Casualty Benefits of Measures Influencing Head to Windscreen Area Protection

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Abstract This study aims to understand the potential effect on pedestrian and cyclist casualty populations should the Adult Head to Windscreen Area Protection measure be adopted, and the potential impact of other primary safety measures that are being considered for implementation as part of the General Safety Review. The target population of the measures was defined at the national level of Great Britain over a five-year period based on collision data from 2011 to 2015. The casualty benefit of a Pedestrian Protection Airbag (PPA), covering the Scuttle and A-pillars of the M1 vehicles, and Intelligent Speed Assistance (ISA) and Autonomous Emergency Braking for Pedestrians and Cyclists (AEB-PCD) were assessed. The PPA only protects head contacts to the A-pillar and Scuttle, and was predicted to be effective for 13.26% of fatally injured and 0.58% of seriously injured pedestrians struck by the front of M1 vehicles; no cyclist casualties were in the sample. The primary safety measures were more effective and were predicted to have a much greater casualty benefit. The implementation of AEB-PCD and ISA on M1 vehicles is likely to create significant casualty benefits, but there is still a residual casualty population that requires protection from the A-pillar, Scuttle and windscreen.

Keywords Pedestrian, Head impact, Pedestrian protection airbag, Windscreen, Regulation.

I. INTRODUCTION

Regulation (EC) 78/2009 is the EU's type approval for motor vehicles with regard to the protection of pedestrians and other vulnerable road users (VRUs), and it updated Directive 2003/102/EC with modified and more advanced provisions, adapted to recent technical progress. This includes passive safety requirements to mitigate the risk of critical injury in the case of a collision between a vehicle and a person.

As required by the General and Pedestrian Safety Regulations (GSR and PSR), the European Commission (EC) has been conducting a review of those regulations in order to develop proposals for amendments and, potentially, to include new safety features. A first stage of the review considered more than 50 candidate measures that could be included in the GSR or PSR [1]. The outputs of the initial investigation were indicative cost-benefit analyses, which were provided in order to differentiate between measures that are very likely, moderately likely or very unlikely to provide a benefit consistent with the cost of implementation.

A second stage of the review focused on the 24 measures that were most likely to be cost-beneficial and therefore potentially included in the regulation by the Commission [2]. This research examined the measures in a higher level of detail than the previous investigation, to establish potential target populations (TPs) and expected effectiveness of the measures. These factors were then used in an in-depth cost-benefit model. In the process, the review revealed knowledge gaps in the literature for some of the measures, including the Adult Head to Windscreen Area Protection (HED) measure. A work programme was initiated, led by the European Automobile Manufacturers' Association (ACEA), to provide more evidence with respect to the likely casualty benefits that could be realised with some of the proposed GSR and PSR changes, including HED.

The current PSR excludes all areas behind the bonnet. The proposed HED measure would extend the current PSR adult head impact test zone to include the structures behind the bonnet. A larger test area will represent a greater proportion of casualties suffering head impacts when struck by the front of M1 vehicles [2]. Increasing the test zone to 2.3 m Wrap Around Distance (WAD) from the German In-Depth Accident Study (GIDAS) would increase the coverage of head contacts to 80% of all head impacts [3-5]. This would require testing to the windscreen and surrounding areas, which could include the windscreen Scuttle, A-pillars and windscreen glass. While cyclists typically have larger WAD than pedestrians [3], the measure is expected to influence pedestrian

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and cyclist casualties. Improving the secondary safety of these areas would require design changes to the vehicle exterior.

The GSR and PSR reviews involved consultation with key stakeholders, including members of ACEA, to understand the impact of implementing the measures on the automotive industry. One outcome of the process was an understanding of the engineering challenge involved in making the windscreen area passively safe for head contacts, and the attendant cost implications [2]. The most viable technical solution currently available was identified by the industry representatives as a state-of-the-art Pedestrian Protection Airbag (PPA), e.g. Volvo's pedestrian airbag technology [6]. The PPA detects a pedestrian or cyclist impact at the front of the vehicle and deploys an external airbag that covers the A-pillars and Scuttle.

The GSR review process for the EC highlighted that the proportion of pedestrian and cyclist casualties who contact the windscreen area was not known and that, as a consequence, the potential benefits of changes to the unregulated windscreen area could not be quantified. Accordingly, the effectiveness of the PPA was not understood in sufficient detail for the GSR review to accurately analyse the cost-effectiveness of implementing the HED measure.

The GSR review also sought to understand the overall cost-effectiveness of implementing primary safety measures in combination with secondary safety measures, as the primary measures can avoid some collisions and lower the collision speed of vehicles, complementing the injury mitigation effect of the secondary safety measures [7]. Autonomous Emergency Braking for Pedestrians and Cyclists (AEB-PCD) and Intelligent Speed Assistance (ISA) were considered for implementation with the HED measure [2]. It was not clear, however, how the implementation of these primary safety systems would alter the TP of a PPA by either avoiding the casualty or reducing the impact speed, while ensuring casualty savings are not overestimated.

This study aimed to conduct novel collision analysis to accurately identify the relevant TP for a PPA and derive effectiveness estimates for the primary and secondary measures. The results are intended to be used to predict the potential casualty savings in Britain if all three measures were implemented, with the important caveat of ensuring the predicted effect did not overestimate casualty savings for any measure by double-counting casualties prevented. The analysis output was shared with the EC for the third stage of the GSR review.

II. METHODS

Macro and micro collision data in Britain were taken from the Department for Transport's (DfT) STATS19 National Accident Statistics database and the Road Accident In-Depth Studies (RAIDS) database, respectively. STATS19 data for 2011 and 2015 and the on-scene investigation dataset of RAIDS for Collision years from 2000 to 2015 (excluding 2010 to 2011 when no data collection occurred) were used for this study.

The fitment or uptake of each safety measure in the vehicle fleet is not being modelled. It is assumed that all measures are found on 100% of vehicles. This is regardless of the measure and its stage of development in the market. While this means the results are not representative of the expected casualty savings in the five years following implementation of the measures, this limitation is true for all of the measures assessed in the GSR review, which allows a comparison to be made

During the analysis it was found that a proportion of vehicles were misclassified as N1 instead of M1 and vice versa. Using an enhanced STATS19 dataset, which adds vehicle-specific information (e.g. make and model), the misclassified vehicles were corrected.

Identifying target populations

Identifying the relevant TPs for each of the three measures is the first step in modelling the casualty benefits.

1) Pedestrian Protection Airbag (PPA)

The PPA TP was defined by selecting collisions with pedestrians or pedal cyclists impacted by the front of M1 vehicles (First point of impact = Front) from the STATS19 data. These criteria do not accurately define the PPA TP because STATS19 does not capture any greater detail on the impact configuration or precise head contact location, so the proportion of these collisions that fall into the PPA TP cannot be defined with STATS19 only. The RAIDS dataset was used to estimate the proportion of collisions within this sample that resulted in a relevant head contact, in order to further refine the TP.

Other impact configurations may result in a relevant collision for the PPA TP, but as the information captured in STATS19 is insufficient to robustly identify these collisions, they have been excluded from the analysis. Furthermore, when multiple vehicles are involved, STATS19 does not capture details of which vehicles impacted with each other or in what order. Therefore, collisions involving multiple vehicles have been excluded.

Pedestrians and cyclists struck by the front of M1 vehicles in RAIDS were reviewed case-by-case by researchers to identify which collisions involved a head contact to the relevant areas for the HED measure. The windscreen area was grouped into the areas shown schematically in Fig. 1. Cases involving child casualties (under 13 years old) were excluded from the case-by-case analysis and PPA assessment.

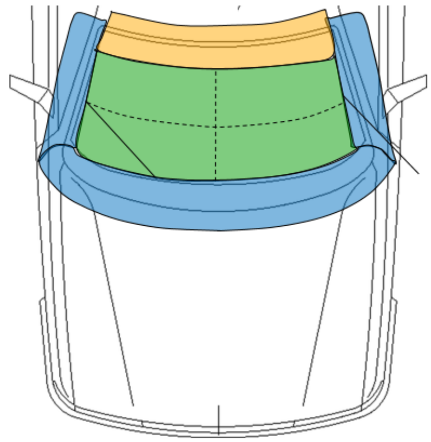

Fig. 1. Windscreen zones: A-pillar and Scuttle (blue); header rail (orange); and central windscreen (green).

The photographs and head contact evidence (based on lateral position and WAD measurements) of all RAIDS cases were reviewed to classify the head contacts into the individual zones. The A-pillar, Scuttle and header rail zones include the 10 cm of windscreen closest to each of these regions because this region of glass is well supported by the surrounding structures and is, therefore, much stiffer than the central windscreen area [8]. The risk of injury may be expected to be higher for these parts of the windscreen, and they are likely to be protected by the presence of a PPA.

The parameters of the PPA examined in this study are based on the current state-of-the art PPA available in the market, provided by consultation with ACEA members. The PPA only offers protection to head contacts to A-pillar and Scuttle area resulting in an AIS2+ head injury so the parameters defined the TP as a proportion of the KSI casualties suffering AIS2+ head injuries associated with those areas of the vehicle front. Vehicle speed at the point of impact was restricted to 20–60 kph because the source data for the injury risk functions was only collected from 20 kph and the PPA was shown to make negligible difference above 60 kph [9]. Based on the current state-of-the-art sensing technology from ACEA, sensor activation is only reliable if the first point of contact is within the central 80% of the vehicle width. Therefore, deployment of the PPA is assumed to be possible only when casualties are struck in this region.

2) Autonomous Emergency Braking for Pedestrians and Cyclists (AEB-PCD)

The TPs for the primary safety measures modelled in the analysis were defined from the STATS19 data, without the need for use of the RAIDS dataset, and used the same definitions as the GSR review [2]. The AEB-PCD TP was defined as all pedestrians or cyclists impacted by the front of M1 vehicles (First point of impact = Front).

3) Intelligent Speed Assistance (ISA)

The ISA TP was defined in STATS19 by selecting all collisions where the contributory factor ‘Excessive Speed’ was present. Collisions that also recorded contributory factors involving driver violations associated with risky behaviour [10] were excluded, as these drivers are assumed to be unlikely to abide by an ISA system.

Effectiveness Estimates

Modelling the casualty benefits the measures will have on their respective TPs required effectiveness estimates to be derived from injury risk functions of the casualties in the datasets.

1) Pedestrian Protection Airbag (PPA)

Head Injury Criterion (HIC) values from head-form tests to the Scuttle and A-pillars [9] were used to create new AIS2+ head injury risk functions. The new injury risk functions were used to calculate the injury risk and predicted effectiveness of the PPA for the individual casualties in the PPA TP by calculating the sum of AIS2+ injury risk for all cases that could be addressed by the PPA with the different injury risk curves. From this, the calculated percentage risk reduction was assumed to be the expectancy value and was calculated separately for killed and seriously injured pedestrians and cyclists for the PPA and AEB-PCD.

The in-depth collision sample is limited in size so the effectiveness estimate assumed that the casualties within the TP suffer their most severe injury at the head and not at other body regions. As the PPA is only able to address severe head injuries and not injuries to other body regions, this may result in an overestimation of the PPA effectiveness in terms of casualty class. However, while the overall casualty class may not change in the real world, the injury outcome could be greatly improved by reducing the severity of injuries to the head.

It was also assumed that head contact in the windscreen area is the source of maximum AIS (MAIS) head injury. However, all of the casualties in the PPA TP had a confirmed head contact to the A-pillar and Scuttle areas and the PPA system is designed to mitigate the injuries sustained in the contact between the head and the injurious structures of the vehicle exterior. Subsequent secondary collisions were not investigated in this analysis due to data limitations which would require case-by-case analysis to establish the injury mechanism which may result in an overestimation of the PPA effectiveness.

2) Autonomous Emergency Braking for Pedestrians and Cyclists (AEB-PCD)

The evaluation of the AEB-PCD is based on all killed and seriously injured (KSI) pedestrians and pedal cyclists who were impacted by the front of an M1 vehicle. In order to evaluate the effect of an AEB-PCD system, a simulation is conducted using state-of-the-art system parameters. As no simulation files are available for RAIDS, simulation files – so called Pre-Crash Matrix (PCM) files – from GIDAS were used in the first step [11]. Impact speed was considered in the methodology but did not account for changes in impact configuration. This methodology was used in [12,13]. The simulations were used to calculate vehicle collision speed for each case and to generate the associated appropriate MAIS2+ injury risk, based on the functions in Fig. 4.

For every collision, the AEB-PCD system is simulated. The simulation calculated if the system was triggered and if the collision was avoided or mitigated, resulting in a new collision speed being calculated for every collision based on the system's parameters (Table II). In order to account for different collision speed distributions between the PCM files and the RAIDS data, the average speed reduction within the PCM simulations in classes of 10 kph is calculated and transferred to the original collision speed in RAIDS (Table I).

TABLE I

AVERAGE COLLISION SPEED REDUCTION BASED ON THE ORIGINAL COLLISION SPEED DERIVED FROM GIDAS ANALYSIS

Simulated collision speed from PCM (kph)	Average speed reduction for cyclist collisions (kph)	Average speed reduction for pedestrian collisions (kph)
0–10	1.30	5.04
10–20	4.48	11.21
20–30	13.39	15.05
30–40	21.05	20.75
40–50	29.72	26.81
50–60	25.88	23.38
60–70	41.60	23.98
70–80	15.15	24.06
80–90	24.79	28.05
90–100	25.91	26.87
100–110	0.00 (not available)	0.00
110–120	0.00 (not available)	22.28

Based on the original and the simulated collision speed reduction, the change in MAIS2+ injury risk is calculated using injury risk functions from [14] for each individual casualty using Equations (1) and (2), with the injury risk shown in Fig. 4. If the collision was avoided the injury risk was set to 0.

Age of VRU < 60:

$$P(MAIS2+) = \frac{1}{1+e^{(3.016-0.079\,v_k)}} \quad \text{(Eq. 1)}$$

Age of VRU >= 60:

$$P(MAIS2+) = \frac{1}{1+e^{(2.223-0.113\,v_k)}} \quad \text{(Eq. 2)}$$

where P(MAIS2+) is the probability of MAIS2+ injury risk and *Vk* is the collision speed of the vehicle.

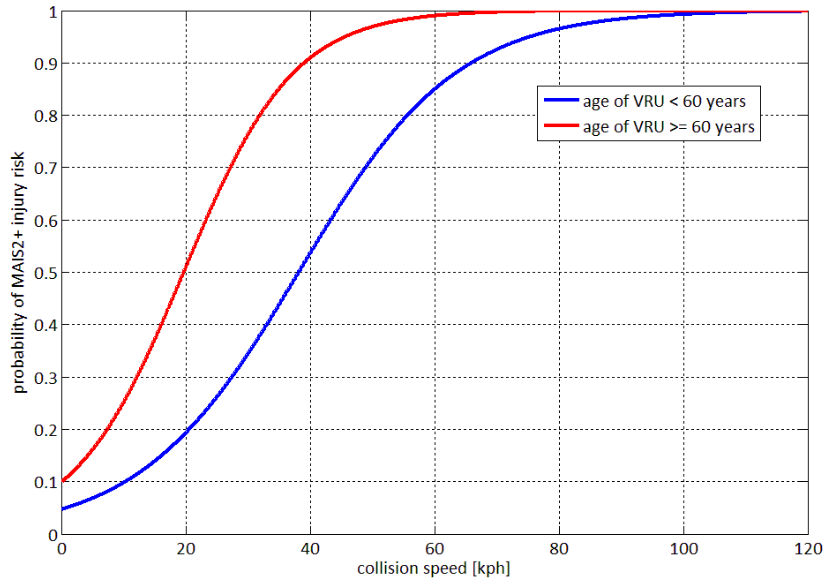

Fig. 2. Whole-body MAIS2+ injury risk based on collision speed for VRUs age <60 and >=60 years.

TABLE II
AEB-PCD SYSTEM PARAMETERS

Sensor	State-of-the-art system parameters
Opening angle	2 x 30° (60°)
Range	80 m
Mount (longitudinal)	On windshield (1.80 m behind front of vehicle)
Mount (lateral)	Centre
Object detection	100% in view for classification (complete pedestrian, cyclist w/o bike)
Acquisition time	0.15 s
Cycle time	0.015 s
Angle between rays	0.05°
Intervention	TTC 1.0 s and VRU detected

Within the analysis, 983 collisions between VRUs and passenger cars were simulated using the rateEFFECT tool [13]. The simulated AEB-PCD system consists of a perfect ray-based sensor, an algorithm and a brake system (**Error! Reference source not found.** II). There is no consideration of sensor availability or climatic conditions within the simulations.

The sensor field of view is modelled as a circle sector with an opening angle of 60° and a radius of 80 m (range). The sensor itself is mounted at the windshield, assumed to be 1.8 m behind the front. In order for the sensor to be able to detect the VRU, the complete VRU (i.e. the pedestrian or the cyclist without the bicycle) must be in the field of view. After the first detection, an object is generated, if the object is in the circle sector for 150 ms (acquisition time). The sensor measures distances, velocities and positions every 15 ms (cycle time). The field of view is modelled with rays in a distance of 0.05° between the rays.

The AEB-PCD is triggered if the object is detected and is in the field of view for at least 150 ms and the time-to-collision (TTC) goes below 1.0 s. After the AEB-PCD signal is triggered by the algorithm, the brakes are applied, assuming a brake delay of 200 ms before the actual onset of braking. Furthermore, a brake gradient of 24.525 ms^{-3} is modelled with a maximum deceleration of 1 g (e.g. build-up time of 400 ms at a friction coefficient of 1.0). If, in the original accident scenario, the driver was already applying the brakes before the AEB-PCD intervention, the brake delay is set to 0 ms.

3) Intelligent Speed Assistance (ISA)

The effectiveness assessment of the ISA system was conducted in parallel to this study, and as a result the mitigation effect was not incorporated into the adjusted injury risk curves but was expressed as a separate value, expressed as a percentage of all casualties who had a reduction in casualty class (i.e. fatal to serious injury or serious to slight injury). The effectiveness estimate for ISA was based on a novel case-by-case analysis of 100 RAIDS collisions involving M1 vehicles that were exceeding the speed limit [15]. The collisions in the sample included multiple collision types and were not limited to M1 vehicles impacting VRUs. The likelihood of ISA to either avoid or mitigate the severity of the collision was assessed by collision investigators, resulting in a predicted effectiveness estimate of 19.0% for avoidance and 6.0% for mitigation. Mitigation was classified as a reduction in casualty injury severity class (e.g. 6.0% of fatalities became seriously injured). The sample of RAIDS cases was not exclusively pedestrians and cyclist collisions, however, so the real-world effectiveness estimate of ISA within the context of the overall casualty population may vary.

Modelling casualty savings

The casualty saving model applies the effectiveness values for all three measures to the relevant TPs of casualties within the overall GB casualty population from 2011 to 2015 without double counting casualties who could be prevented by either of the primary safety measures and the PPA. The effectiveness values generated for AEB-PCD and PPA take into account the reduction in impact speed when AEB-PCD would have activated but could not avoided the collision but do not consider the resulting change in WAD or impact location. The effectiveness value for ISA was generated in parallel to this analysis and does not integrate the predicted impact speed reduction the system is likely to produce. Each effectiveness value is applied to the relevant target population to estimate the number of casualties avoided by the measures.

The overall casualty population of VRU casualties struck by the front of a car contains sub-populations of casualties that are in collisions relevant to one or more of the assessed measures. The model applies the effectiveness of the primary safety measures before the PPA to eliminate casualties from the population and prevent double counting for a more accurate casualty benefit assessment. The order in which the primary safety measures are applied does not affect the overall casualty savings but does change the number of casualties each measure is estimated to save because some of the casualties appear in both TPs. Therefore, the casualties eliminated by primary safety measures are shown as a combined value because the analysis must be repeated within the context of each measure's own TP to provide a true assessment of their casualty benefit.

III. RESULTS

Target population for PPA

In Britain (GB), 53,955 pedestrians and 35,096 cyclists were hit by the front of M1 vehicles from 2011 to 2015 (Table III). STATS19 casualty severity definitions were used where serious casualties are detained in hospital as in-patients or suffer predefined injuries that are generally analogous to AIS2+ injuries and survived at least 30 days after the collision [16].

From a total sample of 255 pedestrians and cyclists (all injury severities) that struck the front of an M1 vehicle in the RAIDS dataset, 36.1% (n=92) struck the windscreen area. However, 125 were KSI casualties and 74 of the 125 had a reliable known collision speed calculated as part of the in-depth reconstruction (Table III). The multiplication factors in Table III that scale the in-depth data to the national figures are used to determine the estimated effectiveness values for the PPA (Table VII).

The distribution of pedestrians (n=54) and cyclists (n=20) struck by the front of an M1 vehicle by the incidence and position of head contacts to the windscreen zones (A-pillars and Scuttle (blue); header rail (orange); central windscreen (green)) are detailed in Table IV. The coloured areas relate to the different windscreen areas defined in Fig. 1.

The PPA only protects head contacts to the A-pillar and Scuttle (blue) areas. Grouping the contact points into the colour-coded sections of windscreen (green), A-pillars (blue), Scuttle (blue) and all other contact points, the Maximum AIS Head injury score is shown in Table V.

TABLE III
CASUALTIES IN COLLISIONS WITH FRONT OF M1 VEHICLES

	Severity	Pedestrians	Cyclists	Total
GB (STATS19)	Fatal	961	181	1,142
	Serious	11,825	5,338	17,163
	Total	12,786	5,519	18,305
In-Depth (RAIDS)	Fatal	6	3	9
	Serious	48	17	65
	Total	54	20	74
Scaling factor	Fatal	160.17	60.33	
	Serious	246.35	314.00	

TABLE IV
INCIDENCE OF WINDSCREEN ZONE HEAD IMPACTS FOR RAIDS PEDESTRIANS (PED) AND CYCLISTS (CYC)

Vehicle feature	OS A-pillar		OS half of W/S		NS half of W/S		NS A-pillar		None		Total
Road user type	Ped	Cyc	Ped	Cyc	Ped	Cyc	Ped	Cyc	Ped	Cyc	
Header rail	0	1	0	0	0	1	0	0	0	0	2
Top half of W/S	0	1	1	0	3	0	0	0	0	0	5
Bottom half of W/S	2	0	5	0	6	2	2	0	0	0	17
Scuttle	0	0	2	0	3	2	0	0	0	0	7
None	0	0	0	0	0	0	10	4	20	9	43
Total	2	2	8	0	12	5	12	4	20	9	74

Some of the cyclists were wearing helmets, but there were no incidences of cyclists wearing a helmet suffering an AIS2+ head injury in this sample so helmeted cyclists are not included in the TP definition and effectively excluded from the analysis.

Table V shows 54 KSI pedestrians in frontal collisions with M1 vehicles (in all head impact locations) at known collision speeds, with 43% (n=23 of 54) suffering an AIS2+ head injury. Of the KSI pedestrians, 13% (n=7 of 54) suffered an AIS2+ head injury associated with the A-pillar or Scuttle area and 13% (n=7 of 54) associated with the glazed windscreen area.

TABLE V
MAXIMUM HEAD AIS SEVERITY FOR KSI PEDESTRIANS AND CYCLISTS BY INCIDENCE OF HEAD CONTACT TO WINDSCREEN AREA

	MAIS head	Windscreen	A-pillar	Scuttle	Others	Total
Pedestrians	0–1	6	1	3	21	31
	2–6	7	5	2	9	23
	Unknown	0	0	0	0	0
	Total	13	6	5	30	54
Cyclists	0–1	1	1	1	13	16
	2–6	0	1	1	1	3
	Unknown	1	0	0	0	1
	Total	2	2	2	14	20

A total of 20 pedal cyclists were KSI in frontal collisions with M1 vehicles at known collision speeds, with 15% (n=3 of 20) suffering an AIS2+ head injury in all head impact locations. Of these, 10% of KSI cyclists (n=2 of 20) suffered an AIS2+ head injury associated with the A-pillar or Scuttle areas. No cyclists suffered an AIS2+ head injury associated with the glazed windscreen area.

To define the PPA TP, the analysis considered the M1 vehicle's collision speed for the pedestrians and cyclists with AIS2 to AIS6 head injuries, shown in Table VI. All (n=14) pedestrians and one cyclist (5% of all cyclists) with AIS2+ head injury associated with the windscreen zones reported collision speeds of between 20 kph and 60 kph.

Four of the seven pedestrians who had an AIS2+ head injury associated with the A-pillar or Scuttle in Table VI (one fatal, three seriously injured) contacted the car within the central 80% of the vehicle width. The remaining cyclist collided with the car at the outer 10%, resulting in four pedestrians and 0 cyclists in the final PPA TP. The PPA TP represents 57% of KSI pedestrians and 0% of KSI cyclists who suffered an AIS2+ head injury associated with A-pillar or Scuttle areas at collision speeds between 20 kph and 60 kph and had their first contact with the M1 vehicle within the central 80% of the vehicle width. The PPA TP represents 7% (n=4 out of 54) of KSI pedestrians and 0% (n=0 out of 20) of KSI cyclists who were impacted by the front of an M1 vehicle.

TABLE VI
M1 COLLISION SPEED FOR KSI PEDESTRIANS AND CYCLISTS WITH HEAD AIS2+ INJURIES BY INCIDENCE OF HEAD CONTACT TO WINDSCREEN AREA

	Collision speed (kph)	Windscreen	A-pillar	Scuttle	Others	Total
Pedestrians	<20	0	0	0	4	4
	20–60	7	5	2	4	18
	>60	0	0	0	1	1
	Total	7	5	2	9	23
Cyclists	<20	0	0	0	0	0
	20–60	0	1	0	1	2
	>60	0	0	1	0	1
	Total	0	1	1	1	3

Effectiveness estimates for measures

The calculated percentage risk reduction for killed and seriously injured pedestrians and cyclists for the PPA and AEB-PCD are shown in Table VII, based on the injury risk functions [9] applied to the individual cases in the PPA TP to determine the AIS2+ injury risk and estimate the PPA effectiveness (Fig 2 and Fig 3).

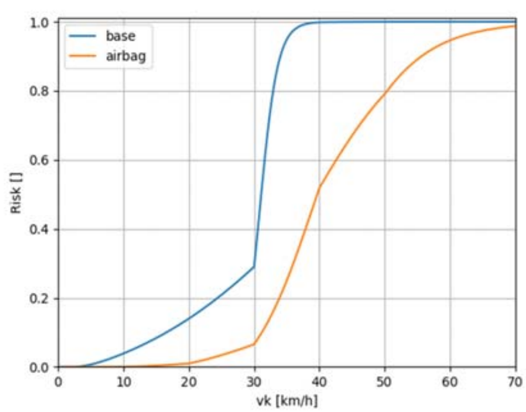

Fig. 3. AIS2+ head injury risk for lower windshield/Scuttle impacts by collision speed (*Vk*).

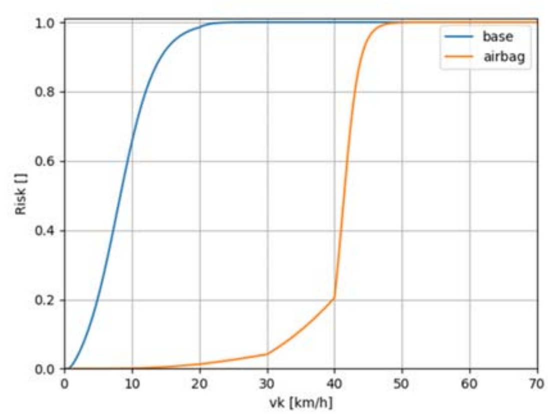

Fig. 4. AIS2+ head injury risk for A-pillar impacts by collision speed (*Vk*).

Overall, the combined effectiveness for all severities and VRU types scaled to STATS19 is 1.07% in frontal collisions with M1 vehicles, and the AEB-PCD results in an overall effectiveness of 55.89% for all KSI VRUs. No relevant cyclist collisions were captured in the RAIDS dataset, therefore it is not possible to estimate the effectiveness for cyclists because there is no evidence that a PPA would affect cyclists. This is reflected in the combined scaled effectiveness value for the PPA.

TABLE VII
PPA AND AEB-PCD EFFECTIVENESS EVALUATION FOR KSI PEDESTRIANS AND CYCLISTS SCALED TO STATS19

	Fatally injured	Seriously injured
Pedestrians	E_{PPA}= 13.26%	E_{PPA}= 0.58%
	$E_{AEB\text{-}PCD}$= 39.12%	$E_{AEB\text{-}PCD}$= 58.67%
Cyclists	E_{PPA}= 0%	E_{PPA}= 0%
	$E_{AEB\text{-}PCD}$= 44.44%	$E_{AEB\text{-}PCD}$= 53.12%

Predicted Casualty Savings

The effect of the three studied measures on their respective TPs and the resulting casualty savings to the overall population of pedestrians and cyclists struck by the front of M1 vehicles over five years of collision data in GB are shown in Table VIII.

AEB-PCD and ISA are predicted to prevent 459 (378 pedestrians, 81 cyclists) fatalities and 9,724 (6,885 pedestrians, 2,839 cyclists) seriously injured casualties over a five-year period in GB. Furthermore, ISA was modelled to mitigate 41 (35 pedestrian, six cyclist) fatalities to serious injuries and 400 (256 pedestrian, 144 cyclist) seriously injured casualties to slightly injured. From the remaining casualty population (542 fatal and 4,583 seriously injured pedestrians; 94 fatal and 2,358 seriously injured cyclists), a PPA is predicted to prevent 72 fatally injured and 27 seriously injured pedestrians over the five-year period. No prediction for cyclists prevented by the PPA was possible.

TABLE VIII
TARGET POPULATIONS WITH PREDICTED CASUALTY SAVINGS AND REMAINING CASUALTIES

		Fatal	Serious	Slight	Total
Pedestrians	GB VRUs struck by M1 front	955	11,724	-	12,679
	AEB-PCD + ISA casualties prevented	378	6,885	-	7,263
	ISA casualties mitigated	35	256	-291	-
	PPA effect	72	27	-	99
	Total Savings	*450*	*6,912*	-	*7,362*
	Remaining Casualties	*470*	*4,556*	*291*	*5,317*
Cyclists	GB VRUs struck by M1 front	181	5,341	-	5,522
	AEB-PCD + ISA casualties prevented	81	2,839	-	2,920
	ISA casualties mitigated	6	144	-150	-
	PPA effect	-	-	-	-
	Total Savings	*81*	*2,839*	-	*2,920*
	Remaining Casualties	*94*	*2,358*	*150*	*2,602*

IV. DISCUSSION

The prevalence of head contacts to the areas of the vehicle not currently regulated by the PSR was 41.9% (n=31 of 74) of KSI pedestrians and cyclists who are struck by the front of M1 vehicles (Table IV). The unregulated windscreen areas pose a serious head injury risk as 21.6% (n=16 of 74) of those KSI casualties suffered an AIS2+ head injury associated with the head contact to that area of the vehicle exterior (Table V).

In the sample of 26 casualties with an AIS2+ head injury, over a quarter (26.9%) are believed to have sustained their injury as a result of an impact with the windscreen glass. Further research is required to understand if windscreen design and/or the material properties of the glass can be improved to reduce the risk of these injuries. Some VRU casualties suffered head contacts to the windscreen that did not result in AIS2+ head injuries. Further work is needed to understand the influence of impact type with regard to car speed, location of contact and pedestrian characteristics, such as stature, age and gender, in order to understand the potential opportunity to improve the secondary safety of windscreens for pedestrian and cyclist impacts.

Once the system parameters were taken into account, the PPA was able to provide protection for 7.4% (n=4 of 54) of the KSI pedestrians, but there were no cyclists in the sample to demonstrate the injury mitigation benefits of the PPA, so the effectiveness was modelled as null for cyclists. Although the PPA is the best measure to protect the head currently available, this study found it is able to influence a TP of 5.4% of the overall casualty population before its effectiveness is considered.

There were no cyclists in the in-depth sample to demonstrate the benefit of the PPA on lowering head injury risk, but the benefits of a PPA are also believed to extend to cyclists with head contacts to the A-pillar and Scuttle. In general, cyclists have a greater WAD for head contacts than pedestrians [4,5,7], but they are underrepresented in the PPA TP, despite 30% (n=6 of 20) of the overall cyclist casualty population striking their heads in the unregulated windscreen area (Table V). WAD was not analysed in detail in this study, however, the distribution of head contacts in Table V shows a greater proportion of cyclists contacting areas with larger WADs. Of the cyclists who suffered head strikes above the bonnet line, 42.9% (3 of 7) were in the top half of the windscreen zones compared to 16.7% (4 of 24) for pedestrians which is indicative of the different impact mechanics between the road user types.

There are proposals on how to adapt the pedestrian head impactor angle and velocity for cyclists given the different collision dynamics between the road user types [8], however, no decision has been taken on exactly how to adapt the test procedures for the proposed measure. This analysis assumes the PPA would yield the same reduction in HIC as determined by the data from pedestrian head-form testing [9], it is not based on a new validated test procedure.

While it is likely that a softer engagement with the vehicle exterior afforded by a PPA is likely to benefit all head injuries types, the PPA TP will include some casualties with brain injuries associated with head rotation. The effectiveness value for the PPA only considers injury reduction based on linear acceleration to the head based on HIC. Therefore, the PPA effectiveness value calculated in this analysis may vary for those casualties sustaining brain injuries associated with head rotation. Furthermore, the proportion of casualties in the TP who sustained their head injuries from secondary contact with other surfaces (e.g. the road surface), for which a PPA offers no protection, has not been defined in this analysis. The PPA effectiveness values and resultant casualty benefit estimates calculated in this study could be further refined by giving considering to these sub-populations of casualties within the PPA TP.

Helmeted cyclists were included in the analysis of head contacts distribution to the vehicle front (Table IV) but they were effectively excluded from the PPA effectiveness analysis because there were no incidences of AIS2+ head injuries in any cyclist wearing a helmet in the in-depth sample. Therefore, it was not possible to demonstrate the effectiveness of a PPA on the helmeted cyclist casualty population due to the in-depth data limitations. It is expected that the PPA would yield benefits for helmeted cyclists as well as non-helmeted cyclists, however, more detailed analysis of the interaction between a PPA and the helmeted cyclist is required before it can be determined if there are negative consequences for a PPA.

The lack of helmeted cyclists suffering serious head injuries could be an indication of the injury mitigation effect of wearing a cycle helmet, or an artefact of the small sample size. Helmet types, wearing rates and exposure were not examined in detail in this analysis, therefore no conclusion should be drawn on the efficacy of cycle helmets.

Children were excluded from the PPA effectiveness assessment, however, it is expected that children and adults with small stature who sustain head strikes to the relevant areas of the vehicle front will experience some injury mitigation effect from a PPA. However, STATS19 does not capture sufficient data to determine the proportion of casualties that sustained a head contact to a PPA relevant area on the vehicle that struck them (e.g. stature, impact speed and vehicle geometry). Furthermore, the precise injury risk reduction effect could not be calculated as the injury risk curves are based on adult head injuries [9]. Due to these limitations this analysis makes an optimistic assumption that the injury mitigation benefits of a PPA could extend to the entire casualty population, including casualties with small stature and will likely result in an overestimation of the real-world effectiveness of a PPA.

Effectiveness estimates for the PPA and AEB-PCD are both expressed as the percentage of KSI casualties prevented (Table VII). The analysis shows a much greater AEB-PCD effectiveness and resulting casualty benefit than PPA for all casualty groups. The primary safety system has a broader TP definition, which includes the PPA's TP as it has the potential to positively influence all of the 74 KSI pedestrians and cyclists in the in-depth sample and is not limited to one body region and hence, independent of head contacts to the windscreen areas.

More than half of the pedestrian (57.3%) and cyclist (52.9%) KSI casualties were predicted to be prevented by the combined implementation of ISA and AEB-PCD in GB. The casualties that could not be avoided represent the remaining casualty population at risk of having a head contact to the unregulated windscreen areas of the vehicle front. It is this portion of the TP that might benefit from improved secondary safety measures of the vehicle's exterior, however not all of the remaining casualties have head injuries or head contacts at the windshield area, so only parts of the remaining percentage can be addressed. In this study the overall incidence of head contact to those areas was found to be 41.9% (n=31 of 74, Table IV). However, the PPA was predicted to prevent only 1.8% of the remaining KSI pedestrians, and no casualty benefit for cyclists could be shown in this analysis, resulting in a residual casualty population of 7,919 KSI pedestrians and cyclists that would not be prevented by any of the measures.

The effectiveness values for all three measures were used to predict casualty benefits in GB over the five years of national collision data by categorising the individual casualties from the national sample into the one or multiple TPs based on the collision type. Some casualties were injured in collisions or vehicles that are relevant to multiple measures, resulting in overlapping sub-populations within a TP. The analysis is able to consider the effect of all the relevant measures on the TP so that casualties who were present in more than one TP are not counted as prevented more than once, i.e. no double-counting. The model predicts the casualty benefits for all pedestrians and cyclists impacted by the front of M1 vehicles if all three measures were implemented with 100% fitment in the GB vehicle fleet.

None of the individual measures nor the combination of measures results in total protection for pedestrians or cyclists. Even with the implementation of all these measures, pedestrians and cyclists will be killed and seriously injured when struck by M1 vehicles and some will sustain the most severe injury to the head, caused by contact with the areas not currently regulated by the PSR. The results show that it is crucial for all VRU collisions to reduce the collision speed, as the injury risk directly correlates with the collision speed. The AEB-PCD system can avoid collisions completely, while secondary safety measures are only able to mitigate the consequences of the collisions. Continued research into the incidence and severity of serious head injury risk from these areas is important to steer regulatory requirements so that they are applicable to the collisions and casualties occurring in the real world [17].

Future changes in the vehicle fleet in Europe may have an influence on the kinematics of pedestrian and cyclist collisions, and the resulting injuries. New vehicle registration data in Europe show an increasing proportion of SUVs and small and medium segment cars (A, B and C segments), comprising more than half of new car registrations in Europe [18]. Vehicle designs with smaller bonnets and larger windscreens have been shown to influence VRU kinematics and can potentially increase the severity of head injuries [19].

With a changing vehicle fleet, including more Electric Vehicles and a move towards more automation, future secondary safety impact tests must represent the areas on the vehicle where pedestrian and cyclist body regions will be struck in the event of a collision, because collision incidents will continue whilst there is a mixed fleet during the period of technological transition.

V. CONCLUSIONS

Collision speed and the resulting head collision speed are critical factors for the serious head injury risk of the unregulated windscreen and surrounding areas. The primary safety measures were quantified in terms of their ability to reduce the collision speed and were shown to have the potential to reduce overall injury risk or even avoid some collisions. The overall predicted effectiveness of AEB-PCD (56%) and ISA (19%) was considerably greater than that of the PPA (1%), which has a much smaller TP. When the potential casualty benefits on the GB collision population were modelled in this study, 99% of the prevented casualties were due to the primary safety systems.

The analysis is sensitive due to a small sample of in-depth pedestrian collisions, and the benefits for cyclists were not demonstrated in this study because of data limitations. The implementation of primary and secondary safety measures together has been shown to provide a greater overall casualty benefit in the total number of casualties prevented.

A residual casualty population of pedestrians and cyclists who will be killed and seriously injured remains, despite modelling an optimised 100% fitment rate of the systems. The proportion of casualties striking the unregulated windscreen areas and the incidence of serious head injuries that occur as a result demonstrates the importance of continued research interest in those areas of M1 vehicles' exteriors, although this is expected to be technically challenging.

Overall, this modelling of the target populations and effectiveness indicates that the primary safety systems of AEB-PCD and ISA, by preventing the collisions from occurring, have the greatest effect for reducing pedestrian and cyclist casualties. The PPA could help to mitigate the remaining head injuries that do occur, but its TP is quite restricted.

VI. ACKNOWLEDGEMENTS

The authors acknowledge the funding from ACEA that contributed to the GSR and PSR reviews. The authors also acknowledge the permission to use the RAIDS database, granted by the UK Department for Transport.

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