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Surviving the bang: Evaluating the best option for combat vehicle survivability

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Abstract: The use of available and simple to operate yet lethal weapons, such as improvised explosive devices and rocket propelled grenades, against lightly armoured vehicles has become very common in recent years. It has been shown that current lightly armoured combat vehicles cannot be used for patrol or convoy missions in hostile environments without sustaining casualties. Also the use of add-on armour and other protection options is limited because of size and weight restrictions.

Combat vehicle design has traditionally focussed on the use of new and improved protective technologies to provide an appropriate level of survivability against a range of threats. However, other factors such as sensors, firepower, manoeuvrability, tactics, situational awareness and communications all play a role in increasing or decreasing the survivability of the crew and the platform. Although a layered approach has become standard in analysing vehicle survivability the inclusion of all possible layers will substantially increase the complexity of the problem. In this analysis the following layers are used for establishing various options: Don't be there, Acquire enemy before detection, Defeat enemy before detection, Don't be detected, Don't be acquired, Don't be hit, Don't be penetrated and Don't be killed. In addition the different types of operational scenarios and threats provide a challenge to the analyst in providing a clear answer to the problem of determining the 'best' survivability option.

The modelling approach used to calculate the benefits of competing survival options is a combination of qualitative and quantitative models. A decision tree analysis provides a clear picture of what options are viable in each survivability layer in order to provide protection against a specific threat. Rather than constructing a global quantitative survivability model this allows the calculation of only the appropriate probabilities of detection, acquisition, hit, penetration and kill for common battlefield sensors and weapons. These probabilities are then combined to give a probability of survival for each threat which consists of a sensor and weapon system. Finally by assigning a weight to each threat it is possible to estimate the overall probability of survival.

Keywords: *Combat Vehicle Survivability, Survivability Layers, Integrated Survivability, Probability of Kill*

1. INTRODUCTION

A combat vehicle that is in a hostile environment faces a variety of threats. In recent years the use of simple to operate and inexpensive weapons such as improvised explosive devices (IEDs), land mines, small arms and rocket propelled grenades (RPGs) has become common. For lightly armoured combat vehicles such as patrol vehicles and troop carriers the lethal effects of such weapons are well known.

Survivability for these vehicles can be described in terms of vehicle system survival and crew/passenger survival. The system must have sufficient survivability to ensure the completion of the combat mission. It is essential that there exists a level of survivability that can avoid or withstand damage to the platform and sub-systems such as communications. The principal aspect of survivability, however, is simply the ability of the crew and passengers to survive a hostile engagement even if the vehicle is destroyed.

In order to provide an appropriate level of survivability against a range of threats the designers of combat vehicles have traditionally invested in specific protective technologies such as armour and fire suppression systems. For example, some of the different types of armour are passive armour, active armour, reactive armour, smart armour, add-on armour, ceramic armour and composite armour. Yet other factors including sensors, jammers, firepower, manoeuvrability, tactics, situational awareness and communications all contribute to the survivability of the crew and the platform.

The aim of this paper is to establish a methodology to calculate the effectiveness of competing survival options based on a survivability layer approach (Horton, 1996). The methodology presented is intended to give indicative results enabling examination of vulnerabilities and trade-offs in survivability approaches, rather than a definitive answer. In order to illustrate this methodology the case of a basic lightly armoured combat vehicle facing low-level threats is considered. This allows the establishment of a baseline level of effectiveness suitable for comparison purposes as other survivability options and/or threats are considered.

Instead of constructing a complex quantitative survivability model that includes all possible survival layers, an approach consisting of a combination of qualitative and quantitative models is chosen. This permits the calculation of only the required probabilities that impact on survivability. These probabilities can then be combined to give a probability of survival for each individual threat. It is possible to prioritise the threats by assigning weights to each threat and consequently one can estimate the overall probability of survival.

2. QUALITATIVE ANALYSIS

In this analysis the following survivability layers are used for evaluating the ability of a lightly armoured combat vehicle to survive a low-level attack:

- Don't be there (level 7)
- Acquire enemy before detection (level 6)
- Defeat enemy before detection (level 5)
- Don't be detected (level 4)
- Don't be acquired (level 3)
- Don't be hit (level 2)
- Don't be penetrated (level 1)
- Don't be killed (level 0)

The particular threats that are considered include small arms, RPGs, IEDs and land mines.

A decision tree analysis is used as the basis for the qualitative analysis. For each threat it is possible to step through the different survivability layers to give a qualitative assessment as to the effectiveness of every component within each layer. This provides a clear picture of what options are viable in each survivability layer in order to provide protection against a specific threat.

For example, in the case of small arms and RPGs the possibility exists that the enemy can be acquired and defeated at an early stage (levels 6 and 5). This would require either an easily detectable enemy or a sophisticated sensor network. In addition, a deliberate decision would need to be made in order to engage the enemy, possibly at the expense of abandoning or delaying the original mission.

In the case of IEDs and land mines the problem is complicated by the fact that various types of these weapons are available with very different employment methods and lethality.

For the analysis of a basic combat vehicle facing the given low-level threat it can be assumed that there is only a rudimentary command, control and communications system supporting the vehicle. In general these vehicles are confined to established routes and are consequently easily detectable. Thus the qualitative conclusion is that only the lower levels of survival (levels 0 to 3) contribute significantly to the survivability of the combat vehicle.

3. QUANTITATIVE ANALYSIS

A quantitative estimate of vulnerability is made by estimating the probabilities of threats succeeding in each of the identified layers. This is done here for the lower layers (levels 0 to 3) of the qualitative model presented in section 2, giving values that can be used to generate a probability of kill for a particular threat, as follows:

$$P_K^{threat} = P(kill \mid pen)_K^{threat} P(pen \mid hit)_K^{threat} P(hit \mid acq)_K^{threat} P(acq)_K^{threat}$$

As indicated by this defined kill chain, a ‘threat’ is defined in this paper as a weapon and sensor coupled as a system, for example, an RPG aimed by a human eye, or a land mine triggered by a pressure plate. More complex threat systems, for example, weapons cross-cued by multiple sensors require additional calculations than presented here to formulate an overall $P(acq)_K^{threat}$. A vehicle’s vulnerability in a scenario involving an array of threats can be estimated as an overall probability of kill using a weighted sum approach

$$P_K = \sum_{threat_j} \left(w_j P_K^{threat_j} \right)$$

The weightings, w_j, can be adjusted to prioritise threats, thus modelling different engagement scenarios.

Threats are chosen to represent the current environment from a recent assessment of threats encountered on operations. Threats are modelled as a composite system: a weapon used in conjunction with a sensor or triggering mechanism.

3.1. P(acq)

A probability of acquisition by a threat is modelled based on capabilities of the sensor system and the vehicle signature. A range of sensors and acquisition aids are modelled: the human eye, magnifying sights, an image intensifier (night vision device), and a thermal imager, all affecting probability of acquisition and a laser range finder, enhancing probability of hit. The modelling process for acquisition by the human eye and electro-optic sensors is substantially as outlined by (Waldman and Wootton, 1992), using an empirical formula for threshold contrast for visual search (Koopman, 1986), and a target transfer probability function method for acquisition for electro-optic sensors (O’Connor et al, 2003) shown in Figure 1. The output probabilities vary over engagement range, so $P(acq)_K^{threat}$ is produced as a function of range for these threats.

Land mines and IEDs are assigned a probability of acquisition based on their triggering mechanism; effectively, $P(acq)_K^{threat}$ for IEDs and landmines becomes a probability of the vehicle triggering the device. IEDs are triggered using a variety of different observed mechanisms, which were assigned different probabilities of acquisition (triggering) based on subject matter expert opinion.

3.2. P(hit|acq)

Hit probability for small arms is derived from accuracy data from DSTO experimental data comparing optical rifle sights. Accuracy with these weapons varies over range, so $P(hit \mid acq)_K^{threat}$ is a function of range for these threats, modelled using the same ranges as for the $P(acq)_K^{threat}$ calculation. Hit probability for RPGs is estimated from estimates appearing in technical databases, and is uniform over their effective engagement range from this data. The modification of hit probability due to the use of a laser range finder is estimated by subject matter experts.

Land mines are assigned a $P(hit \mid acq)_K^{threat}$ =1. IEDs are assigned high P(hit|acq) values, according to their different triggering mechanisms and warhead types.

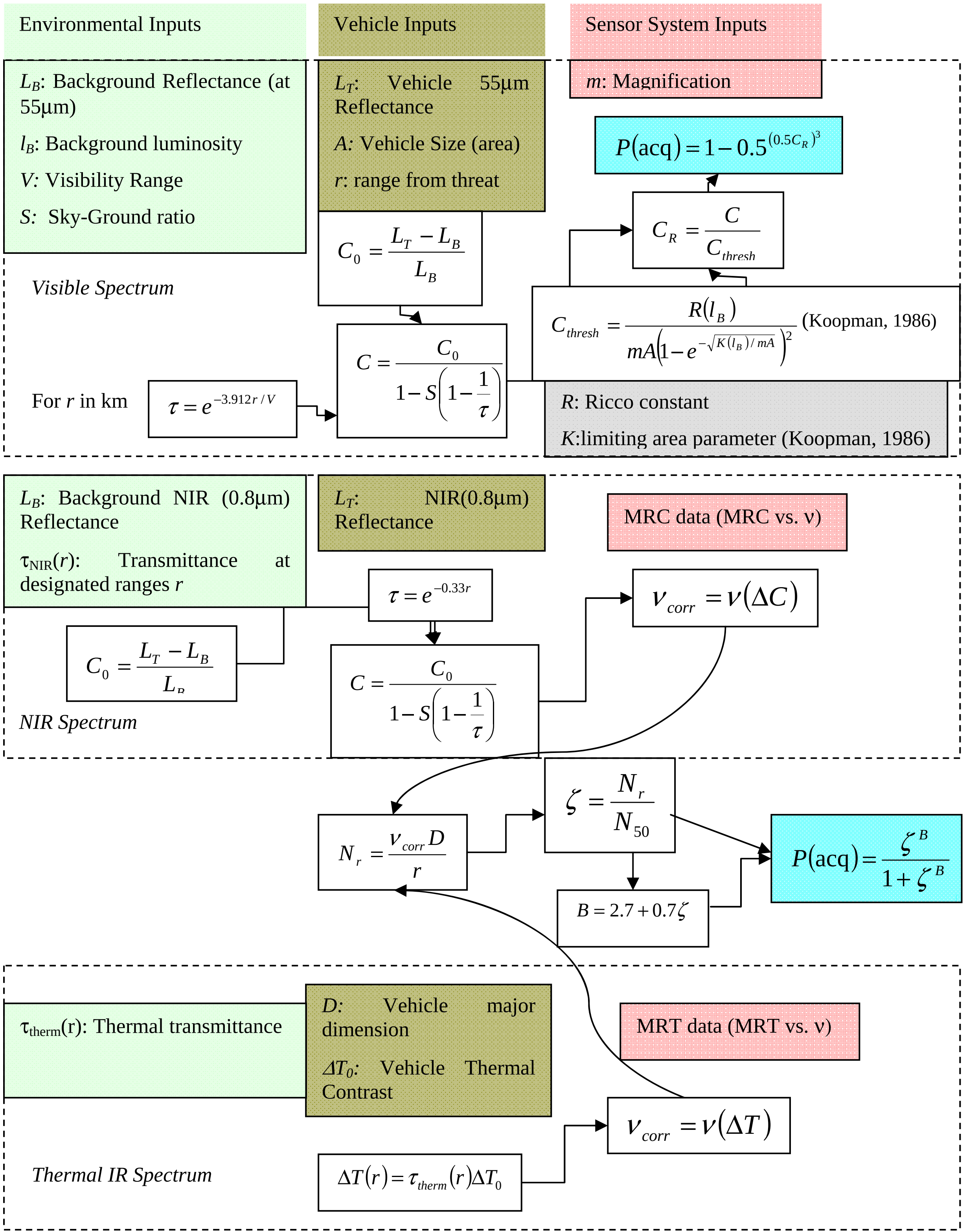

Figure 1: P(acq) modelling diagram.
Acquisition modelling framework from Waldman and Wootton (1992). NIR: Near Infra-red; C: Contrast; MRC: Minimum Resolvable Contrast (sensor system parameter); MRT: Minimum resolvable temperature; ν: sensor spatial frequency; K: an empirically determined area value beyond which no further increase in apparent area will increase probability of acquisition; N_{50}: Number of cycles for 50% probability of success at acquisition task, here N_{50} = 11.5 (O'Connor et al, 2003)

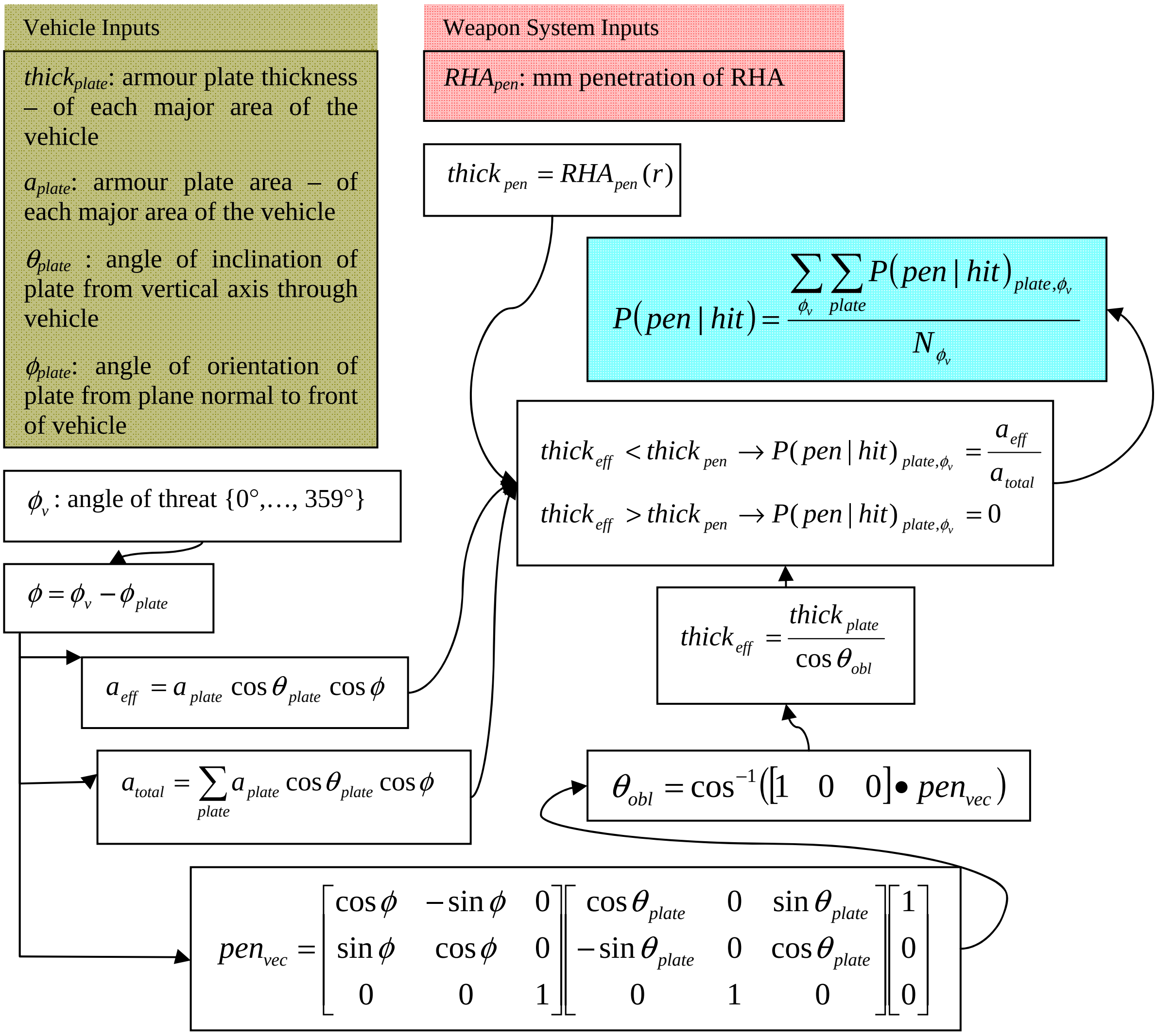

Figure 2: $P(pen|hit)_K^{threat}$ **inputs and modelling process diagram**

RHA: Rolled Homogeneous Armour, N_{ϕ_v} **:Total Number of threat angles modelled**

3.3. P(pen|hit)

We model $P(pen|hit)_K^{threat}$ based on literature data on penetration of armour by the weapons modelled. A simple model of the vehicle simply as a box made of armoured plates is described in Figure 2. We compute the thickness of the armour of a plate exposed from any firing angle (occluded plates return a negative a_{eff} in this construct and are removed from the calculation of total exposed plate area). This is compared to the penetrative capability of the projectile ordinance and the resulting penetration is averaged for several firing angles the around the vehicle, producing an average probability of penetration if hit, is described in Figure 2. As projectile penetration capability reduces with range, $P(pen|hit)_K^{threat}$ is a function of engagement range. A range cut-off is applied to this probability for weapons with limited minimum and maximum effective ranges. This simple construct is only used for low fidelity modelling, for example, where exploring trade-off between armour and other forms of survivability enhancement. Higher fidelity vehicle penetration modelling would be appropriate for investigating questions regarding placing of armour and specific vehicle design, and for modelling complex terrain effects in firing angles.

IEDs and landmines are assigned $P(pen|hit)_K^{threat}$ values based on warhead type and explosive mass. If the explosive mass is greater than the vehicle's protection level specification (as specified in NATO, 2004), the blast or fragments will be assumed to penetrate the vehicle. Thus, $P(pen \mid hit)_K^{IED/landmine}$ is a function of explosive mass, except where specialist warheads increasing penetrative power are deployed.

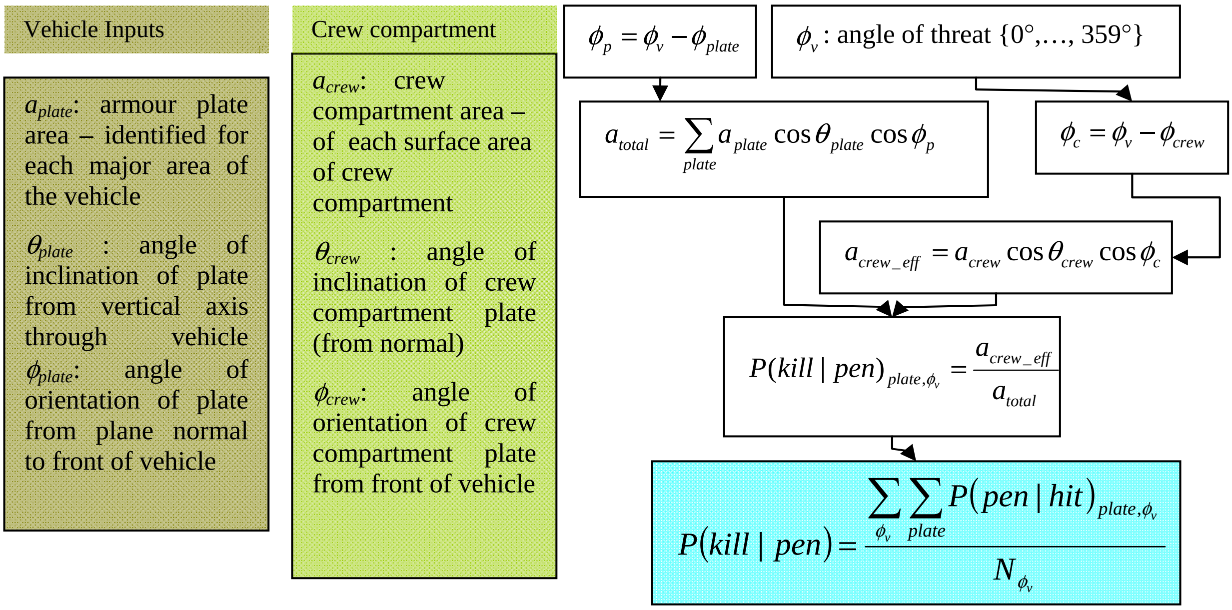

Figure 3: $P(kill \mid pen)_K^{threat}$ **inputs and modelling process diagram**

N_{ϕ_v} **:Total Number of threat angles modelled**

3.4. P(kill|pen)

For small arms, $P(kill \mid pen)_K^{threat}$ is modelled as a ratio of crew compartment area apparent to the firer's location to the vehicle area exposed. Conceptually, this is the probability of the bullet penetrating the crew compartment, given that it penetrated the vehicle somewhere. This modelling process is detailed in Figure 3. $P(kill \mid pen)_K^{threat}$ is not range dependent.

For RPGs, $P(kill \mid pen)_K^{threat} = 1$ for basic, unmodified light armoured vehicles within the weapon's effective range, and 0 outside the effective range. For land mines and IEDs, very high $P(kill \mid pen)_K^{threat}$ values are assigned, according to variations in explosive type.

4. PROPOSED EXTENSIONS OF THIS WORK

4.1. Assessing potential survivability enhancements

The estimated probabilities of kill in the previous section can be used to construct a survivability enhancement measure, ΔS_{tech}^{threat} , describing the enhancement to survivability of the vehicles against threats due the application of some technological improvement.

Then, the application of a technological improvement is modelled to produce a modified probability of kill, $P_K^{threat,tech}$. For example, a signature management technology reducing vehicle signature leads to a reduced value of $P(acq)_K^{threat,tech}$; a pre-triggering technology providing a capability to pre-detonate an IED or landmine leads to a reduced value of $P(hit \mid acq)_K^{threat,tech}$, a spall liner providing damage mitigation against RPGs leads to a reduced value of $P(kill \mid pen)_K^{threat,tech}$.

We are able to define ΔS_{tech}^{threat} for combinations of survivability-enhancing technologies:

$$\Delta S_{tech}^{threat} = P_K^{threat}\left[1-\prod_{tech_i}\left(P(acq)_K^{threat,tech_i}\right)\left(P(hit \mid det)_K^{threat,tech_i}\right)\left(P(pen \mid hit)_K^{threat,tech_i}\right)\left(P(kill \mid pen)_K^{threat,tech_i}\right)\right]$$

We model the problem of which combinations of survivability enhancing technologies to apply by maximising the objective function, F_{tech}, which is the product of ΔS_{tech}^{threat} weighted by the priorities, w_j, of each of the threats.

$$F_{tech} = \sum_{threat_j}\left(w_j \Delta S_{tech}^{threat_j}\right)$$

This function can be constrained in various ways, to analyse the trade-off between survivability improvement and other vehicle utility metrics, such as mobility and lethality. Proposed survivability enhancing technologies, or vehicle design strategies, can be assessed for their impact on other vehicle utility metrics, and their effect on those metrics can be assessed against the overall survivability enhancement. For example, added weight can be used as a simple proxy for mobility. Examining the change in survivability enhancement over a range of weight limits allows an assessment of the trade-off between added weight and protection level.

The problem can also be constrained by apportioning survivability ‘effort’ to the layers – for example, to assess the potential benefits of emphasising hit avoidance technologies against the benefits of heavier armour.

4.2. Assessing survivability over different scenarios

This analysis, originally completed for a scenario reflecting current threats, could be adapted to other operational scenarios or expected future scenarios, by specifying weapon systems, engagement ranges and weighting threats according to expected threat level. Alternative scenarios can be created by adding to the types of weapons and surveillance technologies in the threat array. Future combat scenarios can be modelled by including extant advanced systems (for example, guided missiles, aircraft launched bombs, advanced electro-optic or radar surveillance systems) or by estimating improvements in capabilities of existing weapons (for example, extrapolating improvements in range and accuracy for RPGs, or improvements in penetrative power of land mines).

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