Moving beyond the V50 for armour performance evaluation

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Abstract. Evaluating the V_{50} (velocity at which 50 percent of projectiles perforate) performance of an armour system is a standard test technique to assess a protective system, but provides limited indication on the resulting injury outcome. In some situations, the threat may not be completely stopped. This paper describes a process used to measure armour overmatch performance and put it into context of the reduction of injury. This process allows a wider set of performance metrics to be generated, using 20 or more shots. An appropriate backing was required, allowing 'as worn' measured performance, along with residual velocity estimates from shots that defeat the armour. Ballistic testing was designed to cover the range of velocities from just below the V_{50} to approximately 1.5 times the V_{50}. Equations for the probability of armour perforation and residual velocity were generated and used to feed a vulnerability model. The body armour was positioned in the body model and a grid of shotlines were run at a range of velocities to establish the average vulnerability/injury risk to a given area (both with and without the armour). By taking the average injury across the body region of interest for the different velocities, a reduction in injury risk was calculated compared to an unprotected case. The UK Tier 1 Pelvic Protection was evaluated to demonstrate this process. With 30 shots, a V_{50} could be calculated and coupled with the additional shotline model analysis demonstrated the protection gave reduction in the number of injuries at velocities over the V_{50} and V_{100}. This approach combines a coverage assessment, along with the armour's ballistic performance, allowing the development of optimised protection over the widest velocity range, with a small change to the practical testing.

1. INTRODUCTION

1.1. Overview

Traditionally, Personal Protective Equipment (PPE) ballistic performance is measured using either a V_{50} or a V_{proof} assessment. The V_{50} is the velocity at which 50 percent of projectiles perforate the PPE. V_{proof} is the maximum velocity below which there is a specified confidence that projectiles will not perforate the armour. Statistical models, in this case probit or logit equations can be fitted to the (dichotomous) data to determine the risk (probability) of perforation across a range of velocities to give a broader description of the PPE perforation response. In this paper, consideration is only given to penetrating injuries and assumes that any threat stopped by the PPE does not cause a Behind Armour Blunt Trauma (BABT) risk. Where required, BABT risks can be assessed separately.

V_{50} and V_{proof} ballistic assessment methods do not articulate the protective performance, e.g. in terms of injury reduction to the user. If a shot to the PPE is above the V_{50}, it may be expected to perforate the PPE and injure the person. However, the extent of that injury (which may be reduced due to energy absorption from the PPE system) is not easily determined.

In terms of injury mitigation, a more meaningful evaluation would be to compare the overall change in injury risk, or expected injury outcome, to an unprotected case or to a baseline PPE system. This paper outlines the methodology used to generate injury reduction-based measures of PPE performance. This used practical experiments to generate the required PPE perforation response data to feed into a computer based human vulnerability Shot Line Model (SLM). The SLM is a 3D representation of a person and their tissues, along with the PPE for analysis. To demonstrate this methodology and the types of outcomes produced, the UK Tier 1 Pelvic Protection (PP) is used as the PPE and compared to an unprotected case.

Dstl has different injury and vulnerability models for different purposes. The Human Injury Modelling and Analysis (HIMA) project generated the SLM used within this paper, and so the model is referred to as the HIMA SLM. The injury risk-based PPE evaluation has a number of steps:

1. Experimental determination of probit or logit model for the PPE perforation response, and the identification of V_{50} with shots that spanned the V_{50}.
2. Experimental determination of impact versus residual velocity of the PPE for impacts up to approximately 1.5 times the V_{50}.
3. Fitting of the experimental data to required equations, to derive estimates for residual velocity.
4. Running HIMA SLM with required PPE geometry.
5. Analysis to generate injury reduction based outputs.

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1.2. Experimental method (steps 1&2)

For this demonstration UK Tier 1 PP [1] was chosen as it has been well characterised by Dstl, and the area of the body is comparatively simple (in terms of geometry and limited variety of tissue types) with the required tissue parameters well understood within the SLM.

A 6 mm glass sphere (nominal 0.28 g, density 2.50 ± 0.05 g cm^{-3} and a diameter tolerance of $\pm$ 0.05 mm), as defined in Reference [2]) was chosen to represent the threat to the UK Tier 1 PP[1], being similar density to stones and soil generated from buried Improvised Explosive Device (IED) events against which the PPE was designed to mitigate.

A Sabre Ballistics A1G+ gas gun was used with compressed air and compressed helium with pressures up to 30 MPa (300 Bar). A 6.05 mm smooth bore barrel was used to fire the glass spheres.

It is known that the method used to back an armour material during ballistic assessments can affect its measured perforation performance [3] and an unrepresentative backing could therefore lead to misleading results. This could lead to the acceptance of PPE or materials that do not meet the ballistic requirements or impose an unnecessary burden. The TP5 pack was chosen as it was specifically developed and validated to provide a realistic backing for soft armour assessment, as well as a representative skin perforation response [4].

The TP5 pack was critical to this methodology as:

- It enabled direct assessment of the skin perforation outcome for each shot.
- It provided validated biofidelic compliance – ensuring the measured V_{50} or outcome of the PPE matched 'as worn' performance as close as possible.
- For any shots perforating the PPE, the depth of penetration (DoP) into the pack could be measured, which allowed the DoP to be converted into residual velocity with data from some calibration shots against a bare pack.

A system response for the skin/PPE ballistic outcome was used: in cases where the PPE was not perforated, but the skin of the TP5 pack was perforated (due to pencilling of the soft armour), it was classed as a system perforation. This means it was the onset of potential injury that was used to determine the outcome of the shot. Assessing the outcome via the system performance method allowed subsequent alignment of analysis when it came to the comparison to an unprotected case within the HIMA SLM.

Projectile velocities were measured using a Photron NOVA High Speed Video (HSV) camera at 20,000 frames per second and 896x512 pixels resolution. The velocities calculated from the HSV were initially validated against 5 shots with two Oehler model 57 infra-red gates with 500 mm separation, connected to an Oehler model 36 chronograph. Validation showed velocities from each system were consistent to within 0.1 m s^{-1}, when accounting for air drag due to the measurement from the Oehler system conducted 500 mm closer to the weapon. The Oehler model 57 infra-red gates were then removed which allowed a shorter barrel to target distance.

A minimum shot-spacing of 50 mm was used, avoiding shots within 50 mm from the edge of the packs. 20 shots were conducted to generate a system perforation response relationship. A probit model within the statistical program R [5; 6] to generate this relationship. This probit determination was used to ensure the PPE response had been properly characterized over the velocities of interest. Once complete, an additional 10 shots were conducted between the V_{50} and approximately 1.5 times the V_{50}. For every shot, the system outcome was recorded. For every shot that had a system perforation, the DoP into the TP5 pack was measured.

Corresponding impacts from below the TP5 pack skin V_{50} (resulting in DoP=0) up to velocities corresponding to the maximum velocity conducted for the Tier 1 PP assessment were also conducted against the TP5 pack, but bare, i.e. no PPE covering. This enabled an estimate of residual velocity to be determined from the DoP for the shots that perforated PPE.

1.3. Analysis of the experimental data (step 3)

Although the experimental method used a probit analysis to determine the system perforation response, the HIMA SLM used a logistic regression (logit) model. This was because the bias reduction in binary-response general linear models [6] implemented within R, could not be implemented within the SLM code. The experimental outcomes were used to generate the parameters for a logit model, in the form of Equation (1):

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$$Probability\ of\ perforation = \frac{1}{\left(1+e^{-(aV_S+b)}\right)} \tag{1}$$

Where, for the Tier 1 PP with a 6 mm glass sphere; Vs= Strike velocity (or Impact Velocity) in m s^{-1}, a=0.342 and b=-88.03.

For the HIMA SLM, stochastic perforation outcomes used a random number generator with Equation (1) to predict the PPE outcome separately for each individual shotline. If the random number was lower than or equal to the probability of perforation, the projectile defeated the PPE/skin system. If the random number was higher than the probability of perforation, the projectile was stopped by the PPE and there was no skin perforation and residual velocity set to zero. If the PPE system was defeated for a given shotline, the residual velocity was required as an input to the SLM. The method used to generate the residual velocity input was based on the DoP overmatch data into the TP5 pack.

A linear fit applied to the data for the DoP into the bare pack (excluding any non-perforation data) was used to convert the DoP following overmatch of the Tier 1 PP into a residual velocity.
A residual velocity equation (based on conservation of energy, assuming a constant projectile mass) from Reference [7] was used. It is a non-linear least squares regression model, given by Equation (2).

$$V_R = \begin{cases} 0, V_s < V_{50} \\ \alpha\left({V_s}^P - {V_{50}}^P\right)^{1/P}, V_s \geq V_{50} \end{cases} \tag{2}$$

Where V_R is the residual velocity (m s^{-1}), α and P are parameters bounded by: $0 \leq \alpha \leq 1$ and $P>1$ [7].

In Reference [7], the 'limit velocity' V_L is used rather than V_{50} in Equation (2). However, for any material exhibiting a zone of mixed results in the perforation data (as occurred within this dataset), where the regression equation is allowed to solve for the V_{50} (or V_L), then there will be perforation data below this value. For clarity the V_{50} has been used, as the meaning of V_L may be open to interpretation but is not synonymous with V_0 for Equation (2).

Whilst parameters α, P and V_{50} can all be calculated through Equation (2), in this case for the Tier 1 PP; α was forced to be 1, which ensured that $V_R \rightarrow V_S$ as $V_S \rightarrow \infty$ (i.e. residual velocity will approach strike velocity as strike velocity approaches infinity), and the V_{50} was fixed based on the value previously calculated from the probit analysis. The fixing of α=1 was only necessary due to the transform from DoP into V_R from the TP5 pack. The parameter P could then be calculated by Equation (2), run in Microsoft Excel (2016).

This left an issue, as the logit fit to the PPE system perforation response meant that perforations could be predicted for velocities below the V_{50}, but these would always result in V_R=0 based on Equation (2), which is not realistic. Therefore, a modification was applied: a straight line fit between (V_S=V_{01}, V_R=0) and (V_S=1.01V_{50}, V_R as calculated from Equation (2)). The straight-line fit was applied to end at 1% over the V_{50}, to ensure that residual velocity predictions would not equal 0 when it switched from one model to the other. The final equation is given by Equation 3.

$$V_R = \begin{cases} 0, V_s \leq V_{01} \\ mV_s + c, V_{01} > V_s \geq 1.01V_{50} \\ \alpha\left({V_s}^P - {V_{50}}^P\right)^{1/P}, V_s > 1.01V_{50} \end{cases} \tag{3}$$

For the Tier 1 PP on the TP5 pack with the 6 mm glass sphere, Equation 3 was fitted to the data with the following parameters: V_{01}=248.6 m s^{-1}, V_{50}=258.4 m s^{-1}, (1.01V_{50}=261.0 m s^{-1}), m=12.63, c=-3139.1, α=1, P=5.62.

Equation 3 fitted to the experimental data is shown in Figure 1 (red curve). Also shown in Figure 1 is the part of the non-linear regression model (Equation 2) that was removed and substituted with the linear fit between the V_{01} and 1.01V_{50} (dashed grey line). The black line is where residual velocity equals strike velocity, or a bare pack response.

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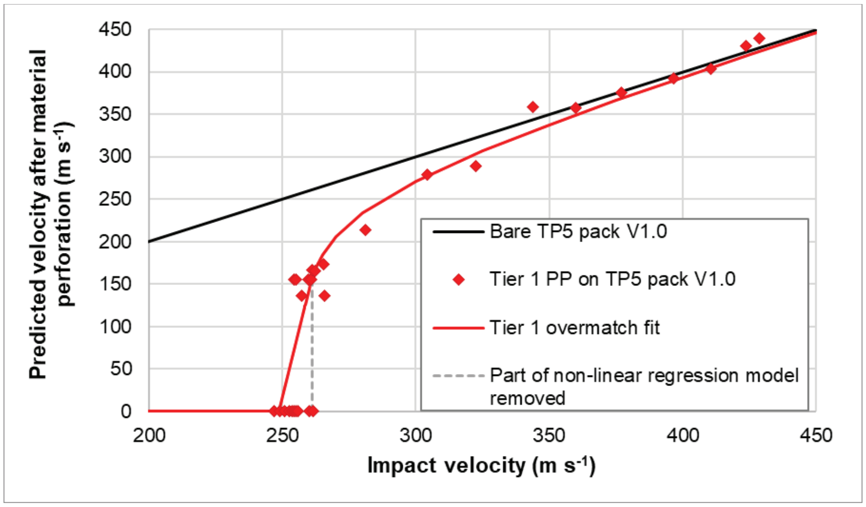

Figure 1. The predicted residual velocity, accounting for perforations below the V_{50}, for the Tier 1 PP covering the TP5 pack with 6 mm glass sphere, plotted with the raw data.

The residual velocity model and V_{50} are based on the system (combined TP5 pack skin and PPE) response. This is required to accurately model the residual velocity in the body in the HIMA SLM.

1.4. Shotline model analysis (step 4)

The HIMA SLM uses the ($50^{\%ile}$ male) Zygote model [9] for its 3D avatar representation. The current implementation of the Zygote body model within the HIMA SLM has 3D representations of 94 organs and soft tissues, 263 bones, and skin, with a fixed geometry and posture. Figure 2 shows the Zygote skin model, Tier 1 PP (area of protection in blue), alongside some of the organs and skeleton models.

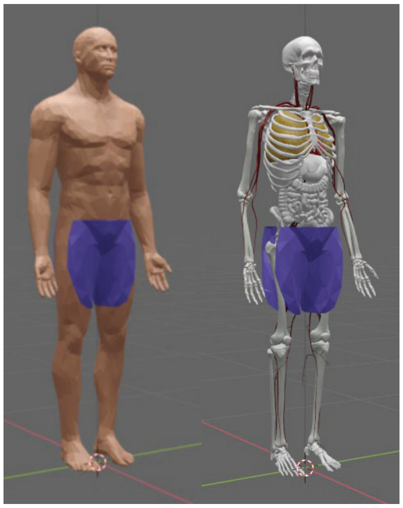

Figure 2. 3D Zygote models with Tier 1 Pelvic Protection

The SLM works by imposing user defined shotlines (rays) onto the avatar and returning the impact coordinates for each individual 3D component within the model. From these coordinates, the model indicates which PPE or tissues the projectile transects at each millimetre step of the shotline. If the shotline intersected the PPE before hitting the body, Equation (1) with a random number generator, combined with Equation 3 allowed the occurrence of /PPE/skin perforation and residual velocity (post skin as the PPE and skin were treated as a system) to be calculated. This was then used as the velocity for the next step. Equations within Reference [8] allowed the probability of skin perforation and residual velocity after perforating the skin to be estimated for impacts directly to the body (not covered by PPE). Deterministic skin perforation calculations were used.

At each millimetre step following PPE and skin or skin perforation; tissue specific retardation was applied [8], based on the residual velocity from the previous millimetre step, until the projectile came to a stop or exited the body. The retardation profile at each millimetre step was used to calculate an injured volume within each tissue type, which in turn was used to calculate the percentage volume of each tissue that was damaged. An injury score based on the percentage damage to each tissue was applied to all penetrated tissues, in a similar approach to that described in Reference [10]. The Abbreviated Injury Scale (AIS) scoring descriptions (update 2015) [11] were used as a guide with a trained and experienced AIS coder to relate each severity score allowed for that tissue from a penetrating injury to a damage volume threshold. The severities predicted through the SLM are not AIS scores or severities, nor are they directly comparable. The severity scores in the SLM serve to provide an indication of the relative injury severity outcome. For validity, the SLM is used as a comparator: either to compare multiple PPE solutions, or to compare the effect of a single PPE solution against bare skin.

The injury for each shotline could then be expressed as the maximum injury for that shotline (injury scores from 0-6, with 0 being no injury), or the overall injury which was calculated as the summed square of the three worst injuries (injury scores from 0 to 75, where any single level 6 organ injury resulted in a combined score of 75 regardless of any other injuries). This mirrors the calculation method of the New Injury Severity Score (NISS), although the scores calculated for the SLM are not NISS severities, nor are they directly comparable. Shotlines that missed the body were excluded from further analysis. Shotlines stopped by PPE were assigned an injury score of 0.

In this paper, comparison of injuries between the unprotected case and that with Tier 1 PP protection was performed by comparison of histograms of the frequency of the overall injury scores. This was because a direct comparison through averaging of scores generated from an 'AIS-like severity' system, where scores are non-linear in terms of severity and/or mortality, would lead to illogical outputs (i.e. an injury severity score of 2 is not twice as severe as a score of 1, and two injuries with a score of 1 are not equal to a single injury with a score of 2).

Future development of the HIMA SLM is to generate an injury scoring system that allows summation and averaging of scores (for example probability based), to allow a single value output from a grid for comparison between scenarios.

A grid over the entire thigh, with 10 mm spacing between shotlines was employed, at 0° incidence in the coronal plane (straight on from the front). Although, grids and/or shotlines can be specified from any impact direction and elevation, this angle was chosen for demonstration purposes and is not a representation of the expected threat to the Tier 1 PP. For simplicity and to reduce run-time the grid covered one thigh, although the outcomes (at a resolution of 10 mm spacing between shotlines) were considered symmetrical.

The grid was run at 10 impact velocities, all with the 6 mm glass sphere, from 200 m s^{-1} (0.77V_{50}) to 400 m s^{-1} (1.55V_{50}) both with and without PPE. These grids resulted in >30,000 shotlines, of which around 22,000 impacted the body. All velocities were above the TP5 pack skin perforation velocity and the skin perforation velocity calculated within the HIMA SLM for this projectile.

From the overall injury score for each shotline, a scoring heatmap was created to illustrate the predicted injury. An example of this scoring map is shown in Figure 3, showing the outcomes for a protected and unprotected thigh.

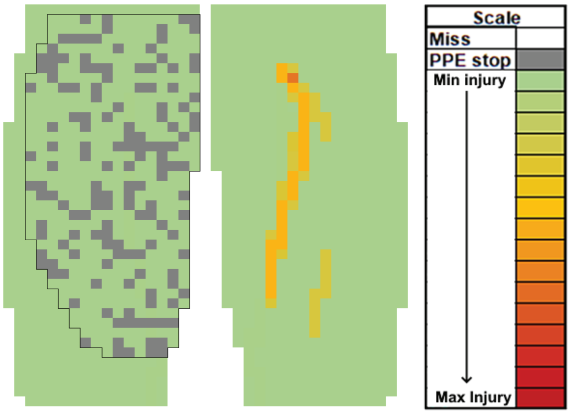

Figure 3. Injury Scoring Map based on the combined injury score for a given shotline. The leg shown on the left has the Tier 1 PP (outlined); the leg on the right has no covering. Impact velocity: 260 m s^{-1}

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The colours in Figure 3 correspond to the overall injury score predicted by the HIMA SLM for a fragment impacting at a fixed velocity (close to the Tier 1 PP V_{50}). Each pixel in the scoring map corresponds to the 10x10 mm grid spacing. Although the impact velocity was the same for both protected and unprotected, the defeated armour still reduced the predicted injury.

To assess the effect of the PPE, the number of shotlines corresponding to the overall injury severity was compared between the unprotected and Tier 1 PP. For both the unprotected and Tier 1 PP cases, all injuries were calculated as one of six scores (plus 0 for PPE stops). For simplicity in displaying the data, the six different scores were combined into 3 categories: low (scores of 1 and 2), medium (scores of 17 and 18) and high (scores of 33 and 48). Figure 5 shows the proportion of injuries changed at the different score levels. A positive change meant an increase in the number of shotlines with that overall injury severity score with the Tier 1 PP compared to the unprotected case, and a negative change meant a decrease in the number of shotlines with those injury scores with the Tier 1 PP.

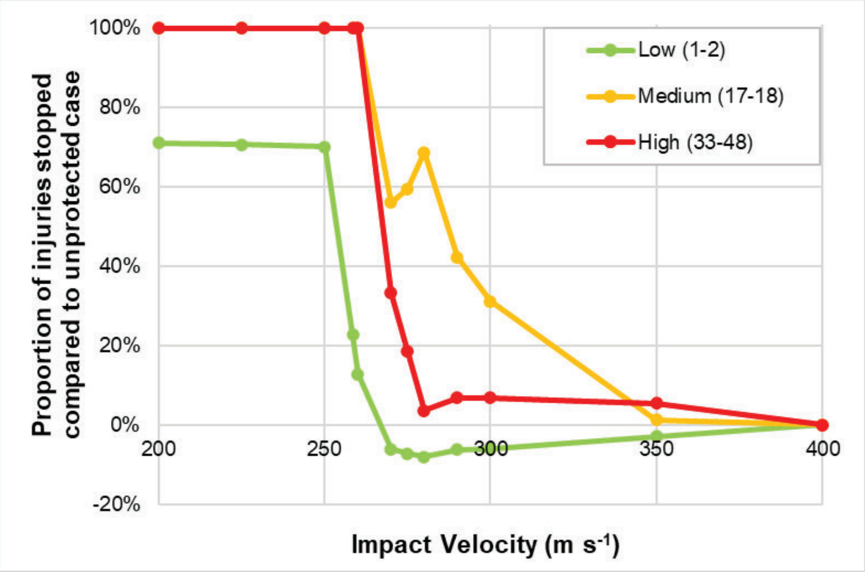

Figure 4. The proportion of injuries stopped by the Tier 1 PP at each overall injury score.

Figure 5 shows the proportional change at each overall score level as the impact velocity is varied. The Tier 1 PP shifted the injury scores to lower score levels and to PPE stops (0 injury score, not shown due to no PPE stops in the unprotected case for a proportional comparison). The increase in the proportion of injuries with a score of 1 and 2, shown by negative values at velocities ≥270 m s^{-1} with the Tier 1 PP is due to the medium and higher score injuries (17-48) being reduced to scores of 1 or 2, but not being stopped completely. At higher velocities over 280 m s^{-1}, the Tier 1 PP has limited mitigation of the higher scored injuries; <10% of 'high' (33 and 48) scored injuries are reduced to lower score levels. Figure 5 appears to show the Tier 1 PP is more effective against the higher scored injuries, but this is due to low numbers of those injuries sustained and the fact they are displayed as a proportion of those in the unprotected case.

At 400 m s^{-1}, no change in jury was observed, as this corresponds to only a 6 m s^{-1} reduction in velocity due to perforating the Tier 1 PP (Figure 1). The limit of effectiveness of the Tier 1 PP in reducing injuries determined through this SLM method is approximately 350 m s^{-1}, which corresponds to 1.35 times the V_{50}.

1.5. Comparison to other methods

To contrast this overmatch injury reduction approach to other assessment techniques, comparisons were made to the following methods (also assessed through the HIMA SLM):

- A deterministic V_{50}. This uses an experimentally determined V_{50} and assumes that any impacts below the V_{50} are stopped, those above are assumed to perforate with V_R=V_S. This method essentially equates the V_0, the V_{50} and the V_{100} as the same point. Therefore, there is no benefit from PPE when the impact velocity is greater than the V_{50}.

- A stochastic perforation method, based on a logit probability of perforation. Impacts that are calculated to perforate the PPE have $V_R=V_S$. This method multiplies the probability of perforation of the PPE system with the expected injury score. The benefit is inversely proportional to the probability of perforation, therefore the benefit is zero as soon as the impact velocity increases over the V_{100}. As it is stochastic, impacts within $V_0<V_S<V_{100}$ can create a mix of perforation outcomes across the PPE.
- Pure coverage assessment. Data for the PPE performance is not used. All shotlines that impact the PPE are assumed to be stopped at all velocities. Those that miss PPE have an injury calculated.

The outcomes of the four techniques in relation to the unprotected SLM case are shown in Figure 6. For simplifying the comparison, the injury scores were grouped: for the overmatch and coverage approach, injury scores were grouped into low (1-2), medium (17-18) and high (33-48). These low/medium/high groups are for comparison purposes, noting the scoring scale goes to a maximum of 75. For the deterministic and stochastic approach, all injuries were affected to the same degree, so were combined into a single group labelled 'all' (scores 1-48).

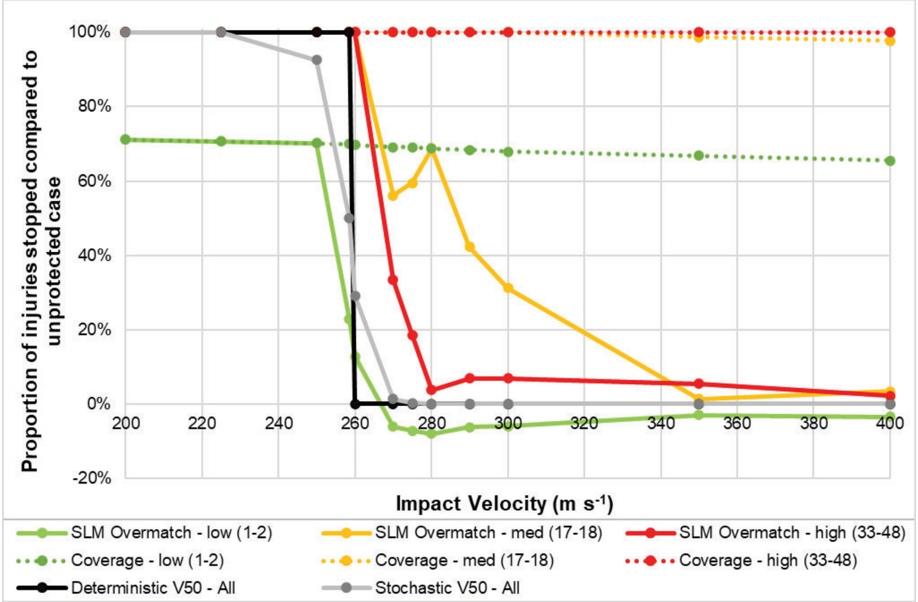

Figure 5. Proportion of injuries stopped compared to unprotected case for each model type.

Figure 6 shows that the overmatch analysis with the HIMA SLM overmatch technique indicates the Tier 1 PP is more effective (in that it gives a larger reduction in injury scores, over a wider range of impact velocities) than is indicated by the deterministic or stochastic perforation methods. The exception is that more shotlines are observed with low injury scores for the SLM overmatch method, as the higher injury scores are reduced into the low band.

Figure 6 shows large differences in the percentage injury score reduction for velocities over 260 m s^{-1} between the simple coverage and full assessment using the Tier 1 PP overmatch data. The differences highlight where the full assessment using the Tier 1 PP overmatch data may provide additional insight.

1.6. Non SLM based comparison of PPE

Noting that the development or acquisition of a SLM and underpinning resource to exploit the model is not trivial, a comparative assessment solution may be possible that utilises much of the same approach described previously but provides a simplified PPE performance comparison (rather than injury reduction prediction). This proposed, but as yet unvalidated approach, uses the same experimental procedure is followed (Section 1.2) with parameters fitted for Equation 3 to the PPE of interest to generate V_S-V_R curves (Section 1.3). If the TP5 pack skin V_{50} is then subtracted from the calculated residual velocity data, this accounts for the fact that even with no material covering, the skin layer on the pack itself has a threshold below which it will not be penetrated (i.e. no injury would be predicted to

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have occurred). The V_S-V_R curves (with subtracted skin V_{50}) are then integrated to determine the area under each curve. The integral can be performed on V_S between the TP5 skin V_{50} and a suitable upper velocity limit.

To highlight this different approach and how/why it could lead to selection of different materials than standard test methods, data was collected for some low areal density protective materials using the same experimental approach as outlined in Section 1.2, but using a 3 mm glass sphere. The V_S-V_R curves generated for 5 materials are shown in Figure 7.

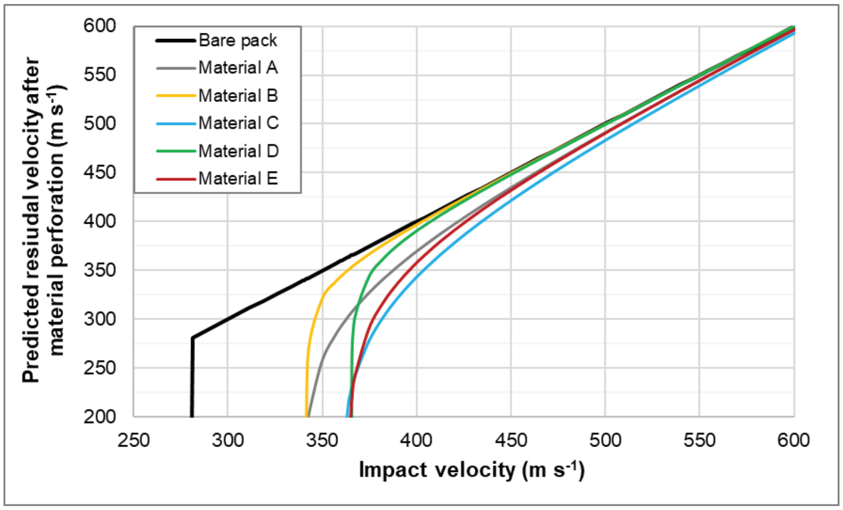

Figure 6: Residual velocity curves (Equation 3) for different materials.

Note that the data collected were not optimised for V_{01} calculations. This is a limitation of this approach and needs to be considered carefully when analysing the data to ensure sensible V_{01} velocities are used in the residual velocity predictions.

The area under the curve, the integral for V_S between the TP5 pack V_{50} (281 m s^{-1}) and 1.6 times the V_{50} of the best performing material (585 m s^{-1}) was conducted, with the TP5 pack skin V_{50} first subtracted from the calculated residual velocity. This maximum velocity of 585 m s^{-1} corresponded to the limit of the data collected. The outcomes of these integral, relative rankings and comparison to V_{50} performance is shown in Table 1.

Table 1. Performance and relative rankings of materials based on the residual velocity overmatch integral and V_{50} testing with a 3 mm glass sphere.

Material	Overmatch integral value	Overmatch % reduction to bare pack	Overmatch integral rank	V_{50} (m s^{-1})	V_{50} % increase to bare pack	V_{50} rank
Material C	4908	28.9	1	360	27.9	3
Material E	5173	25.0	2	364	29.3	2
Material A	5462	20.9	3	340	20.8	5
Material D	5656	18.1	4	365	29.9	1
Material B	5462	8.8	5	342	21.4	4
Bare pack	6901	n/a	n/a	281	n/a	n/a

Table 1 shows that the performance rankings of the materials were different when considered in terms of their overmatch or V_{50} performance. Material D had the highest V_{50}, but comparatively poor overmatch performance. In the context of these materials, they are not designed to prevent all injuries, but reduce the overall injury burden that may occur by covering a comparatively large area, but with low (mass) burden. V_{50} testing alone may result in selection of a sub-optimal protection system. Based on ballistic performance alone, Table 1 shows the optimal performing material was Material C. It also shows that considering this integral value, fabric Material A outperformed Material D, despite having a lower V_{50}.

Whilst this approach in general and these data specifically have yet to be analysed through the HIMA SLM to confirm the rankings of the integral method, Figure 7 and Table 1 are provided to demonstrate how this methodology could be utilised and the types of differences in V_{50} and residual velocities that may be encountered, potentially leading to selection of different materials. It is a similar approach to that suggested within Reference [7], mapping the region under the V_S-V_R curve to a finite area.

This integral method on the overmatch data aids in providing the additional insight to rank the PPE performance, but without the requirement for a shotline model. The main benefit of the SLM additional analysis is that it puts the performance in context, in terms of injury reduction, so that any benefits can be more confidently judged as to the required trade-offs (burden, mobility, comfort, etc.), as well as the ability to directly compare the effectiveness of solutions with different coverage areas (in addition to different ballistic performance), and articulate those differences in terms of injury reduction.

2. DISCUSSION

This study has examined the development and benefits of using an overmatch approach, coupled with vulnerability analysis for the comparison or selection of PPE. The SLM overmatch methodology could allow:

- Optimised PPE to be selected, where the threat cannot be completely protected against.
- Benefits of PPE to be quantified in terms of reduction of the number of injuries of given scores.
- Direct comparison of PPE with different areas of coverage.
- Benefits of enhancing PPE to be quantified (i.e. does adding additional PPE make a significant difference to injury outcome).
- Assessment of the relative vulnerability/protection offered by the PPE from different threats.
- Specific threat-based analysis. For example, vulnerability analysis can be run against any type of shot line grid/pattern. This could be generated via blast trial or modelled weapon fragment distributions and velocities to feed in realistic threat information. However, the key advantage is that such analysis will be based on PPE injury reduction metrics rather than simply on perforation measures.

It is important to note that being a proof of concept study, this work comes with caveats and is not intended to be used as a definitive representation of the Tier 1 PP performance, but demonstrates that using the HIMA SLM with overmatch data could lead to a better understanding of the performance of protection systems; improving operational models. This approach also allows a more complete assessment process for procurement or comparison of PPE in terms of injury reduction rather than PPE perforation.

Further development is also required with the HIMA SLM in terms of injury scoring and expansion of the available parameters within some of the algorithms used (such as appropriate tissue retardation and damage algorithms).

3. CONCLUSIONS

This study has demonstrated the benefit PPE provides across a variety of velocities, including those (significantly) over the PPE V_{50} which are not normally considered or quantified. It has demonstrated that PPE is more effective than would be understood from evaluation by traditional V_{50} type test methods. If threats cannot be stopped within the mass/burden budget of PPE, to maximize effectiveness, PPE could be optimised to provide the maximum reduction in injury over the (widest) range of expected impact conditions using this approach. This is a different approach, which may favour a different solution to selecting PPE with the highest V_{50} performance. It also allows an option for the assessment of the residual risk after mitigation.

Using the Tier 1 PP as an example, the HIMA SLM with overmatch data has been able to show a reduction in injury well above V_{50} and the V_{100}. This showed decreases in injury outcome are expected up until approximately 1.35 times the V_{50} for the Tier 1 PP (i.e. relating to a real, tangible benefit).

Using a simpler methodology, by ranking performance via the area under the V_S-V_R curve, rather than shotline vulnerability analysis, may provide a lower resource approach to comparison of PPE performance. It indicated that materials with the highest V_{50} may not provide optimised protection.

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