INTEGRATED PEDESTRIAN COUNTERMEASURES
Potential of Head Injury Reduction Combining Passive and Active Countermeasures

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ABSTRACT

A rapid development of passive and active pedestrian safety systems is in progress. Using real-life accident data, this study shows that a combination of both these concepts offers a considerably increased potential for head protection compared to either of the two systems alone. The passive countermeasure considered in this study was designed to mitigate head injuries caused by the bonnet area, A-pillars, and the remaining windscreen area up to 2.1 m wrap around distance. The active countermeasure was designed to autonomously activate the brakes one second prior to impact if the pedestrian was visible to a forward-looking sensor.

Keywords: pedestrian, head injury, integrated safety, deployable devices, autonomous braking

FOR SEVERE (AIS3+) PEDESTRIAN INJURIES from vehicle crashes, US and Japanese data has shown that the head is the most frequently injured body region (Longhitano et al., 2005, Maki et al., 2003b, Zhang et al., 2008). Fatal injuries in German and Japanese studies are most frequently head injuries when considering single causes only (Ehrlich et al., 2009, Maki et al., 2003b). Child data was studied in a small German study where head injury was most frequent for all severities (Yao et al., 2007). Head injury was also the most frequent cause of child pedestrian fatalities in a Berlin, Germany study (Bockholdt and Schneider, 2003).

Legal and New Car Assessment Program (NCAP) tests have considered this and requirements or ratings of passive pedestrian head protection in the bonnet area have been subsequently introduced (EU, 2003, EU, 2009, EuroNCAP, 2009). In addition EuroNCAP tests the windscreen area and has recently included the pedestrian rating in the overall rating of the car, placing a sharper focus on passive (i.e. in-crash) pedestrian protection. Several authors have, using real-life data, also pointed out the necessity of head protection in the windscreen area and the stiff parts of the windscreen area in particular (Mallory and Stammen, 2006, Okamoto et al., 2003, Yao et al., 2008). Fredriksson et al. (2010) concluded that when developing head injury countermeasures focus should be on the bonnet, lower windscreen, and A-pillars. This has led to the development of technologies aimed at mitigating head injuries. These include both structural solutions with extra space under the bonnet as well as deployable bonnets and various airbags (Fredriksson et al., 2001, Maki et al., 2003a, Nagatomi et al., 2005, Oh et al., 2008, Pinecki and Zeitouni, 2007).

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% (Rosén and Sander, 2009). Currently, active systems such as autonomous braking are being rapidly developed and the first systems will reach the market this year. These systems consist of a pre-crash sensor that detects a dangerous situation where a pedestrian is about to be hit. If unnoticed by the driver the system will automatically brake the car and prevent impact at low speeds and mitigate pedestrian injury at higher speeds by decreasing the impact speed. These systems are potentially very effective in reducing impact severity of pedestrian crashes (Rosén et al., 2009).

It has been argued by some that autonomous braking systems could even replace passive protection systems. It is then interesting to estimate how effective these systems are, and in particular, answer the question: if one of these systems, such as an active system, is implemented, would there be any additional benefit in adding a passive system, or vice versa?

The aim of this study was, therefore, to investigate the potential reduction of pedestrians sustaining severe head injury from either a passive or active countermeasure compared to an integrated system that is a combination of both. Since these countermeasures do not yet exist in cars, or have just been introduced, no accident data, with these systems involved, is available to aid in estimating effectiveness. The alternative solution would then be to use crash tests and head injury criteria with accompanying risk curves along with incidence data to estimate effectiveness. Although legal and NCAP tests may be effective in leading the development towards safer car fronts for pedestrians, they have major limitations in estimating real-life benefits, and no connection between selected injury criteria and head injury risk has been proposed for pedestrian impact. Therefore, ideal passive and active countermeasures were considered in this study. The focus was not on estimating and comparing the exact effectiveness of the individual systems, but rather on the improved benefit of combining the two.

METHOD

In this study, we considered both a passive and active countermeasure for AIS3+ head injuries. The AIS scale comprises six levels of injury severity, where AIS1 denotes minor injury, 2 moderate, 3 serious, 4 severe, 5 critical, and 6 maximal injury. Henceforth, AIS3+ (AIS3 and higher) injuries will be referred to as “severe” injuries in this study. The passive countermeasure was designed to mitigate head injuries caused by the bonnet area, A-pillars, and the remaining windscreen area up to 210 cm wrap around distance (WAD) (see Figure 1). The selection was made based on a previous study of injury frequency from different car sources (Fredriksson et al., 2010) where these car sources were found to produce the most head injuries. This can be achieved either by increased deformation distance (e.g. underneath the bonnet) or deployable devices such as pop-up bonnets or airbags. 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 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. Figure 2 shows the level of protection, $e(v)$, as a function of car impact speed. We see that $e(v)$ had a maximum protection level up to 40 km/h with a linear decrease up to 70 km/h. The active countermeasure comprised a forward-looking sensor with a 180º field of view mounted at the centerline of the vehicle front end and an image processing computer algorithm able to detect and track pedestrians. The vehicle brakes were then autonomously activated at one second prior to predicted impact in order to avoid or mitigate the collision. The sensor operated perfectly in all light and weather conditions. However, pedestrians that were obstructed from view during the pre-crash phase were not detected. This included, for example, pedestrians coming from behind parked vehicles or stepping off buses.

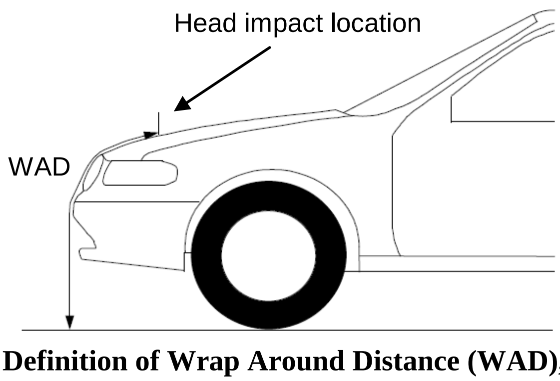

Figure 1. Definition of Wrap Around Distance (WAD), (EU, 2009)

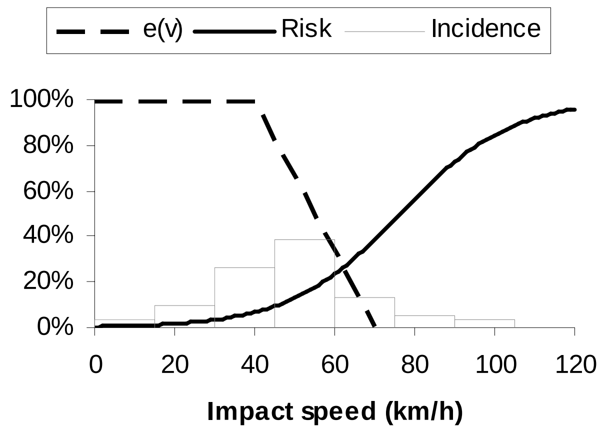

Figure 2. Protection Level of Passive Countermeasure, e(v); and Risk and Incidence of Severely (AIS3+) Head Injured

EFFECTIVENESS: In this section, we refer to pedestrians with severe (AIS3+) head injuries as "severely injured" and pedestrians without such injuries as "slightly injured". Considering all frontal car-to-pedestrian accidents from 1999 to 2008 in Germany, a total of N pedestrians were severely injured (i.e. sustained AIS3+ head injuries). The aim of this study was to estimate the reduction of severely injured pedestrians if certain passive and/or active countermeasures had been present in all striking cars. As is common practice in traffic safety research, we refer to the reduction of severely injured pedestrians as the effectiveness of the countermeasure defined as $\mathrm{Eff} \equiv 1 - N'/N$, where N' is the new number of severely injured pedestrians. (Note that this quantity takes no consideration to pedestrians that would have sustained AIS4 head injury instead of AIS5 head injury, or those sustaining no head injury instead of AIS2 head injury. It only depends on the proportion of pedestrians that would have sustained AIS2- head injuries instead of AIS3+ head injuries.) For each countermeasure, we assumed that some pedestrians would be helped by it, which implies a lower injury risk, and that all other pedestrians would not be affected. In particular, uninjured pedestrians would remain uninjured. Hence, it is sufficient to consider only severely injured pedestrians (AIS3+ head injury) and neglect those not injured. It is then straight forward to realize that

$$N' = \sum_{i=1}^{N} \frac{p'_i}{p_i}, \tag{1}$$

where p'_i and p_i are the risks of severe injury for the i:th pedestrian with and without the countermeasure and the sum runs over all severely injured pedestrians. The quantity p'_i / p_i is the relative risk of severe injury for the i:th pedestrian with and without the countermeasure. If $p'_i = p_i$ for all pedestrians, then $N' = N$. If $p'_i = 0$ for all pedestrians, then $N' = 0$. From equation (1) it follows that the effectiveness becomes

$$\mathrm{Eff} \equiv 1 - \frac{N'}{N} = 1 - \frac{1}{N}\sum_{i=1}^{N} \frac{p'_i}{p_i} = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{p'_i}{p_i}\right). \tag{2}$$

To evaluate this sum, the relative risk must be determined for each pedestrian. It is then worthwhile to introduce the delta function δ_i which equals one if the *i*:th pedestrian would have been helped by the countermeasure and zero if he/she would not have been helped. For example, if the *i*:th pedestrian would have been detected by the sensor of the active system so that autonomous braking had been applied, then δ_i^{active} =1. Similarly, if the i:th pedestrian struck the car in an area where the passive countermeasure would have been present, then $\delta_i^{\text{passive}}$ = 1. Furthermore, observe that $\sum_{i=1}^{N} \delta_i$ equals the number of severely injured pedestrians that would have been protected by the corresponding countermeasure and that $\sum_{i=1}^{N} (1-\delta_i)$ equals the number of severely injured pedestrians that would not have been helped by the countermeasure. The relative risk for a pedestrian not helped by the system is one, since the risk has not changed. The relative risk of a pedestrian helped by the system is p'_i / p_i. Hence, the argument of the sum in equation (2) may be re-written as

$$1-\frac{p'_i}{p_i} = \delta_i \cdot \left(1-\frac{p'_i}{p_i}\right). \tag{3}$$

To proceed further, the passive, active, and integrated systems must be considered separately. In Appendix B, we show that the effectiveness in equation (2) can be interpreted as the expected value of the risk reduction averaged over the incidence distribution.

Passive countermeasure: A pedestrian striking the protected area of the car has a relative risk of $1-e(v)$ where $e(v)$ is the protection level presented in Figure 2. Hence, combining equations (2) and (3), the total effectiveness of the passive system becomes

$$\text{Eff}_{\text{passive}} = \frac{1}{N}\sum_{i=1}^{N} \delta_i^{\text{passive}} \left(1-\left(1-e(v_i)\right)\right) = \frac{1}{N}\sum_{i=1}^{N} \delta_i^{\text{passive}} e(v_i)\ . \tag{4}$$

Active countermeasure: A pedestrian detected by the active system, so that autonomous braking could be activated, would be struck at an impact speed $v' \leq v$. Hence, the relative risk becomes $p(v')/p(v)$ where we use the injury risk function $p(v)$ = 1/(1+exp(5.5-0.072v)) derived by Fredriksson et al. (2010) (see Figure 2). Hence, equation (2) becomes

$$\text{Eff}_{\text{active}} = \frac{1}{N}\sum_{i=1}^{N} \left(1-\frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)}\right). \tag{5}$$

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

$$\begin{aligned}\text{Eff}_{\text{integrated}} &= \frac{1}{N}\sum_{i=1}^{N} \delta_i^{\text{passive only}} e(v) + \frac{1}{N}\sum_{i=1}^{N} \delta_i^{\text{active only}} \left(1-\frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)}\right) + \\ &\frac{1}{N}\sum_{i=1}^{N} \delta_i^{\text{both}} \left(1-\left(1-e(v')\right)\frac{1+\exp(5.5-0.072v_i)}{1+\exp(5.5-0.072v'_i)}\right)\end{aligned} \tag{6}$$

ESTIMATION USING GIDAS DATA: Having derived equations (2) and (4)-(6), it remains to carry out the calculations. Note that the sum in equation (2) runs over all severely injured pedestrians (i.e. AIS3+ head injury) in Germany from 1999 to 2008. However, sufficient information on impact speeds, head impact points, and pre-crash scenarios are not available for all casualties. A statistical approach for estimating the effectiveness would be to consider a random sample of severely injured pedestrians during these years. Such a sample does exist in the German In-Depth Accident Study (GIDAS) database (Otte et al., 2003). Therefore, we conducted the remaining calculations using data from all pedestrians with AIS3+ head injuries in the GIDAS database, which uses the AIS 1998 protocol. The GIDAS database was therefore queried for pedestrians struck by the front of a passenger car or van. Striking vehicles coded as vans (also known as multi-purpose vehicles, MPV) were included, since their front geometry is quite similar to small modern cars. Sport utility vehicles (SUV), on the other hand, have a different front geometry than passenger cars and should be treated separately. Since GIDAS contained very few SUV-to-pedestrian crashes, they were excluded from this study. Further, pedestrians lying on the ground prior to impact were excluded, as well as cases with insufficient information. This yielded 54 cases.

GIDAS is an ongoing on-scene study that investigates accidents from Dresden and Hanover and surroundings. The sampling area contains both rural and urban traffic and was chosen to represent, as closely as possible, a “mini Germany”. Work shifts are equally distributed between day and night, attending accident sites using “blue-light” vehicles along with police and ambulance personnel when personal injuries are suspected. To investigate vehicle and human factors in maximum detail, the GIDAS teams consists of both technical and medical personnel. In each case, the team uses all relevant information available to determine the most likely source for each injury. Medical journals are later collected from the hospitals. Note that at least one personal (AIS1+) injury needs to be confirmed for inclusion in the database.

<u>Passive countermeasure:</u> For each of the 54 cases in the sample, the injury sources of AIS3+ head injuries were studied. Pedestrians that sustained all their AIS3+ head injuries from impacts to protected areas of the car were considered helped by the passive countermeasure; $\delta_i^{\text{passive}} = 1$. However, a pedestrian that sustained AIS3+ head injury from both an impact against a protected area (e.g. the bonnet) and then from an impact to an unprotected area (e.g. the ground) were considered not helped by the passive countermeasure, i.e., $\delta_i^{\text{passive}} = 0$. Furthermore, the risk reduction, *e*(*v*), for a pedestrian that struck only protected areas of the car was 100% at impact speeds up to 40 km/h, declining linearly to 0% risk reduction at 70 km/h (see Figure 2 and Figure 3). Both legal requirements and NCAP tests focus on protection up to 40 km/h, which means that countermeasures are optimized for this impact speed. However, it is likely that the systems would offer some protection at higher impact speeds and the chosen speed of 70 km/h should be seen as an estimate of an upper limit above which protection is minimal. In Appendix C, the maximum protection level and end point of the function *e*(*v*) were altered in order to investigate the robustness of the findings.

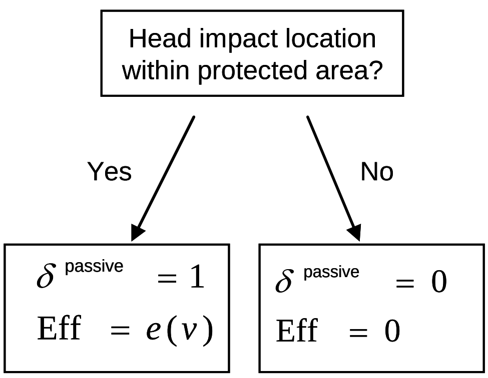

Figure 3. Workflow for Passive Countermeasure

<u>Active countermeasure:</u> For each of the 54 cases in the sample, information on the vehicle’s travel speed, impact speed, deceleration from driver braking, and distance of driver braking was combined to derive the location of the car at one second prior to impact. Assuming the accident point would not

change even if the autonomous system was activated, new impact speeds were derived for pedestrians that would have been visible to the sensor (see Figure 4). In cases where the driver had braked, the original impact speed was kept if it was lower than the one provided by the autonomous braking system. Furthermore, the autonomous braking generated a vehicle deceleration of 0.6g (~5.9 m/s^2) with a linear ramp-up time of 300 ms (full braking achieved after 300 ms). In Appendix C, the braking initiation time and maximum deceleration were altered in order to investigate the robustness of the findings.

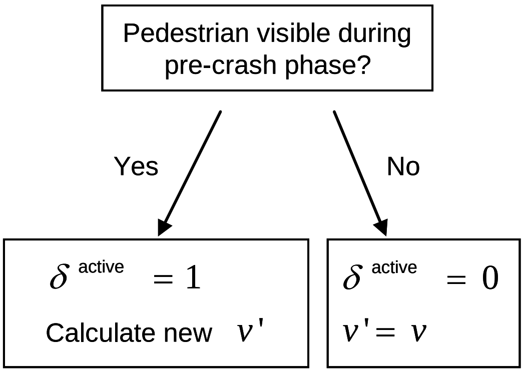

Figure 4. Workflow for Active Countermeasure

Integrated countermeasures: The integrated countermeasure combined both the passive and active countermeasures. To derive its effect, we first estimated new impact speeds from the active system (see Figure 4) and then estimated the risk reduction from the passive system using the new impact speeds (Figure 3).

Furthermore, the head WAD could change due to the autonomous braking. Since the passive countermeasure only covered the windscreen up to a WAD of 210 cm, it is possible that the autonomous braking system could affect whether a pedestrian would be helped by the passive countermeasure. We believe that there are two main effects that influence the WAD, namely car pitching and pedestrian sliding. Due to cars pitching forward when decelerated, the head WAD is greater for a pedestrian struck by a car that is braking compared to not braking. In-house tests have shown that cars typically pitch about 5 cm under full braking. It was therefore estimated in this study that the head WAD would have increased by 5 cm in all cases where the driver had not braked in the original crash, but where the autonomous braking system would have been activated. If the driver had already braked in the original crash, no further pitching was added from the autonomous braking. Furthermore, when struck by a car it is common for pedestrians to slide along the car front so that the head WAD is greater than the pedestrian height (Kerrigan et al., 2007, Subit et al., 2008). The sliding effect is likely to depend on the impact speed of the car, where greater speeds lead to greater sliding (Ivarsson et al., 2007, Maki et al., 2003b). Thus, if the autonomous braking system would have reduced the car impact speed for a particular pedestrian, the new WAD would likely be smaller than the original WAD (neglecting the pitching effect).

To investigate the sliding effect, the GIDAS database was queried for all pedestrians, with a documented head WAD, that were struck by the front of a passenger car or van. Cases where the WAD was less than 60% of the pedestrian height were removed, since this indicated that the pedestrian was not in an upright position. Furthermore, only pedestrians taller than 140 cm were included, since the sliding effect could be different for short pedestrians, and we were only interested in pedestrians that could reach a WAD of 210 cm. This yielded 166 cases with documented head WAD, car impact speed, and pedestrian height. In the next step, a linear regression analysis was conducted with WAD as dependent variable and car impact speed and pedestrian height as independents.

$$\mathrm{WAD}_{\mathrm{model}}(v,h) = a + b_v v + b_h h \,, \tag{7}$$

where v is the car impact speed in km/h and h the pedestrian height in cm.

Having quantified both the pitching and sliding effects, new head wrap around distances, WAD', were estimated for each pedestrian in the sample used for the effectiveness study ($N = 54$). Three scenarios were identified: 1) The autonomous braking system would not have been activated or would not have braked more than the driver had done. The original WAD was then kept. 2) The driver had braked, but the autonomous braking system would have decreased the impact speed further, from v to v'. In these cases, only the sliding effect was taken into account. The new wrap around distance was then derived as $\text{WAD}' = \text{WAD}_{\text{old}} + (\text{WAD}_{\text{model}}(v', h) - \text{WAD}_{\text{model}}(v, h)) = \text{WAD}_{\text{old}} + b_v(v' - v)$. 3) The driver had not braked, but the autonomous braking system would have been activated. Then $\text{WAD}' = \text{WAD}_{\text{old}} + b_v(v' - v) + \Delta_{\text{pitch}}$, where $\Delta_{\text{pitch}} = 5$ cm. Note that only the slope parameter for impact speed, b_v, was needed from the regression analysis.

STATISTICAL METHODS: The most important statistical methods for this study were described earlier in the Method section. Here, we note that confidence intervals for binomial proportions were derived using exact methods. Furthermore, to derive confidence intervals for the estimated effectiveness, we applied the bootstrap method (Efron and Tibshirani, 1993). In this procedure, the original sample of 54 cases was used to generate another 1000 samples, each containing 54 cases, by random re-sampling with replacement from the 54 original cases. The effectiveness was then re-derived for each of the 1000 samples. Finally, the lower and upper 95% confidence bounds were chosen as the 2.5th percentile and 97.5th percentile of the 1000 estimates of effectiveness respectively (i.e. the value of the 975th largest and 25th largest estimates of effectiveness) The bootstrap samples were further used to compare the difference between the integrated system and the passive and active countermeasures respectively. For each bootstrap sample, the ratio of the integrated effectiveness and the passive and active effectiveness, respectively, were calculated. 95% confidence intervals for these ratios were formed as the 2.5th and 97.5th percentiles of the 1000 bootstrap estimates.

A sensitivity study of the results is provided in Appendix C.

RESULTS

The sample comprised 54 pedestrians that sustained severe (AIS3+) head injuries when struck by the front of a passenger car (52 cases) or van (2 cases). Some descriptive statistics of this sample are provided in Table 1. A histogram of the impact speed distribution is included in Figure 2. Furthermore, 19 of the adult pedestrians (15+ years old) were struck during the day and 27 in the night (including dusk and dawn). Considering the children (0-14 years old), 7 were struck during the day and only 1 in the night.

Table 1. Descriptive Statistics for the Pedestrians in the Sample (N=54)

	N	Mean	Median	S.D.	Min	Max
Impact speed	54	48 km/h	46 km/h	18 km/h	14 km/h	100 km/h
Age	54	50 years	53 years	26 years	3 years	96 years
Height	36	165 cm	169 cm	19 cm	103 cm	190 cm
Weight	35	67 kg	71 kg	21 kg	17 kg	97 kg
Head WAD	37	190 cm	200 cm	43 cm	69 cm	270 cm
Car reg. year	53	1996	1995	5.5 years	1981	2006

PASSIVE COUNTERMEASURE: It was found that 48% (95% CI: 34-62%) of the pedestrians sustained all AIS3+ head injuries from impacts to car areas that would have been protected by the passive countermeasure. Of these, 58% were struck at impact speeds below 40 km/h. From equation (4), the effectiveness of the passive countermeasures was estimated to $\text{Eff}_{\text{passive}}$ = 34% (CI: 23-46%), see Figure 5. Thus, 34% of pedestrians with AIS3+ head injuries were estimated to sustain only AIS2- (AIS2 or lower) head injuries if all vehicles had been equipped with the passive countermeasure.

Observe that 31% (CI: 20-46%) of the pedestrians with AIS3+ head injuries sustained at least one of these injuries from the ground or other external or non-contact sources. These pedestrians were treated as not protected by the passive countermeasure and therefore served to decrease the estimated effectiveness.

ACTIVE COUNTERMEASURE: It was found that 67% (CI: 53-79%) of the pedestrians with AIS3+ head injuries were freely visible during the pre-crash phase, while the remaining 33% were obstructed from view by other vehicles, road furniture, buildings, trees or bushes. Note that GIDAS did not code the timing of the sight obstruction. Thus, some of the obstructed pedestrians may have been visible to the sensor at 1 s prior to crash, but they were still treated as obstructed from view in this study. From equation (5), the effectiveness of the active countermeasure was estimated to $\mathrm{Eff}_{\mathrm{active}}$ = 44% (CI: 34-53%), see Figure 5.

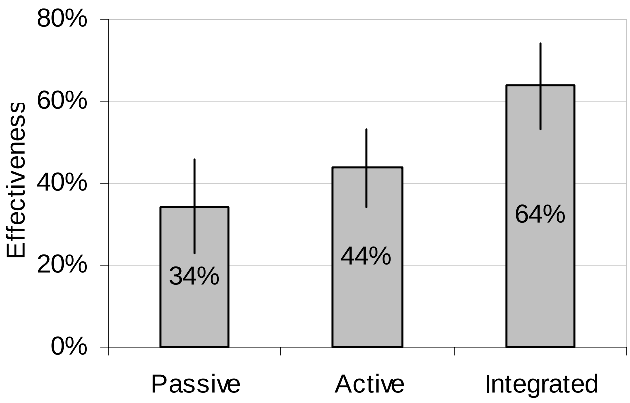

Figure 5. Effectiveness for the Passive, Active, and Integrated Countermeasures. (error bars give 95% confidence intervals)

INTEGRATED COUNTERMEASURE: The results of the linear regression analysis showed that the predicted head WAD increased by 0.49 cm for every km/h increase in car impact speed (see equation (A1)). Further results from the regression analysis are provided in Appendix A (Figure A 1, Figure A 2, and Table A 1). With this information available, new wrap around distances could be estimated after the implementation of the autonomous braking system.

Using the new wrap around distances and impact speeds together with equation (6), the effectiveness of the integrated countermeasure was estimated to $\mathrm{Eff}_{\mathrm{integrated}}$ = 64% (CI: 53-74%), see Figure 5.

The ratio of the integrated and passive countermeasures was $\mathrm{Eff}_{\mathrm{integrated}}/\mathrm{Eff}_{\mathrm{passive}}$=1.9 (CI: 1.5-2.5) and the ratio of the integrated and active countermeasures was $\mathrm{Eff}_{\mathrm{integrated}}/\mathrm{Eff}_{\mathrm{active}}$=1.5 (CI: 1.3-1.7). Thus, the effectiveness of the integrated countermeasure was significantly higher than either of the passive and active countermeasures alone. (See also the sensitivity study in Appendix C.)

If the active and passive countermeasures were independent of each other, their combined effectiveness should fulfill the following relation

$$\mathrm{Eff}_{\mathrm{integrated}}^{\mathrm{theory}} = 1 - \left(1 - \mathrm{Eff}_{\mathrm{active}}\right)\left(1 - \mathrm{Eff}_{\mathrm{passive}}\right) = 63\% . \tag{8}$$

It is important to notice that one can not simply add the effectiveness of the passive and active systems, which indeed could generate results exceeding 100% if the contributing values were large enough. Equation (8) is intuitively clear, since if the passive countermeasure has an effectiveness of $\mathrm{Eff}_{\mathrm{passive}}$ = 34%, the new number of injured would be $N' = \left(1 - \mathrm{Eff}_{\mathrm{passive}}\right)N = 0.66N$. Hence, 66% would still be injured. If the active countermeasure has an effectiveness of $\mathrm{Eff}_{\mathrm{active}}$ = 44%, it would save 44% of the remaining casualties, thus leaving 56% of the 0.66N injured, which becomes $N' = 0.56 \cdot 0.66N = 0.37N$. The case-by-case analysis yielded an empirical estimate of $\mathrm{Eff}_{\mathrm{integrated}}$ =64%, which is close to the theoretical estimate of $\mathrm{Eff}_{\mathrm{integrated}}^{\mathrm{theory}} = 63\%$ assuming independent systems. (See also the sensitivity study in Appendix C.) This does not imply that the two countermeasures are independent of each other, but that the positive and negative interaction effects counterbalance each other.

DISCUSSION

This study considered hypothetical passive and active countermeasures for pedestrian head protection. Both systems were ideal in the sense that that the passive system had a protection level of 100% up to 40 km/h for pedestrians striking the protected areas of the car (see the protection level function $e(v)$ in Figure 2), whereas the sensor of the active system detected all visible pedestrians in all weather and light conditions within a 180° field of view. Further, the linear decrease of the effect of the passive system above 40 km/h may be too simplified. These assumptions were made to facilitate a simple investigation of the incremental benefit of an integrated system compared to either an isolated passive or active countermeasure. It is easily realized that the effect of the passive system can be studied by altering the protection level function $e(v)$; if $e(v)$ is multiplied by some positive factor $c \leq 1$, the total effectiveness changes by the same factor (from 34% to $c \cdot 34\%$). This means, e.g., that a maximum protection level of 50% would provide a total effectiveness of 17% for the passive countermeasure.

For practical reasons, the sensor of the active countermeasure had a 180° field of view. Actual autonomous braking systems will likely have substantially smaller fields of view. However, we note that Rosén et al. (2009) have shown that the potential fatality reduction of an autonomous braking system only decreased from 44% to 40% when the field of view decreased from 180° to 40° and the estimated reduction of severely injured decreased from 33% to 27%. The careful reader may notice that the effectiveness of severe head injury reduction calculated in this study ($\mathrm{Eff}_{\mathrm{active}}$ = 44%) differs from the effectiveness of severe injury reduction calculated by Rosén et al. (2009) (Eff = 33%). The two systems were identical and one may therefore expect the effectiveness to be the same in the two studies. For that reason we note that this study considered only the head whereas Rosén et al. considered the whole body. Furthermore, due to the finite sample sizes, there are uncertainties related to both estimates (see e.g. the confidence intervals in Figure 5).

The passive countermeasure in this study was based on a system designed for NCAP tests with additional protection for the A-pillars. It was proposed by Fredriksson et al. (2010) that such a system would protect many head injured pedestrians but still be limited in size. It is interesting to compare this with a system designed only for legal requirements. This requires protection of the bonnet area only to a WAD of 2100 mm (2.1 m). The same calculation as for the larger system resulted in an effectiveness of 5%. In the same way, a system covering the complete bonnet and windscreen area (including A-pillars and roof front edge) provided a total effectiveness of 41%.

In this study, 31% of pedestrians with severe head injuries received at least one of these injuries from impacts to the ground or other objects than the car. These pedestrians were treated as unprotected by the passive countermeasures, which served to considerably decrease its effectiveness. It is sometimes very difficult to determine whether an injury was caused by the car or surroundings, which results in varying figures in different studies. Studies using US or German data, for different severity levels (AIS1+ to AIS3+), indicated that 17-31% of all pedestrian injuries were caused by ground impacts (Fredriksson et al. 2010, Liers, 2009, Otte and Pohlemann, 2001, Zhang et al., 2008). Roudsari et al. (2005) studied individual body regions (of all severities; AIS1+) and reported that 7% of head injuries were caused by ground impact.

In this study, the effectiveness of a countermeasure was defined as the expected reduction of pedestrians with severe head injuries in Germany during the past ten years if all cars had been equipped with the countermeasure. Furthermore, it was assumed that the countermeasure would not cause severe head injuries to pedestrians that originally did not sustain such injuries. We then showed that the effectiveness could be estimated considering only pedestrians with severe head injuries. This conclusion is likely to hold under more general circumstances as well. Finally, it was argued that the GIDAS database comprised an appropriate sample of such pedestrian casualties.

LIMITATIONS: This study considered only one type of active countermeasure, namely autonomous braking. The conclusions cannot be directly generalized to other countermeasures, such as warning systems.

The selected population in Germany resulted in a selection consisting mainly of passenger cars. This changes the car distribution especially in relation to North America, which has a larger share of sport utility vehicles (SUVs). Further, the typical size of a passenger car in northern Europe is larger than in Asia and developing countries. This could influence the distribution of injuries to the bonnet and windscreen areas, since smaller cars are likely to cause more injuries from the windscreen area compared to the bonnet, while SUVs are likely to cause more head injuries in the bonnet area. To conclude, this limits the possibility of generalising our results to other countries.

CONCLUSIONS

Autonomous braking, which has a high potential on its own, would benefit greatly from the addition of passive countermeasures for the bonnet, A-pillars, and lower windscreen areas, and vice versa. Since the exact specifications of the passive and active countermeasures in this study were hypothetical, the absolute quantitative results should be taken only as indicative. To conclude, the study shows that integrated systems combining passive and active pedestrian countermeasures offer a considerably increased potential for head injury reduction compared to either of the two systems alone.

REFERENCES

Bockholdt, B. & Schneider, V. 2003. The injury pattern to children involved in lethal traffic accidents in Berlin. *Leg Med (Tokyo),* 5 Suppl 1, S390-2.

Efron, B. & Tibshirani, R. J. (eds.) 1993. *An introduction to the bootstrap*: Chapman & Hall/CRC.

Ehrlich, E., Tischer, A. & Maxeiner, H. 2009. Lethal pedestrian - Passenger car collisions in Berlin Changed injury patterns in two different time intervals. *Leg Med (Tokyo),* 2, 2.

EU 2009. REGULATION (EC) No 78/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 January 2009 on the type-approval of motor vehicles with regard to the protection of pedestrians and other vulnerable road users, amending Directive 2007/46/EC and repealing Directives 2003/102/EC and 2005/66/EC. *In:* UNION, T. E. P. A. T. C. O. T. E. (ed.). Strasbourg: Official Journal of the European Union.

Fredriksson, R., Håland, Y. & Yang, J. 2001. Evaluation of a New Pedestrian Head Injury Protection System with a Sensor in the Bumper and Lifting of the Bonnet's Rear Part. *Proceedings of 17th ESV Conference.* Amsterdam, Netherlands.

Fredriksson, R., Rosén, E. & Kullgren, A. 2010. Priorities of pedestrian protection--A real-life study of severe injuries and car sources. *Accident Analysis & Prevention*, In Press, Corrected Proof.

Ivarsson, B., Crandall, J., Fredriksson, R., Burke, C., Stadter, G. & Fakhry, S. 2003. Pedestrian head impact – what determines the likelihood and location? *Proceedings of 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Lyon, France.

Kerrigan, J. R., Crandall, J. R. & Deng, B. 2007. Pedestrian kinematic response to mid-sized vehicle impact. *International Journal of Vehicle Safety,* 2, 221-240.

Liers, H. 2009. Benefit estimation of the Euro NCAP pedestrian rating concerning real world pedestrian safety. *21st International Technical Conference on the Enhanced Safety of Vehicles*, Stuttgart, Germany.

Longhitano, D., Henary, B., Bhalla, K., Ivarsson, J. & Crandall, J. 2005. Influence of vehicle body type on pedestrian injury distribution. *SAE*. Detroit, Michigan, USA.

Maki, T., Asai, T. & Kajzer, J. 2003a. Development of future pedestrian protection technologies *Proceedings of 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Nagoya, Japan.

Maki, T., Kajzer, J., Mizuno, K. & Sekine, Y. 2003b. Comparative analysis of vehicle-bicyclist and vehicle-pedestrian accidents in Japan. *Accid Anal Prev,* 35, 927-40.

Nagatomi, K., Hanayama, K., Ishizaki, T. & Sasaki, S. 2005. Development and full-scale dummy tests of a pop-up hood system for pedestrian protection. *Proceedings of 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Washington D.C., USA.

Oh, C., Kang, Y. & Kim, W. 2008. Assessing the safety benefits of an advanced vehicular technology for protecting pedestrians. *Accident Analysis and Prevention,* 40, 935-942.

Otte, D. & Pohlemann, T. 2001. Analysis and load assessment of secondary impact to adult pedestrians after car collisions on roads. *Proceedings of IRCOBI Conference,* Isle of Man. 143-157.

Otte, D., Krettek, C., Brunner, H. & Zwipp, H. 2003. Scientific approach and methodology of a new in-depth investigation study in Germany so called GIDAS. *Proceedings of 18th International Technical Conference on the Enhanced Safety of Vehicles.* Nagoya, Japan.

Pinecki, C. & Zeitouni, R. 2007. Technical solutions for enhancing the pedestrian protection. *Proceedings of 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Lyon, France.

Rosén, E., Källhammer, J.-E., Eriksson, D., Nentwich, M., Fredriksson, R. & Smith, K. 2009. Pedestrian injury mitigation by autonomous braking.*Proceedings of 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Stuttgart, Germany.

Rosén, E. & Sander, U. 2009. Pedestrian fatality risk as a function of car impact speed. *Accid Anal Prev,* 41, 536-42.

Roudsari, B. S., Mock, C. N. & Kaufman, R. 2005. An Evaluation of the Association Between Vehicle Type and the Source and Severity of Pedestrian Injuries. *Traffic Injury Prevention,* 6, 185 - 192.

Subit, D., Kerrigan, J., Crandall, J., Fukuyama, K., Yamazaki, K., Kamiji, K. & Yasuki, T. 2008. Pedestrian-vehicle interaction: kinematics and injury analysis of four full-scale tests. *Proceedings of IRCOBI Conference.* Bern Switzerland.

Yao, J., Yang, J. & Otte, D. 2007. Head injuries in child pedestrian accidents--in-depth case analysis and reconstructions. *Traffic Inj Prev,* 8, 94-100.

Zhang, G., Cao, L., Hu, J. & Yang, K. H. 2008. A field data analysis of risk factors affecting the injury risks in vehicle-to-pedestrian crashes. *Annu Proc Assoc Adv Automot Med.*

APPENDIX A - WAD AS FUNCTION OF SPEED AND HEIGHT

The results from the linear regression analysis for head WAD as a function of car impact speed and pedestrian height are provided in equation (A1), Table A1, and Figures A1-A2. Note that adjusted R-square=0.22. Furthermore, equation (A1) holds only for pedestrians taller than 140 cm.

$$\mathrm{WAD}_{\mathrm{model}}(v,h) = -28 + 0.49v + 1.2h\,, \tag{A1}$$

where the WAD and pedestrian height, *h*, are given in cm and the car impact speed, *v*, in km/h.

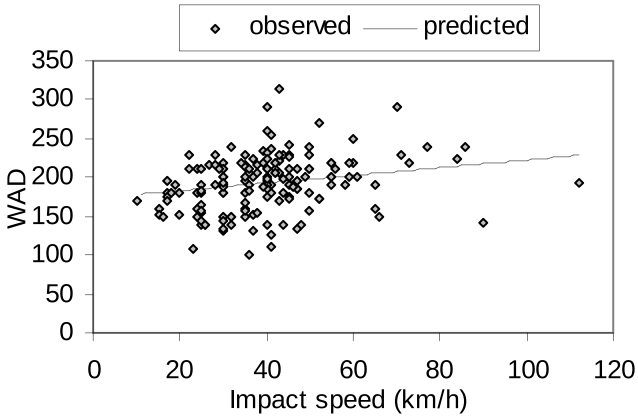

Figure A 1. Observed and Predicted Head WAD vs. Car Impact Speed

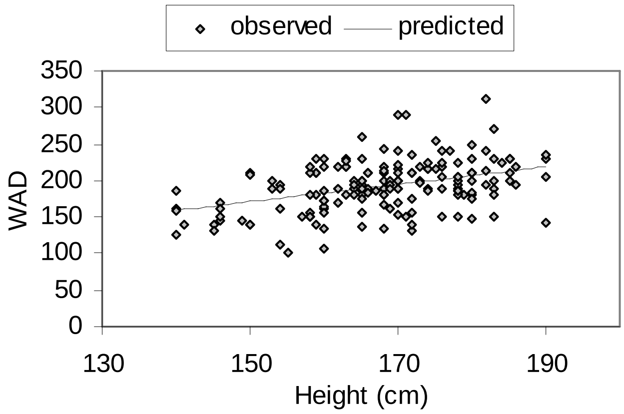

Figure A 2. Observed and Predicted Head WAD vs. Pedestrian Body Height

Table A 1. Parameter Estimates From the Linear Regression Analysis of Head WAD

	Estimate	S.E.	P-value
Intercept, a	-28	36	0.43
Impact speed, b_v	0.49	0.16	0.0027
Height, b_h	1.2	0.22	<0.0001

APPENDIX B - THEORY BEHIND EFFECTIVENESS

Let us rewrite the sum in equation (2) by aggregating on each integer value of impact speed, v = 1, 2, 3,… At each impact speed, v, there was $I(v)$ injured pedestrians, so that $\sum_{v=1}^{\infty} I(v) = N$, where N is the total number pedestrians with AIS3+ head injuries that were struck by the front of a car in Germany from 1999 to 2008. Note that $I(v)$ was zero for some impact speeds, in particular for small and very large values of v. (It is e.g. hard to believe that any pedestrians were struck at impact speeds exceeding 300 km/h. Thus $I(v)$=0 for v greater than 300 km/h.) We may refer to $I(v)/N$ as the incidence distribution of crashes, since $\sum_{v=1}^{\infty} I(v)/N = 1$. It is now fairly easy to see that the formula for effectiveness in equation (2) equals

$$\text{Eff} = \sum_{v=0}^{\infty} \left(1 - \frac{p'(v)}{p(v)} \right) \frac{I(v)}{N}, \tag{B1}$$

where $p'(v)$ and $p(v)$ are the average injury risks at impact speed v with and without the countermeasure. We may refer to the quantity $1 - p'(v)/p(v)$ as the local effectiveness (or risk reduction) at impact speed v. The total effectiveness can then be interpreted as the expectation value of the local effectiveness averaged over all impact speeds with probability density function $I(v)/N$:

$$\text{Eff} = E\left(1 - \frac{p'(v)}{p(v)} \right). \tag{B2}$$

It is straight forward to pass to continuous v by exchanging the sum in equation (B1) for an integral as

$$\text{Eff} = \int_0^{\infty} \left(1 - \frac{p'(v)}{p(v)} \right) \frac{I(v)}{N} dv , \tag{B3}$$

which still carries the interpretation of an expectation value of the local effectiveness $1 - p'(v)/p(v)$ with probability density function $I(v)/N$.

APPENDIX C – SENSITIVITY ANALYSIS

Table C1 shows how moderate variations of some input parameters influenced the effectiveness of the passive, active, and integrated countermeasures, respectively. The theoretical effectiveness of the integrated countermeasure was re-calculated for each variation (assuming independence of the passive and active countermeasures, see equation (8)). Finally, confidence intervals of the ratios $\text{Eff}_{\text{integrated}}/\text{Eff}_{\text{passive}}$, $\text{Eff}_{\text{integrated}}/\text{Eff}_{\text{active}}$ were calculated using a bootstrap analysis. For the active countermeasure, the brake initiation time and maximum brake deceleration were varied. For the passive countermeasure, the maximum protection level and end point of the function e(v) were varied (see Figure 2). Table C1 clearly shows that the effectiveness of the integrated countermeasure was close to the theoretical effectiveness in all cases. Furthermore, the ratios $\text{Eff}_{\text{integrated}}/\text{Eff}_{\text{passive}}$, $\text{Eff}_{\text{integrated}}/\text{Eff}_{\text{active}}$ were significantly greater than 1 in all cases.

Table C 1. Results from the Sensitivity Analysis (numbers within parentheses are 95% CI)

		E_{pass}	E_{act}	E_{integ}	$E_{int\ th}$	E_{int}/E_{pass}	E_{int}/E_{act}
Baseline effectiveness (%)		**34%**	**44%**	**64%**	**63**%	**1.9 (1.5-2.5)**	**1.5 (1.3-1.7)**
Active countermeasure parameters							
Braking initiation time (1 s)	-0.2 s	*34%*	33%	58%	56%	1.7 (1.4-2.2)	1.8 (1.5-2.3)
	+0.2g	*34%*	55%	69%	70%	2.0 (1.6-2.8)	1.3 (1.1-1.4)
Braking deceleration (0.6g)	-0.2g	*34%*	28%	55%	52%	1.6 (1.3-2.1)	2.0 (1.6-2.5)
Passive countermeasure parameters							
Max protection level (100%)	-20%	28%	*44%*	60%	60%	2.1 (1.7-3.0)	1.4 (1.2-1.6)
	+20 km/h	39%	*44%*	65%	66%	1.7 (1.4-2.2)	1.5 (1.3-1.8)
e(v) end point (70 km/h)	-20 km/h	24%	*44%*	62%	57%	2.6 (1.9-4.2)	1.4 (1.2-1.7)