SAFETY BENEFIT EVALUATION OF SECONDARY COLLISION MITIGATION BRAKING

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ABSTRACT

Current accident statistics evaluate that multi-collision crash events represent 25~30% of all crashes. A post-crash feature introduced a few years ago attempts to mitigate the impact severity and quantity of these secondary impacts.

The feature has several names: Post-crash braking (PCB), Multi-collision Braking (MCB) or Secondary Collision Mitigation Braking (SCM or SCMB).

SCMB uses the crash sensing systems and the brake systems. After a significant crash event, the vehicle will attempt braking in order to reduce the residual velocity with the goal to reduce, even possibly avoid, subsequent collisions.

The first objective is to confirm the safety field problem of multi-collision events and further evaluate their devastating effects in terms of fatalities and injuries.

The second objective is to evaluate the increase in fatality and injury risks from single to multiple collision events. A theoretical potential safety benefit is evaluated, considering an SCMB feature with the capability to avoid all secondary collisions in multi-collision events.

Finally, in the third and deepest analysis, 3 realistic levels of braking decelerations are considered for SCMB. The risks levels for other major post-collision risks were quantified. The potential safety benefits of SCMB with the braking decelerations are evaluated for the avoidance of these 3 post-collision risks: subsequent collisions, VRU impacts, and rollovers.

Disambiguation: in this paper, "secondary collision" does not mean another accident which occurs as a result of congestion caused by a primary accident. "Secondary collisions" are defined as the subsequent collisions (impacts), after the first impact of a vehicle involved in an accidental event containing a chain of impacts.

SECONDARY COLLISION FIELD ISSUE

Method to quantify the field issue

The field issue consists mainly of the observation of the passenger cars' accident field. The overall accidents' field is analyzed for its quantities of vehicles and their related quantities of Injuries slight, severe and fatal. The next step repeats this quantification on a filtered down vehicle set with the specific event of "multi-collisions".

Secondary collision field quantification

The complete GIDAS database between (~2005 & ~2012) is used. The database is filtered for passenger vehicles involved in an accident. After removing cases without enough reconstruction information, like DeltaVs, the vehicle set includes 24333 cars. The resultant set is then filtered once more to identify the vehicles involved in more than 1 collision. This smaller set has 5224 vehicles.

At this very high level, it shows that ~21.5% of the passenger vehicle accidents are in fact multi-collisions.

By processing further each set, it is possible to quantify the number of slight injuries, severe injuries or fatalities in this multi-collision set. The results are in this Table 1.

Table 1: Injuries and fatalities caused specifically by subsequent events and their % in relation to all multi-collisions events.

	GIDAS Accident set	All single coll.	All Multi-coll.	Multi-coll. in % of field
Veh.	24333	19109	5224	21.5%
No Inj.	20245	17785	2460	12.2%
Slight	11186	7374	3812	34.1%
Severe	3080	1621	1459	47.4%
Fatal	313	147	166	53.0%

As a group, the multi-collision group present 21.5% of the passenger vehicles accidents, yet include 53% of the fatalities. Therefore a safety feature designed to address secondary collisions could address a portion of these fatalities, providing valuable safety benefits.

SECONDARY COLLISION FIELD POTENTIAL IN TERMS OF FATALITIES AND INJURIES

The "field issue" described above is the observation and quantification of injuries and fatalities related to multi-collisions. Whereas the "field potential" looks at the reality behind addressing this issue.

Not all injuries and fatalities in the multi-collision field can be addressed. A theoretical SCMB feature removing all multi-collisions would bring down the risk levels from that of multi-collisions events down to single-collision events. The risks of single collisions are not null, therefore the field potential is lower than the total field issue.

The maximum potential safety benefit for SCMB is evaluated by first identifying the risk differential then by calculating the reduction of injuries and fatalities if all secondary collisions were avoided.

This quantification still results in an unattainable field potential since a theoretical feature would avoid and remove all secondary collisions, which is not realistic. The realistic evaluation of an SCMB feature's performance is conducted in the last paragraph of this paper.

Method to quantify the field potential

Sorting out events and defining severity levels

GIDAS Database (~2005-2012) includes sufficient accident reconstructions details to enable the analysis of multi-collision events. All multiple collision events were sorted out and analyzed. For each impact, the severity is defined by the DeltaV, the relative loss of velocity of the impact. In the chain of impacts, the 2 most significant impacts and their respective severity are identified and classified.

As a baseline for the risk differential, single impact events are processed with the same severity classification.

A proposed SCMB feature triggers the braking only after the deployment of a non-reversible restraint system (ie. Pretensioners or Airbags).

Therefore, a collision is considered relevant as an SCMB trigger only if its DeltaV is high enough to deploy some restraint system. Let's define the 1st Relevant Impact as "RI1". RI1 is the first impact in the crash sequence with a DeltaV above deployment threshold. In this paper, we assume it is at 18km/h. Below this severity threshold, the feature would not be triggered therefore no safety benefit could occur.

The 2nd relevant impact "RI2" is considered to be the highest severity event following the first relevant impact RI1 defined above.

For example, an accident with 6 impacts with this DeltaV sequence: DV1=5km/h, DV2=14km/h, DV3=22km/h, DV4=17km/h, DV5=35km/h, DV6=5km/h

"RI1"= first impact with DeltaV above 18km/h is DV3=22km/h

"RI2"= highest severity impact after RI1 is DV5=35km/h

Rationale of sequence characterization

The rationale for this crash sequence characterization is that, in GIDAS, the longest sequence of crashes was up to 9 impacts. There are many impacts with more than 2 or 3 impacts. Therefore, it is imperative to bucket the sequences in order to quantify average risk levels afterward.

RI1 is defined as the "first impact with DeltaV above 18km/h". There are 2 reasons for this choice. The first reason is that the SCMB feature is only active beyond this level. The second reason is that below this level, most vehicles would provide sufficient protection without the non-reversible restraint system. Generally, it is expected that most vehicles are designed to deploy restraint systems when the injury risks become significant.

The 2nd relevant impact RI2 is defined as the "highest severity impact afterward". The main reason to reduce to rest of the sequence to the highest severity event is that it is precisely that event which would be the most injurious to the occupants being in this "already-crashed vehicle". The most severe injuries resulting from the rest of the sequence will be determined by this highest severity event.

Risk categories

The risk level for a given impact falls into 3 categories: low, medium and high. These are related to the 3 different ranges of vehicle performance:

<u>Low risk</u>: below the deployment threshold.

<u>Medium risk</u>: impact severity within the typical restraint system's design range for safety performance.

<u>High risk</u>: impact severity beyond the typical restraint system design range for safety performance.

The 2 separation levels (Low/Medium and Medium/High) need to be defined. The 1st level is already set at 18km/h. The 2nd level is set at the impact severity on the high-end of the vehicle/restraint system design range. This severity level is driven in Europe and the North America by the NCAPs: 56km/h-100% and 64km/h-40% offset. The DeltaV for the 2nd level separation between medium and high risk is set at 56km/h of DeltaV. Beyond this DeltaV velocity, it is considered that the impact severity will overwhelm the vehicle structure+restraint system, thereby generating relatively elevated occupant injury risk levels.

Cases with unknown DeltaV are excluded. If RI1 is the last impact in the sequence, it is excluded from the safety benefit evaluation.

Bucketing events with similar risk levels and determining risk levels for multi-collision events

All multi-collision events are now characterized by 2 most significant events RI1 and RI2, and their respective DeltaV. In a 2 dimensional space, with the axis RI1 DeltaV and RI2 DeltaV, each multi-collision event can be represented by a dot with the coordinates (RI1 deltaV, RI2 DeltaV). See Figure #1.

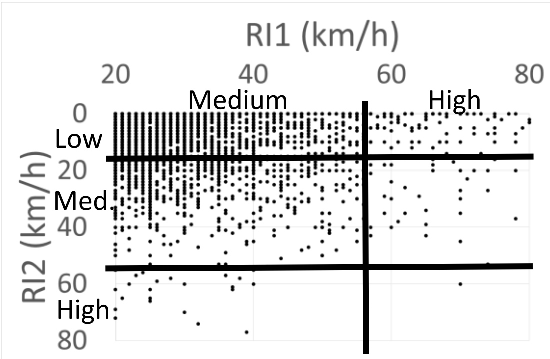

***Figure 1*. Multi-collision events distribution by (RI1, RI2) in 2-dimensional space of DeltaVs.**

As expected, this Ant-hill plot has a distinctive shape. The distribution density is highest in the top left corner, fading to a low density going towards high RI1 and/or RI2.

RI1 and RI2 DeltaVs are each sorted in the 3 categories of risk (low, medium, high). However, because of RI1's definition, there are no RI1 with low risk. A safety benefit for the SCMB feature is present only for the crashes represented in this plot.

Each SCMB relevant event belongs into one of the 6 buckets represented on the plot in Figure 1.

Multi-collision field
The multi-collision field is complex. There is a substantial number of multi-collision which can never be addressed by an SCMB feature. There are multi-collision which have all collisions in the low-risk category (RI1 and RI2 <18km/h). There are also multi-collisions in which the last impact in the sequence is the most relevant impact (RI1>18km.h, no RI2 event). These 2 instances need to be separated from the SCMB relevant vehicle set.

Table 2: Multi-collision field categories

	All Multi-coll.	Multi-collisions breakdown		
		Multi-coll. with ALL DVs <18 km/h	Multi-coll. with RI1> 18km/h but no RI2	SCMB relevant: multi-coll. with RI1>18km/h with RI2
Veh.	5224	2002	586	2636
No Inj.	2460	1314	183	963
Slight	3812	1397	425	1990
Severe	1459	293	243	923
Fatal	166	14	27	125

Bucketing single-collision events for baseline risk levels
In order to be able to quantify the risk differential, single collision events need to be bucketed in the same fashion as RI1. Indeed, the SCMB theoretical feature would remove the secondary collisions altogether, stopping the crash sequence at RI1.

The GIDAS database is processed for passenger car events containing only single crashes. These events are characterized by their sole impact's DeltaV. The DeltaV is compared to the same 2 thresholds as above.

The first threshold is set at the same 18km/h for the low/medium risk separation.
The second threshold is set at the same 56km/h for the medium/high-risk separation.

As mentioned previously, cases with unknown DeltaV are excluded.

The multi-collision cases in which RI1>18km/h but no RI2 impacts (only the last crash is above the threshold) share a similarity with single collision events: There is only 1 relevant impact driving the risk of injuries and fatalities. Going forward these multi-collisions are considered inside the baseline set of vehicles. They will participate in the calculation of baseline risks below.

Baseline collision set = Single collisions + Multi-collisions without RI2.

Baseline collisions and Multi-collisions risk levels

The number of cars in each bucket is determined for both groups (baseline and multi-collisions). The respective numbers of slight injuries, severe injuries and fatalities are extracted from GIDAS. The risk level for the each injury severity and fatality is calculated as their ratio to the number of cars in the respective bucket. The risk levels are considered to be constant within each bucket.

Table 3: Baseline collisions risk levels.

	Medium Risk		High Risk	
Vehicles	5369	Risk%	333	Risk%
Slight	4129	76.9%	123	36.9%
Severe	1381	25.7%	245	73.6%
Fatal	64	1.2%	98	29.4%

Table 4: SCMB Multi-Collisions risk levels.

Risk Levels			RI1			
			Medium Risk		High Risk	
RI2	Low Risk	Vehicles	1870	Risk%	66	Risk%
		Slight	1473	79%	20	30%
		Severe	558	30%	47	71%
		Fatal	39	2%	17	26%
	Medium Risk	Vehicles	645	Risk%	31	Risk%
		Slight	479	74%	10	32%
		Severe	291	45%	17	54%
		Fatal	51	8%	10	32%
	High Risk	Vehicles	22	Risk%	2	Risk%
		Slight	7	32%	1	50%
		Severe	9	41%	1	50%
		Fatal	8	36%	0	0%

Analysis of the risk differential between baseline collisions and multi-collisions

In Table 5, the increase in risk levels of severe injuries is compared between the baseline and multi-collisions sets, for RI1 medium and high risk.

Table 5: Comparison of severe injury risks levels increase from baseline to multi-collision

Risk Levels		RI1					
			Medium Risk		High Risk		
Single Collisions		Veh.	5369	Risk%	333	Risk%
		Severe	1381	26%	245	74%
RI2	Low Risk	Veh.	1870	Risk%	66	Risk%
		Severe	558	30%	47	71%
	Med Risk	Veh.	645	Risk%	31	Risk%
		Severe	291	45%	17	55%
	High Risk	Veh.	22	Risk%	2	Risk%
		Severe	9	41%	1	50%

First observation for bucket RI1=medium / RI2 low: This is the largest bucket in multi-collision events. Even if the secondary impacts are below the restraint deployment threshold, the risk of severe injuries increases from 26% up to 30%

Second observation for bucket RI1 and RI2 medium: This bucket is the second largest. The risk of severe injuries increases from 26% to 45%, a factor of *1.73.

In Table 6, the increase in risk levels of fatality is compared between baseline and multi-collisions sets.

Table 6: Comparison of fatality risks levels increase from single to multi-collision

Risk Levels Of Fatalities			RI1			
			Medium Risk		High Risk	
Single Collisions		Veh.	5369	Risk%	333	Risk%
		Fatal.	64	1.2%	98	29.4%
RI2	Low Risk	Veh.	1870	Risk%	66	Risk%
		Fatal.	39	2.1%	17	25.8%
	Med. Risk	Veh.	645	Risk%	31	Risk%
		Fatal.	51	7.9%	10	32.3%
	High Risk	Veh.	22	Risk%	2	Risk%
		Fatal.	8	36.4%	0	0.0%

First observation, when RI1 is medium risk and RI2 low risk, again the largest bucket in multi-collision events: Even if the secondary impacts are below the restraint deployment threshold, the risk of fatality increases from 1.2 to 2.1, a factor of *1.75.

Second observation, when both RI1 and RI2 are medium risk: The risk of fatality increases from 1.2 to 7.9%, a factor of *6.

These increases of injuries and fatality risk levels are very significant and quantify the devastating effects of multi-collisions.

Safety potential of Secondary collision avoidance

The paragraphs above quantifies precisely the number of injuries and fatalities in each bucket and assess the increase in risk levels from baseline to multi-collision. However, this does not yet provide an outlook on the potential for an SCMB feature.

Method to quantify the safety potential

This is an occurrence avoidance calculation. The potential safety benefit of this real SCMB feature is evaluated by removing the relevant secondary collisions from the field. The quantification is done by changing the risk levels of the 6 buckets of interests, from their original levels with secondary impacts, to the levels of the respective single collision.

For example, in Table 6, for the 3 buckets with RI1 medium risk, the fatality risks are changed to the baseline collision fatality risk with same RI1 (1.19%). See Table 7 for the calculations.

Table 7. SMCB Fatalities saved calculation

Fatalities saved	RI1	
	medium	high
SCMB relevant vehicles RI2 low + medium + high	2537	99
New risk% single collision same RI1	1.19%	29.4%
Predicted fatalities (SCMB veh*new risk%)	30.2	29.1
SMCB relevant fatalities	98	27
Fatalities saved (old-new)	67.8	-2.1
Total lives saved	66	

It is worth noting that with RI1 high, the risk of fatalities is very high in all cases, single and multi-collisions. The risk trends going from RI1 single collision to RI2 low to RI2 medium shows a relatively stable fatality risk level (29%, 26%, 32%). The buckets are comparatively small to RI1 medium. The bucket RI1 high/RI2 low has a slightly lower fatality risk%, creating the situation that the impact on fatalities is negative.

For RI1 high and RI2 high, the bucket has only 2 vehicles, making risk% meaningless.

Similar calculations are conducted for the other injuries levels, sight and severe. These numbers constitute the SCMB's safety potential for a feature capable of avoiding all secondary collisions. The numbers of injuries and fatalities are put into perspective relative to the overall field, in % of injuries and lives saved. The complete outcome is in Table 8.

Table 8. SMCB safety benefit in terms of % injuries and fatalities.

	Total Field Accidents	SMCB Potential Safety Benefits	SMCB Potential Safety Benefits in % from Total Field
Nbr cases	24333		
Slight Injuries	11186	2	0.0%
Severe Injuries	3080	198	6.4%
Fatalities	313	66	21.1%

Summary of results for the Multi-collision Field and SCMB Safety Potential

In this GIDAS analysis, Multi-collision events represent 21.5%% of all accidental events. They contain 53% of the fatalities. (see Table 1.)

About 40% of the overall field fatalities and 30% of severe injuries are in multi-collisions relevant for an SMCB feature. (See Table 9.)

However because eliminating secondary can not address the injuries occurring in the first relevant crashes, some risks will remain. After evaluation of this differential risk, the SCMB Safety Potential appears to be ~21.1% of the overall field fatalities. (See Table 8.)

Table 9. Percentage of Multi-collisions and SMCB relevant accidents in the field.

	Total Field Accidents	Single Accidents	SCMB Relevant Accidents	% of SMCB Relevant Accidents
Nbr cases	24333	20221	2636	11%
Slight Inj.	11186	8136	1990	18%
Severe Inj.	3080	1952	923	30%
Fatal.	313	181	125	40%

SECONDARY COLLISION MITIGATION FEATURE SAFETY EVALUATION

This deeper analysis looks at other types of multi-collision risk such as rollovers, subsequent VRUs (Vulnerable Road Users) impacts and post-crash fires. Because successful avoidance is dependent on the braking performance, deceleration levels were factored in, for a more realistic safety benefit evaluation.

A dataset of all multi-collision events was created with all relevant details pertaining to each impact including VRU impacts and rollovers. Similarly to the impact filtering and sorting described above, the first significant impact RI1 is identified by its severity and its potential to deploy the restraint system. The second most significant impact RI2 and its distance to RI1 are determined. Using the first significant crash's residual velocity and the distance RI1-RI2, the necessary deceleration to reach a stop is calculated. This deceleration is the target to achieve avoidance. The comparison of deceleration with the SCMB braking performance enables the quantification of avoidance of subsequent collisions, VRU impact or rollover for the 3 braking levels.

SCMB Feature Description with realistic performance

Until this point in the analysis, the feature was theoretical, perfectly avoiding all secondary collisions. In reality, the feature's success will depend nearly exclusively on the post-crash braking performance and the distance between RI1 and RI2. Therefore, the feature is now defined as triggering the brakes immediately after the RI1 with one of 3 levels of braking deceleration: 0.3 G's, 0.6 G's & 1.0 G's. These 3 are chosen to cover a broad range of braking performance with 0.3 G's a moderate braking, 0.6 G's a strong braking achievable in most normal road conditions and 1.0 G's being the maximum achievable in perfect braking conditions.

Post collision risks

It is valuable to consider other risks resulting from multi-collisions: For instance, Roll-over, pedestrian and fire risks.

Roll-overs do happen significantly in multi-collisions. It is worthwhile to investigate if an SCMB feature would reduce the instances of secondary Roll-overs. Another interesting consequence to consider would be Pedestrian impacts resulting from multi-collision. There is indeed a portion of pedestrian impacts which are not the typical single car-to-pedestrian impacts. In the following analysis, all VRUs are considered.

Another interesting analysis would consider the risk of subsequent fire. This is documented in GIDAS. After an initial look, the number of instances appears too low to make a meaningful analysis. Therefore, this risk is not included in the analysis

Assumptions

Assumption #1: The car can still brake: RI1 is the first significant impact with a restraints deployment. The vehicle would have significant damage on 1 side of it. The modern ABS/ESP braking systems are able to control braking independently at each wheel. Even with one or more wheel damaged, the braking system will attempt to brake and keep the vehicle in a stable condition.

Assumption #2: The crash sequence remains the same, despite a different Ego-vehicle behavior: The Ego-vehicle brakes. It is considered nonetheless that other impacts due to unintended consequences of this braking would be negligible. Indeed, it is theoretically possible, but highly unlikely, that another vehicle was crossing the ego vehicle's path between RI1 and RI2.

Assumption #3: It is also considered that the traveling path would remain the same, even if RI2 is not the next impact following RI1.

Method to quantify the feature's performance

In this analysis, only successful avoidance is considered. This is defined here as reaching a stop before reaching the RI2 event. Mathematically the avoidance is achieved if the SMCB's prescribed braking deceleration is greater than the necessary deceleration to reduce the RI1 exit velocity to zero over the distance RI1-RI2. This GIDAS dataset (~2005-2014) contains 6283 vehicles having altogether 15.346 impacts in total. All multi-collision events are extracted with the relevant details, such as the 15346 crash types, DeltaVs, exiting velocity & distance between impacts to name a few.

The avoidance prediction is straightforward: The target deceleration to achieve avoidance is calculated using 2 variables: the exit velocity after RI1 and the distance RI1-RI2. The GIDAS reconstruction provides these 2 variables. In the case of multiple events between RI1 and RI2, the distances between all the impacts are added to evaluate the total RI1-RI2 traveled distance.

Even though GIDAS crashes are very detailed and well reconstructed, in some instances the reconstruction dataset is incomplete and does not allow to complete the calculation due to missing distances or velocities. These case are excluded from the resulting performance evaluation.

Results: Safety Performance of feature

Table 11 gives the breakdown of SCMB performance according to the RI1's direction of impact.

Table 11: Results breakdown for SMCB feature's avoidance performance

Subsequent events	Secondary Collision		Rollover		VRU	
RI1 is FRONT IMPACT	348		459		97	
Avoidance with 0.3G braking	24	7%	42	9%	20	21%
Avoidance with 0.6G braking	98	28%	137	30%	27	28%
Avoidance with 1.0G braking	161	46%	277	60%	39	40%
RI1 is RIGHT SIDE IMPACT	108		184		19	
Avoidance with 0.3G braking	5	5%	9	5%	4	21%
Avoidance with 0.6G braking	25	23%	49	27%	5	26%
Avoidance with 1.0G braking	55	51%	121	66%	9	47%
RI1 is LEFT SIDE IMPACT	147		185		31	
Avoidance with 0.3G braking	13	9%	13	7%	2	6%
Avoidance with 0.6G braking	41	28%	60	32%	6	19%
Avoidance with 1.0G braking	83	56%	115	62%	11	35%
RI1 is REAR IMPACT	158		63		49	
Avoidance with 0.3G braking	19	12%	5	8%	17	35%
Avoidance with 0.6G braking	46	29%	20	32%	26	53%
Avoidance with 1.0G braking	78	49%	36	57%	32	65%

It is interesting to note that the 3 subsequent risks (secondary collision, Roll-over or VRU impact) are not mutually exclusive. It is actually possible to have all 3 in a complex crash sequence. The SCMB may be successful in avoiding a combination of the 3. In Table 12, the combined results are given, because avoidance of these secondary events is additive in such an event

Table 12: Avoidance performance results summary for the SMCB feature

Subsequent collisions with	Secondary collisions, Rollover, or VRU	
RI1 is FRONT, SIDE or REAR IMPACT	1848	
Avoidance with 0.3G braking	173	9%
Avoidance with 0.6G braking	540	29%
Avoidance with 1.0G braking	1017	55%

Discussion on SCMB's avoidance performance

The intuitive performance trend is confirmed: the higher the braking performance, the higher the percentage of subsequent collision avoidance.

For 0.3G braking, avoidance is in the ~10% range.
For 0.6G braking, avoidance is in the ~30% range.
For 1.0G braking, avoidance is in the ~55% range.

Altogether showing a linear trend with ~6.6% additional avoidance for every increase in 0.1 G's braking.

RI1's direction of impact has a relatively minor influence on the performance outcome. The feature's performance remains significant for all RI1 types of impact. This indicates that, by design, an SCMB feature should trigger in all types of RI1 impacts.

Discussion on SCMB's Safety performance

In the previous section, the theoretical maximum performance for perfect avoidance all subsequent collision was evaluated at 21% of fatalities based on a risk differential calculation.

With this number and the avoidance numbers above, the following can be inferred:
For 0.6G braking with an avoidance capability of about 30%, the fatality reduction may amount to 6.3% of all field fatalities. A deeper analysis combining the avoidance calculation with the actual injuries is necessary to confirm this estimation.

It is likely that the maximum performance is limited by some relatively small distances between RI1 and RI2. Nonetheless, this safety benefit is substantial already, yet it is also incomplete. Through the velocity reduction, the unavoidable subsequent collisions will have reduced DeltaVs. This will contribute to further risk reduction for subsequent collisions. Additional injuries and fatalities will be avoided thanks to the mitigation effects of SCMB.

CONCLUSIONS

Multi-collisions crashes are significantly more severe than single crashes. In fact, they include 53% of the field fatalities for about 21% of all accidents. A theoretically perfect avoidance of subsequent collisions would target 40% of the field fatalities and provide a potential safety benefit of 21% reduction in fatalities.

However complete avoidance is only theoretical. Taking into consideration an achievable braking deceleration of 0.6G's, SCMB enables a reduction of ~30% of subsequent collisions, rollovers, and VRUs impacts, potentially saving a predicted 6% of field fatalities.

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