# INTEGRATED BICYCLIST PROTECTION SYSTEMS - POTENTIAL OF HEAD INJURY REDUCTION COMBINING PASSIVE AND ACTIVE PROTECTION SYSTEMS

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Paper Number 15-0051

## ABSTRACT

In recent years both pedestrian passive and active safety systems, such as pedestrian bonnets/airbags and autonomous braking, have emerged on the market and are estimated to be effective to reduce injury of vulnerable road users in car crashes. A natural next step is to develop similar protection systems for bicyclists. The aim of this study was to investigate the potential bicyclist head injury reduction from passive and active protection systems compared to an integrated system.

The German In-Depth Accident Study (GIDAS) database was queried from 1999 to 2014 for severely (AIS3+) head injured bicyclists when struck by passenger car fronts. This resulted in 34 cases where information was sufficient for both the pre-crash and the in-crash part of the event. The default passive protection system was designed to mitigate head injuries caused by the bonnet area, A-pillars, and the lower windscreen (instrument panel) area (deployable hood and windshield airbag). To estimate the hood and airbag performance risk reduction functions were used based on experimental tests with and without the systems. The active protection system was an autonomous braking system, which was activated one second prior to impact if the bicyclist was visible to a forward-looking sensor. Maximum speed reduction was estimated using road condition information in each case. 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. For the integrated system, the influence of the active system on the passive system performance was explicitly modelled in each case. A sensitivity analysis was performed varying the coverage area of the passive protection system and the activation criteria of the active system.

The integrated system resulted in 29%-62% higher effectiveness than the best single system of active respectively passive protection system in reducing the number of bicyclists sustaining severe (AIS3+) head injuries. These values were statistically tested and found to be significant. The study is based on representative data from Germany, but may not be representative to countries with a different car fleet or infrastructure. This study indicates that integrated systems of passive and active vulnerable road user countermeasures offer a significantly increased potential for head injury reduction compared to either of the two systems alone.

## INTRODUCTION

World-wide it is estimated that over 500 000 pedestrians and bicyclists are killed annually in road traffic (Naci, Chisholm et al. 2009). Virtually all road pedestrian fatalities and a majority of the cyclist road fatalities are caused by crashes with vehicles (SIKA 2009). In larger European cities, bicycle transportation is increasing (Thiemann-Linden 2010), likely due to congestion, fuel prices and an increasing awareness of its health benefits. Pedestrians and bicyclists already make up roughly half the traffic fatalities in urban areas in the EU (ERSO 2012), risking fatalities to increase with increased bicycle use.

In research studies pedestrians have been the dominant subject group. Legal regulations as well as consumer rating tests for pedestrians have influenced car design during the last decade in Europe and Japan. Cars on these markets are now often equipped with energy absorbing bumpers and hoods, as well as deployable hoods. Furthermore, airbags for the windshield area, attempting to mitigate head injury have been introduced (Volvo 2012; Jaguar-LandRover 2014). Pedestrian passive countermeasures have proven effective in reducing pedestrian injury. Strandroth et al. (2014) showed, in a study on Swedish accidents, that cars with higher pedestrian ratings in EuroNCAP consumer tests resulted in less severe injuries. A natural next step is to design the airbag to protect also for bicyclists. The major difference between pedestrians and bicyclists is the higher head impact point of bicyclists on the car (Fredriksson, Bylund et al. 2012; Fredriksson and Rosén 2012). Fredriksson et al (2014) showed a potential protection system with a higher protection area designed to protect both pedestrians and bicyclists. Another way to reduce injury is to reduce impact speed, where even moderate speed reductions can significantly decrease risk for the vulnerable road user in an impact. For example, Rosén and Sander 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% (2009). Currently, active systems such as autonomous braking are being rapidly introduced on the market. 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 and bicyclist crashes (Rosén, Källhammer et al. 2010; Rosén 2013). In 2016 EuroNCAP begins assessing autonomous emergency braking (AEB) or warning for pedestrians (EuroNCAP 2014), and in 2018 it is planned to begin testing active systems also for bicyclists.

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? In an earlier study it was shown beneficial for pedestrians to combine active and passive systems regarding injury reduction potential.

The aim of this study was, therefore, to investigate the potential reduction of bicyclists sustaining severe head injury from either a passive (in-crash) or active (pre-crash) 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 limitations in estimating real-life benefits, and the connection between selected injury criteria and pedestrian head injury risk has not been thoroughly investigated. 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 three systems to reduce head injury of bicyclists 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, windshield frame 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 bicyclist 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. This method was developed in an earlier study estimating effectiveness of pedestrian protection systems (Fredriksson and Rosén 2014).

We estimated the potential of these systems to reduce severe (AIS3+) head injury. Note that a bicyclist may sustain multiple severe head injuries from different impacts to the car, ground and other external objects in the same crash. In this study, bicyclists that sustained at least one of the 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 bicyclists 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 bicyclist was severely (AIS3+) head injured when impacted by the car front. The database consisted of 4789 cases with bicyclists injured when struck by passenger cars between 1999-2014. 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 34 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 34 cases.

### Passive protection system

**Head impact speed** The head impact speed was, just like in the previous pedestrian study, assumed to be equal to the car impact speed. For pedestrians studies have shown head impact speeds both higher and lower than the car impact speed, ranging from 68%-146% in car-to-pedestrian post mortem human subject (PMHS) 40 km/h tests (Masson, Serre et al. 2007; Kerrigan, Crandall et al. 2008; Kerrigan, Arregui et al. 2009). For bicyclists no PMHS tests have been performed. Limited full-scale crash tests with the Polar II dummy showed head/car impact speed ratios of 87%-147% (van Schijndel, de Hair et al. 2012). Therefore the assumption that head impact speed was equal to car impact speed was made also in this study.

**Deployable hood system** The deployable hood performance was estimated in a previous study (Fredriksson and Rosén 2014) based on a study with headform tests at 40 km/h (Fredriksson, Håland et al. 2001) using a method by Searson et al (2012) to estimate performance at other impact speeds. Five different impact points were chosen distributed on the hood surface. The estimated HIC values for the reference hood and version 1 deployable hood was based on these tests. 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). The HIC values were used to calculate risk of AIS3+ head injury for the reference configuration and the active hood systems (Fredriksson and Rosén 2014).

**Windshield airbag** The airbag performance was also estimated in the previous study using the headform test method of Euro NCAP but varying the headform impact speed from 20-60 km/h for two different impact points (Fredriksson and Rosén 2014). 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. The tests were performed on a small family car in the standard condition as well as equipped with the windshield airbags as in Figure 1. 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 (Fredriksson and Rosén 2014).

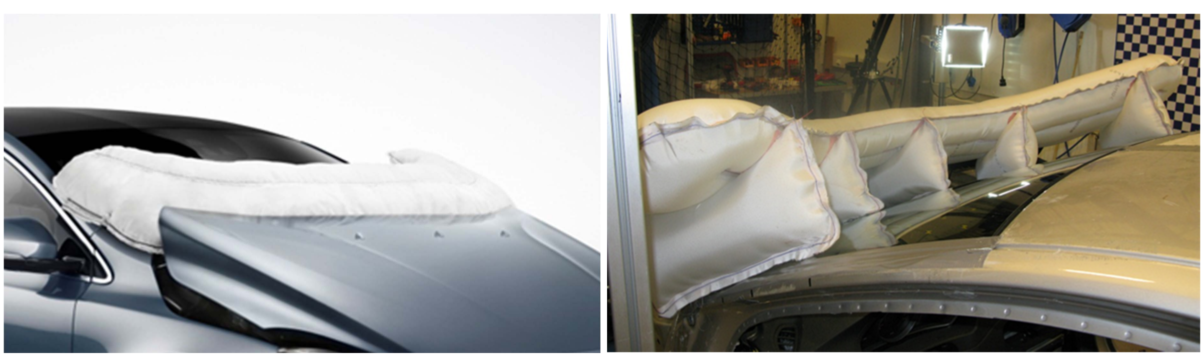

***Figure 1. Pedestrian airbags used in the headform tests in the previous study to estimate airbag performance, left: version 1 airbag, right: version 2 airbag (Fredriksson and Rosén 2014)***

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 for System 1 and 2. In System 3, version 2 airbag was extended to protect also in the area of the roof front edge. See Table 1. 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.

**Table 1. Deployable system parameters for the three versions used in the study**

| ***Deployable system parameters*** | ***System 1*** | ***System 2*** | ***System 3*** |
|---|---|---|---|
| Hood lifter | Version 1 | **Version 2** | Version 2 |
| Airbag design | Version 1 | **Version 2** | Version 2 |
| Coverage area | Hood | Hood | Hood |
| | Low WS | Low WS | Low WS |
| | A-pillars | A-pillars | A-pillars |
| | | | **Roof front edge** |

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 (1995). The risk reduction was then calculated (Fredriksson and Rosén 2014).

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 risk reduction potential in that case was set to 0. Also, for both systems, activation was limited to a minimum speed of 20 km/h.

**Risk reduction functions** In the earlier study (Fredriksson and Rosén 2014) risk reduction functions were developed for the two protection systems, deployable hood and windshield airbag (Figure 2). 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.

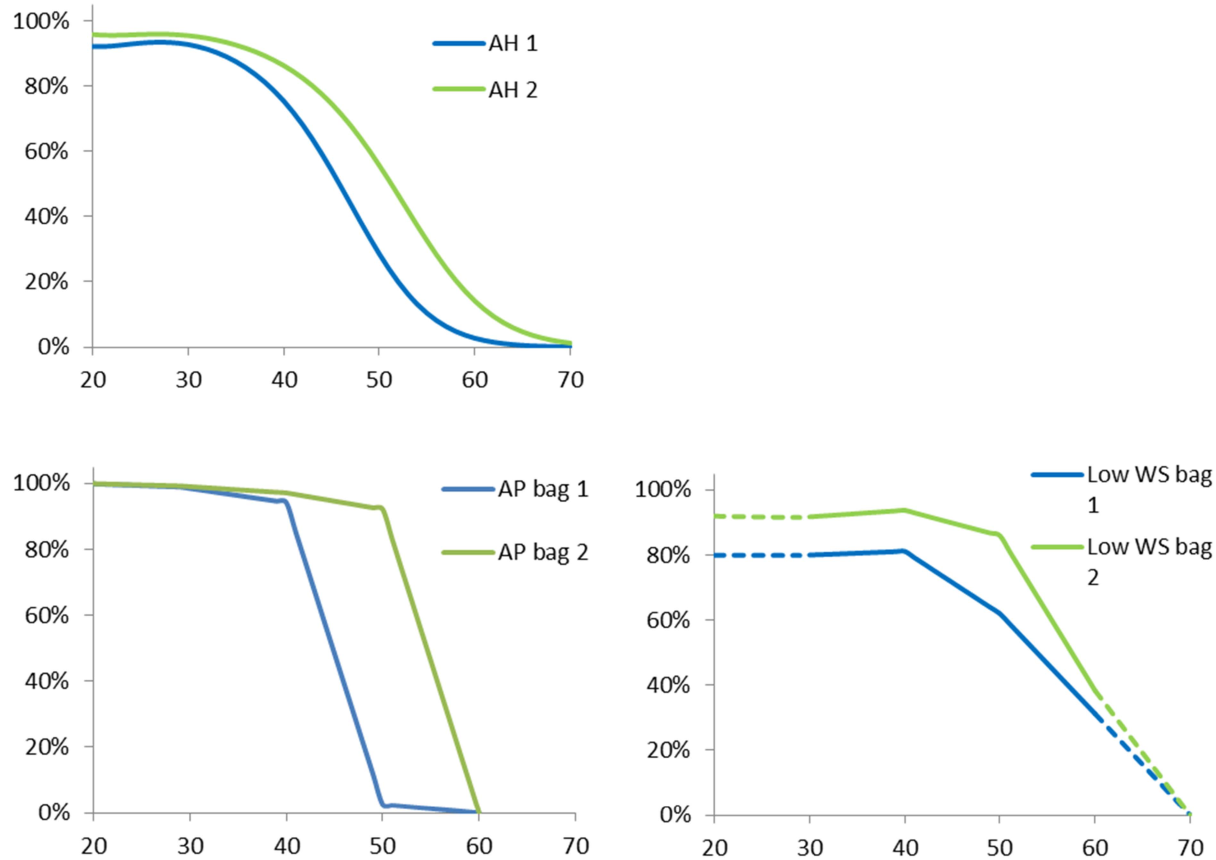


***Figure 2. Head AIS3+ injury risk reduction for active hood average (top) and windshield airbag (below) for two impact locations; A-pillar (left) and lower windshield (right)***

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 could be calculated as:

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

The rationale behind this effectiveness calculation method is described in more detail in a previous study (Fredriksson and Rosén 2012).

**Active protection system**

The active (AEB) system was estimated to detect all visible bicyclists within the field of view independent of weather and light conditions, and activate automatically the brakes 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: sensor field of view, trig width and cut-off speed for activation; the system was activated for bicyclists within the vehicle path or up to 1.0 or 3.0 m beside it (trig width), either up to 60 km/h or at all impact speeds, and during all light conditions (see Table 2). For further details on the AEB system, see earlier study by Rosén (2013).

**Table 2. AEB parameters for the three versions used in the study (in bold parameters that are varied)**

| *AEB parameters* | *System 1* | *System 2* | *System 3* |
|---|---|---|---|
| Field of view | 40° | 40° | **60°** |
| TTC max | 1.0 s | 1.0 s | 1.0 s |
| Trig width | 1 m | 1 m | **3 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 | **No limitation** | No limitation |
| Light conditions | All | All | All |

In order to derive injury risk functions for AIS3+ head injury, logistic regression analysis was conducted following Rosén and Sander (2009). The risk as a function of impact speed, p($v$), was assumed to have the following form (logistic regression) p($v$) = 1/(1 + exp(– a – b$v$)), where $v$ is the impact speed and a, b two parameters to be estimated by the method of maximum likelihood.

A bicyclist 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 so

$$E_{active}^{total} = \frac{1}{N}\sum_{i=1}^{N} 1 - \frac{1 + \exp(-a - bv_i)}{1 + \exp(-a - bv'_i)} \tag{2}$$

**Integrated protection 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 bicyclist 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 (lowering) of the car front which results in increased sliding. This was considered in a previous study for pedestrians and these two effects more or less cancelled each other out and resulted in no total effect for pedestrians. We do not have this information for bicyclists so for simplicity we decided not to adjust the impact point for braking in this study.

A bicyclist that would have been helped only by the passive countermeasure has a relative risk of $1-e(v)$. A bicyclist that would have been helped only by the active countermeasure has a relative risk of $\left(1+\exp(-a-bv)\right)/\left(1+\exp(-a-bv')\right)$. Finally, a bicyclist that would have been helped by both countermeasures has a relative risk of $\left(1-e(v')\right)\left(1+\exp(-a-bv)\right)/\left(1+\exp(-a-bv')\right)$. Putting the pieces together, we get

$$E_{integrated}^{total} = \frac{1}{N}\sum_{i=1}^{N}\left(1-(1-e(v_i'))\frac{1+\exp(-a-bv_i)}{1+\exp(-a-bv'_i)}\right) \qquad (3)$$

where $v_i' = v_i$ if the active countermeasure is not used and $e(v_i') = 0$ if the passive countermeasure is not helping. See also earlier study by Fredriksson & Rosén (2012) for more details and derivation of the effectiveness functions.

**Statistical methods**

To derive confidence intervals for the estimated effectiveness, we applied the bootstrap method (Efron and Tibshirani 1993). In this procedure, the original sample of 34 cases was used to generate another 1000 samples, each containing 34 cases, by random re-sampling with replacement from the 34 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 25$^{th}$ 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 2.5$^{th}$ and 97.5th percentiles of the 1000 bootstrap estimates.

**RESULTS**

In total we had 34 cases with sufficient information to estimate both passive and active protection potential. The bicyclists, who had no limitation on age, were on average 48 years old with a body height of 169 cm, and the car mean model year was 1996. Note that information on stature and model year was not available for all cases. The impact speed for the 34 cases, which were all AIS3+ head injured when impacted by a passenger car front, ranged from 12-91 km/h, with a mean value of 43 km/h (Table 3). 8 of the 34 bicyclists were fatally injured. GIDAS does not conclude what injury was fatal.

**Table 3. Descriptive statistics for the bicyclists in the sample (N = 34)**

| | *mean* | *median* | *min* | *max* | *n* |
|---|---|---|---|---|---|
| age (years) | 48 | 55 | 13 | 81 | 34 |
| stature (cm) | 169 | 171 | 107 | 191 | 28 |
| car model year | 1996 | 1996 | 1986 | 2011 | 33 |
| car impact speed (km/h) | 43 | 38 | 12 | 91 | 34 |

In 1 of the 34 cases (3%) the bicyclist was severely head injured by the hood area alone, 6% from the lower windshield / I-panel area alone, 21% from the A-pillars alone, 24% from the roof edge alone, 9% from the remaining glass area alone, while 3% had at least one severe head injury from other parts of the car and 35% from the ground/surrounding. See Figure 3. This means that the passive system can potentially address all AIS3+ head injuries for 29% of the bicyclists for the system 1&2 protection systems and 53% for the more advanced system covering also the roof edge (system 3).

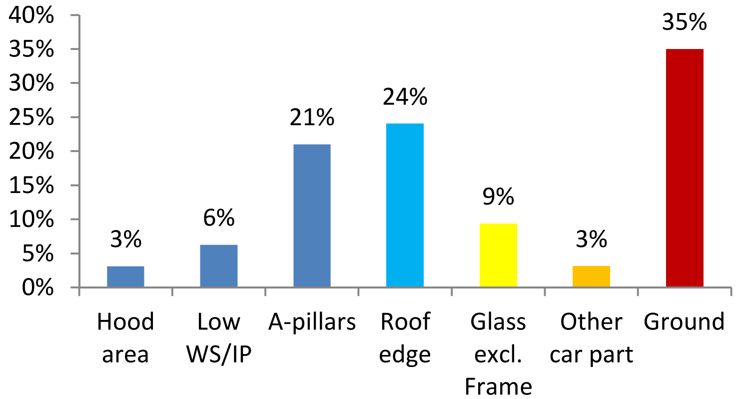


***Figure 3. Distribution of injury sources (all AIS3+ head injuries for an injured bicyclist caused by the given area, except for "other" where only one injury from this area is sufficient to classify as "other")***

The risk curve for AIS3+ bicyclist head injury was developed, see Figure 4. It shows the observed rates of AIS3+ head injured bicyclists at different intervals of impact speed and the best-fit logistic regression curves. The risk of severe (AIS3+) head injury is given in the function, $p(v) = 1/(1+\exp(6.1-0.080v))$.

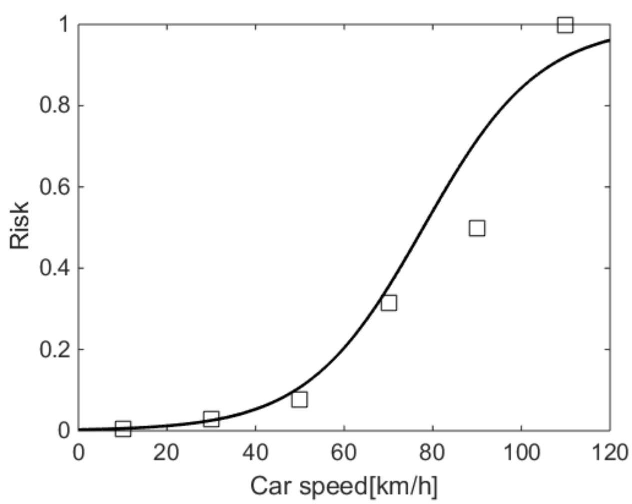


***Figure 4. AIS3+ head injury risk for bicyclists impacted by passenger cars, and the corresponding empirical injury rates***

Hence, the total effectiveness for active systems becomes:

$$E_{active}^{total} = \frac{1}{N}\sum_{i=1}^{N} 1 - \frac{1 + \exp(6.1 - 0.080v_i)}{1 + \exp(6.1 - 0.080v'_i)} \tag{4}$$

and for integrated systems:

$$E_{integrated}^{total} = \frac{1}{N}\sum_{i=1}^{N}(1 - (1 - e(v_i'))\frac{1+\exp(6.1-0.080v_i)}{1+\exp(6.1-0.080v'_i)}) \tag{5}$$

**Estimated effectiveness**

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 34 cases was summarized. The passive protection system, based on a deployable hood and a windshield airbag, was estimated in the baseline version to protect 21% of the severely head injured bicyclists from their AIS3+ head injury (system 1); that is, the AIS3+ head injury effectiveness was estimated to be 21% (CI: 10-34%). For system 2, with a different airbag design protecting better at higher speeds, but with the same coverage area, the effectiveness increased to 28% (CI: 14-45%). Finally if the passive system coverage area was increased to also protect the roof edge (system 3), the effectiveness increased to 38% (CI: 24-54%).

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 bicyclist visibility) and maximum braking level allowed depending on the road friction condition.

The AEB system was estimated to protect 26% (CI: 14-38%) with the baseline version (system 1), activated up to 60 km/h with the 40 degree field of view sensor and narrow trig width. When the active system was enhanced to activate for bicyclists in all impact speeds (system 2), the effectiveness increased to 30% (CI: 15-43%). Finally, if the system was enhanced further to activate also at a higher field of view and trig width (system 3), it could potentially save 48% (CI: 32-63%) of the bicyclists from their severe head injury.

By combining the passive and active protection systems a system is created that first brakes the car autonomously when a bicyclist 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 38% (CI: 24-52%). The more advanced system, with version 2 passive and active systems, increased the effectiveness to 48% (CI: 32-64%), while the most advanced system, with version 3 passive and version systems, resulted in an integrated effectiveness of 62% (CI: 47-76%) (see Figure 5). The integrated systems had 29%-62% higher effectiveness than the best individual systems.

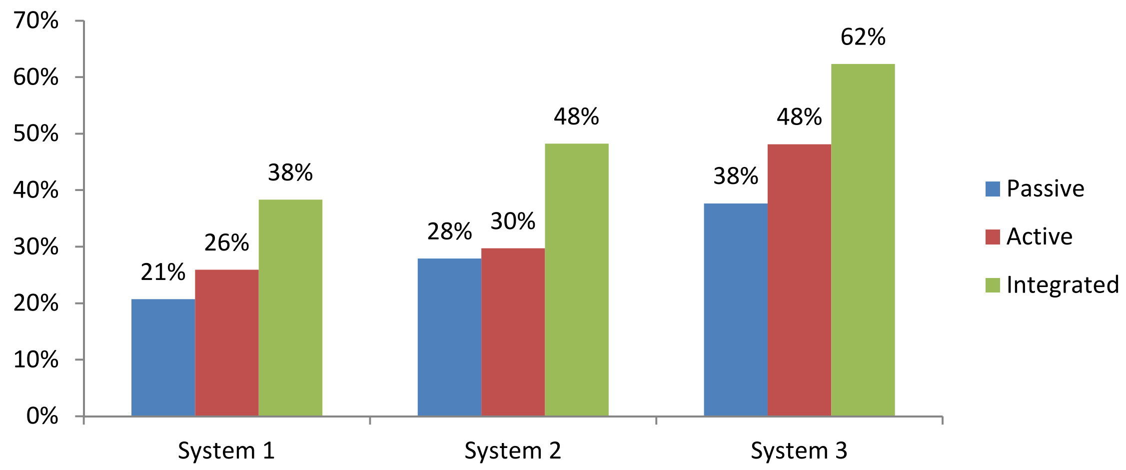


***Figure 5. Estimated effectiveness of the active, passive and integrated systems for three different combinations***

**Significance estimation** The ratios of the integrated and passive respectively active countermeasures were calculated, see Table 4. In all cases, the confidence intervals contained values constantly larger than 1. Thus, the effectiveness of the integrated countermeasures was significantly higher than either of the passive and active countermeasures alone.

**Table 4. Significance calculations of integrated effectiveness relative to active and passive effectiveness**

| | $E_{integrated}/E_{passive}$ (95% CI) | $E_{integrated}/E_{active}$ (95% CI) |
|---|---|---|
| Version 1 | 1.9 (1.2-3.2) | 1.6 (1.2-2.3) |
| Version 2 | 1.8 (1.2-2.9) | 1.7 (1.2-2.7) |
| Version 3 | 1.7 (1.2-2.5) | 1.3 (1.1-1.7) |

## DISCUSSION

Just like in the earlier study on pedestrians we made the assumption that head impact speed was equal to the car impact speed. Earlier studies on pedestrians and bicyclists have shown both higher and lower head impact speeds compared to the car impact speed. We also used the same passive risk curves for severe (AIS3+) head injury as in the previous study on pedestrians, since this is a risk curve based on HIC value, i.e. the loading that the head experiences, so it should not differ for different road users. However, the most important difference between pedestrians and bicyclists is the head impact point, the injury source on the car, and that was considered in this study.

For the active system we used a new risk curve since this is developed for the respective road user type and includes e.g. the difference in injury location. Here we assumed that the head impact point did not change however when an active protection system was introduced. This is a simplification, but as discussed in the method section, also this parameter could change in both directions. The decrease in impact speed by an auto-brake system is known to result in less sliding of the vulnerable road user on the car (less wrap around distance to head impact) but in the same time the pitch of the car front leads to more sliding (larger wrap around distance). Therefore the assumption was made that the head impact point was unchanged. In a future study this could potentially be studied in full-body simulations with a human body model, but then very precise information about the accident, pedestrian direction, exact gait position, arm position, body angle etc is necessary which is often not known.

This study was performed using the same analysis method and data source as a previous study for pedestrians (Fredriksson and Rosén 2014). Bicyclist accidents are in one sense more challenging to the active sensor since bicyclists have a higher speed than pedestrians, but also to the passive system to some extent since bicyclists impact higher on the car. The current study on bicyclists accounted for this by increasing the field of view of the active sensor, and the coverage area of the passive systems for the most advanced system. But in the same time bicyclist accidents occur more frequently in day-light and dry conditions (Fredriksson, Bylund et al. 2012; Fredriksson and Rosén 2012) which increases the ability of especially the active sensor. These studies show that there is a benefit to combine active and passive protection for bicyclists as well as for pedestrians, which shows that that active and passive systems if designed right have the potential to protect both pedestrians and bicyclists in car crashes.

We performed this study using the probably most representative and extensive traffic injury database available. By doing so, and selecting the severely head injured bicyclists, we can estimate the effectiveness of reducing severe head injury of bicyclists with different countermeasures. (Note, that we make the assumption then that we do not raise the injury level for any person.) Although our estimations of the individual systems' effectiveness could be argued to be somewhat ideal (we estimate that the passive sensor activates for all crashes and that the active sensor has no other limitations than the parameters we chose), we made the same assumptions/simplifications for the integrated as for the individual systems so the conclusions of the benefit of the integrated system compared to the individual systems should therefore be sound.

### Limitations

The data which this study is based on is from Germany, and the conclusions are therefore not valid for countries where the car fleet or infrastructure is different.

## CONCLUSIONS

This study analyzed the benefit of combining car-mounted passive and active protection systems for bicyclists. If more and more cars in Europe are equipped with auto-brake functions is there still a need for passive protection, or can the active systems replace the passive systems?
The analysis was performed using the most representative and extensive traffic injury database in Europe, GIDAS, where all severely head injured bicyclists in car crashes were selected to study how many of those could be protected with the different protection systems. The passive system consisted of deployable hood lifters and windshield airbag, while the active system used autonomous braking. To analyze the sensitivity of the analysis three different, but according to the authors reasonable, versions of passive respectively active protection systems were included in the study. The performance of the systems was estimated based on experimental tests at different impact speeds for the passive system, and by using computer reconstructions where the sensor system was modeled for the active system.
The study shows that there is a significant benefit in combining car-mounted active and passive protection systems for bicyclists. For the different versions of the systems, the integrated system was 29%-62% more effective in protecting from injury than the best individual system.

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