Evaluating the effect of vehicle modification in reducing injuries from landmine blasts. An analysis of 2212 incidents and its application for humanitarian purposes

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\textbf{A R T I C L E   I N F O}

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\textbf{A B S T R A C T}

Introduction: Anti-vehicle (AV) mines have been laid indiscriminately in conflict areas for the past 100 years. With an indeterminate life-span they continue to pose a significant threat to the civilian population, as well as restrict the movement of people, aid and goods to vulnerable populations. The aim of this study was to analyse unique casualty data from 2212 mine incidents to determine if simple vehicle modifications can reduce fatality and injury rates from mine explosions.

Method: We analysed casualty data from the Rhodesian War (1972–1980), to assess the effects of basic vehicle modifications (V-shaped hull, increased ground clearance, widened axles, heavy vehicles and blast defectors) on injury rates. A multinomial regression statistical model was developed for vehicle modifications and number of alterations to explore these effects.

Results: Incident data was available on 2212 vehicle mine incidents involving 16,456 people. The overall fatality rate was 3.3\% (544/16,456) and the overall injury rate was 22.7\% (3741/16,456). Explosions against mine-protected vehicles resulted in a fatality rate of 1.2\% (150/12,919); occupants in unprotected vehicles sustained a fatality rate of 11.4\% (395/3537). The injury rate in mine protected vehicles was 22.2\% (2868/12,919) compared to 24.7\% in unprotected vehicles (873/3537).

Utilising a multinomial logistical-regression model, we show that each design feature significantly reduced fatality rate (from 45\% in unprotected vehicles to 0.8\% in protected vehicles); each of these designs had a cumulative effect in fatality reduction. In isolation, blast defectors, whilst reducing fatality rates, increased injury rates.

Conclusions: Our data clearly demonstrates that simple vehicle modifications can have a significant effect on reducing fatality and injury rates from AV mine explosions. Given that the modifications described were produced using commercially available vehicles with basic engineering requirements, we believe that similar processes could be employed in post-conflict environments in a cost-effective manner.

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1. Introduction

1.1. The effects of anti-vehicle mines on humanitarian efforts

Anti-vehicle mines (AV mines) have been regularly deployed in conflict zones since their inception in World War I. They are used by governments and insurgents alike because this method depletes opposing forces, inhibits their ability to react rapidly and flexibly, and challenges the morale of troops. Furthermore, it allows casualties to be inflicted from a distance, with minimal risk of injury to the mine-layer. Often used to disrupt strategic transport links and logistic hubs, they are placed on or near roads, live-stock grazing routes, and bridges. As they are detonated by pressure activated fuses, they explode indiscriminately, posing a significant threat to civilian and military forces.

Anti-vehicle mines do not contain internal mechanisms to limit their active lives and therefore act as a persistent threat to civilian populations in the post-conflict environment. Their effects are not limited to those injured or killed in an explosion; a single AV mine can close transport routes for months, and obstruct the movement of goods, essential relief supplies and people in huge areas. Such restrictions hamper relief, reconstruction and economic development of war torn societies throughout the world. For humanitarian organisations, the presence of AV mines poses significant risks.

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From 1990 to 2000, International Committee of the Red Cross (ICRC) staff were involved in 20 separate mine incidents resulting in 16 killed and 63 injured. After each incident, relief efforts in those areas had to be suspended. In order to maintain relief operations, air transportation is often used, which increases the transportation costs by a factor of 10–20 (ICRC, 2002). In many cases, even the perceived threat of AV mines may be sufficient to block access, and thereby prevent humanitarian organisations from reaching the intended beneficiaries directly, as well as blocking the return of refugees and internally displaced people to their place of origin.

Traditionally, this threat has been countered by the deployment of demining teams to remove the mines. This manual process is both resource and time intensive, with the associated risks of death and injury to the workforce. Progress is often painstakingly slow, and due to limited knowledge of the whereabouts of the mines, can be fruitless. For example, during the demining operations in Angola, a 27 km length of road took 6 months to clear at a cost of $475,000. Ironically, not a single mine was found (Dirschler, 2004).

A second parallel approach has been to develop mine resistant vehicles capable of shielding the effects of the mine from the vehicle occupants. This approach has been applied most recently in Iraq and Afghanistan by military forces aiming to mitigate the threat posed by the improvised explosive devices (IEDs) frequently used by the insurgents (NATO, 2009; Ramasamy et al., 2008, 2009a,b). However, these vehicles are extremely expensive, costing in excess of $500,000 each and require specialist maintenance, thus making them unsuitable for many post-conflict environments which are characterised by difficult climatic conditions, social and political instability, and poor general infrastructure. Thus any mine-protected transportation needs to be robust, mechanically simple and cost-effective (Dirschler, 2004). In order to develop appropriate vehicle modification, careful considerations should be taken to mitigating against the complex mechanism of injury that occurs in an AV mine blast.

1.2. Landmine detonation and its effects on occupants

In the classical “underbelly blast” scenario, an anti-vehicle explosive device is designed to detonate under the vehicle releasing a blast wave, followed immediately afterwards by an inverted cone of super-heated high pressure detonation gases surrounded by soil ejecta (detonation products, Fig. 1).

Primary blast injury (blast-wave mediated) to vehicle passengers is caused by hull breach through penetration or structural failure, whilst secondary blast injury results from energised fragments (Tremblay et al., 1998; Champion et al., 2009). The most significant mode of injury occurs when the detonation products impact the vehicle hull producing localised elastic and plastic floorboard deformation. This results in the transfer of high axial loads into the vehicle occupants often causing severe lower limb and spinal injuries (NATO, 2007). In addition, the vehicle itself can be displaced as a result of the force transfer, causing deceleration injuries when it impacts the ground or other objects.

1.3. Development of mine protection vehicles

AV mines were used en masse during the Rhodesian Bush War (1972–1980) (Stiff, 1986). In this conflict, the Rhodesian security forces fought a counter-insurgency operation. The insurgents’ principal weapon of choice was the Russian designed TM-46 and TM-57 anti-tank mine, and they accounted for 97.1% (669/689) of devices identified in 1979 (D-Branch, 1980). The TM-46 and TM-57 mines were Russian designed weapons which contained 5.5–5.8 kg of TNT and were activated by a pressure dependent fuze with an operating pressure of 180 kg. The high operating pressure reduced the likelihood of detonation by pedestrians or small carts, although

there were anecdotal case reports of landmine detonation by elephants and 5 cases of mine detonation by bicycles and motorbikes throughout the whole war (Stiff, 1986).

These devices, produced in huge quantities over the past 40 years, remain the most prevalent AV mines found currently in Afghanistan, Angola, and Cambodia (Kim, 2004). In the preceding 40 years, AV mine design has altered very little. The simplicity of its mechanism, relatively low cost and easy deployment, allows it to be used by untrained personnel and still remain a potent threat. Indeed, the main difference in AV mine construction has been the change from metallic parts to plastic elements in order to reduce the effectiveness of metal detectors to detect them (King, 2010). Hence, there is an even greater need to develop vehicles that can withstand the effects of blast.

The Rhodesian government, limited in their ability to purchase armoured vehicles or armour because of international sanctions, set up a counter-mine protection committee to develop measures to counter this threat. In the ensuing 6 years of the conflict, this committee, with both significant medical and engineering input, oversaw the production of a suite of mine-resistant vehicles which incorporated a number of novel design principles borne out of anecdote and iterative experience. These designs were based on the modifications of commercially available vehicles (cars and trucks) with both military and civilian variants produced (Fig. 2). Driven by economic considerations, these designs had to be cost-effective, and had to be engineered with relatively basic manufacturing set-ups. As such, these designs would have direct applicability to vehicles currently found in post-conflict developing nations, where the financial and manufacturing infrastructure is not present to either manufacture or maintain highly complex vehicle platforms.

The specific design features included:

Increased ground clearance. If the passenger compartment is in contact with the soil, the shock wave will be directly transmitted into the target as the impedance match between soil and solid is much closer than that between soil and air (Grujicic et al., 2008). Increasing the ground clearance reduces this effect as well as the amplitude of the blast wave experienced by the target (Tremblay et al., 1998). It also allows better venting so that gas pressure can dissipate away from the vehicle body and, hence, its occupants.

Increased vehicle mass (>2.5 tonnes). The mass of the vehicle has a significant effect on the load transferred to its occupants. Based on the equation \( F = \frac{mv^2}{2} \) (acceleration); for a given mine threat \( F \) and the same vehicle geometry, lighter vehicles will suffer a greater acceleration. The lighter vehicles also reach higher velocity and greater displacement compared to heavier ones. Consequently, the occupants of lighter vehicles are more at risk of suffering a serious vertical acceleration injury such as lumbar spine or lower limb injury (NATO, 2007).

V-shaped hull. The V-shaped hull is superior to a flat-bottom hull in resisting load transfer from an explosive blast (Fig. 3). Under a flat bottomed hull the blast wave will reflect and coalesce with the resultant pressures many-fold higher (Baker et al., 1983). Conversely, the V-shaped hull would allow for the blast wave and the detonation products to be directed away from the passenger compartment (Baker et al., 1983; Nettleton, 1987; Slater et al., 1994; Smith and Rose, 2002). The effectiveness of the V-shaped hull to direct the detonation products away from the passengers was related to the angle of the hull; the more acute the angle, the better the energy dissipation. However, a more acute hull reduced the carrying capacity of the vehicle as well as potentially making the vehicle more unstable and more likely to overturn. Based on multiple mine blast tests, a standardised 52° V-shaped hull design was introduced throughout the Rhodesian fleet (Stansfield, 1982).

Widened axle length. The spacing of wheels away from the vehicle body allows for stand-off distance resulting in reduction of the load transferred to the vehicle. The majority of AV mines are det-
onated when a wheel of a vehicle drives over it. As the detonating gases expand in a vertical inverse-cone configuration, the ‘cab over wheel’ configuration will place the crew compartment within the zone of possible injury. Therefore, the crew compartment will be more protected when there is a lateral stand-off from this zone of vertical flow.

Blast deflectors. Blast deflectors around the wheels can allow venting of detonation gases and, similarly, framing of the wheels can offer containment of the detonation gases, both resulting in reduction of peak pressure in the vehicle (Fig. 4).

Where possible, the Rhodesian engineering directorate, aimed to standardise their modifications across their fleet. However, variations had to be introduced, in order to allow for the differences amongst the different commercial vehicle chassis used. This was most noticeable with the blast deflectors, which had to be designed to fit around the wheel arch of each vehicle type. Of the other design modifications, ground clearance was set as a minimum 58 cm above the ground, vehicle mass was set as greater than 2.5 tonnes and the V-shaped hull had a 52° angle configuration.

Whilst there have been a number of computer simulations on the effect of blast on military vehicles (Grujicic et al., 2009a,b), there has been neither an attempt to assess the effectiveness of retrofit design modifications (common place in modern anti-vehicle mine protected vehicles) on blastworthiness, nor an analysis of blast mitigation technologies in terms of clinical outcome for blast victims. This has been due to a number of factors including security issues as well as a lack of large scale casualty data from AV mine blasts.

Fig. 1. The physics of a mine blast. (a) Triggering of the mine results in an exothermic reaction and formation of a blast wave. The blast wave is mainly reflected at the soil-interface and (b) causes fracture of the soil cap. (c) The detonation products are vented through the fractured soil cap, resulting in the release of the soil ejecta. (d) The overall result is an inverted hollow cone of super-heated detonation gases surrounded by the soil ejecta. They both then act on the floor of the vehicle, resulting in injury to the occupants. After Ramasamy et al. (2011).

Fig. 2. The crocodile vehicle was modified from commercially available trucks similar to the vehicle shown (left). The modifications were performed using standard sheet steel. Photograph supplied by Don Blevin.
Fig. 3. A cross-section view of the V-shaped hull of the crocodile vehicle. Manufactured from standard sheet steel, the V-shaped hull is welded onto the chassis of the commercial truck. The V-shaped hull helps to dissipate the effects of the blast wave and detonation products. Photograph supplied by Don Blevin.

1.4. Aim

In order to assess the effectiveness of these new designs and inform further development the Rhodesian security forces kept meticulous records of injuries and fatalities from vehicle mine explosions. We hypothesize that the vehicle retrofit modifications undertaken by the Rhodesian security forces had a beneficial effect in reducing the proportion of killed and injured casualties from an AV mine explosion.

Therefore, the aim of this paper is firstly to evaluate the individual and cumulative effectiveness of the mitigation measures taken by the Rhodesian forces in casualty prevention through first-time analysis of detailed historic data, and secondly to interpret this data in order to evaluate and guide vehicle engineering design concepts that could potentially be applied to the humanitarian sector.

2. Methods

Original source materials obtained from the Engineering Directorate of the Rhodesian Army Headquarters from the Rhodesian Bush War were collated and supplemented with the personal archives of Colonel IR Stansfield, Chairman of the Rhodesian Mine Protection Committee (Stansfield, 1982). Incident data was collected on all vehicle mine incidents in Rhodesia between 1972 and 1980. Data was available on 2212 vehicle mine incidents involving 16,456 people; 12,919 were travelling in mine protected vehicles, and the remaining 3537 were in unprotected vehicles. Vehicle type, characteristic and mine location were documented for each mine explosion; this data was linked to the outcome of the vehicle passengers by recording total number killed, injured and unharmed. The unprotected vehicles described in this series were vehicles that had not been modified, and thus had a similar chassis to the mine-protected vehicles.

There were five vehicle modifications that were included and analysed in this study: blast deflectors, increasing ground clearance to greater than 58 cm, increasing the weight of the vehicle to over 2.5 tonnes, V-shaped hull, and increasing the axle width. The vehicle mass and ground clearance criteria were stated on the design specifications developed at the time of vehicle development (Stansfield, 1982).

2.1. Data analysis and statistical modelling

Statistical analysis was performed using Stata v.10 (Stata Corp, TX, USA). Simple summary analysis of the data was performed to determine the difference in the proportion of those killed and injured in protected and unprotected vehicles.

A multinomial logistic regression statistical model was developed in order to explore the relationship between the proportion of those killed, injured or unharmed, and the 5 design modifications. In order to estimate the proportions of interest, it was necessary to adjust the model for the number of incidents involved. Each of these modifications were dichotomised into categorical variables. Due to the small number of variables being analysed, a manual method was employed to maintain the hierarchical principle of only accepting interaction effects when the component main effects are retained in the predictive model (Collet, 1994). From this analysis, the individual effect of the vehicle designs was quantified by calculating the odds ratio, \( \exp(\beta) \), derived from the exponential of the \( \beta \) coefficient. A \( p \)-value less than 0.05 was considered statistically significant. In each case, the reference category was set as the least injurious outcome (i.e. unharmed followed by injured followed by killed). Therefore a negative coefficient indicated a protective effect of the variable being analysed. From the derived logistic regression model equation, predicted proportions of killed, injured and unharmed were calculated. The change in predicted probability was calculated by introducing each variable in turn whilst holding all other independent variables constant at zero.

In order to evaluate the effects of cumulative design modifications, a second multinomial logistic regression model was developed. In this model, the vehicles with either no or single alteration were combined into a single group to form the reference category for the analysis, as the number of zero alteration vehicles was too small for analysis. A \( p \)-value less than 0.05 was considered statistically significant.
3. Results

3.1. Descriptive statistics

The overall fatality rate was 3.3% (544/16,456) and the overall injury rate was 22.7% (3741/16,456). There were 1815 mine incidents involving mine-protected vehicles resulting in a fatality rate of 1.2% (150/12,919). Occupants in unprotected vehicles sustained a fatality rate of 11.4% (395/3537) from 397 incidents. The proportions of unharmed: injured: killed in the unprotected and protected vehicles is shown in Fig. 5.

3.2. Individual design features

The vehicle modifications incorporated into the vehicles analysed in this study is summarized in Table 1.

A multinomial logistic regression model adjusted for the number of incidents was developed in order to deconstruct the root cause of this protective effect in relation to the vehicle modifications incorporated (Table 2). All the design features significantly reduced the proportion of killed to unharmed, and all but heavy vehicles and increased axle length reduced the proportion of killed to injured. Increased ground clearance, heavy vehicles and increased axle length also resulted in a significant reduction in the proportion of injured to unharmed. Conversely, the introduction of blast defectors increased the proportion of injured to unharmed.

The change in the proportions of those unharmed, injured and killed derived from the predictive model is represented in Fig. 6. The predicted probabilities were calculated from:

\[ P(Y = j) = \frac{Z_j}{1 + \sum_{j=1}^{J-1} Z_j} \quad j = 1, \ldots, J - 1 \]

where \( j \) is the number of categories and \( j \) is the category of interest (i.e., injured, killed or unharmed).

\[ Z_j = \exp(\alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \ldots) \]

The reference category was calculated by:

\[ P(Y = j) = 1 - \sum_{j=1}^{J-1} P(Y = j) \ldots \]

The predictive equations were:

\[ Z_{injured} = \exp(-0.584 + 0.218 \text{Blast defectors} - 0.393 \text{Ground clearance} - 0.934 \text{Heavy vehicle} - 0.08V \text{ Shaped hull} - 0.198 \text{Increased axles} + 0.003) \]

\[ Z_{killed} = \exp(-0.665 + 0.917 \text{Blast defectors} - 1.23 \text{Ground clearance} - 1.01 \text{Heavy vehicle} - 0.899 \text{ Shaped hull} - 0.699 \text{Increased axles} - 0.0007) \]

\[ Z_{unharmed} = \exp(-0.08 - 1.135 \text{Blast defectors} - 0.839 \text{Ground clearance} - 0.077 \text{Heavy vehicle} - 0.814 \text{ Shaped hull} - 0.5005 \text{Increased axles} - 0.004) \]

Then

\[ P(\text{injured}) = \frac{Z_{injured}}{1 + Z_{killed} + Z_{injured}} \]

\[ P(\text{killed}) = \frac{Z_{killed}}{1 + Z_{killed} + Z_{injured}} \]

\[ P(\text{Unharmed}) = 1 - (P(\text{Injured}) + P(\text{Killed})) \]

Ground clearance was noted to have the greatest effect in reducing the proportion of killed and injured with blast defectors having the smallest effect, but significantly causing more injuries.

3.3. Cumulative effects model

The cumulative effects model is presented in Table 3. When presented as a proportion of the observed events, the cumulative number of vehicle protective measures had a substantial effect on the distribution of outcome after an explosion (Fig. 7). The ratio of killed:unharmed and killed:injured reduced significantly with 2 vehicle alterations, but after that the number of alterations appeared to make little difference. Conversely, after 3 design modifications the proportion of injured: unharmed increased significantly.

From this model, the predicted proportion of killed, injured and unharmed as a function of the number of alterations was calculated in a similar manner to the main effects model.

The change in predicted proportions of killed, injured and unharmed in relation to the reference category (zero or one alteration) is represented in Fig. 6. After 2 alterations, the proportion of killed remains stable, whilst the proportion of injured continues to reduce until 4 alterations.

A comparison between the fitted and observed proportions of unharmed, injured and killed is presented in Fig. 8, demonstrating excellent correspondence between model and observed effects.

4. Discussion

Our results clearly demonstrate that all the vehicle modifications introduced during the conflict had a protective effect in significantly reducing the ratio of those vehicle occupants killed to unharmed from the AV mine blast. In addition blast defectors, increased ground clearance and a V-shaped hull also significantly reduced the proportion of killed to injured. In contrast, when considering the proportion of injured to unharmed, the presence of blast defectors appeared to cause an increase in injuries. Despite this effect, the overall proportion of injured fell from a peak of 47% to 16% (Fig. 8). The paradoxical effect of the blast defectors may be explained by the design of these modifications. Blast defectors act...
Table 1
A summary of the individual design modifications incorporated into the vehicles analysed in the study.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>No. of incidents</th>
<th>No. of passengers carried</th>
<th>Blast deflectors</th>
<th>V-shaped hull</th>
<th>Increased ground clearance</th>
<th>Increased mass</th>
<th>Widened axles</th>
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<tbody>
<tr>
<td>Rhodef 45</td>
<td>338</td>
<td>2252</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Puma</td>
<td>327</td>
<td>3230</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Bedford</td>
<td>322</td>
<td>2594</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Protected L/Rover</td>
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<td>573</td>
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<td>X</td>
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Table 2
Main effects model of vehicle modifications.

<table>
<thead>
<tr>
<th>Vehicle modification</th>
<th>Multinomial logit estimates, Odds ratio (top line) with logistic co-efficient β (95% CI in parentheses) (italics)</th>
<th>Change in predicted probabilities</th>
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<tbody>
<tr>
<td>Blast deflectors</td>
<td>0.40&lt;sup&gt;<strong>&lt;/sup&gt; &lt;br&gt;0.32&lt;sup&gt;</strong>&lt;/sup&gt; &lt;br&gt;−0.92 (−1.20, −0.64) &lt;br&gt;−1.14 (−1.43, −0.85) &lt;br&gt;0.22 (0.12, 0.32)</td>
<td>−0.02 &lt;br&gt;+0.07 &lt;br&gt;−0.06</td>
</tr>
<tr>
<td>Ground clearance</td>
<td>0.29&lt;sup&gt;**&lt;/sup&gt; &lt;br&gt;0.43 &lt;br&gt;−1.23 (−1.95, −0.51) &lt;br&gt;−0.84 (−1.59, 0.09) &lt;br&gt;−0.39 (−0.65, −0.13)</td>
<td>−0.17 &lt;br&gt;−0.23 &lt;br&gt;+0.40</td>
</tr>
<tr>
<td>Heavy vehicle</td>
<td>0.36 &lt;br&gt;−1.01 (−1.70, −0.33) &lt;br&gt;−0.08 (−0.78, 0.63) &lt;br&gt;−0.93 (−1.15, −0.71)</td>
<td>−0.07 &lt;br&gt;−0.14 &lt;br&gt;+0.21</td>
</tr>
<tr>
<td>V-shaped hull</td>
<td>0.41&lt;sup&gt;**&lt;/sup&gt; &lt;br&gt;0.44 &lt;br&gt;−0.90 (−1.39, −0.41) &lt;br&gt;−0.81 (−1.31, −0.31) &lt;br&gt;−0.09 (−0.23, 0.05)</td>
<td>−0.06 &lt;br&gt;−0.11 &lt;br&gt;+0.16</td>
</tr>
<tr>
<td>Increased axle length</td>
<td>0.50&lt;sup&gt;**&lt;/sup&gt; &lt;br&gt;−0.70 (−1.31, −0.09) &lt;br&gt;−0.50 (−1.12, 0.12) &lt;br&gt;−0.20 (−0.33, −0.07)</td>
<td>−0.04 &lt;br&gt;−0.09 &lt;br&gt;+0.13</td>
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<sup>**</sup> p < 0.05.  <sup>**</sup> p < 0.01.

by containing the blast wave and the detonation products, thereby reducing the forces experienced by the passenger compartment. By the nature of their location, their geometry is determined by the dimensions and shape of the wheel arch. These constraints could result in a blast deflector design that causes the blast wave to reflect and coalesce to form a peak pressure many fold greater than the incident wave (Tremblay, 1998). This may lead to rupture along welded joints and penetration of the passenger compartment leading to injury. Hence, serious consideration should be given when

Fig. 6. Bar-chart depicting change in predicted probabilities of unharmed, injured and killed as a function of vehicle modification. <sup>**</sup> p < 0.05, <sup>**</sup> p < 0.01.
designing blast deflectors in order to mitigate the effect of structural failure.

Of all the design features that were proposed, increased ground clearance was the only modification noted to have a beneficial effect in reducing the ratio of killed:injured, killed:unharmed and injured:unharmed. Considering that large commercial trucks have naturally high ground clearance, this feature will require little modification in order to raise it further, thereby providing an extremely cost-effective measure in developing a mine-resistant vehicle fleet for developing countries. The V-shaped hull also significantly reduced the proportion of those killed, and further demonstrates that simple, easily manufactured modifications can have a significant effect on improving clinical outcome.

Many of the modern anti-mine vehicles in use by demining organisations and military forces are directly derived from the design processes developed during the Rhodesian conflict (Stiff, 1986; Cross, 2009). These vehicles incorporate all the design modifications described and are enhanced with improved armour materials. Anecdotal information from conflict zones would suggest that these vehicles are very successful in protecting their occupants from the effects of blast, although no published clinical data is available (Army, 2010). The cumulative effect analysis in our study strongly suggests that the inclusion of 2 protective measures is sufficient to reduce the fatality rate significantly. By limiting the

**Table 3**

Summary of cumulative effects model.

<table>
<thead>
<tr>
<th>No. of vehicle modifications</th>
<th>Multinomial logit estimates. Odds ratio (top line) with logistic co-efficient $\beta$ (95% CI in parentheses) (italics)</th>
<th>Change in predicted probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Killed vs. unharmed</td>
<td>Killed vs. injured</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>2</td>
<td>0.12 ($p &lt; 0.05$)</td>
<td>0.1 ($p &lt; 0.05$)</td>
</tr>
<tr>
<td></td>
<td>$-2.19 (-4.11, -0.28)$</td>
<td>$-2.35 (-4.29, -0.42)$</td>
</tr>
<tr>
<td>3</td>
<td>$-1.09 (-4.8, 2.64)$</td>
<td>$-2.5 (-6.27, 1.26)$</td>
</tr>
<tr>
<td>4</td>
<td>3.26 (−2.41, 8.94)</td>
<td>−0.11 (−5.84, 5.61)</td>
</tr>
<tr>
<td>5</td>
<td>7.84 (−0.33, 16.02)</td>
<td>2.72 (−5.56, 11.00)</td>
</tr>
</tbody>
</table>

$^*$ $p < 0.05$.  
$^{**} p < 0.01$.

**Fig. 7.** Cumulative effects model showing the change in predicted proportions of killed, injured and unharmed in relation to the reference category of zero and one alteration only.

**Fig. 8.** Comparison of fitted and observed results on the proportion of unharmed, injured, and killed as a function of the number of vehicle modifications. The observed results are represented by solid lines and the fitted results by dotted lines.
number of alterations required, this will significantly reduce the engineering complexity of vehicle design for the developing world, and making it more likely that these measures could be adapted in a relatively short time-scale.

One of the limitations of this study is that injury severity was not recorded. It is conceivable that although the proportion of those killed and injured reduced significantly with the alterations, the severity of injury may have increased. However, medical statistics from the final year of the conflict reported that of the casualties in mine protected vehicles, 16.2% were killed, 16.7% were seriously injured and 67.1% sustained only minor injuries. In comparison, of the casualties in unprotected vehicles, 32.5% were killed, 26% were seriously injured and only 41.6% suffered minor injuries (D-Branch, 1980). This effect bears similarity with automotive safety modifications, where seatbelts have not only reduced fatality rates but have also significantly reduced overall injury severity (Bédard et al., 2002; Orsay et al., 1998).

As with any data collected in conflict, there are often significant difficulties in obtaining detailed forensic data on the exact mechanism of injury. The non-permissive environment of war often precludes the opportunity for incident investigators to analyse the scene, as would happen in civilian automotive accidents. Thus, it is often difficult to discern injuries that resulted from the blast to those caused by the vertical acceleration of the vehicle. However, given the significant decrease in both injury and fatality rates, combined with experimental mine-test data conducted at the time, which reported reduced vehicle displacement after blast, it is likely that these modifications had an effect in reducing both effects.

Other limitations include the lack of demographic data about the occupants of the vehicles. The dataset included all AV mine events involving civilian and military vehicles. It is therefore possible that there may be some differences in injury and fatality rates based on the age of the vehicle occupants. As the conflict progressed, both civilian and military variants of the mine-protected vehicles were produced, as the risks of driving unprotected vehicles escalated. The major differences between the variants was the addition of side armour and bullet-proof glazing to protect military forces from small arms fire, when ambush after a mine-strike became an increasingly frequent feature (Stansfield, 1982; Stiff, 1986).

In automotive crash analysis, clinical data has in the past and continues to inform, evaluate and drive the development of protective measures to improve survivability and reduce long-term disability (Fredricksson et al., 2010). To date such analysis has not been applied to blast injury research and vehicle designers and manufacturers are forced to resort to numerical simulations or extrapolating injury data from the automotive crash industry (Yang et al., 2006; Tai et al., 2007; Grujicic et al., 2009a). We believe that the key to developing future protective measures relies on gaining a better understanding of the interaction between the occupants and the vehicle platform. This requires a collaborative effort between automotive engineers, scientists and clinicians, so that clinical, incident and vehicle data are combined in order to continually reassess design effectiveness and focus future research.

5. Conclusions

The V-shaped hull, increased ground clearance, blast deflectors, widened axles and heavy vehicles developed by the Rhodesians in response to the threat of an AV blast mine have all been shown to reduce fatality rates. In isolation, the inclusion of blast deflectors resulted in lower fatality, but a higher injury rate. The addition of 2 vehicle alterations resulted in a significant decrease in fatality rates with further decreases in injury rates noted with up to 4 vehicle alterations.

This study is the most comprehensive to date that utilises clinical data to detail the effects of these changes on vehicle occupant survival, and as such, can be used for the design of future blast mitigation measures. Given that the designs outlined were modifications of commercial vehicles, we believe that similar measures can be applied to vehicles in high mine-threat regions in a cost and resource effective manner in order to reduce the impact of AV mines in these areas. The knock-on effects in terms of aid distribution, freedom of movement and post-conflict reconstruction will likely outweigh the initial capital expenditure required to make these modifications.

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References


