A Bicyclist Airbag Vest on the SAFER Human Body Model: Protection of Shoulder, Thorax, and Head

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A Bicyclist Airbag Vest on the SAFER Human Body Model: Protection of Shoulder, Thorax, and Head

Bei Li, Jolyon Carroll, Bengt Pipkorn, Nils Lubbe

Abstract Bicyclists are the most seriously injured road user in Sweden. For fatal crashes car-to-bicycle is the most common configuration and the most frequently injured body part is the head. However, the most frequent crash configuration is single-bicycle with the shoulder as the most injured body part. Shoulder injuries are non-fatal but often result in long-term consequences. Shoulder-thorax-protection for bicyclists is underdeveloped. The objective of the study was to evaluate the protection provided by a conceptual airbag vest. Twenty-four car-to-bicycle and eight single-bicycle crash simulations with a Human Body Model rider (SAFER HBM) were carried out, varying impact speed and impact angle. The airbag was coupled with the SAFER HBM and the shape covers the outer surface of the torso, particularly the shoulder and thorax. Shoulder peak contact force, risk of mild traumatic brain injury (mTBI), Head Injury Criterion (HIC), and the risk for two or more fractured ribs were assessed for bicyclists with and without an airbag vest. The airbag vest showed potential for shoulder protection. In single-bicycle crash simulations, a substantial reduction in shoulder contact force was observed. Additionally, the airbag vest showed potential to reduce the risk of mTBI and HIC, particularly in single-bicycle crash simulations. For all evaluated loadcases, the risk of fractured ribs remained low, both with and without the airbag vest. The detachment and position upward next to the head provided unexpected head injury protection and could be incorporated deliberately in future designs of the airbag vest. Shoulder contacts with stiff elements of the car produced the highest shoulder contact forces and biggest challenge for the airbag vest design. These contacts could be further simplified into worst-case component testing to aid the development of better protection. A tissue-based injury risk prediction is desirable as injury prediction capability of human body model need to be developed in the future. Nevertheless, the conceptual airbag vest substantially reduced loading to the shoulder and had protective effects on head and thorax.

Keywords: Bicycle crash, Shoulder injury, Virtual testing, Vulnerable road users

I. INTRODUCTION

Cycling is recognised as an inexpensive, accessible and environmentally friendly mode of transport, with the number of cyclists growing substantially each year [1]. However, bicyclists already account for 21% of serious road traffic injuries in the EU [2] and are the most commonly seriously-injured traffic participant in Sweden [3], despite substantial underreporting of cyclist injuries [4]. The forecast for 2030 is serious: even with substantial investments in infrastructure serious cyclist injuries will not be reduced as cycling increases [3].

In the EU in 2023, 45% of bicyclist fatalities result from crashes with a passenger car [5]. Similarly, in Sweden, about half of the bicyclist fatalities involved passenger cars and fatal injuries were predominately to the head (70%), followed by thorax (15%) [6]. However, when considering non-fatal injuries, most bicyclists sustain these in single-bicycle crashes [7]. Worldwide, single-bicycle crashes account for 48-95% of cyclists being admitted to hospital or treated at an emergency care department [8-9]. In Sweden, approximately 80% of the bicycle crashes are single-bicycle crashes [10]. Shoulder injuries are the most frequent injury in single-bicycle crashes (25%) [11] and often have long-term consequences [10][12]. Contrary to motorcyclists [13], thorax injuries are not common for bicyclists [14-15].

For car-to-bicycle crashes, the most common crash configuration is a car front impacting the side of a bicycle when the car is moving forward [16-17]. Car impact speeds average at 27 km/h for frontal collisions causing

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MAIS2+ injuries and at 36 km/h for MAIS3+ while bicycles move at an average speed of 15 km/h [18] or 15 to 20 km/h [19]. For fatal car-to-bicycle crashes, 90% occur at car speeds up to 60 km/h and bicycle speeds of up to 25 km/h [20]. This range of relevant speeds is reflected in the test procedures of various New Car Assessment Programmes (NCAPs) where headform and legform impact test are conducted at 40 km/h [21-22].

For single-bicycle crashes, the most common crash type in Sweden is skidding on ice or snow, where the surface friction is low [12] at speeds of 10 to 20 km/h [4]. Other common reasons include a “sudden stop” caused, for example, by a kerb [23] and “lost balance” at low or no speed [12]. The GIDAS data indicate that bicycle speeds are somewhat lower, at around 10 km/h to 15 km/h on average, when bicyclists fall or make contact with a kerb [23].

The protective effect of different countermeasures has been evaluated to improve bicyclist safety. In 2014, the Swedish Transport Administration estimated the potential of a number of different countermeasures to reduce bicycle crashes and injuries, for example, improved maintenance of bicycle infrastructure, the use of bicycle helmets, adjustment of kerbs, and the use studded winter tyres for bicycles [3][7]. However, it was found that 36 % of crashes could not be addressed by any of included countermeasures, among which single-bicycle crashes account for 69% [7]. A similar study showed that 91% of bicyclist fatalities could potentially be prevented with known countermeasures, while it was estimated that it will take a long time until the relevant and potentially effective vehicle safety technologies become widely available in the fleet [6]. A wearable airbag protective vest for cyclists was not included in these studies.

Airbag vests are generally fitted outside or inside a motorcycle jacket or a leather suit and are designed to prevent thoracic injury. Several studies evaluated the protection offered by airbag vests for motorcyclists in car-to-motorcycle crashes [24-25]. Thorax protection is likely generalisable to bicyclists in similar crash configurations. The protection offered by an equivalent design for bicyclists is available on the market via a backpack airbag. The previous study assessed the protective effect of a cycling backpack airbag and found that the airbag failed to deploy in time and was not positioned correctly to protect the shoulders or thorax of the bicyclist in car-to-bicycle or bicycle fall tests [26]. In addition, the crash dummy used did not allow for detailed injury assessment. Therefore, to quantify the injury risk to bicyclist, alternative techniques are needed.

Cyclist’s head, shoulder and thorax injury risks can be evaluated by means of full-body Finite-Element Human Body Model (HBM) simulations [27-28]. The SAFER HBM was developed to predict human kinematics and injury risk both for road users inside and outside of vehicles [29]. For Version 10, a strain-based probabilistic method to predict rib fracture risk and the risk for mild traumatic brain injury (mTBI) was developed. As with other FE models and HBMs, use of the SAFER HBM allows to measure shoulder forces.

The objective of this study is to evaluate the protection provided by a conceptual airbag vest with coverage of the outer surface of the shoulder and thorax parts, with a focus on shoulder loading reduction, thorax and head injury were analysed to evaluate broader protective effects of the airbag vest. Particular attention is given to potential interactions between the airbag vest and the head that may influence head injury. Twenty-four car-to-bicycle and eight single-bicycle crash simulations with a SAFER HBM rider were carried out, varying impact speed and impact angle. The HBM outputs: shoulder peak contact force, risk of mTBI, Head Injury Criterion (HIC), and the risk for two or more fractured ribs (NFR2+) were evaluated for the bicyclist with and without an airbag vest.

II. METHODS

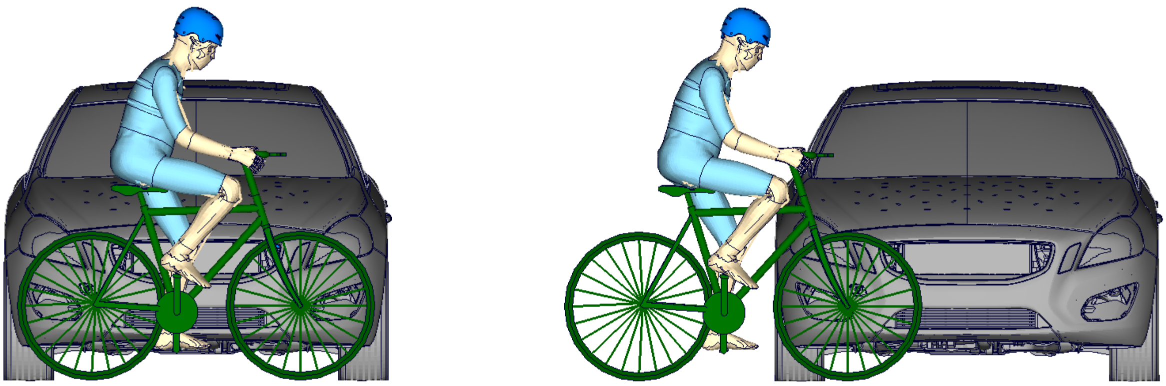
The SAFER HBM Version 10 was positioned on the saddle of a generic deformable bicycle model based on average posture data from [30] to represent a 50^{th} percentile male bicyclist. The generic bicycle model consisted of a frame, handlebar, pedals, wheels with spokes and a saddle. A previously developed helmet model [31] was fitted in all simulations. Two different crash configurations were evaluated. First, the study simulated a common situation in which a bicycle was hit by a car while crossing the road (the path of a car). Second, single-bicycle crash simulations were performed to simulate the crash, occurring due to a loss of friction at the tires, lost balance and “sudden stop”. Simulation duration varied depending on the scenario (as shown in Table 1 and Table 2). To ensure it was suitable for analysis, each simulation was reviewed to confirm that it either terminated normally or progressed beyond the peak shoulder contact force, with torso and head impacts completed before any error termination occurred. All simulations were solved with LS-Dyna (MPP971_s_R 9.3.1 R140922, LSTC) on 32 cores. To assess the numerical accuracy for long-duration simulations, a representative subset of case was re-run using double precision. Comparisons of kinematics and injury prediction showed no relevant differences between single and double precision results. Based on this comparison, single precision simulations were considered sufficient for the analysis presented in this study. The pre-processing was performed using PRIMER Version 20.0, and post-processing was carried out using META Version 23.1.3.

Car-to-bicycle Crash Simulations

In the car-to-bicycle crash simulations, the bicycle was stationary or moving straight-ahead at 15 km/h and impacted on the left by a mid-sized station wagon car (model year 2014) moving straight from a perpendicular direction to the bicycle at four different speeds (20, 30, 40 and 60 km/h). The car model with detailed bonnet, windshield, A-pillar, and roof-rail representations was used. No dedicated validation against physical tests was conducted within this study. The bicyclist was coupled to the bicycle using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword without kinematic constraints, allowing free relative motion once impact occurred. Friction coefficients were set to 0.2 for contacts between the bicyclist and the car or bicycle, 0.3 between the bicyclist and the ground. The simulation matrix is presented in Table 1. The impact position was described as the relative position of the bicyclist head centre of gravity (COG) against the front-vertical centre of the car. In the first configuration, the head COG was aligned with centre of the car. In a second configuration, it was moved 1900 mm to the offset (Fig. 1). All twelve configurations were conducted twice: once with and once without an airbag vest.

TABLE 1
Car-to-bicycle crash simulation matrix

Car speed (km/h)	Bicycle speed (km/h)	Impact position	Countermeasure	Duration (ms)
20	0	Centre	With and without airbag vest	400
30	0			320
40	0			270
60	0			250
20	15	Centre	With and without airbag vest	670
30	15			600
40	15			340
60	15			260
20	15	Offset	With and without airbag vest	400
30	15			310
40	15			270
60	15			270



(a) (b)

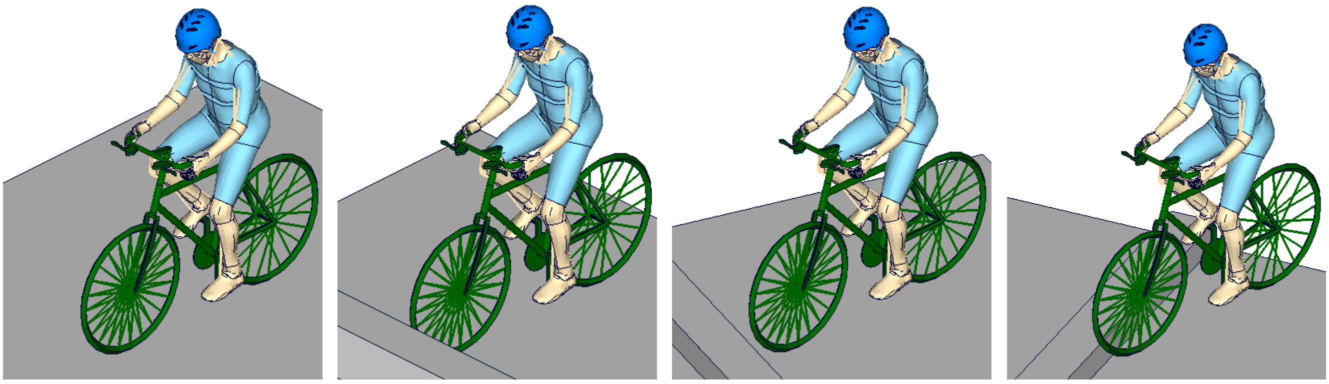
Fig. 1. Car-to-bicycle crash configurations: (a) centre impact, (b) offset impact

Single-bicycle Crash Simulations

In the single-bicycle crash simulations, two crash configurations were evaluated. First, the bicycle was initially stationary to represent a simple tip-over event with loss of balance, a sideway falling motion to the ground was simulated under gravity. Secondly, a bicycle was moving at 15 km/h hitting a square-edged rigid kerbstone on the floor at three impact angles, 90, 70 and 20 degrees, to simulate crashes that resulted from a loss of friction and a "sudden stop" (Fig. 2). The kerbstone height was 150 mm in the 70 and 20 degree impact angle simulations as in [32]; it had to be increased to 300 mm in the 90 degree simulation to initiate falling instead of overriding. The kerbstone was modelled with rigid material. The bicyclist was coupled to the bicycle without kinematic constraints. The friction coefficient was set to 0.3 for contact between the bicyclist and the kerbstone. All four configurations were conducted twice: once with and once without an airbag vest.

TABLE 2
Car-to-bicycle crash simulation matrix

Bicycle speed (km/h)	Impact angle (degree)	Kerbstone height (mm)	Countermeasure	Duration (ms)
0	-	-	With and without airbag vest	2500
15	20	150		890
15	70	150		1000
15	90	300		900



(a) (b) (c) (d)
Fig. 2. Single-bicycle crash configurations: (a) stationary, (b) impact angle: 90 degree, (c) impact angle: 70 degree, (d) impact angle: 20 degree

Airbag Vest Model

The airbag vest evaluated in this study represents a conceptual protection system intended to investigate the potential of injury mitigation. The interaction between the bicyclist and the airbag vest was modelled using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword with a friction coefficient of 0.2, without additional constraints or tethers. During the airbag inflation the airbag shape was covering the outer surface of the torso, particularly the shoulder and thorax. Airbag vest deployment was prescribed at the start of simulation using the AIRBAG_ADIABATIC_GAS_MODEL keyword. A peak internal pressure of 97.8 kPa, an inflation time of 3ms, and a total gas volume of 13.4 L were defined to ensure full deployment prior to first contact while avoiding excessive stiffness. As the inflator was not modelled, inflator-specific parameters such as mass flow, gas temperature, and trigger time were intentionally not included.

Injury Assessment

Head injury and rib fracture risk, as well as the loading to the shoulder (i.e. contact force), were evaluated for the helmeted bicyclist with and without airbag vest. To assess the risk of mTBI the 99th percentile value of the maximum principal strain (MPS) of the brain tissue was extracted from the head model. The strain values were translated into risk predictions [33]. Risk of skull fracture (AIS2+) was assessed by HIC 15 [34]. The shoulder contact forces were measured using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword which was defined between the shoulder and car or ground (including the kerbstone). The shoulder comprised the clavicle, acromion, proximal humeral regions and the soft tissue and skin around these components. In addition, the contact force between shoulder and the airbag vest was extracted for simulation with the airbag vest. Shoulder force was not translated to injury risks, but a higher force was assumed to lead to higher injury risk. The rib fracture risk was predicted using a strain-based and age-adjusted rib cortical bone fracture risk function [35]. The predicted risk for NFR2+ for a 45-year-old bicyclist was evaluated.

III. RESULTS

Car-to-bicycle Crash Simulations

After the bicycle is hit by the car, the rider is scooped up on the bonnet. Two other kinematics trends were also observed. In central impacts with a moving bicycle and a slow car, the bicyclist slides along the front of the car in line with their own travel direction and falls on the ground without substantial bonnet contact. In the offset impacts, at 60 km/h impact speed, the bicyclist contacts the side of the car rather than the bonnet. Figures of the bicyclist at time of torso impact are in Appendix A.

Shoulder Loading Analysis

As the principal area for protection, we analysed shoulder forces. In the stationary bicycle scenario, the falling motion to the side causes the elbow and shoulder to make contact with the bonnet, wiper or windshield before the head impact. Shoulder force increased with car impact speed, reaching about 4.3 kN at 60 km/h in a contact with the windshield (Fig. 3). In the scenario where a moving bicycle hits the centre of the car, however, the shoulder contact force did not follow the trend of increasing with car speed and instead peaked at the lower car speeds (20 and 30 km/h). This was due to the elbow impacting the bonnet and the rider sliding sideways over the left edge of the bonnet, resulting subsequently in the shoulder impacting the ground. The peak shoulder contact forces when the car was travelling at 40 and 60 km/h were lower than the equivalent stationary bicycle scenarios. The moving bicycle leads to more rotation of the torso of the rider (around the caudal-rostral axis), which then results in the contact point moving away from the lateral aspect of the shoulder after impact. In the offset scenario, the bicyclist generated a low contact force for car speeds of 20, 30 and 40 km/h (all below 2.0 kN). Still, the highest shoulder contact force in all simulations occurred in this scenario at 60 km/h car speed (6.9 kN) as the shoulder contacts the roof-rail, which is a particular stiff element of the car.

When wearing the airbag vest, shoulder contact forces were reduced for the car travelling at 40 and 60 km/h in the stationary bicycle scenario. However, in the scenario where a moving bicycle is hit in the centre of the car, a small increase in the 60 km/h case was observed. This was due to the force generated by the interaction between the shoulder and the airbag vest. Small reductions were consistent with the observation of the airbag parts, initially positioned around the shoulders, but then allowed to detach after inflation, resulting in an airbag interaction with the head rather than the shoulder (Appendix B). On the contrary, the shoulder of the bicyclist was covered by the airbag vest when the torso was in contact with the ground in the moving bicycle. The airbag vest provided an energy absorbing and impact attenuating structure between the shoulder and the ground. However, it produced substantial loading to the shoulder at the same time. Therefore, only a small reduction of shoulder contact forces was found for the ground impact scenarios. A large reduction in shoulder contact force was seen in the 40 and 60 km/h offset scenario with reduction from 1.6 kN to 0.5 kN and from 6.9 kN to 5.0 kN.

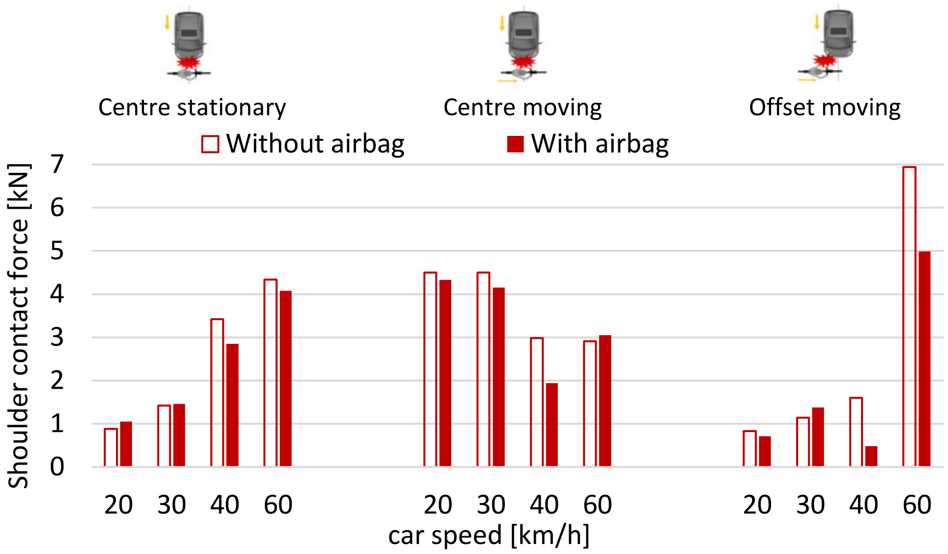


Fig 3. Shoulder contact force for car-to-bicycle crashes

Head Injury Analysis

In the scenario where a moving bicycle is hit by the centre of the car, the head impacted to the ground for low car speeds and close to the A-pillar for car speeds of 40 and 60 km/h with a 100% risks for mTBI were predicted by the strain of brain tissue, except for the 30 km/h bicycle moving scenario with 68% risk of mTBI (Fig.4). This was due to, in this case, the bicyclist falling onto the ground with the crown of the head taking the initial impact, which is associated with a lower risk of mTBI compared with the remaining cases involving lateral or occipital head impacts. This observation is consistent with previous studies, which have found higher brain strain level in lateral and occipital impacts [36-37]. In the offset scenario for the car travelling at 60 km/h, the head did not directly contact the car, however, severe rotational loading in the coronal plane was induced at the head due to shoulder contact with the roof-rail.

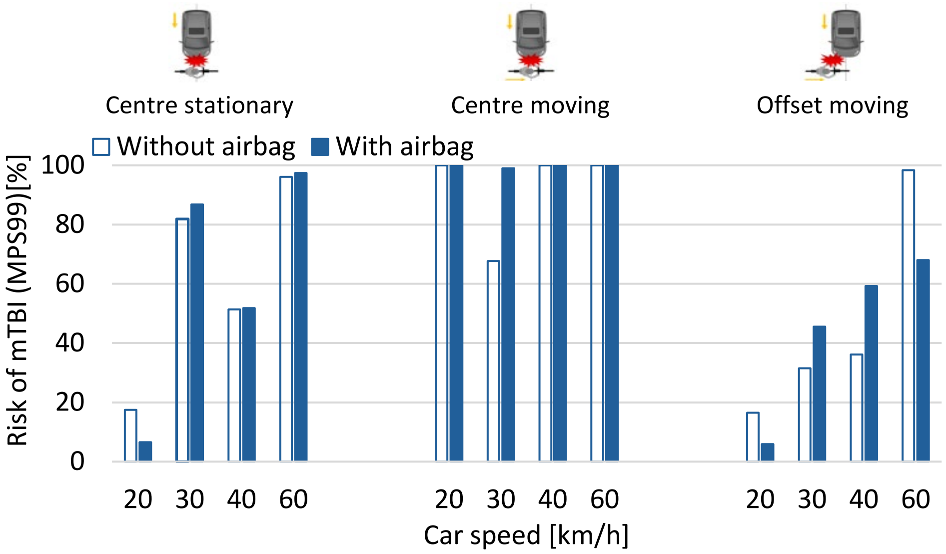


Fig 4. Risk of mTBI for car-to-bicycle crashes

HIC results from crash simulations are shown in Fig. 5. The highest HIC of 1557 was obtained for the car speed of 40 km/h in the scenario where a moving bicycle hits the centre of the car, due to the head impacting close to the A-pillar of the car. A HIC 15 value of 1557 relates to a 67% risk of skull fracture (AIS2+). The HIC 15 ranged from 19 to 618 for the remaining cases, well below the threshold of 650, a limit for achieving maximum score in NCAPs, and indicating a risk of skull fracture of less than 20% (AIS2+).

When wearing the airbag vest, the upper body rotated around the pelvis and moved toward the bonnet after being impacted by the front end of the bonnet, causing the abduction of left arm that resulted in an interaction between airbag and head. In the scenario where a moving bicycle hits the centre of the car, the risk of mTBI was generally similar with or without the airbag vest, however, in the 30 km/h bicycle moving scenario the bicyclist slides along the front of the car in line with their own travel direction and falls on the ground without car contact. The left posterior parietal region takes the initial impact, then the head rotated rapidly and generated more rotational loading in the coronal plane and the sagittal plane. Therefore, the risk of mTBI was higher compared to the case without the airbag vest. In the offset scenario, a large reduction of risk of mTBI occurred in the 60 km/h offset case (from 98% to 67%).

In the scenario where a moving bicycle hits the centre of the car, a reduction in HIC was observed, except when the car was striking at 60 km/h, the HIC was increased from 618 to 667. This can be explained by the fact that the contact between the airbag vest and the head prolonged the duration of interaction between the head and the car, giving more time for high linear acceleration loading. In addition, the linear acceleration along z-axis increased when the airbag vest was added. In the offset scenario, the HIC values were lowest for the bicyclist without the airbag vest.

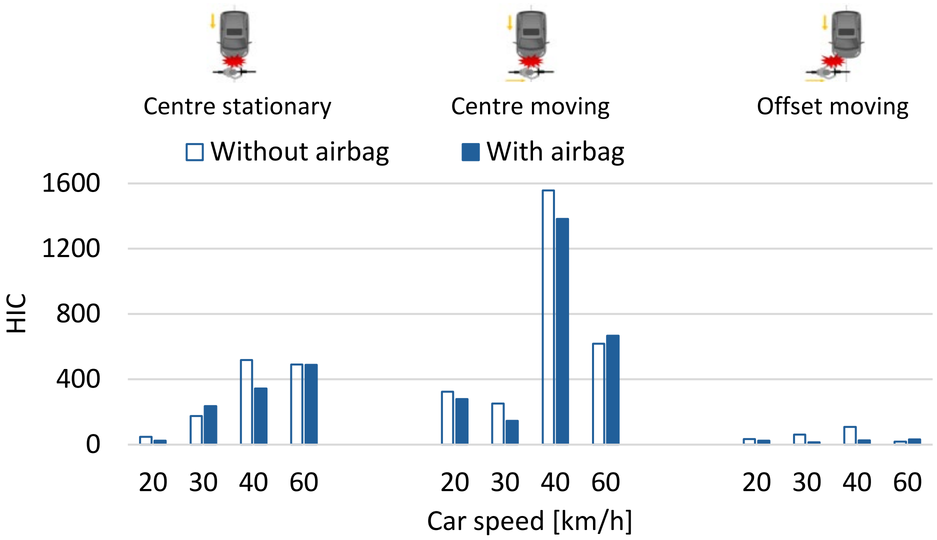


Fig 5. HIC for car-to-bicycle crashes

Rib Fracture Analysis

In the stationary bicycle scenario, the torso impacted the bonnet and the windshield. The bicyclists obtained low rib fracture risk, with all predicted risks remaining below 6% (Fig.6). In the scenario where a moving bicycle hits the centre of the car travelling at 20 km/h, the bicyclist generated a falling motion to the side with the torso hitting the ground, resulting in a 43% risk for two or more fractured ribs. However, when the car speed increased to 30 km/h, the head took the initial hit to the ground before the torso, which led to a low risk for fractured ribs. For the car travelling at 60 km/h, the thorax contacted the wiper spindle which is a stiff element of the car. A 20% risk for two or more fractured ribs was predicted. In the offset scenario, the thorax generated a 100% risk for fractured ribs when the car speed was 60 km/h due to loading from the roof rail. The thorax made little contact with the bonnet, as indicated by very low risk for fractured ribs for the remaining cases.

When wearing the airbag vest, the bicyclist obtained similar risk for fractured ribs with or without the airbag vest in the stationary bicycle scenario. A substantial reduction was found in the scenario where a moving bicycle hits the centre of the car, where the ground impact case showed a reduction from 43% to 11% for car travelling at 20 km/h. However, the risk for fractured ribs increased to 24% when the car was travelling at 60 km/h. In the offset scenario, similar risk for fractured ribs was seen for the bicyclist with or without the airbag vest.

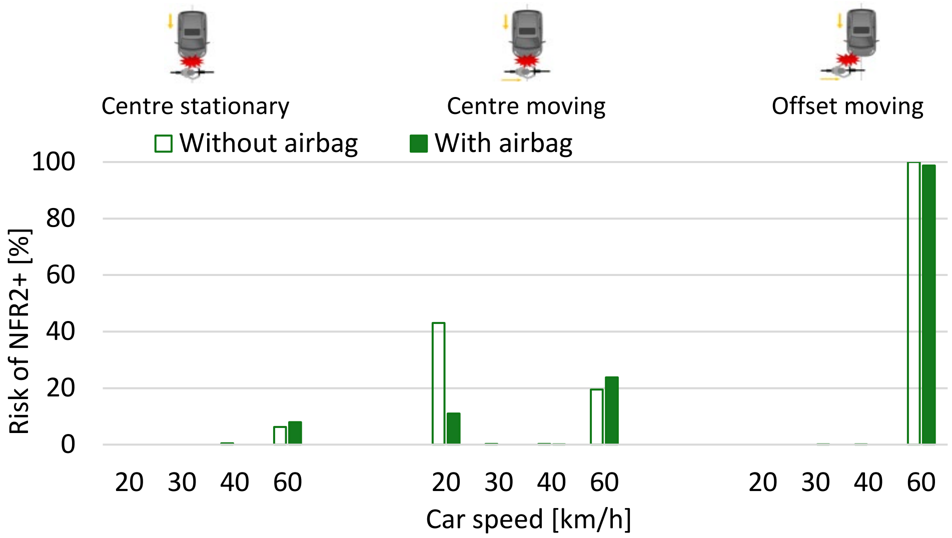


Fig 6. Predicted rib fracture risk for car-to-bicycle crashes

Single-bicycle Crash Simulations

In the single-bicycle crash simulations, the perpendicular impact (90 degree impact angle) resulted in a falling motion over the handlebar with the head taking the initial hit to the ground before the shoulder. For the remaining three cases the tilt of the front wheel resulted in a falling motion to the side with foot, knee, hip, shoulder and head hitting the ground sequentially.

Shoulder Loading Analysis

The shoulder contact forces for moving bicycle scenarios were higher than the stationary bicycle scenario. The highest shoulder contact force was obtained for the 20 degree impact angle (3.3 kN) (Fig.7).

The reduction in shoulder peak contact forces was seen for the bicyclist wearing the airbag vest in all cases. A large reduction was found for the 20 degree impact angle and with reduction from 3.3 kN to 1.3 kN. In the 90 degree impact angle, the left shoulder was completely covered by the airbag vest, and no direct contact between the shoulder and the ground was observed. The shoulder contact force of 1.87 kN resulted from the interaction between the shoulder and the airbag vest. The coverage by the airbag vest was partial for the falling motion to the side scenarios. However, the airbag vest reduced the force that comes from the ground. The shoulder generated a force transmitted through the airbag vest, in general, the loading experienced by the shoulder was reduced with the airbag vest.

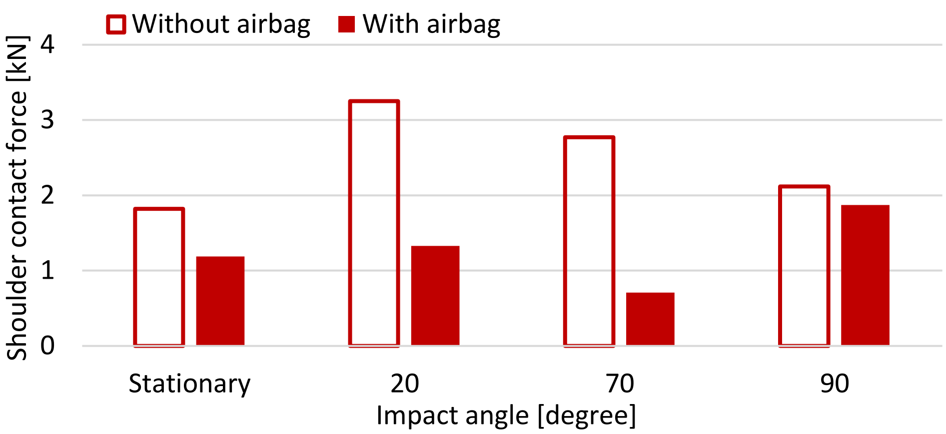


Fig 7. Shoulder contact force for single-bicycle crashes

Head Injury Analysis

The predicted risk of mTBI was highest in the stationary bicycle scenario (99%) (Fig.8). In the scenario where a moving bicycle hits the kerbstone, risk of mTBI ranged from 75% at 20 degree impact angle of to approximately 39% at 70 and 90 degree impact angles. HIC values followed a different trend. The highest HIC 15 of 423 was obtained for the 70 degree impact angle (Fig.9), indicating a 14% risk of skull fracture (AIS2+).

The airbag vest occupied the space between the torso and the ground, and no interaction between the head and the airbag vest was observed in any of the cases. A reduction in risk of mTBI and HIC were observed in the stationary and at 70 degree impact angle scenarios, while smaller or negligible changes were observed in the remaining cases.

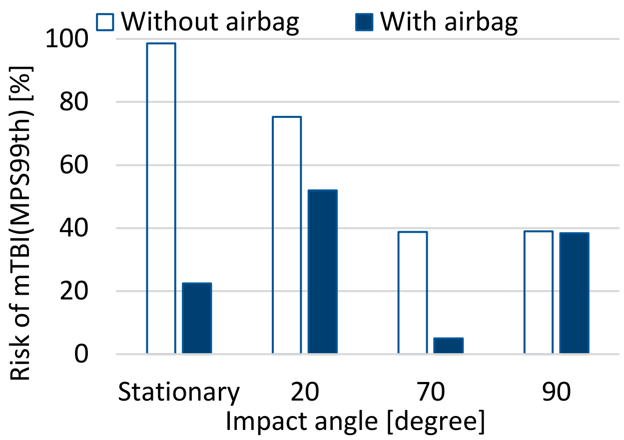


Fig 8. Risk of mTBI for single-bicycle crashes

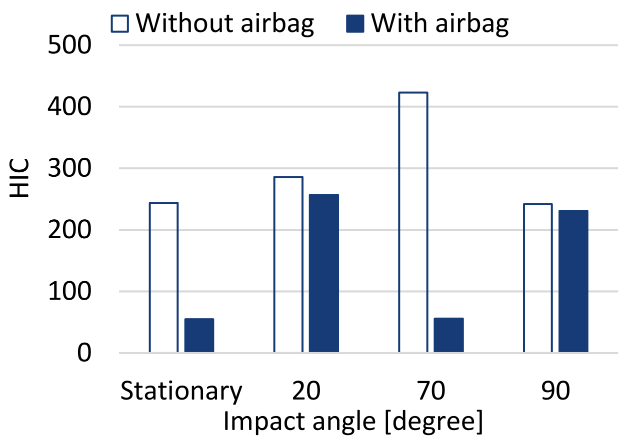


Fig 9. HIC for single-bicycle crashes

Rib Fracture Analysis

The bicyclists obtained a low risk of fractured ribs throughout the single-bicycle event simulations, with all predicted risks (for two or more ribs being fractured) being below 3%, as shown in Fig. 10. The stationary bicycle scenario showed no rib fracture risk at all with or without the airbag vest. In all other cases, a similar risk of fractured ribs was generated for the bicyclist with and without airbag vest sometimes 2% higher with the airbag vest (as in the 20 degree impact) and sometimes 2% lower (as in the 90 degree impact).

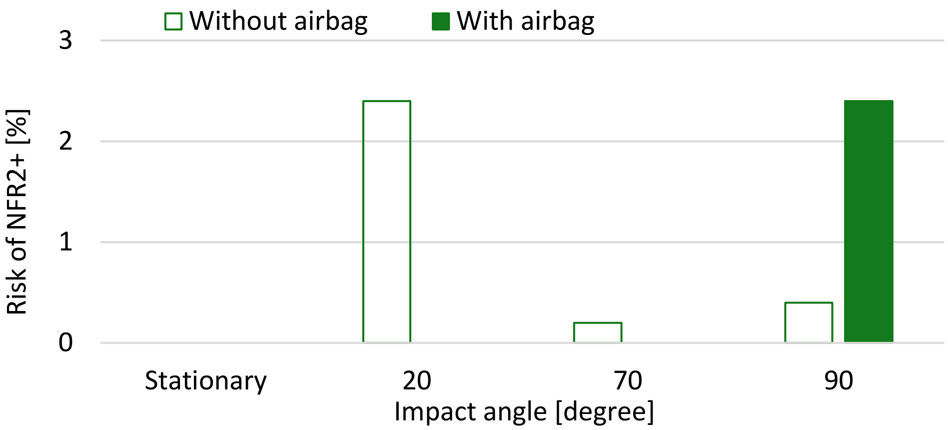


Fig 10. Predicted rib fracture risk for single-bicycle crashes

IV. DISCUSSION

The objective of the study was to evaluate the protection that could be provided by a conceptual airbag vest with shoulder coverage. Two crash configurations, car-to-bicycle and single-bicycle crash were simulated with the SAFER HBM Version 10. Both show that the airbag vest reduced shoulder contact forces in all simulated scenarios, with reductions up to 60% in single-bicycle crashes. With the explored design, the space between the head and impact surface was unintentionally occupied by the airbag vest. Even though this may seem advantageous, such an unintended feature may need to be designed out of future iterations to guarantee its intended purpose with shoulder coverage. Accordingly, the head protection status would need to be re-evaluated with each design update.

The airbag vest has the potential to protect the shoulders. Particularly in the single-bicycle crash simulations, the airbag vest occupied the space between the shoulders and the ground and provided energy absorption. A substantial reduction in shoulder contact force was observed in these simulations, even showing a marginal reduction in the head-over-handlebar 90-degree impact. In the ground contacts after primary car impact, smaller reductions were observed. Initial contact forces were lower, and the airbag pressure was likely too high to reduce forces more. During primary car-to-bicycle contacts, the airbag had only a marginal effect on the shoulder contact force, as this design did not cover the shoulder effectively. Lacking injury risk predictions for the shoulder, contact force was used as an indicator of impact severity. The reference to shoulder contact force of approximately 1 kN is not intended as an injury threshold but as an order-of-magnitude comparison to highlight relative loading reduction. We speculate that a reduction from around 3.0 to 1.0 kN in the single-bicycle crashes is the appropriate design to mitigate injuries. However, contact force does not capture tissue deformation, stress, or failure mechanisms in the shoulder complex. As we advance our tools and knowledge to predict shoulder injuries, new designs may be invented to achieve non-injurious levels.

We suggest two ways forward to address bicyclist shoulder injuries in the future:

First, to improve HBM injury predictions. We need to model shoulder movement under impact and injury mechanism from PMHS testing and crash reconstructions. To assess shoulder injury, a tissue-based injury risk prediction is desirable, based on stress, strain, or failure criteria within anatomical structures since shoulder injury involves complex mechanisms including joint dislocation, ligament rupture and bone fracture, which cannot be captured by a single force measure. Such risk predictions would allow us to evaluate various countermeasures for shoulder protection. An updated HBM, a version of the SAFER HBM, is being prepared with a revised shoulder and scapula, making it technically ready to incorporate risk predictions and for subsequent use in evaluating protective systems [38-39].

Secondly, the identified worst-case contacts could be further simplified into component testing. Previous full-scale physical testing with a POLAR dummy evaluated the shoulder-protection performance of a protective backpack [26]. Challenges for the airbag to deploy in time, to position correctly to protect the shoulders and for test repeatability were highlighted. These full-scale crash test evaluations appear to remain difficult and costly. Therefore, an even more simplified component test, like the NCAP headform and legform tests, may be more appealing. Substantial efforts are needed to establish such test methods.

The effects of the airbag vest on head injury influenced by the interaction between the airbag vest and the head. In car-to-bicycle crash simulations, certain parts of the airbag vest occasionally moved upward and occupied the space between the head and the impact surface, providing unintended head interaction. As a result, both reduction and increases in risk of mTBI were observed. While this resulted in reduced head injury metrics, it should not be interpreted as a reliable protective effect, as the behaviour was not controlled or optimized. Future designs should ensure stable positioning of the airbag around the shoulder region.

Rib fracture risk was evaluated to assess whether changes in shoulder loading introduced adverse thorax effects when the airbag vest was worn. Rib fracture risks were low in most scenarios, particularly in single-bicycle crashes, where predicted risks for two or more fractured ribs remained below 3% regardless of airbag vest use. This is consistent with epidemiological findings reporting that thorax injuries are relatively uncommon in single-bicycle crashes compared to head and shoulder injuries [14-15] and suggests that the proposed airbag vest does not introduce a meaningful increase in thorax injury risk in single-bicycle crashes. In car-to-bicycle crash, rib fracture risk was highly dependent on the involvement of stiff components of the car. Evaluated rib fracture risks were observed primarily in configurations where the thorax contacted stiff components such as the roof rail or wiper spindle, particularly at higher car impact speed (e.g. 60 km/h) and it remained high with and without the airbag vest. This indicates that the airbag vest is less effective in configuration dominated by direct loading from stiff components of the car and would likely require dedicated thorax protection design features.

Suggesting this future work clearly points at the limitations of the current study. Tissue-based injury risk predictions for shoulder were not available for SAFER HBM Version 10. Therefore, we chose to use shoulder contact force as an indicator of impact severity. We did not translate contact force into injury risk so as to not indicate false accuracy of such a measure. We believe, nevertheless, that the demonstrated achievable reduction in shoulder forces suggests strong enough evidence that injury mitigation can be achieved in the field if such protective devices were deployed. The study used a car model without dedicated validation against physical test, which may limit the generalisability of the results. This is particularly relevant for the windshield, where complex pattern of failure and its composite structure may influence interaction with the bicyclist.

Even with the limitations in the tool, we believe we also provide further important suggestions to future design. We observed that the shoulder protection can move upward and fill the space between the head and the impact surface instead of the intended space between the shoulder and the impact surface. Future designs should establish a firmer positioning around the shoulders for their protection, acknowledging that airbag products to protect the head exist already.

V. CONCLUSION

This study highlighted the potential of an airbag vest in shoulder protection for bicyclists. The airbag vest reduced shoulder contact force in both car-to-bicycle and single-bicycle crash simulations. We only assessed shoulder force, as no other injury prediction metric with the HBM is available yet. Nevertheless, the conceptual vest airbag reduced loading to the shoulder substantially. Therefore, this study shows a valuable application for virtual testing with an HBM and whilst complementing the strengths from full-scale system-level validations.

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VII. REFERENCES

[1] European Commission, European Parliament, and Council of the European Union. (2023). European Declaration on Cycling. [Online]. Available at: http://transport.ec.europa.eu/system/files/2023-11/European_Declaration_on_Cycling_en_0.pdf

[2] European Commission. (2023). Annual Statistical Report on Road Safety in the EU 2023. European Road Safety Observatory. [Online]. Available at: http://road-safety.transport.ec.europa.eu/

[3] Swedish Transport Administration. (2023). Analysis of Road Safety Trends 2022: Management by objectives for road safety work towards the 2030 interim targets. [Online]. Available at: http://bransch. trafikverket.se/globalassets/dokument/vision-zero/analysis-of-road-safety-trends-2022.pdf

[4] Gildea K, Hall D, Simms C K. (2021) Configurations of underreported cyclist-motorised vehicle and single cyclist collisions: Analysis of a self-reported survey. Accident Analysis & Prevention, 159: 106264.

[5] European Commission. (2023). Road Traffic Statistics 2023. [Online]. Available at: http:// transport.ec. europa.eu/background/road-safety-statistics-2023_en

[6] Kullgren A, Stigson H, Ydenius A, Axelsson A, Engstrm E, Rizzi M. (2019) The potential of vehicle and road infrastructure interventions in fatal bicyclist accidents on Swedish roads—What can in-depth studies tell us?. Traffic injury prevention, 20(sup1): S7-S12.

[7] Rizzi M C, Rizzi M, Kullgren A, Alguren B. (2020) The potential of different countermeasures to prevent injuries with high risk of health loss among bicyclists in Sweden. Traffic injury prevention, 21(3): 215-221.

[8] Beck B, Stevenson M R, et al. (2019) Crash characteristics of on-road single-bicycle crashes: an under-recognised problem. Injury prevention, 25(5): 448-452.

[9] Schepers P, Agerholm N, et al. (2015) An international review of the frequency of single-bicycle crashes (SBCs) and their relation to bicycle modal share. Injury prevention, 21(e1): e138-e143.

[10] Rizzi M, Stigson H, Krafft M. (2013) Cyclist injuries leading to permanent medical impairment in Sweden and the effect of bicycle helmets. Proceedings of the IRCOBI Conference. 2013, Gothenburg, Sweden.

[11] European Cyclists' Federation, European Commission and European Transport Safety Council. (2014). Safer Cycling – A Common Strategy for the period 2014-2020. [Online]. Available at: http://worldcat.org/isbn/9789174675443

[12] Algurén B, Rizzi M. (2022) In-depth understanding of single bicycle crashes in Sweden-Crash characteristics, injury types and health outcomes differentiated by gender and age-groups. Journal of Transport & Health, 24: 101320.

[13] Gidion F, Carroll J, Lubbe N. (2021) Motorcyclist injuries: analysis of German in-depth crash data to identify priorities for injury assessment and prevention. Accident Analysis & Prevention, 163: 106463.

[14] Meredith L, Kovaceva J, Bálint A. (2020) Mapping fractures from traffic accidents in Sweden: How do cyclists compare to other road users?. Traffic injury prevention, 21(3): 209-214.

[15] Leo C, Klug C, et al. (2019) Analysis of Swedish and Dutch accident data on cyclist injuries in cyclist-car collisions. Traffic injury prevention, 20(sup2): S160-S162.

[16] Lindman M, Jonsson S, et al. (2015) Cyclists interacting with passenger cars; a study of real world crashes. Proceedings of the IRCOBI Conference. 2015, Lyon, France.

[17] Schubert A, Campolettano E T, Scanlon J M, Mcmurry T L, Unger T. (2024) Bridging the gap: Mechanistic-based cyclist injury risk curves using two decades of crash data. Traffic Injury Prevention, 25(sup1): S105-S115.

[18] Zander O, Hamacher M. (2017) Revision of passive pedestrian test and assessment procedures to implement head protection of cyclists. Proceedings of the 25th International Technical Conference on the Enhanced Safety of Vehicles. 2017, Detroit, MI, USA.

[19] Schindler R. (2025) A GIDAS analysis of crashes between bicycles and cars for personal protective equipment evaluation. Proceedings of the 33rd Annual Congress of the European Association for Accident Research and Analysis. 2025, Brașov, Romania.

[20] Maki T, Kajzer J, Mizuno K, Sekine Y. (2003) Comparative analysis of vehicle–bicyclist and vehicle–pedestrian accidents in Japan. Accident Analysis and Prevention, 35:927-940.

[21] European New Car Assessment Programme (Euro NCAP). (2025). Crash Protection: Vulnerable Road User

Impacts, Version 1.1, September 2025. [Online]. Available at: http://cdn.euroncap.com/cars/assets/euro_ncap_protocol_crash_protection_vulnerable_road_user_impact_v11_a403cb3d2f.pdf
[22] China New Car Assessment Programme (C-NCAP). (2024). VRU Protection: Headform and Legform Test Protocol, 2024. [Online]. Available at: http://www.c-ncap.org.cn/cncap-guicheng-detail?id=8
[23] Schindler R. Lubbe N. (2024) A GIDAS analysis of single-bicycle-crashes for personal protective equipment evaluation. Proceedings of the 12th Internation Cycling Safety Conference. 2024, Imabari, Japan.
[24] Serre T, Masson C, et al. (2019) Airbag jacket for motorcyclists: evaluation of real effectiveness. Proceedings of the IRCOBI Conference. 2019, Florence, Italy.
[25] Cherta Ballester O, Llari M, Honoré V, Masson C, Arnoux P J. (2021) An evaluation methodology for motorcyclists' wearable airbag protectors based on finite element simulations. International journal of crashworthiness, 26(1): 99-108.
[26] Carroll J, Pipkorn B, Stigson H. (2025) Observation on the protective effect from a bicyclist backpack airbag system evaluated in crash tests. Proceedings of the IRCOBI Conference. 2025, Vilnius, Lithuania.
[27] Pipkorn B, Alvarez V, Fahlstedt M, Lundin L. (2020) Head injury risks and countermeasures for a bicyclist impacted by a passenger vehicle. Proceedings of the IRCOBI Conference. 2020, Munich, Germany.
[28] Katsuhara T, Miyazaki H, Kitagawa Y, Yasuki T. (2014) Impact kinematics of cyclist and head injury mechanism in car-to-bicycle collision. Proceedings of the IRCOBI conference. 2014, Berlin, Germany.
[29] Pipkorn B, Jakobsson L, Iraeus J, Östh J. (2023) THE SAFER HBM–A human body model for seamless integrated occupant analysis for all road users. Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles. 2023, Yokohama, Japan.
[30] European Automobile Manufacturers' Association. (2018) Bicyclist target – ACEA specifications, Version 1.0. [Online]. Available at: http://www.acea.auto/files/Bicyclist_target-ACEA_specifications.pdf
[31] Feist F, Klug C. (2016) A numerical study on the influence of the upper body and neck on head kinematics in tangential bicycle helmet impact. Proceedings of the IRCOBI Conference. 2016, Malaga, Spain.
[32] Niska A, Wenäll J. (2019) Simulated single-bicycle crashes in the VTI crash safety laboratory. Traffic injury prevention, 20(sup3): 68-73.
[33] Fahlstedt M, Meng S, Kleiven S. (2022) Influence of strain post-processing on brain injury prediction. Journal of biomechanics, 132: 110940.
[34] Hertz, E. (1993) A Note on the Head Injury Criterion (HIC) as a Predictor of the Risk of Skull Fracture. Proceedings of the 37th Association for the Advancement of Automotive Medicine. 1993, San Antonio, Texas, USA.
[35] Larsson K-J, Blennow A, Iraeus J, Pipkorn B, Lubbe N. (2021) Rib Cortical Bone Fracture Risk as a Function of Age and Rib Strain: Updated Injury Prediction Using Finite Element Human Body Models. Frontiers in Bioengineering and Biotechnology, 9: 677768.
[36] Kleiven S. (2007) Predictors for traumatic brain injuries evaluated through accident reconstructions. 51st Stapp car crash conference. 2007, Pennsylvania, USA.
[37] Liu W, Su S, Qiu J, Zhang Y, Yin Z. (2016) Exploration of pedestrian head injuries—collision parameter relationships through a combination of retrospective analysis and finite element method. International Journal of Environmental Research and Public Health, 13(12): 1250.
[38] HBM SHOULDER | Safer [Online]. Available at: http://www.saferresearch.com/projects/hbm-shoulder
[39] Trafikverket. (2023) Human Body Model for Bicyclist Shoulder Injury Assessment and Countermeasures (TRV 2021/127378). FoI-Portalen. [Online]. Available at: http://foiportalen.trafikverket.se/seprojekt/264

VIII. APPENDIX

Appendix A: Bicyclist posture at time of torso impact for car-to-bicycle and single-bicycle crash simulations

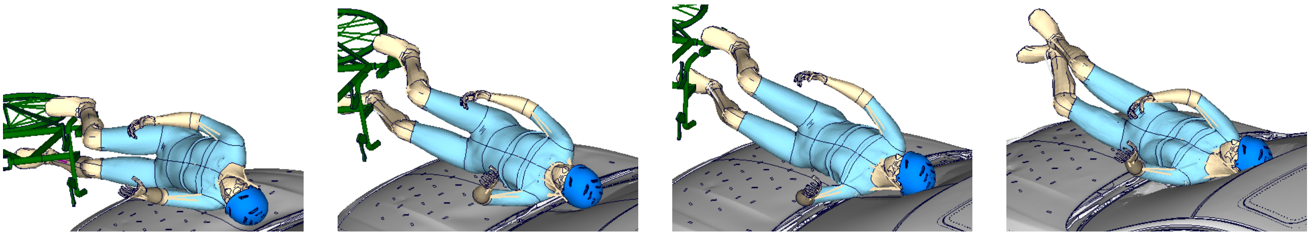


Fig. A1 Bicyclist posture at time of torso impact for stationary bicycle for centerline impacts (from left to right: car travelling at 20 km/h, 30 km/h, 40 km/h and 60 km/h)

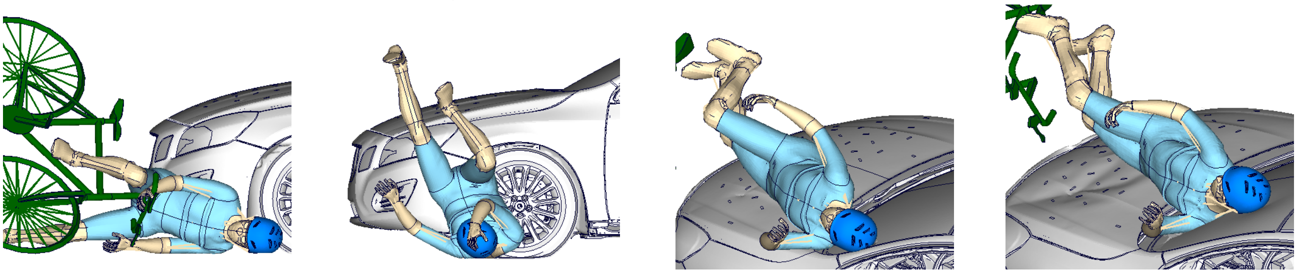


Fig. A2 Bicyclist posture at time of torso impact for bicycle moving at 15 km/h for centerline impacts (from left to right: car travelling at 20 km/h, 30 km/h, 40 km/h and 60 km/h)

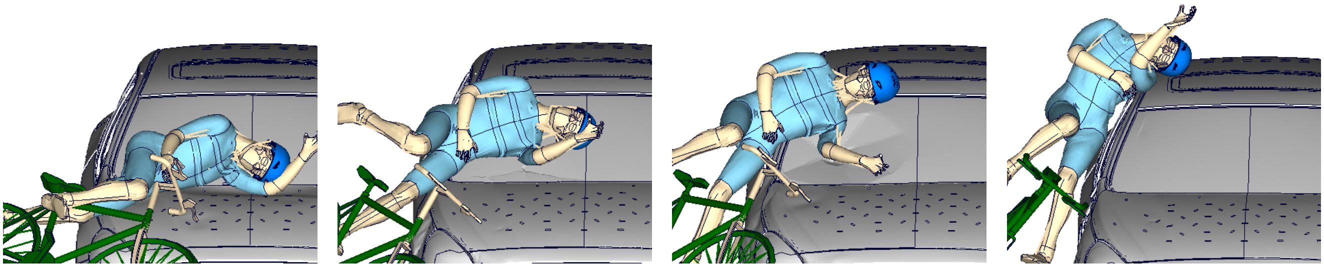


Fig. A3 Bicyclist posture at time of torso impact for bicycle moving at 15 km/h for offset impacts (from left to right: car travelling at 20 km/h, 30 km/h, 40 km/h and 60 km/h)

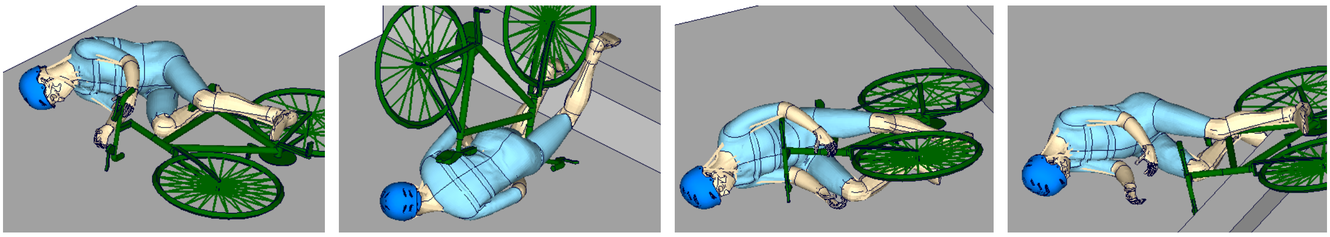
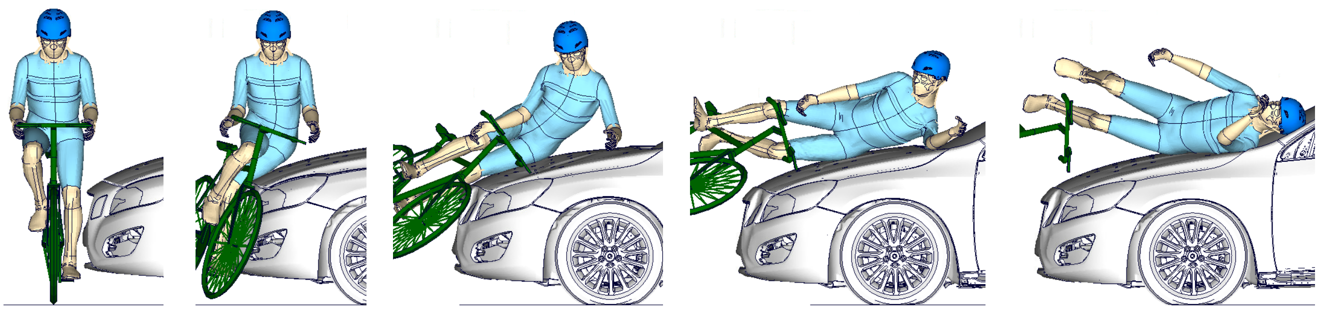
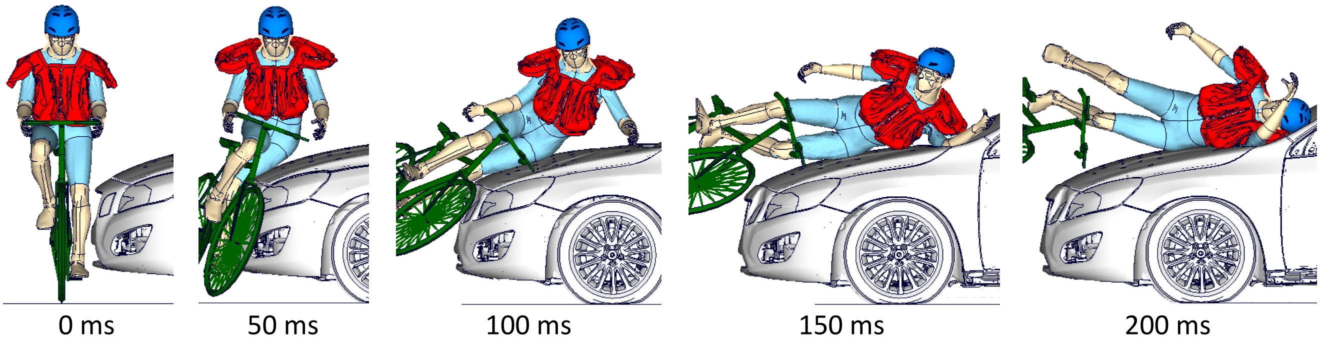


Fig. A4 Bicyclist posture at time of torso impact for single-bicycle crash (from left to right: stationary; impact angle: 90 degree; impact angle: 70 degree; impact angle: 20 degree)

Appendix B: Comparison of simulation without airbag vest (top) and with airbag vest (bottom) for car-to-bicycle crash at car speed of 40 km/h in the moving bicycle scenario

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