Head Injury Reduction Potential of Integrated Pedestrian Protection Systems Based on Accident and Experimental Data – Benefit of Combining Passive and Active Systems

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Abstract The aim of this study was to investigate the potential pedestrian head injury reduction from passive and active protection systems compared to an integrated system.

The GIDAS database was queried from 1999 to 2013 for severely (AIS3+) head injured pedestrians when struck by car fronts. This resulted in 68 cases. To estimate the protecting performance, headform tests to different impact locations in the hood, A-pillar and lower windshield areas were performed on cars with and without deployable hood and airbags. The active protection system was an autonomous braking system, which was activated one second prior to impact if the pedestrian was visible to a forward-looking sensor. The integrated system was a direct combination of the passive and active protection systems. Case by case the effect from each of the active, passive and integrated systems was estimated.

The individual active (AEB) and passive (deployable hood and windshield airbag) pedestrian protection systems were effective to reduce severe head injury, but combining the two systems was more effective than either of the two systems alone, with 32-42% higher integrated effectiveness than the best single system. Even for the most advanced single system there was a benefit to combine into an integrated system.

Keywords Pedestrian, protection system, passive safety, active safety, integrated safety, benefit

I. INTRODUCTION

Pedestrian fatalities and injuries are a problem worldwide, with 270 000 pedestrians estimated being killed every year globally [1]. The most frequent fatal and severe (AIS3+) injury is to the head [2-4], most often from the windshield area of the car and especially its frame [5, 6], but children and smaller adults are often injured by the hood area. This has led to improved energy absorption of the hood and its underlying structures as well as introduction of deployable hoods and windshield airbags. Another way to reduce injury is to reduce impact speed, where even moderate speed reductions can significantly decrease risk for the pedestrian in an impact. For example, a recent study showed that reducing the impact speed from 50 km/h to 40 km/h reduced the pedestrian fatality risk by 50% while a reduction (from 50 km/h) to 30 km/h reduced the risk by as much as 80% [7].

Regulations and consumer test programs have acknowledged this and have introduced tests of the passive pedestrian safety of cars [8-11]. A Swedish study showed that these measures have been successful, with a significant benefit in reduced pedestrian injuries for cars with higher Euro NCAP ratings [12]. In addition to this cars are recently being equipped with systems that automatically brake the car in case of risk of running into a pedestrian. These systems are estimated to have a high potential in reducing the number of pedestrians killed and severely injured [13]. The consumer program Euro NCAP therefore has decided to introduce tests of so-called Automatic Emergency Braking (AEB) systems and cars with these systems can from 2016, if performing well in tests, benefit by getting a higher overall rating of the car. It is expected that these systems will increase in the market, and therefore it is important to question whether high performance of passive protection is still needed or if it can be replaced by active safety AEB systems alone.

In an earlier study the authors estimated a significant benefit of combining active and passive pedestrian

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safety systems in reducing head injury by studying pedestrians who were severely head injured when impacted by passenger car fronts in the GIDAS database [14]. This was based, however, on a theoretical estimation of the airbag performance. Further, the pre-crash matrix (PCM), where the pre-crash motion of the pedestrian has been estimated, has since been updated with substantially more cases. Finally, the GIDAS database has since collected four more years of data. Therefore the aim of this study was to update the previous study, estimating the potential benefit of combining active and passive pedestrian protection systems, with airbag performance based on head impactor test data, as well as addition of cases for the pre-crash matrix and the complete GIDAS database.

II. METHODS

In this study three systems to reduce head injury of pedestrians in car crashes were considered, i.e. a passive deployable system, an active auto-brake system and finally a combined system of the active and passive system. The passive protection system consisted of a deployable hood and a windshield airbag and was designed to mitigate head injuries caused by the bonnet area, A-pillars and the lower windshield area where the instrument panel was in close proximity to the windshield glass. The active system was a so-called autonomous emergency braking (AEB) system that, if a pedestrian can be detected and is estimated to be impacted by the car, applies full braking to avoid or mitigate the crash. The combined system was a direct combination of the two systems with autonomous braking of the car first, followed by an activation of the passive system, in case the accident was not avoided and the remaining impact speed was sufficient to be estimated to cause severe head injury.

We estimated the potential of these systems to reduce severe (AIS3+) head injury. Note that a pedestrian may sustain multiple severe head injuries from different impacts to the car, ground and other external objects in the same crash. In this study, pedestrians that sustained severe head injuries from an impact to the ground, external objects or unprotected areas of the car were not considered helped by the passive countermeasure. Only pedestrians that sustained all severe head injuries from impacts to the protected areas of the car were considered protected by the passive countermeasure.

To estimate the injury saving potential of the different systems we searched the GIDAS database for all cases where a pedestrian was severely (AIS3+) head injured when impacted by the car front. The database consisted of 1843 cases with pedestrians injured when struck by passenger cars between 1999-2012. When excluding the non-relevant cases (lower injury level, side/rear impacts to the car and cases when no severe head injury was sustained), it resulted in 68 cases where information was sufficient to estimate both passive and active protection potential. We then estimated the potential of the passive, active and the integrated system in reducing the risk of severe head injury case by case for the 68 cases.

Passive protection system

The deployable hood performance was estimated based on a previous study with headform tests with a large passenger car tested both in the standard condition as well as equipped with a deployable hood, lifted 100 mm in the rear part of the hood [15]. Five different impact points were chosen distributed on the hood surface. The headform impact speed was 40 km/h and the average of these five tests was used as the estimate of the active hood performance at 40 km/h. Performance at other impact speeds was estimated using a function by Searson et al [16]:

$$HIC(v) = HIC40 * (v/40)\text{^}2{,}5 \quad (1)$$

where HIC40 is the HIC value measured in the test at 40 km/h and v is the velocity at which HIC is estimated. The average values of the five tests were used as input values to this estimation for the reference system respectively the Active hood system (HIC 2838 for reference tests and 688 for Active hood tests). See Table 1. Since the active hood tested was designed to meet earlier Euro NCAP requirements on HIC1000 for full score with a 20% margin, it is likely that a system designed today would aim at keeping 20% below the current target of HIC650. Version 2 of the active hood was therefore estimated as a deployable hood designed to keep HIC 20% below the Euro NCAP level for full score in the hood area (HIC=0.8x650=520).

Table 1. Headform test results from previous study, version 1 of active hood in study

	HIC15	
Point	Standard	Active hood
P1	3257	648
P2	7056	735
P3	1486	525
P4	1438	753
P5	953	778
Average	2838	688

The airbag performance was estimated by headform tests using the method of Euro NCAP but varying the headform impact speed from 20-60 km/h for two different impact points. One impact was chosen as the most severe, i.e. an impact directly to the A-pillar. The other impact was considered less severe, but still a frequent cause of severe head injuries, i.e. impact to the lower windshield glass with, in this case, 25 mm distance to the instrument panel (Figure 1). The tests were performed on a small family car in the standard condition as well as equipped with the windshield airbag systems as in Figure 2. Version 1 is a standard airbag design with a thickness of approximately 200 mm. Version 2 is a new design that increases the energy-absorbing distance achievable without increasing the airbag volume.

Figure 1. Impact locations in the windshield headform tests, left: A-pillar impact location, right: lower windshield impact location.

Figure 2. Pedestrian airbags used in the headform tests to estimate airbag performance, left: version 1 airbag, right: version 2 airbag.

For the effectiveness estimation it was assumed that the airbag was designed to cover the lower windshield where the instrument panel is within the head line of motion and the complete A-pillars. If the head injury or injuries resulted from what was judged as an A-pillar impact, fully or partially, or a direct hit to the lower windshield frame, we used the data from the A-pillar tests for estimation of the risk. If the impact was to lower windshield glass and instrument panel, we used the data from the lower windshield tests to estimate the risk.

When these data were collected, the severe head injury risk, for each impact speed and protection system, could be estimated for each case (i) using the risk function from NHTSA [17]:

$$\mathrm{Risk}_{AIS3+}(\mathrm{i}) = \frac{1}{1+\exp\left(\left(3{,}39+\frac{200}{\mathrm{HIC}_{15}(i)}\right)-0{,}00372\ \mathrm{HIC}_{15}(i)\right)} \tag{2}$$

The risk reduction for each case (i) could be calculated as:

$$\mathrm{e}_{passive}(i) = 1-\frac{risk_{prot\ system}\ (i)}{risk_{ref}(i)} \tag{3}$$

Note that if the impact location of any of the AIS3+ head injuries in a case is other than that protected by the protection system, i.e. other areas of the car or the surrounding/ground, then $\mathrm{Eff}_{\mathrm{passive}}$=0. Also, for both systems, activation was limited to a minimum speed of 20 km/h.

Finally, the total effectiveness of the passive protection system could be calculated as:

$$E_{passive}^{total} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{e}_{passive}(i) \tag{4}$$

The rationale behind this effectiveness calculation method is described in more detail in the previous study [14].

Active protection (AEB) system

The active (AEB) system was estimated to detect all visible pedestrians within the field of view independent of weather, and activate up to 1.0 s before predicted impact. The braking system was estimated to have a ramp-up time of 300 ms and maximum braking level was set to 0.7 g, but reduced if road friction conditions were limited. Finally, three system parameters were varied: trig width, cut-off speed and light conditions for activation; the system was activated for pedestrians within the vehicle path or up to 1.0 m beside it (trig width), either up to 60 km/h or at all impact speeds, and for daylight only or at all light conditions (see **Error! Reference source not found.**). For further details on the AEB system, see earlier study by Rosén [18].

Table 2. AEB parameters for the three versions used in the study

AEB parameters	*Version 1*	*Version 2*	*Version 3*
Field of view	40°	40°	40°
TTC max	1.0 s	1.0 s	1.0 s
Trig width	**0 m**	**1 m**	**1 m**
Braking level max	0.7 g	0.7 g	0.7 g
Ramp-up time	300 ms	300 ms	300 ms
Cut-off speed	**60 km/h**	**60 km/h**	**No limitation**
Light conditions	**Day-light**	**All**	**All**

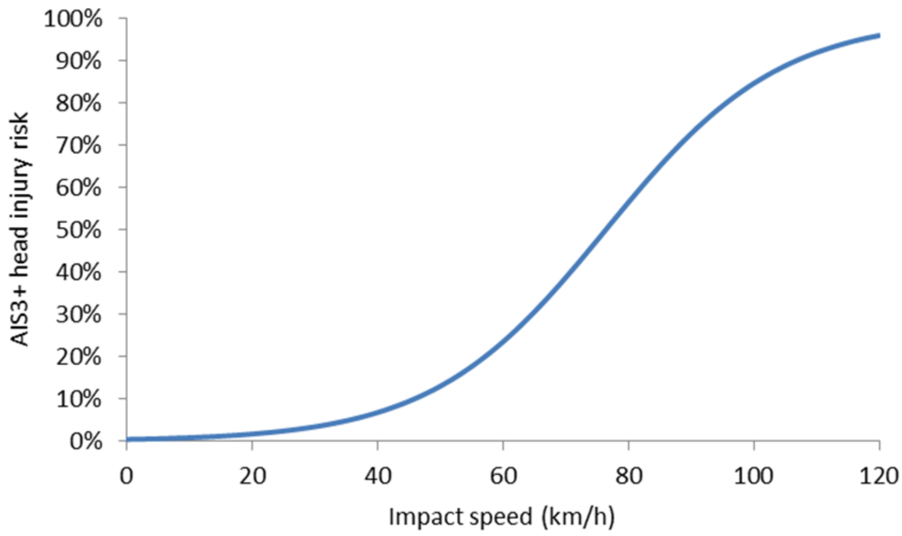

Figure 3. AIS3+ head injury risk for pedestrians impacted by passenger cars, derived from Fredriksson et al. [5]

Risk of severe (AIS3+) head injury was estimated by a risk function, *p(v)* = 1/(1+exp(5.5-0.072*v*)) derived in an earlier study, see Figure 3. A pedestrian detected by the active system, so that autonomous braking could be activated, would be struck at an impact speed $v' \leq v$ (where v is the impact speed without activation). Hence, the relative risk becomes $p(v')/p(v)$ and equation (2) becomes

$$E_{active}^{total} = \frac{1}{N}\sum_{i=1}^{N} 1 - \frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)} \quad (5)$$

Integrated safety system

The integrated countermeasure combined both the passive and active countermeasures. To derive its effect, we first estimated new impact speeds from the active system and then estimated the risk reduction from the passive system with the same method previously used but using the new impact speeds.

Furthermore, the head WAD could change due to the autonomous braking. We know that the sliding effect of the pedestrian on the hood is speed dependent, leading to higher wrap around distance for higher impact speeds. On the other hand, pre-impact braking leads to pitching of the car front which results in higher wrap around distance for a lower speed. This was considered in the previous study and these two effects more or less cancelled each other out and resulted in no total effect. Therefore, in this study this effect was not taken into account.

A pedestrian that would have been helped only by the passive countermeasure ($\delta^{passive\ only} = 1$) has a relative risk of $1-e(v)$. A pedestrian that would have been helped only by the active countermeasure ($\delta^{active\ only} = 1$) has a relative risk of $(1+\exp(5.5-0.072v))/(1+\exp(5.5-0.072v'))$. Finally, a pedestrian that would have been helped by both countermeasures ($\delta^{both} = 1$) has a relative risk of $(1-e(v'))(1+\exp(5.5-0.072v))/(1+\exp(5.5-0.072v'))$. Putting the pieces together, we get

$$E_{integrated}^{total} = \frac{1}{N}\sum_{i=1}^{N}\delta^{passive\ only}e_{passive}(i) + \frac{1}{N}\sum_{i=1}^{N}\delta^{active\ only}\left(1-\frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)}\right) + \frac{1}{N}\sum_{i=1}^{N}\delta^{both}\left(1-(1-e(v'))\frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)}\right) \quad (6)$$

See also earlier study by Fredriksson & Rosén [14] for more details and derivation of the effectiveness functions.

III. RESULTS

In total we had 68 cases with sufficient information to estimate both passive and active protection potential. The pedestrians, who had no limitation on age, were on average 50 years old with a body height of 165 cm, and the car mean model year was 1998. Note that information on stature and model year was not available for all cases. The impact speed for the 68 cases, which were all AIS3+ head injured when impacted by a passenger car front, ranged from 14-116 km/h, with a mean value of 49 km/h (Table 3). Twenty-five of the 68 pedestrians were fatally injured. GIDAS does not conclude what injury was fatal.

Table 3. Descriptive statistics for the pedestrians in the sample (N = 68).

	mean	*Median*	*min*	*max*	*n*
age (years)	49.9	53.5	3	92	68
stature (cm)	165.4	172	103	190	41
car model year	1998	1999	1985	2009	67
impact speed (km/h)	48.7	46	14	116	68

In 5 of the 68 cases (7%) the pedestrians were severely head injured by the hood area alone, 15% from the lower windshield/I-panel area alone, 25% from the A-pillars alone, 9% from the roof edge alone, 12% from the remaining glass area alone, while 32% had at least one severe head injury from other parts of the car or the ground/surrounding. This means that the passive system can potentially address all AIS3+ head injuries for 47% of the pedestrians.

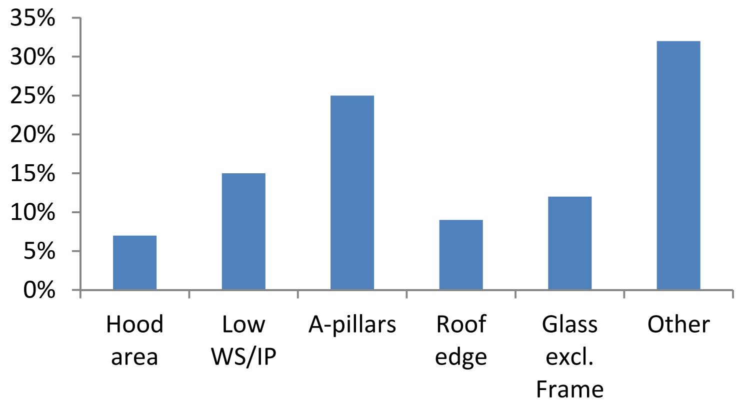

Figure 4. Distribution of injury sources (all AIS3+ head injuries for an injured pedestrian caused by the given area, except for “other” where only one injury from this area is sufficient to classify as “other”)

Passive protection system

Headform to hood tests were performed in a previous study at 40 km/h using standard hood and deployable hood (active hood). The average value from the respective configuration was then used and HIC values at other impact speeds were estimated using the Searson et al method [16] described in the Methods section. The HIC values were used to calculate risk of AIS3+ head injury for the reference configuration and the active hood system (Figure 5).

Headform to airbag tests were performed to obtain head loading of the reference condition as well as the pedestrian airbag condition at different impact speeds (Table 4). HIC values for the reference condition ranged from 427 in 20 km/h to the windshield to over 6000 to the A-pillar at 40 km/h. When these high HIC values were obtained, the testing was not continued at higher impact speeds for the A-pillar to avoid damaging the test equipment. Also, as can be seen in the table, the injury risk was already 100% so it was concluded that higher test speeds would also give a 100% risk. Therefore, a higher test speed to the A-pillar would not give any new information. Note that for both systems, activation was limited to a minimum speed of 20 km/h.

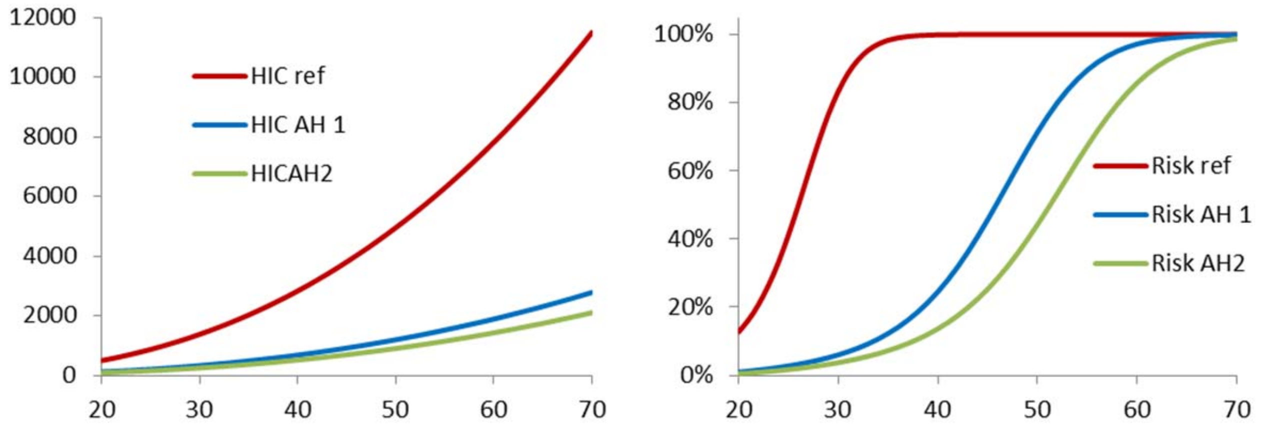

Figure 5. HIC functions (left) and head AIS3+ injury risk functions (right) derived from headform to hood tests

Table 4. HIC values (left) and head AIS3+ injury risk derived from headform to windshield tests at different impact speeds

	HIC15						*Risk*					
Velocity (km/h)	AP Ref	AP Bag 1	AP Bag 2	Low WS Ref	Low WS Bag 1	Low WS Bag 2	AP Ref	AP Bag 1	AP Bag 2	Low WS Ref	Low WS Bag 1	Low WS Bag 2
20	1368	49	28	no test	85	52	83%	0%	0%	no test	0%	0,1%
29	2893	122	103	427	168	108	100%	1%	1%	9%	2%	1%
40	6254	325	212	1879	598	333	100%	6%	3%	97%	18%	6%
50	no test	1912	387	2376	841	524	100%*	97%	8%	100%	38%	14%
60	no test	8152	3072	3756	1169	1088	100%*	100%	100%	100%	69%	62%

**Estimated from tests at lower speed*
AP = A-pillar impact location, Low WS = lower windshield
Ref = reference test without airbag, Bag = pedestrian windshield airbag

Based on headform tests and the method described above, risk reduction functions were developed for the two protection systems, deployable hood and windshield airbag (Figure 6). Linear interpolation between the data points was used for the airbag risk reduction functions. The risk reduction was 0 above 70 km/h for the active hood and above 60 km/h for the airbag in the A-pillar impact location. For the airbag lower windshield impact location the risk reduction was still 31% at 60 km/h. Since we did not have any test data above 60 km/h, we estimated the risk reduction function to continue linearly down to 0 at 70 km/h. Also, the lower windshield reference test at 20 km/h was unsuccessful so the risk reductions from 20-29 km/h for lower windshield were estimated to be horizontal from the values at 29 km/h.

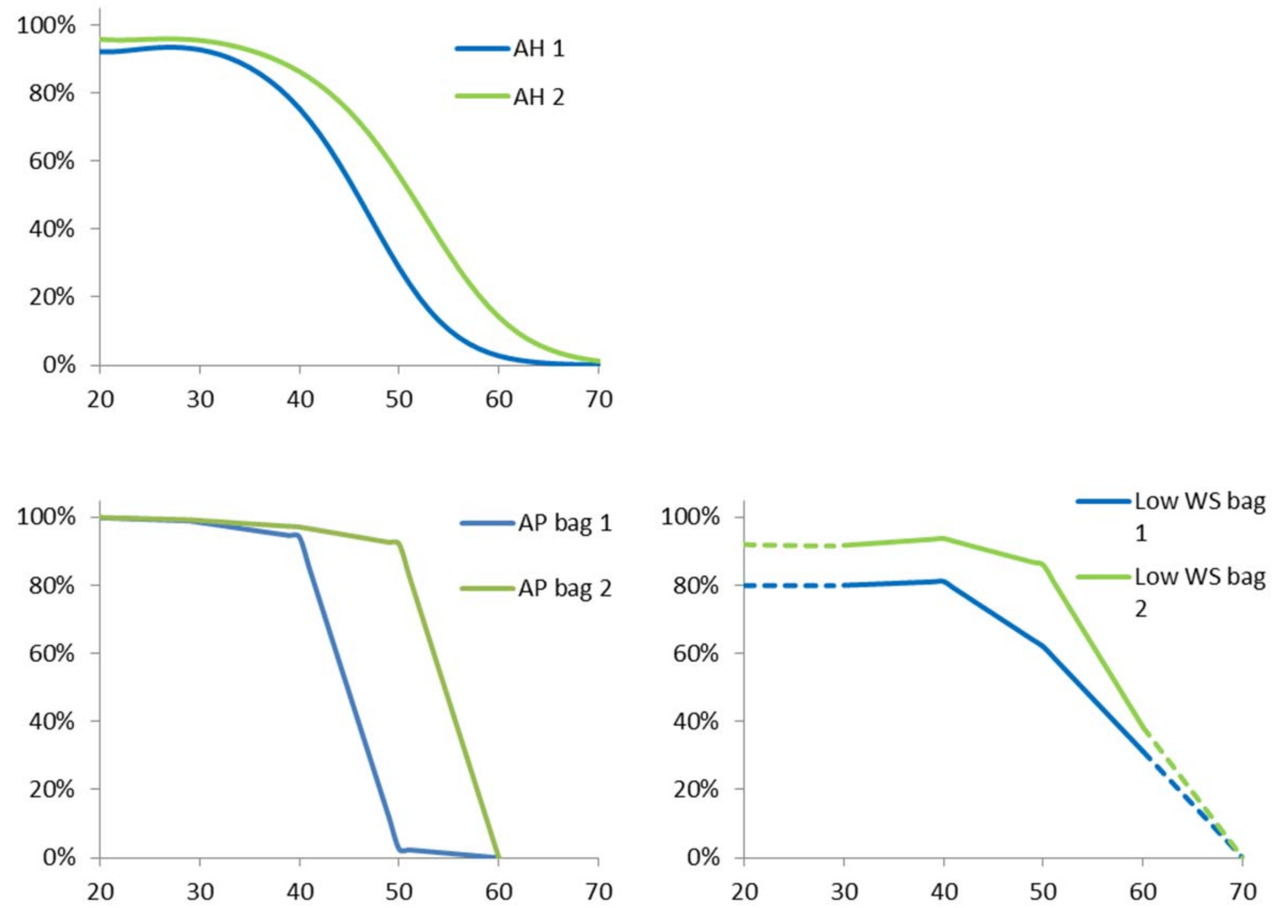

Figure 6. Head AIS3+ injury risk reduction for active hood average (top) and windshield airbag (below) for two impact locations; A-pillar (left) and lower windshield (right)

Using the risk reduction functions the possible effectiveness of the protection system could be estimated for each case. Note that if any of the AIS3+ head injuries was caused by a source outside the protected area, on the car or in the surrounding, the effectiveness of the protection system in that case was set to 0. Finally, the total effectiveness of the passive protection system for the 68 cases was summarized. The passive protection system, based on a deployable hood and a windshield airbag, was estimated in the baseline version to protect 20% of the 68 pedestrians from their AIS3+ head injury (version 1); that is, the AIS3+ head injury effectiveness was estimated to be 20%. For the version 2 system, with a different design protecting better at higher speeds, the effectiveness increased to 30%.

Active protection system

The effectiveness of the active AEB system was estimated in a similar manner, estimating in each case the reduction in risk achievable by applying the AEB system, by estimating the maximum time the brakes could be applied (depending on pedestrian visibility) and maximum braking level allowed depending on the road friction condition.

The AEB system was estimated to protect 11% with the baseline version, activated up to 60 km/h in daylight conditions only and only activating for pedestrians in the direct vehicle path (version 1). When the active system was enhanced to activate for pedestrians up to 1 m outside the vehicle path and in all light conditions (day and night), the effectiveness increased to 38% (version 2). Finally, if the system was enhanced further to activate also at all impact speeds (version 3), it could potentially save 49% of the pedestrians from their severe head injury.

Integrated protection system

By combining the passive and active protection systems a system is created that first brakes the car autonomously when a pedestrian is detected and, if the impact cannot be avoided, the passive system is activated to mitigate the head injury.

For the baseline system, with version 1 passive and active systems, the integrated system effectiveness was 27%. The more advanced system, with version 2 passive and active systems, increased the effectiveness to 54%, while the most advanced system, with version 2 passive and version 3 active, resulted in an integrated effectiveness of 64% (see Figure 7). The integrated system had a 32-42% higher effectiveness than the best individual system.

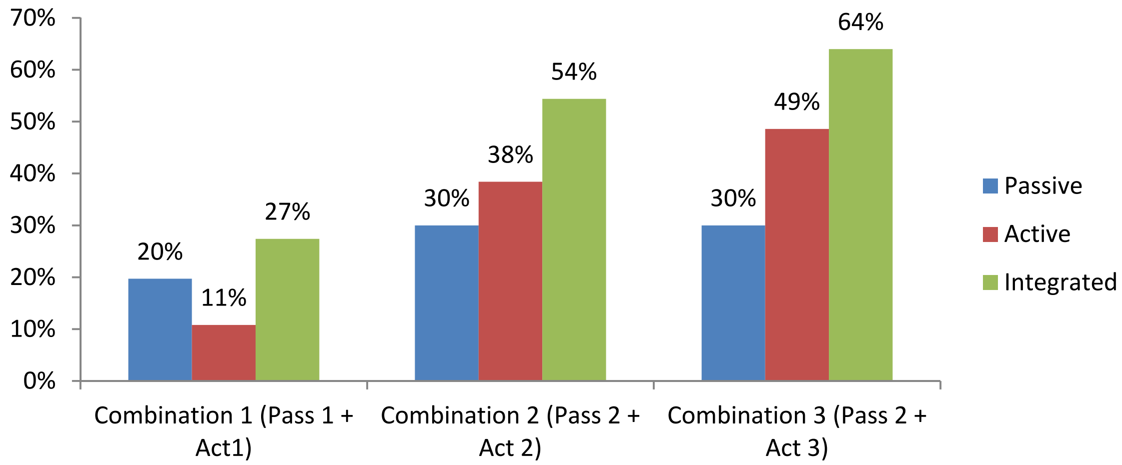

Figure 7. Estimated effectiveness of the active, passive and integrated systems for three different combinations

IV. DISCUSSION

This study is an update of a previous study which had a more theoretical estimation of passive protection performance. The aim of this study was to get a better estimation of effectiveness by using test data as input to passive protection system performance. It could be argued that it is a simplification using a free-flying headform instead of trying to reconstruct each case with a crash dummy, either physical or in simulation, or a human body model. Using a simulation model could be beneficial enabling adjusting the body size of the pedestrian to each case. However, it is a limitation using a model with regard to the actual output of the car and protection system model which may be difficult to validate. This could be solved by using a physical crash dummy, but such dummies are only available in a few body sizes which is a major drawback. For both simulations and crash dummy reconstructions it is very difficult to predict the right pre-impact properties of the pedestrian, such as walking speed, direction, body segment position, that all are known to greatly influence the kinematics and thereby the head impact. Due to these unknowns, it is estimated that it is difficult to perform accident reconstructions and thereby conclude head impact conditions that are closer to reality than the simplified headform test.

In this study the passive protection system performance was studied experimentally, assuming that detection of the pedestrian impact and positioning of the protection system could be managed in all impact speeds used for activation (20-70 km/h). In the lower impact speed range the difficulty for a protection system is the detection phase, since the head impact occurs after a relatively longer time in such impacts. However, this makes the positioning of the protection system in time less challenging. To make sure that activation for pedestrians can be ensured in low speeds there is a risk for activation also when hitting other fixed or moving objects on the road. Therefore, it would be beneficial to use the active system sensor (e.g. camera) to identify the object being hit and therefore improve correct passive system activation decisions. With an integrated system combining active and passive systems this would be possible. For the higher impact speeds the positioning time is more challenging than detection, but since head impacts at higher impact speeds are more frequently located in the windshield area, it is possible to position the protection system in an appropriate timeframe for the head impact, although a conflict may arise with small cars with more vertical fronts which have a short head impact timeframe in the windshield area.

This study resulted in similar but slightly lower effectiveness values compared to the previous study [14] which ranged from 24-39% for the passive part and 28-55% for the active part in a sensitivity analysis. The earlier study was based on theoretical assumptions regarding the passive system performance and a smaller number of cases. The most likely differences between the studies causing the difference in results are the risk reduction functions for the passive systems and the AEB activation parameters. In the earlier study the passive system was theoretically estimated having 100% risk reduction from 20-40 km/h and linearly decreasing from 40 to 70 km/h where it was set to 0, with a sensitivity analysis lowering the maximum risk (-20%) reduction level as well as the end-point (+/- 15 km/h). The risk reduction functions derived experimentally in this study are actually quite close within the sensitivity analysis boundaries. The active system version 3 in this study was similar to the reference system in the earlier study but had a higher maximum braking level, 0.7 g instead of 0.6 g, but lower field of view, 40° compared to the more ideal 180° in the earlier study. In this study the main cause of lower active system effectiveness values however was the introduction of restrictions on the active system activation. For version 1 and 2 of the AEB systems we limited one or more of the following parameters: maximum speed to 60 km/h; the trig width to only activate in the vehicle path; and system activation only in daylight conditions. This influenced the effectiveness substantially from 49% for the high-end system to 11% for the system with all three limited parameters.

It could be discussed what is a reasonable design of the protection system. The passive protection system in this study was designed to protect in the areas tested by Euro NCAP, but also higher up the A-pillars if needed. The roof edge or the remaining glass area which caused 9% and 8% of head injuries, respectively, were not addressed however. So a pedestrian airbag system could both protect a smaller area, e.g. on the A-pillars, but also larger areas, e.g. the roof edge. The active system effectiveness was largely influenced by limiting the activation parameters, limitations that are likely to occur on some production systems. For example, limiting to activations only in the vehicle path is a way to reduce false activations. Further, Euro NCAP in the first phase of assessment from 2016 will only test vehicles up to 60 km/h and in daylight conditions. In 2018 Euro NCAP has indicated that night conditions will be included in the assessment, but higher test speeds have not been discussed. In the study by Rosén [18] he varied more parameters and found an even larger variation of estimated effectiveness. Even though the individual system parameters and estimations could be questioned, the interesting finding in this study is that, when using the same system parameters and estimations when combining the systems into an integrated system, for different levels of parameters, a substantial benefit is realized.

The results from this study showed that it is beneficial to combine passive and active protection systems to reduce severe head injury in car-to-pedestrian crashes. This can be due to several reasons. The passive system alone has shown to provide protection in only 47% of the crashes as the pedestrian was injured by other areas of the car or surrounding in the remaining crashes. At higher impact speeds the passive protection is limited since the system “bottoms out” resulting in insufficient energy absorption distance. The active system however is effective for all injury sources as well as impact speeds. The active system performance however is limited when the pedestrian is obstructed so that he becomes visible very late in the event with a short detection and activation time possible. The passive system overcomes this limitation and activates for an obstructed pedestrian. The integrated system can combine the advantages of both systems. Further, one important feature with the integrated system is that the active system can reduce the impact speed to a level where the passive system is more effective. We see that the passive protection system is very effective up to around 40 km/h and then its performance decreases rapidly. Of the 32 cases where pedestrians were injured from areas potentially possible to protect by the passive system, the impact speed was over 40 km/h in 22 cases (with 18 of the 22 cases between 40 and 70 km/h). Since the passive protection performance increases rapidly for even small speed reductions in this speed range, the active and passive systems complement each other well to yield a large benefit when combined, despite their pros and cons as discussed.

V. CONCLUSIONS

Based on accident data and experiments this study estimated the benefit of combining active and passive protection systems to reduce severe (AIS3+) pedestrian head injury in car crashes. The study concluded that it is beneficial to combine active systems, such as autonomous emergency braking (AEB), with passive protection systems, such as a deployable hood and windshield airbag, to reduce severely (AIS3+) head injured pedestrians in car crashes. The individual systems alone were effective to reduce severe head injury but combining the two systems was more so than any of the systems alone, with 32-42% higher effectiveness than the best single system.

VI. Acknowledgement

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