records. Additionally, motorcycle data is limited, so we were not able to run MD-AEB simulations to obtain vehicle-motorcycle effectiveness numbers. As a surrogate we used the effectiveness numbers from vehicle-vehicle collisions. This assumes that detecting motorcycles will be as easy as detecting passenger vehicles. This may not hold true, as motorcycles are smaller than passenger vehicles and come in a variety of shapes and sizes. Additionally, motorcyclists speed prior to a fatal crash more often than passenger vehicle drivers, which would give the system less time to detect the motorcycle

[1]. Finally, the HLDI curve for front crash prevention was used to predict market penetration, as there is not a curve specific to motorcycle detection systems.

Implementation rates for ADAS take several decades because there is a delay between the introduction of the technology and manufacturers standardizing the features in their vehicles. Additionally, there is a delay between the technology becoming available in modern, affordable cars and consumers buying vehicles equipped with the features. IIHS reports it can take up to three decades for vehicle safety features to reach full market penetration, and up to five decades for systems that include forward collision warning and AEB features [19]. This study predicts it would take approximately four decades for MD-AEB technology to fully penetrate the market. While this is in line with IIHS predictions, it may be an underestimate. This study uses the forward-facing passenger-vehicle-detecting AEB market penetration curve, however it is unknown if MD-AEB will penetrate the market as quickly as passenger-vehicle-detecting AEB is expected to. A longer time frame before reaching full market penetration would result in reduced counts for prevented crashes and injuries between now and 2065.

Future research in this area should build motorcyclist injury risk curves to implement vehicle-motorcycle effectiveness numbers. A previous study by Ding et al. presented motorcyclist injury risk curves, however the models were not a good fit for this study [20]. The Ding et al. models require information not provided in the GES database. Additionally, the study only looked at motorcyclists wearing helmets, as helmet usage is required by law in Europe. Helmet usage is not a federal requirement in the US, so we would expect to see lower helmet use rates. Finally, the Ding et al. study looked at cases where the motorcycle was not struck from behind, a configuration which makes up a large proportion of our study population.

V. CONCLUSIONS

This study presents one of the first examinations of the potential effectiveness of MD-AEB systems in the US fleet, with future crash and injury reduction estimates. Motorcycle crashes that could be mitigated or avoided with vehicle-based MD-AEB technology make up a fraction of all motorcycle crashes, and a smaller fraction of all crashes. MD-AEB has the potential to mitigate or prevent up to 6,513 KAB injury crashes and 13,485 crashes by the year 2045 and even more upon reaching full market penetration (95%) in 2065. These numbers represent an upper bound on the proportion of motorcycle crashes that could be mitigated or prevented, as the methods make several assumptions which may not always hold true.

VI. ACKNOWLEDGEMENT

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