# Recommendation for Modifying the Current Testing Standard for PTW Rider Chest Protectors

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## I. INTRODUCTION

Powered two-wheelers (PTWs, mopeds, motorcycles) are a popular but dangerous means of transport. About 34 million PTWs were circulating in the Europe Union (EU) in 2014 [1], during which the PTW passengers only accounted for 1.9% of all transport users but for 17.6% of traffic fatalities [2]. With little protection against injuries from PTW, PTW riders represent one of the most vulnerable road user groups. The rider thorax was found injured in 50% of the potential fatal injuries (Abbreviated Injury Scale (AIS) $\geqslant$4) [3]. The non-inflatable chest protector is a passive safety device for PTW rider chest protection to absorb and dissipate the impact energy. Before putting it on the market, the non-inflatable chest protectors must meet the performance requirements of the European Standard EN1621-3:2018 [4]. However, the impact energy level of 50J in the standard tests seems to be much lower than the expected PTW impact energy levels [5]. It is uncertain how the testing force limits (24kN and 18kN) were selected or how they should be correlated with the performance of the protectors in PTW collisions. Therefore, the objective of this study was to identify whether the current testing standard EN1621-3:2018 would guarantee sufficient chest protection for PTW riders.

## II. METHODS

The whole study consists of two consecutive parts: performance evaluation of three chest protector configurations against 1) the standard (EN1621-3:2018) impact attenuation tests and 2) against the PTW rider chest impact conditions. These two parts were both performed with finite element (FE) modelling.

### *Standard impact attenuation test*

Three chest protector configurations were considered in this study and the three configurations had the same surface area as the minimum protection zone required in the standard [4]. Protector configuration 1 ('Prot-1') was modelled as hyperelastic rubber material (the first shear modulus $\mu_1$=0.7MPa, the second shear modulus $\mu_2$=-0.5MPa, the first material exponent $\alpha_1$=2.0 and the second material exponent $\alpha_2$=-2.0) with a uniform thickness of 30mm. Protector configuration 2 ('Prot-2') was modelled as elastic material (E=2.5MPa) with a uniform thickness of 15mm while protector configuration 3 ('Prot-3') was modelled as (E=25MPa) with a uniform thickness of 30mm. The thickness and elastic modulus of chest protector were randomly chosen while the material properties of Prot-1 was based on a realistic rubber material from [6]. The anvil and bar impactor (displayed in Figure 1, please refer to [4] for detailed sizes) were both modelled as steel material. As required in the testing standard [4], five impact configurations were determined in current test modelling (Figure 1). The impact sites were chosen respectively at the centre (Figure 1A, cited as 'Imp-Cen'), top (Figure 1C, cited as 'Imp-Top'), bottom (Figure 1D, cited as 'Imp-Bot'), left (Figure 1E, cited as 'Imp-Lef') and right (Figure 1F, cited as 'Imp-Rig') side of the protector. For each impact configuration, the bottom (the leftmost surface in Figure 1B) of the anvil was fixed in the simulation. The bar impactor (length 160mm and mass 5kg) was applied with an initial velocity of about 4.5m/s along -z direction (Figure 1B) to produce an impact energy of 50J. The peak forces transmitted to the anvil in each impact and the averaged peak values for each protector configuration were measured and evaluated.

### *PTW rider chest impact*

Bar impacts to the rider chest with or without (W/WO) a protector were simulated in this section (see Figure 2) to evaluate the efficacy of the protectors on chest protection in PTW collisions. The HUMOS2 model, which has been validated against various car crash scenarios [7] and applied for PTW accident injury investigations [8], was currently used to model the rider. The same bar impactor and protectors as above were also used in current simulations. The impactor and protectors were always centred at the mid-sternum level corresponding to the third costal interspace (Figure 2). The impactor was applied with an initial velocity of 4.5m/s, 10.0m/s

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15.0m/s, 20.0m/s and 25.0m/s respectively to hit the protector or the rider's chest. Symmetric contact groups were defined respectively for the impactor-protector, protector-HUMOS2 and impactor-HUMOS2. Chest responses including the thorax impact force, chest deflection and viscous criterion (VC) [9] were evaluated in this section. The thorax impact force was measured as the contact force of impactor-HUMOS2 in the simulations without protector and as the contact force of protector-HUMOS2 in the simulations with a protector. Chest deflection was measured as the change in length between a node on the skin at the mid-sternum and a node on the skin at the T9 level (Figure 2B and 2D). The VC was calculated with the equation $VC = \frac{d(D(t))}{dt} \times \frac{D(t)}{b}$ as reported in [9]. In the equation, D(t) is the thorax deflection and b is the initial chest depth 260.8mm. The injury risk sustained by the rider was estimated using the peak chest deflection ($\text{Deflection}_{max}$) and peak VC ($VC_{max}$) for the Bar-to-Rider impact configurations, based on the injury risk functions developed by [10-11].

All the simulations in standard impacts and rider chest impacts were performed using the explicit-dynamic FE solver Radioss (Version 2017, Altair HyperWorks Inc.).

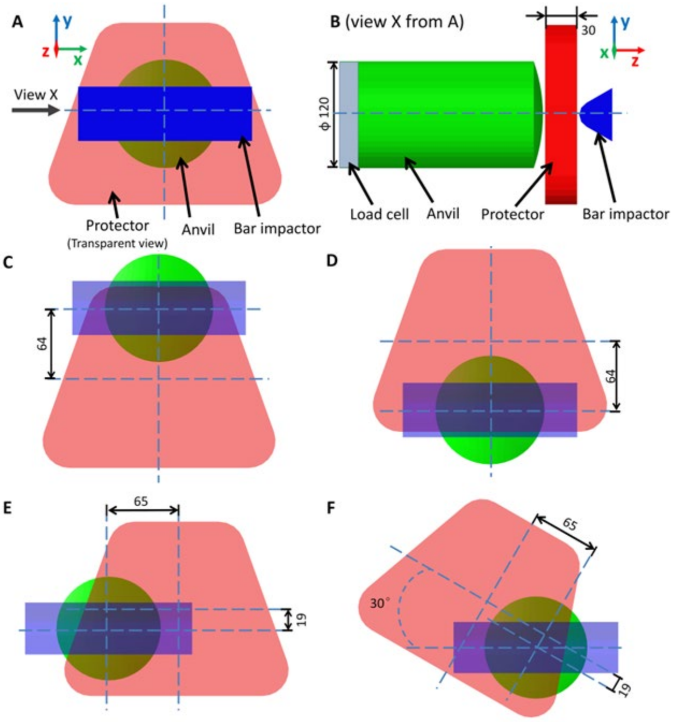


Fig. 1. Standard (EN1621-3:2018) impact attenuation test modelling. A) Top view of the impact at the protector centre; B) The view X (lateral view) of the impact at the protector centre; C) Impact at the top of the protector; D) Impact at the bottom of the protector; E) Impact at the left part of the protector; and F) Impact at the right part of the protector with the protector rotating -30° around Z direction.

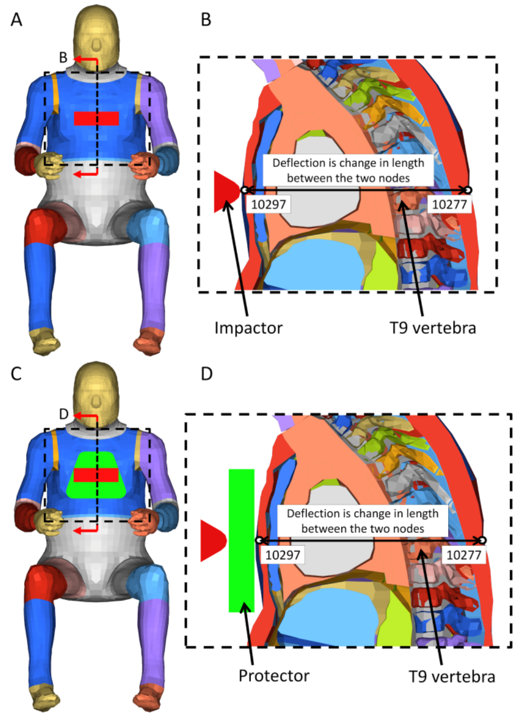


Fig. 2. Simulation setup of rider chest impacts for injury analysis. A) Bar impact to the rider without a protector; B) The cross-section view of the rider's chest to show the measurement of thoracic deflection; C) Bar impact to the rider with a protector; and D) the cross-section view of the rider's chest to show the measurement of thoracic deflection.

## III. INITIAL FINDINGS

The three protectors all passed the standard impact attenuation tests (TABLE I) and thus are expected to provide chest protection for PTW riders. In Bar-to-Rider impacts, the peak chest impact force ($\text{Force}_{max}$), $\text{Deflection}_{max}$ and $VC_{max}$ increased with the increasing impact energy levels for each protector-wearing scenario. $\text{Force}_{max}$ was always below 20kN when wearing a protector and below 16kN without protector in all the impacts (TABLE II). With the standard impact energy level (50J corresponding to 4.5m/s impact velocity), $\text{Deflection}_{max}$ was always below 22mm when wearing a protector and below 26mm without protector (TABLE II). Similar to the peak thorax responses, the risks of different injury severities increased with the increasing impact energy levels, not depending on protector or impact configurations (Figure 3). The risk of any injury level resulting from 50J impact energy (impact velocity 4.5m/s) was always negligible W/WO a protector.

TABLE I

THE PEAK FORCES MEASURED IN EACH IMPACT OF THE THREE CHEST PROTECTOR CONFIGURATIONS SHOWING THEIR CAPACITY TO MEET THE PERFORMANCE REQUIREMENT OF EN1621-3:2018.

| Protector \ Impact site / Force (kN) | Imp-Cent | Imp-Top | Imp-Bot | Imp-Lef | Imp-Rig | Average |
|---|---|---|---|---|---|---|
| *Prot-1* | 8.4 | 8.0 | 8.0 | 6.7 | 7.3 | 7.7 |
| *Prot-2* | 14.6 | 14.4 | 14.0 | 12.9 | 12.9 | 13.8 |
| *Prot-3* | 14.4 | 17.5 | 15.4 | 17.6 | 17.3 | 16.4 |
| Standard limits | | | 24.0 | | | 18.0 |

TABLE II

THE PEAK THORAX IMPACT FORCES, DEFLECTION AND VCP SUSTAINED BY THE PTW RIDER WITH DIFFERENT PROTECTORS IN BAR-TO-RIDER IMPACT

| Velocity (m/s) | $Force_{max}$ (kN) | | | | $Deflection_{max}$ (mm) | | | | $VC_{max}$ (m/s) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | None | Prot-1 | Prot-2 | Prot-3 | None | Prot-1 | Prot-2 | Prot-3 | None | Prot-1 | Prot-2 | Prot-3 |
| *4.5* | 2.7 | 2.8 | 2.6 | 3.0 | 25.1 | 18.7 | 21.1 | 16.6 | 0.22 | 0.16 | 0.19 | 0.14 |
| *10.0* | 5.0 | 5.7 | 5.2 | 8.2 | 59.7 | 47.7 | 54.0 | 38.3 | 0.98 | 0.74 | 1.08 | 0.62 |
| *15.0* | 7.7 | 8.8 | 8.3 | 12.8 | 99.8 | 80.4 | 88.8 | 73.3 | 2.01 | 1.71 | 2.10 | 1.33 |
| *20.0* | 10.8 | 12.1 | 11.6 | 16.8 | 133.4 | 110.4 | 120.3 | 101.2 | 3.48 | 3.05 | 3.19 | 2.38 |
| *25.0* | 15.2 | 15.7 | 15.5 | 19.7 | 143.7 | 129.6 | 136.1 | 122.0 | 5.35 | 4.42 | 4.69 | 3.63 |

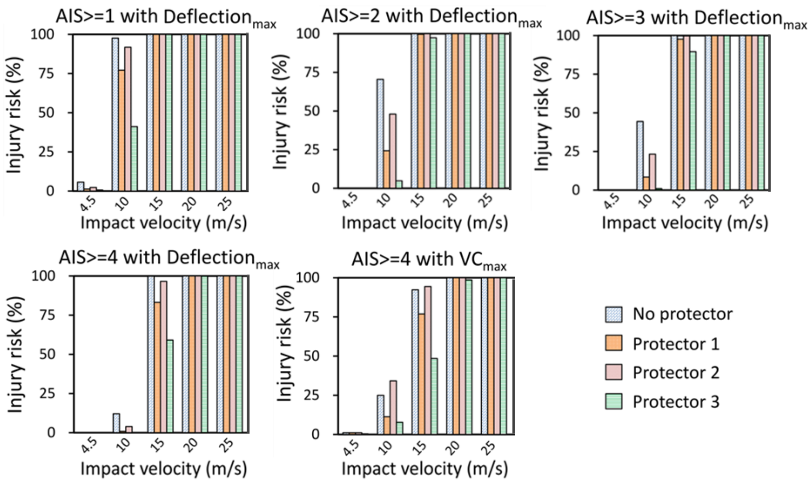


Fig. 3. Injury risk estimation using the peak thorax deflection ($Deflection_{max}$) and VC ($VC_{max}$) sustained by rider W/WO protector in Bar-to-Rider impact configurations.

## IV. DISCUSSION

The $Force_{max}$ sustained by the PTW rider without protector was less than that of the rider with a protector in most impact scenarios. The rider with Prot-3 had the highest $Force_{max}$, followed by the rider with Prot-1 and Prot-2 (Table II). The rider with any protector sustained a $Deflection_{max}$ less than that of the rider without protector (Table II). The rider with Prot-3 had the least $Deflection_{max}$, followed by the rider with Prot-1 and Prot-2. Therefore, from the perspective of $Deflection_{max}$, the current three protectors would provide riders with different levels of protection. However, wearing a protector made little difference in risk reduction for any injury severity for impact energy higher than 562.5J (simply calculated as the kinetic energy of the moving bar with 5kg mass and 15m/s impact velocity) (Figure 3). This suggests that the efficacy of the protectors in injury mitigation would be quite limited in the scenarios with impact energy >562.5J.

The 50J impact energy defined in the testing standard might be insufficient for device evaluations, because the rider without protector would only have an injury risk of AIS1+ below 6% under 50J impact energy (Figure 3). It seems unnecessary to protect the rider from a loading condition free of injury. Moreover, the 50J energy level is far less than the energy level of 1813J proposed by [5] to cover 75% frontal chest impacts. The rider with the 'standard-qualified' protectors could have an injury risk up to 100% for AIS2+ and above 70% for AIS3+ under the impact energy of 562.5J (impact velocity 15.0m/s) (Figure 3). Therefore, the device cannot warrant its protection efficacy in more severe impacts if it is only designed and evaluated against injury-free loading levels (50J).

The force thresholds (18kN and 24kN) of the standard evaluation seem too high to warrant the device's protection for PTW riders. In the rider chest impact analysis, the $Force_{max}$ of any rider was always below 20kN (TABLE II) while the AIS4+ injury risk was 48~100% (Figure 3) during the most severe impacts. That is, the rider W/WO a protector would always have a significant risk of severe injuries if having a $Force_{max}$ up to 24kN. Therefore, the high thresholds of force designed in the standard might easily make the devices qualified but would not warrant their protection efficacy.

Above all, the current testing standard of chest protectors cannot guarantee the protection performance of the devices in PTW collisions due to the inappropriate settings of impact energy level and force thresholds. Lower force thresholds and a series of higher impact energy levels should be taken into account in the future testing standard.

Indeed, this study was limited in certain aspects. Despite multiple human body FE models available, only the HUMOS2 model was used in the current simulations. However, similar to other models (e.g. THUMS and GHBMC), the HUMOS2 model has been validated against a wide range of frontal and oblique thorax impact loading conditions [12]. Therefore, a similar trend regarding the efficacy of the chest protectors in current frontal thorax impacts should be expected in the simulations with other human body models or in real world collisions with the equivalent impact energy levels. Another limitation was that only FE simulations were performed in this study without experimental tests to further consolidate our findings. As far as we know, no experimental tests on cadaver subjects to evaluate the efficacy of PTW rider chest protector could be found in literature. The current simulation results and preliminary findings would lay a foundation for the future experimental studies to improve PTW rider chest protection.

## V. ACKNOWLEDGEMENTS

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