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Effect of Hull Obliquity on Crew Protection, Mass and Space Occupancy of Light Armoured Vehicle: An Optimal Design Approach

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ABSTRACT

Apart from strengthening crew protective capability from gunfire, the hull obliquity in a light armoured vehicle (LAV) affects its weight and comfortable occupancy. Thus, it requires a critical design analysis for the obliqued hull. The study aims to present the optimal design analysis of an obliqued hull structure to ensure comfortable occupancy of the crew along with its minimum attainable weight and higher protection capability from the gunfire. Three geometric models (G1, G2, and G3) were investigated for the LAV hull's optimal design. The analytical approach was used to investigate the hull obliquity's effect, and the results were validated using experimental data reported by other researchers. Digital human modelling was adopted for validating the space adequacy of the hull. It was observed that the hull's crew protection capabilities from the horizontal strike of armour piercing rounds/bullets were improved almost by half and double for G2 and G3, respectively, when compared with G1. The analytical results are also in good agreement with globally accepted experimental data at reasonable variations. The highest protection capability and comfortable occupancy for the targeted users can be achieved by G3 without affecting the mobility of LAV.

Keywords: Oblique angle; Effective thickness; Projectile deflection; Penetration resistance-to-weight ratio; Ergonomic design; DHM

1. INTRODUCTION

Increasing the effectiveness of passive armour protection by inclining hull surfaces has been common while designing light armoured vehicles (LAVs) as well as heavy armoured vehicles (HAVs)[1,2]. The light-weight armour design and analysis is possible by conducting physical experiments or through numerical simulations[3,4]. So far, the hull obliquity was extensively tested for crew protective capabilities[5-8], without considering much about ergonomics (occupant workspace) and weight factors (vehicle weight). Along with protective capability, the effect of hull obliquity on vehicular weight and occupant space is equally important[9, 31]. The hull needs to be designed with minimum weight and maximum resistance to increase vehicle mobility and reduce material costs[10,35,36]. Moreover, the effect of the geometric change on occupant space and vehicular weight is still contradictory, and there is a need to analyse their combined effects[11,12]. The desired oblique angle should be predetermined at the initial design stages, and it highly depends on the roof height and base width of interior space. However, due to the paucity of literature on optimum oblique angle of hull, the random angle has been used by designers during the initial design process towards the enhancement protection capability[1].

Apart from active and reactive armour protection technology, passive protection using hull obliquity systems is supposed to enhance crew protection capabilities from gunfire and improve occupant workspace[2,13]. Previous studies extensively reported about improving protection capabilities using different hull material[33,34]. However, investigating the effect of overall form (hull-shape) on firing protection, mobility (weight reduction), and effective vehicular workspace needs further research[31].

Armoured vehicles generally provide protection from armour piercing (AP) rounds/bullets (or blasts) by enhancing the hull's protective capability. Khan[7], *et al.* noted that evaluating the phenomena of normal and oblique impacts on thin plates is of interest in many engineering applications, like crashworthiness of vehicles and the design of lightweight body armour. The advancement in using different composite materials has also shown progressive improvement in the survivability of armoured vehicles[13]. In order to increase the passive protection, the diamond geometric shape of the hull (oblique armoured surface) is one of the commonly used armour types[14]. The shoulder-launched missiles or rounds/bullets are most likely to hit the hull's surface from a horizontal direction[10]. The obliqued armour plate has been proven to deflect the energy of projectiles/bullets that comes from horizontal direction and minimise surface penetration[15]. Therefore, to increase armour protection effectiveness, the inclination of the hull surface is rather common in LAVs[2].

Regarding ergonomic issues, poorly designed workspaces adversely affects operating performance of the soldiers during

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carrying and combating missions[16]. Therefore, human factors are considered to be most important in military system design[17,18]. While dealing with the ergonomic system design approach in vehicle design, it is necessary to consider a seated person's basic anthropometric dimensions to determine the space height and width[19]. Therefore, armoured vehicle's ergonomic considerations should be given equal importance as protection, mobility, and firing capabilities.

The present research aims to enhance crew protection capabilities of Ethiopian LAVs through hull obliquity (sloping geometry) with due considerations on occupant space and mobility of the vehicle. We hypothesise that the change in geometry of the hull will also change protection capabilities, occupant space adequacy, and mobility/mass of the LAVs. We sought to test whether the optimum oblique angle of the hull increases the energy absorption capacity when hit by horizontal projections, without adversely affecting mobility and occupant space. The three optimal design constraints viz. occupant space, protection, and mobility of the vehicle were considered to achieve this goal. The occupant space is characterised by roof height and base width of the hull[19]; the protection is characterised by energy absorption (Jena[6], *et al.*) and deflection angle, while the weight of the hull[20] characterises the mobility. The penetration capability can be enhanced by increasing the effective thickness and oblique angle of the hull geometry.

2. METHODOLOGY

The effect of the change in hull oblique angles was analysed on the occupant workspace, its weight, and energy required for penetration (energy absorption capability). The protective capability of the hull at different oblique angles was evaluated. It was tested considering occupant space as an important design constraint. The analytical results (from the present study) were then compared with the experimental results conducted by other researchers to verify the reliability of the study. The optimal design solutions were computed by taking into account different design constraints and Ethiopian anthropometry. The agreement of analytical results with experimental data (reported by other researchers) was compared for verification purposes. Finally, to validate the adequacy of occupant space of the targeted users (Ethiopian army personnel), the digital manikin was created and interfaced in a virtual environment using digital human modelling (DHM) module (CATIA V5).

2.1 Design Object (LAV Hull Structure)

The LAV oblique hull structure (Fig.1 (a)) was the targeted object that needs to be evaluated and optimally designed for adequate interior workspace and protective capabilities. The shape and size of the hull affect the workspace as well as its protective capabilities[21]. The oblique angle and the effective thickness of the hull were considered to be two main influencing parameters for crew protection performance[1]. The horizontal projection of armour piercing projectile is considered as the most common direction[1,] and thus, due to the obliquity, the horizontal penetration distance (effective thickness, t_e) of oblique hull would be greater than the actual thickness (t)[15] as shown in Fig.1 (b). The hull obliquity was also supposed to be

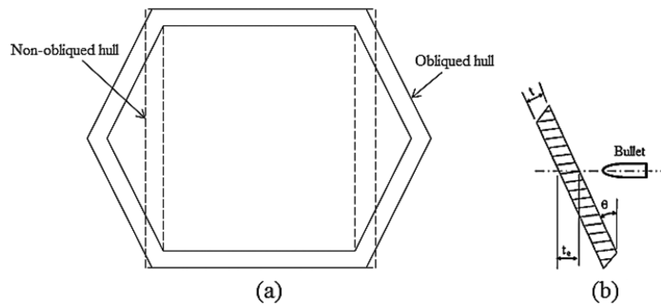

Figure 1. Cross-sectional view of (a) non-oblique and oblique-angled hull geometries and (b) effective thickness (t_e) of oblique plate.

advantageous in deflecting the guided-projectiles[2]. Hence, the protective capability of non-obliqued and obliqued hull was evaluated in terms of the penetration resistance to weight ratio (R). The larger value of R (R >1) indicates higher protective capabilities.

The following design assumptions were taken into consideration for designing the oblique hulls:

- Unlike the roof height and base/floor width, the length of the occupant space was not considered a relevant dimension since it has no effect on optimal design analysis of hull obliquity in this particular study.
- The infantry troops (crew members) seated back-to-back or face-to-face are largely affected by the hull obliquity, therefore, they were the ones tested from an ergonomics perspective. The ergonomic evaluation does not cover workspaces for the gunner, commander, and driver since they are less likely affected by hull obliquity.
- Even though seat height is usually designed by the 5th percentile (p) value of popliteal height, the roof height from the footrest was considered to be the sum of the mean value of 50th p (male and female) of the popliteal height and 95th p (male) sitting height. The purpose is to accommodate larger users in case of using the seat having larger (other than recommended) seat height.
- The space for placements of the equipment and units such as drive train (including electrical power generation system), fuel storage, mission-essential payload, integral auxiliary equipment were not considered while evaluating occupant space dimensions.
- The study comprised only side hull obliquity to protect from horizontal projectiles. Hull obliquity at the bottom (to protect against mine blast), front and back of LAV was not included in the study.
- The hull's thickness was considered insignificant in the study for the determination of hull size.
- The maximum hull width of LAV is assumed not to exceed 2.5 m[22].
- This technical design emphasises only on horizontal projection of AP rounds.

2.2 Interior Space Dimensions w.r.t. Occupant/Crew Anthropometry

The roof height (h_r), the base width (w_b), and seat height (h_s) are considered to be the basic dimensions in an

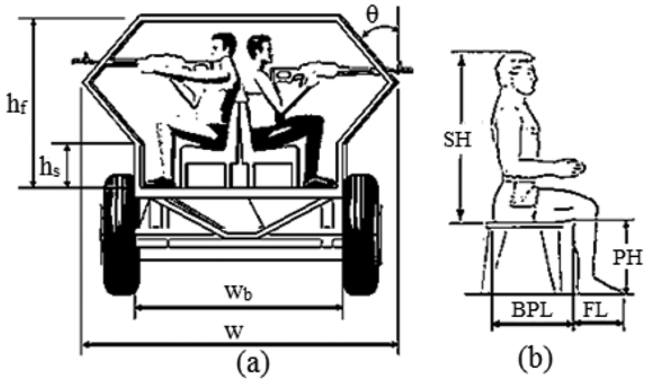

Figure 2. (a) Key design dimensions of the hull, (b) anthropometric design dimensions.

occupant space (Fig. 2). These dimensions need to adequately accommodate a wide range of user populations and are directly related to the basic anthropometry of seated occupant[19]. The basic anthropometric dimensions of seated occupant considered for the interior workspace design were sitting height (SH), popliteal height (PH), buttock to popliteal length (BPL), and foot length (FL) depending on the adopted posture of the infantry troop and geometry of the hull (Fig. 2(a) and 2(b)). The maximum hull width (w) is directly linked with h_r, w_b, h_s, and oblique angle (θ).

The seated crew's anthropometric measurements and their corresponding seat space dimensions are presented and described in Table 1 and Fig. 2, respectively. The minimum and maximum interior space dimensions are often limited by 95th p male and 5th p female anthropometry, respectively. Similarly, the average dimensions are limited by the combined mean of 50th p female and male anthropometry. This study assumed that infantry troops would be seated at a nearly 90-degree knee angle to determine the minimum legroom (Fig. 3(a)). Accordingly, the minimum leg room required for a person was limited by the buttock-popliteal length and foot length.

In a prior study, anthropometric dimensions of 310 Ethiopian armed personnel (250 males and 60 females)[25] were physically measured. Later, they used those anthropometric dimensions to predict the relevant vehicular workspace[26]. The same anthropometric measurements of Ethiopian armed personnel were used in this study. The overall seated height from footrest (roof height) could be approximated from the combination of sitting height (of 95th p male) and mean popliteal height (of 50th p male and female), altogether came out to be 136 cm (Table 1). The half of the base width (w_b) of interior space shall be approximated from the combination of the buttock to popliteal length and foot length (of 95th p male), and found to be 82.5 cm for a single person. Therefore, w_b = 165 cm can be considered effective space width to accommodate two crew sitting back to back in two rows. The height, h_s at a rectangular section of geometric design, G3 (Fig. 2(a)) was defined by the seat height, which can be determined by the 5th p female popliteal height that came out to be 36.3 cm.

2.3 Geometric Models for Conceptual Design of Hull

Three hull geometries (one rectangular and two oblique) of LAV have been presented towards comparing different interventions for better ergonomics and protection aspects, as shown in Fig. 3. The rectangular hull structure (G1) is an ordinary geometric design concept. It has been widely used in the existing vehicular body construction. From the two oblique hull design concepts, G2 and G3, the diamond-shaped hull structure (G2) is an advanced design concept. It has now been the widely used design concept for LAVs and HAVs[1, 14]. The third geometry (G3) is a new design concept. The current study presents a futuristic LAV design to achieve effective workspace benefits by adequate legroom for the infantry troops. Since the injury in the leg portion (due to its dense/bone tissue) is not the most severe issue as compared to other soft tissue/organs (e,g. lever, brain, and abdomen), the protection improvement requirement of the hull for lower legs is ignored in the design concept of G3[23,24].

2.4 Mathematical Modelling for Occupant Space, Penetration Resistance and Mass of the hull

A comparative assessment between non-oblique (G1) and oblique (G2, G3) hulls was made to evaluate the effect of oblique hull angle on occupant space dimensions, protective capability, and weight/mobility. Mathematical relationships to formulate,

(a) Hull width (w_i)
(b) Effective thickness (t_e)

Table 1. Equations for defining interior occupant space dimensions in terms of anthropometry and allowance/clearance

Interior dimensions	Predicting equations Wibneh[26], *et al.*	Predicted values Wibneh[26], *et al.*
Roof height	$h_{r(\min)} = \left(SH_{95^{th}(M)} + 5cm\right) + \left(PH_{50^{th}(F\&M)} + 2cm\right)$	$h_{r(\min)}$ = 1.36 m
Base width	$w_{b(\min)} = \left(BPL_{95^{th}(M)} + FL_{95^{th}(M)} + 6cm\right)$	$w_{b(\min)}$ = 1.65 m
Seat height	$h_{s(\max)} = PH_{5^{th}(F)} + 2cm$	$h_{s(\max)}$ = 0.36 m

SH – sitting height; PH – popliteal height; BPL – buttock to popliteal length; FL – foot length; h_r –roof height; w_b –base width.
5th p (F) – anthropometric value for 5th percentile female
95th p (M) – anthropometric value for 95th percentile male.
50th p (F&M) – the combined anthropometric mean value of 50th percentile female and male.

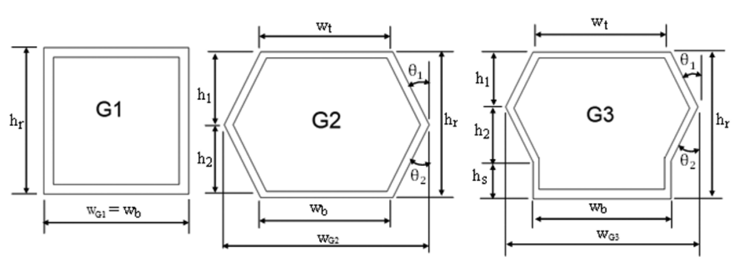

Figure 3. Cross-sectional views and primary design variables for different hull geometries (G1, G2 and G3).

(c) Mass of presented geometries (M_i)
(d) Mass ratio of oblique to non-oblique armour plate (R_{Mi})
(e) The energy required for penetration (E_i)
(f) Ratio of penetration resistance for the oblique to the non-oblique hull (R_{Ei}), and
(g) Penetration resistance to mass ratio (R_i), were established.

2.4.1 Hull Width

The width (w) of a non-oblique hull structure (G1) is the same as the base width (w_b). However, the width, w, of the oblique hull structure (G2 and G3) depends on the roof height, base width, and oblique hull angle. Additionally, G3 also depends on seat height (h_s), as shown Fig. 3.

The relationships of these parameters for the three geometries were formulated (Eqns 1(a), 1(b) and 1(c)). For simplifying the models, the following assumptions are made:

$\theta_1 = \theta_2 = \theta$; $h_1 = h_2$; $w_b = w_t$.

For non-oblique hull (G1):

$$w_{G1} = w_b \tag{1a}$$

For the oblique hull geometry (G2) at $h_s = 0$, the width of hull (w_{G2}) can be evaluated as:

$$w_{G2} = w_b + h_r \tan\theta \tag{1b}$$

For the oblique hull geometry (G3) in a certain value of h_s, the hull width (w_{G3}) can be evaluated as:

$$w_{G3} = w_b + (h_r - h_s)\tan\theta \tag{1c}$$

where, θ is the armour plate oblique angle measured from vertical direction; w_b= base width of hull; h_r = roof height of the hull; h_s = seat height targeted to 5th p female.

2.4.2. Effective Thickness

As it was mentioned earlier, the projection of guided projectiles mostly comes from horizontal directions[15,27]. Thus, the horizontal penetration distance (effective thickness, t_e) will always be greater than the actual thickness, t (non-oblique hull) for the oblique hull. As effective thickness will always vary with oblique angle (Fig. 1(b)), the effective thickness can be determined as follows:

$$t_e = \frac{t}{\cos\theta} \tag{2}$$

where, θ is the armour plate oblique angle measured from vertical direction; t = actual wall thickness of hull; t_e = effective wall thickness of the hull

2.4.3 Mass of Presented Geometries

Mass of non-oblique hull (M_{G1}), the oblique hull (M_{G2}) and (M_{G3}) were formulated (Eqns 3(a), 3(b) and 3(c)) from the three geometries (see Fig. 3), respectively.

$$M_{G1} = 2\rho\ell t(h_r + w_b) \tag{3a}$$

$$M_{G2} = 2\rho\ell t\left(\frac{h_r}{cos\theta} + w_b\right) \tag{3b}$$

and,

$$M_{G3} = 2\rho\ell t\left(\frac{h_r - h_s}{cos\theta} + w_b + h_s\right) \tag{3c}$$

where, θ is the armour plate oblique angle measured from vertical direction; M_{G1} = mass of G_1; M_{G2} = mass of G2; M_{G3} = mass of G3; ρ = material density; t = hull thickness; ℓ = length of the hull having constant cross-section; w_b= base width of the hull; h_r = roof height of the hull; h_s = seat height (targeted as 5th p female).

2.4.4 Mass Ratio of Oblique to Non-oblique Armour Plate

For evaluating the relative change in mass for oblique hull w.r.t. non-oblique hull, the mass ratio of the oblique hull (M_{G2}) w.r.t. non-oblique hull (M_{G1}) was formulated as shown in Eqns (4a):

$$R_{M(G2)} = \frac{h_r + w_b\cos\theta}{(h_r + w_b)cos\theta} \tag{4a}$$

The mass ratio for oblique hull (M_{G3}) and. non-oblique armour (M_{G1}) can be shown as:

$$R_{M(G3)} = \frac{h_r - h_s + (w_b + h_s)\cos\theta}{(h_r + w_b)cos\theta} \tag{4b}$$

2.4.5 The Energy Required for Penetration (Penetration Resistance)

The hull that requires higher energy to penetrate is considered for having a good protection capability. The ballistic limit of a projectile can be determined in terms of kinetic energy required to penetrate the hull[28]. The armour Penetration Formulas[28] was modelled to predict the total loss of incidence energy (with zero residual velocity after piercing) and stop the armour piercing projectile for protecting the crew inside the hull. Therefore, the formula of energy required to penetrate any oblique armour plate (regardless of effective thickness) would be:

$$E_{(G2,G3)} = 8.025\frac{td^2F^2}{\cos^2\theta} \tag{5a}$$

For non-oblique hull (G1) at θ = 0°:

$$E_{G1} = 8.025\,td^2F^2 \tag{5b}$$

where, E_{G1} = kinetic energy needed to penetrate non-sloped hull; E_{G2} = kinetic energy needed to penetrate sloped hull; t = actual hull thickness; d = projectile diameter; F = F-coefficient (dimensionless); θ = oblique angle of hull.

However, the modelled formula (Eqn 5a) does not consider the effective thickness of the oblique-angled hull that was reported by Wibneh & Karmakar (in press) and Yap[15]. The armour piercing projectile that comes from a horizontal direction should also consider the increase of effective thickness (penetration distance) instead of actual thickness[10,15]. Therefore, the formula should be modified by substituting actual thickness (t) to $t_e \approx t/\cos\theta$ (see Eqn 2). Therefore, the modified formula of energy required to penetrate oblique armour plate (G2 and G3) will be:

$$E_{(G2,G3)} = 8.025\frac{td^2F^2}{\cos^3\theta} \tag{5c}$$

2.4.6 *Penetration Resistance for Oblique Hull w.r.t. Non-Oblique Hull*

For comparing the penetration resistances of oblique hull (G2 and G3) w.r.t. non-oblique hull (G1), the energy ratio ($R_{E(G2,G3)} = E_{(G2,G3)}: E_{G1}$) required to penetrate the hull plate can be formulated by substituting Eqns (5b) and (5c):

$$R_{E(G2,\,G3)} = \frac{1}{\cos^3\theta} \tag{6}$$

Since $|\cos^3\theta| < 1$, the ratio $R_{E(G2,G3)}$ will always exceed 1[15]. This implies that penetration resistance of obliqued hull (G2 and G3) will always be greater than G1.

2.4.7 *Penetration Resistance to Mass Ratio*

Similarly, penetration resistance to the mass ratio of obliqued hulls (G2 and G3) w.r.t non-oblique hull (G1) was formulated to investigate the effect of hull obliquity (on its mass) for improved protection capability. It can verify the relative change of penetration resistances w.r.t mass (in terms of hull obliquity). The ratio ($R_{G2} = R_{E2}: R_{M(G2)}$) of energy required for penetration (energy absorption) of the oblique hull (G2) to its mass was formulated by substituting Eqns (4a) and (6) as:

$$R_{G2} = \frac{h_r + w_b}{h_r\cos^2\theta + w_b\cos^3\theta} \tag{7a}$$

Similarly, the ratio ($R_{G3} = R_{E(G3)}: R_{M(G3)}$) of energy required to penetrate oblique hull (G3) to its mass was formulated by substituting Eqns (4b) and (6) as:

$$R_{G3} = \frac{h_r + w_b}{(h_r - h_s)\cos^2\theta + (h_s + w_b)\cos^3\theta} \tag{7b}$$

2.5 Problem Definition of Optimisation

The optimal design variable is the oblique angle θ, and the objective function is used to maximise the penetration resistance to mass ratio, $R_i(\theta)$ of the oblique hull structure w.r.t. non-oblique hull (G1). The constraints of the objective function were defined briefly as follows:

1. $g_1 = w_1(\theta)|_{\theta=0°} - w_{\max} \le 0$. This implies that the width of rectangular hull structure (G1) at oblique angle, θ=0° should not exceed the maximum allowable width, $w_{\max}$=2.5, which ought to be defined by transportability and mobility factors [19, 22].
2. $g_2 = w_2(\theta)|_{h_s=0} - w_{\max} \le 0$. This implies that any geometric hull structure's width at h_s=0 should not exceed the maximum allowable width.
3. $g_3 = w_3(\theta)|_{h_s=c} - w_{\max} \le 0$. This implies that any geometric hull structure's width at a certain value c of h_s should not exceed the maximum allowable width.
4. The roof height, (h_r) (Fig. 3) should exceed the minimum roof height ($h_{r(\min)}$), determined using anthropometry of the user populations (to accommodate a wide range of the seated army personnel or infantry troops).
5. The base width (w_b) (Fig. 3) should exceed the minimum base width ($w_{b(\min)}$) that was determined by anthropometry of the user populations seated back to back or face to face in the LAV.
6. The height of lower rectangular portion of the oblique hulls, determined by the seat height (h_s) (Fig. 3) should not exceed the maximum seat height ($h_{s(\min)}$) to protect the upper portion of the body (upper limb) of a wide range (95%) of soldier population.
7. The design variable θ shall always be positive and should not exceed 60°[29].

The general optimisation problem was addressed as follows:

Find: θ

$$\textit{Maximize}: F_i(\theta) = R_{Gi}(\theta), \quad i = 1,2,3 \tag{8}$$

$$\begin{aligned} \textit{Subjected to}: g_i &= w_{Gi}(\theta) - w_{\max} \le 0, \quad \mathrm{i} = 1,2,3 \\ h_r &\ge h_{r(\min)} \\ h_s &\le h_{s(\max)} \\ w_b &\ge w_{b(\min)} \\ \theta_{\min} &\le \theta \le \theta_{\max} \end{aligned} \tag{9}$$

MATLAB optimisation toolbox was employed for plotting the results of this non-linear optimisation problem[30].

3. RESULT AND DISCUSSION

In this section, the effect of oblique angles of the presented hull geometries on different attributes viz. penetration resistance in terms of the required energy for penetration of the hull, masses of the presented hulls penetration resistance to weight ratio, hull width, roof height, and base width were analysed and presented thoroughly. After verifying the effect of hull obliquity on the above-mentioned attributes, the optimum angles were evaluated for all three hull geometries. The analytical models were also verified using experimental data reported by other researchers.

3.1 Effect of Oblique Angle on Crew Protection and Mass of the Hull

The influence of oblique angle on both crew protection and mass of the hull were investigated analytically with taking into account space occupancy. The space occupancy was constrained by h_r= 1.36 m, w_b= 1.65 m, and h_s = 0.36 m with varying hull width (w) as shown in Table 1.

3.1.1 *Effect of Oblique Angle on Penetration Resistance of the Three Geometries*

The penetration resistance ratio between obliqued and non-obliqued hull (R_E, Eqn 6) was plotted at different oblique angles (Fig. 4(a)).

For the same wall thickness and length, the energy required for penetration of non-oblique hull approximately increased by twice at 40° and eight times at 60° when compared to the non-oblique hull, G1 (see Fig. 4(a)). The two oblique geometries (G2 and G3) showed no difference in penetration resistance regardless of their mass variations. Therefore, the protective capability can be improved using either of them. Therefore, it can be said that obliquity is one of the most crucial factors that increase the protective capability of the hull structure from the piercing projectile that comes from the horizontal direction. Dehart[14], *et al.* also noted that the diamond-shaped (obliqued) hull deflects energy from sources causing minimum damage to the hull.

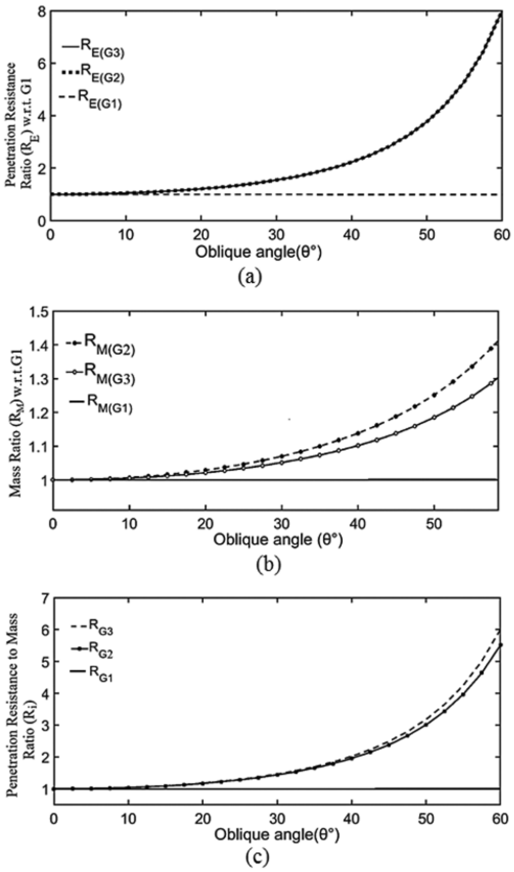

Figure 4. Effect of oblique angle on (a) penetration resistance, (b) mass ratio, and (c) penetration resistance to mass ratios.

3.1.2 Effect of Oblique Angle on Masses of Hulls in the Presented Geometries

The mass ratio of the obliqued and non-obliqued hull structures (R_M, eqn. 4) were plotted at different oblique angles (Fig. 4(b)).

From the Fig. 4(b), it can be noticed that as the oblique angle increases, the mass ratio (between obliqued and non-obliqued hull) also increases. The change of the mass at a larger angle was relatively higher than at a smaller angle. Further, G2 exhibits relatively larger values as compared to G3. It implies G3 to be more advantageous as it gives the same protection capability with minimum weight. In general, the hull obliquity increases its mass w.r.t. non-oblique hull, which is undesired for effective mobility of the LAVs. The increased overall weight (with increased obliquity) of the LAV decreases its mobility and increases material cost. Moreover, mobility is important as it provides the fast movement of the LAVs during military operations such as carrying, patrolling, scouting, transporting, and combating[20]. Therefore, penetration resistance to mass ratio (between obliqued and non-obliqued hull) is important to ensure the worthiness of providing hull obliquity over increased hull weight (see the next section). Effect of Oblique Angle on Penetration Resistance-to-Mass Ratio

The combined effect of penetration resistance-to-mass ratio (R_i, Eqn. 7) was evaluated at different oblique angles as shown in Fig. 4(c).

In both obliqued hull geometries, the R-value is greater than 1 and grows exponentially with higher values of oblique angle (Fig. 4(c)). The G3 exhibits slightly greater penetration resistance to mass ratio (R) values than G2, and thus more preferable than G2. In general, an obliqued hull was conceived to have higher crew/occupant protective capabilities in military operations. Park[1] also noted that the penetration resistance in obliqued hulls (with the same thickness and material type) is relatively higher than in the non-obliqued plate. The obliqued hull has a higher incident angle that increases the penetration distance of the hull. Since LAVs are utilised in dangerous environments during carrying, scouting, patrolling, and combating, the improved protective capabilities have their own justification[14].

3.2 Effect of Oblique Angle on Hull Width and Interior Space

The variation in constraints (w, w_b, and h_r) was graphically tested w.r.t oblique angle. The globally accepted value of the maximum allowable width constraint, w_{max}= 2.5 m was decided based on a previous study by Trajkovski[22], *et al.*, while the values of w_b and h_r were taken as 1.36 m and 1.65 m in accordance with occupant space dimensions in terms of user anthropometry (Table 1). The graphs were plotted taking two of them fixed, and one as axis of ordinates with oblique angle (θ).

3.2.1 Effects of Oblique Angle on Width of the Hull

For fixed/constrained value of h_r =1.36 m, w_b=1.65 m and w_{max}=2.5 m, the effects of oblique angle on vehicular hull width (w) were investigated and presented (Fig. 5a). For the constrained values of h_r, and w_b, it was evident that the hull width G2 and G3 had a direct linear relationship with oblique angle. The larger values of oblique angle lead to higher hull width. However, G3 exhibits a relatively smaller hull width than G2 for the same hull obliquity of any angle (except 0°). Therefore, G3 is desirable to have a compact hull from its size aspect.

3.2.2 Effects of Oblique Angle on Roof Height

For the fixed value of w = 2.5 m, w_b=1.65 m, and $h_{r(\min)}$=1.36 m, the roof height (h_r) of the hull at different oblique angles was investigated graphically, as shown in Fig. 5(b). It was observed that the roof height in both G2 and G3 had an inverse relationship with an oblique angle. The larger values of oblique angle lead to lower roof height of the oblique hull. Therefore, it affects the occupant space height as the obliquity of the hull increases. However, G3 exhibits a relatively larger roof height than G2 in the same obliquity. It is desirable to have an adequate hull space whenever the larger oblique angle is required for survivability enhancement.

3.2.3 Effect of Oblique Angle on Base Width of the Hull

Similarly, for the fixed value of w = 2.5 m, h_r= 1.36 m, and $w_{b(\min)}$ = 1.65 m, the base width (w_b) of the hull was also explored at different oblique angles, as shown in Fig. 5(c).

From Fig. 5(c), it was observed that the base width in both G2 and G3 had an inverse relationship with an obliqued

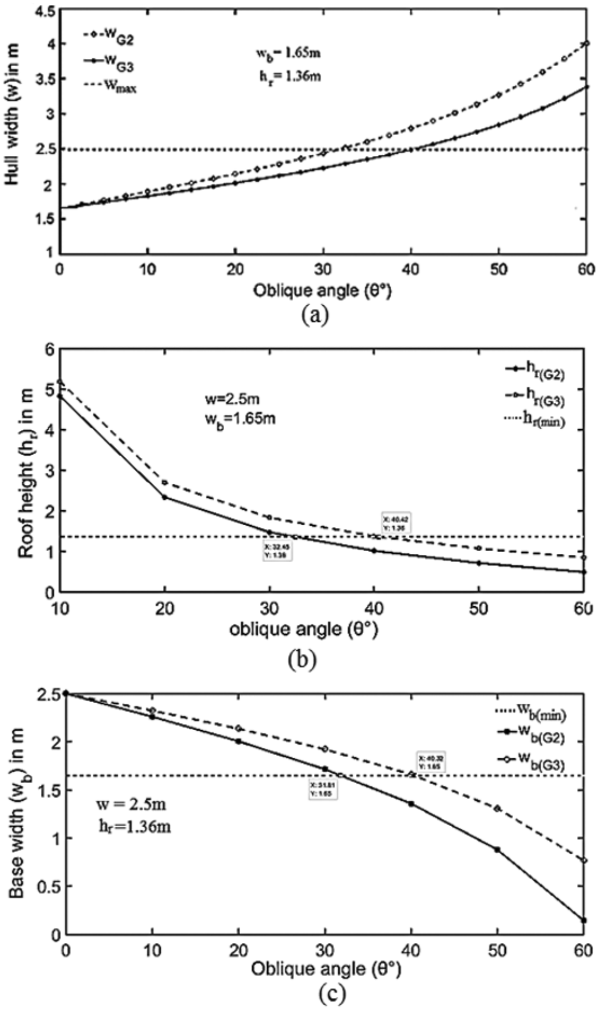

Figure 5. Effect of oblique angle on (a) hull width, (b) roof height, and (c) base width

angle. The larger the oblique angle, the lower the base width of the hull. Therefore, as the obliquity of the hull increases, the base width of occupant space decreases. However, G3 shows a relatively larger base width compared to G2 for the same obliquity and overall hull width. Hence, G3 can be the suitable alternative as it increases the base width without affecting other parameters (oblique angle, hull width, and roof height). Therefore, it may increase legroom and footrest space (in back to back sitting position) of infantry troops, as shown Fig. 2(a).

3.3 Optimum Oblique Angle and Its Corresponding Penetration Resistance for the Three Geometries

As discussed in previous sub-sections, the plotted result in Fig. 4(c) revealed that the higher penetration resistance-to-mass ratio (R) can be obtained at a larger oblique angle. Also, the effect of change in oblique angle was constrained by maximum hull width (w_{max}) (Fig. 5(a)), minimum roof height ($h_{r(min)}$) (Fig. 5(b)) and minimum base width ($w_{b(min)}$) (Fig. 5(c)). The values of w_{max}, $h_{r(min)}$ and $w_{b(min)}$ respectively were decided to be 2.5 m[22], 1.36 m, and 1.65 m (Table 1). Based on these values, the optimum (maximum) oblique angle for the three geometries was found using Eqns (1a), (1b) and (1c). Following the determination of optimum angles in all geometric hulls, penetration resistance-to-mass ratio, $R_{(G1, G2, G3)}$ (in Eqn 8) was determined. The optimum oblique angles and corresponding $R_{(G1, G2, G3)}$ were presented in Table 2.

Table 2. Optimum oblique angles and corresponding penetration resistance-to-mass ratios among three geometric hull models (for the value of h_r = 1.36 m, w_b = 1.65 m, w = 2.5 m and h_s= 0.36 m)

Geometric hulls	Optimum oblique angle	$R_{(G1, G2, G3)}$
G1	0°	1
G2	32°	1.51
G3	40.4°	2.03

As can be seen from Table 2, the maximum optimal angles for G2 and G3 came out to be 32° and 40.4°, respectively. The corresponding maximum attainable penetration resistances to mass ratios were found to be 1.51 and 2.03. It implies that the protection capability of G3 was improved by double while an additional half improved G2 to the non-obliqued hull, G1. This can be a substantial up-gradation of hull geometry without varying mass and mobility.

3.4 Verifications of the Analytical Models

The analytical models were compared with experimental results of energy absorptions (penetration resistance) for armour plate reported by Jena[6], *et al.* (Fig. 6). As shown in Fig. 6(a), the experimenter[6] aimed to investigate the effect of oblique angles on the penetration of Al-7017 plates with non-deformable steel projectiles at a velocity of 840.15 m/s at different angles of impact (0°, 15°, 30°, 45°, and 50°). Primarily, to compare their experimental results (see Fig. 6(a)) with ours (in term of the penetration resistance ratio, R), the experimental result at each aforementioned angle was determined in terms of R-value by dividing the energy absorption at each oblique angle with the energy absorption at 0° (320 Joules) (see Fig. 6(b)).

From Fig. 6(a), it can seen that the energy absorption grows exponentially with higher values of oblique angle[6]. From Fig. 6(b), it was evident that the penetration resistance (energy absorption) in both obliqued hulls (G2 and G3) had a slight variation with experimental data[6]. Therefore, the analytical results were found to be in reasonable agreement with the experimental results, even though the effect of obliquity on mass was not taken into consideration in the empirical study reported by Jena[6], *et al.*. Therefore, the protective designs against the impact of armour-piercing (AP) projectiles should also be taken into consideration to improve the LAV hull protection to increase the survival chances of the occupant/ crew.

3.5 DHM Evaluation of the Proposed Models

While adopting face-to-face and back-to-back sitting posture in LAVs, the chances of head and lower legs getting obstructed is more than other body parts. Therefore, to verify the headroom and legroom adequacy in the proposed

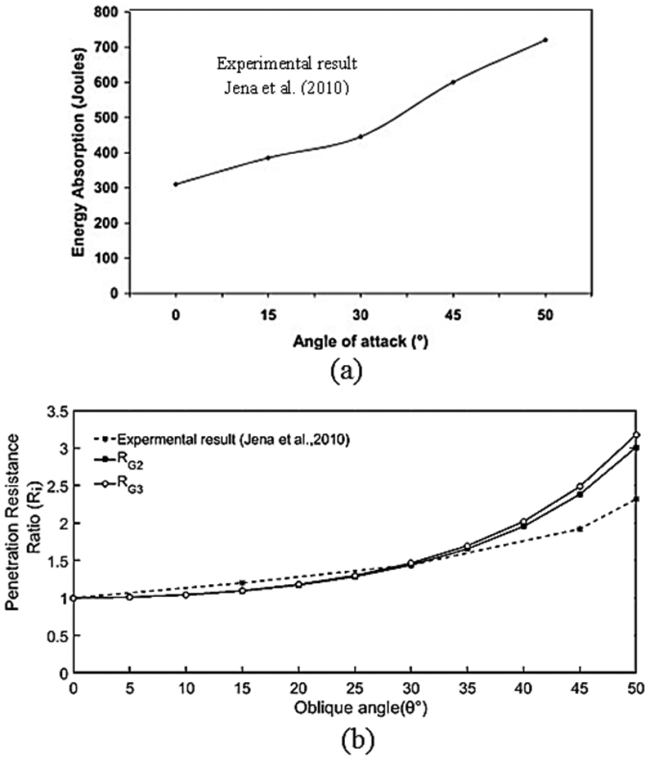

Figure 6. Energy absorption (a) experimental result[6] and (b) comparison of analytical result (present study) with experimental results[6].

hull design, two extreme anthropometric dimensions of the Ethiopian army[31] were used for (female and male) manikins. They were tested to sit (face-to-face and back-to-back) in the virtual environment for both geometric models (G2 and G3), as shown in Fig. 7(a) and (b).

From Fig. 7(a) and (b), it can be ensured that wide ranges of Ethiopian army population (from 5th p female to 95 p male) can be accommodated without any interference/obstruction at the head and/ or leg portions in the face-to-face sitting posture. Similarly, the head and leg rooms are also adequate for the two back-to-back seated manikins in firing operation posture. Therefore, despite the better protection capability of G3 (as discussed in earlier sections), both models are well-suited to accommodate a wide user population. Moreover, from these proposed models, G3 is the highest crew protective model for body parts other than lower legs (with these recommended design dimensions and oblique angles). Hence, it is highly recommended to implement this model in the future after investigating other factors and physiques which were not yet included in the study. Nonetheless, one can choose either of the two models even though the G3 model is proposed as a better protection capability.

In general, apart from the optimal design of the oblique hull model required to enhance protection capability, ergonomic factors are the other desired requirements. Inappropriate hull geometry and hull obliquity may lead to have excessive hull width, reduced protection capability and mobility, and affect the space occupancy adversely[1]. In various literature, different models of LAVs were reported without considering the optimal solutions of design variables for different physiques[1]. As a result, the enhancement of protection capability, mobility, and comfortable space of the hull are vulnerable to reduce.

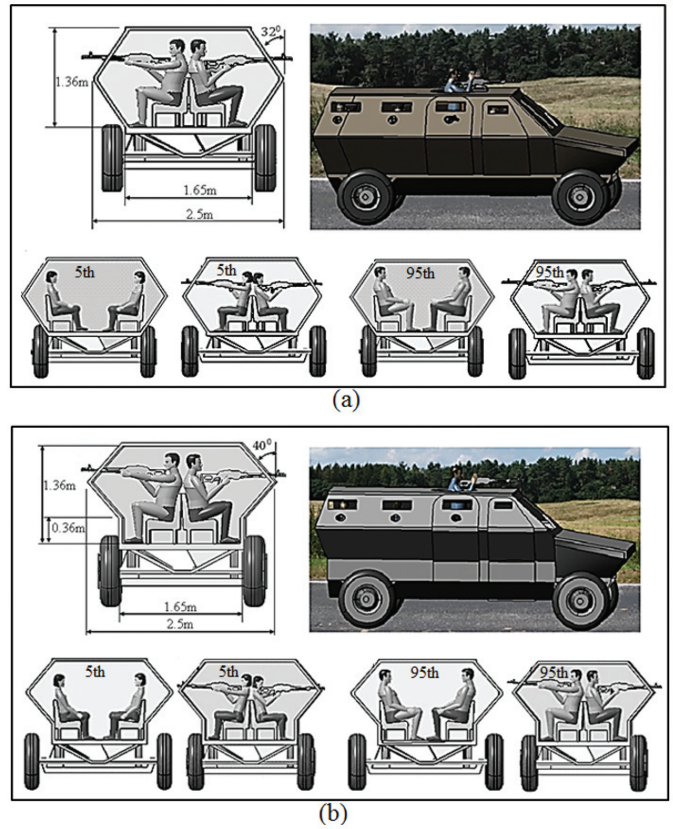

Figure 7. Virtual ergonomic evaluation of the space occupancy using DHM for (a) G2 hull geometry and (b) G3 hull geometry.

This study was not carried out without limitations. Though various studies reported numerical simulations and experimental tests to investigate the protection capabilities in LAVs from hull obliquity aspect[2, 22, 32], there was a need to evaluate optimal hull obliquity parameters for effective occupant space/ergonomics. Therefore, this research was conducted to analytically study the obliquity of LAV armour plate and to explore its tangible benefits for comfortable occupancy and minimum weight, and improved protection capabilities. Future directions may include validating these results using physical experimentation (similar to Dikshit[5]) and numerical simulation (similar to Park[1]) at different vicinities of the hull. The mass that is incurred due to the hull obliquity and geometric form should also be considered during experimental validation for crew protection capability of the hull from AP rounds. Therefore, before experimental validation, one shall be cautious about using the results obtained in this study to conceptualise LAVs at their attainable minimum weight and maximum protection capability. Since the current study focused only on the workspace ergonomics of light armoured vehicles, use of different materials for enhacing crew protection is beyond the scope of this research. However, ease in fabrication of geometry also depend on the material selection which is another critical factor to improve crew protection capability of the hull. The proposed geometries may still require some changes (particularly at the top portion of the hull) even though the simple geometric design and simplified mathematical equation were used for this study. The present study only addresses the optimal design of the side hull. Thus, further studies may be needed to analyse the obliqued features at the bottom, front, and back of the LAV. Moreover, even though the optimal design approach presented in this study is applicable to any LAVs, the design recommendations of the space occupancy is suitable only for the Ethiopian soldiers. Overall, the increased protection capabilities with adequate occupant space resulted from the proportional increase in the LAV hull's effective thickness and deflection angle. Perhaps this is the reason to design an armoured vehicle with obliqued hull structure. Therefore, to minimise terrorist attacks on military troops, significant efforts should be made to improve the performance of LAVs[31]. Along with protection enhancement, the present research focuses on optimal hull design with ergonomics consideration.

4. CONCLUSION

The current study demonstrated that the small variation of oblique angle on hull geometry would substantially change the protection performance and space occupancy of LAVs. The optimal design of LAV was carried out in a way that hull obliquity can be utilised to improve the protection capability without affecting mass/mobility and space occupancy. When the hull is supposed to be pierced by the horizontal projection of launched projectiles/bullets, the study confirmed that the penetration resistance of G2 (with an optimal oblique angle of 32°) could be improved almost by half, without affecting its mass/mobility. Similarly, G3 (with an optimal oblique angle of 40.3°) can improve the penetration resistance by double when compared with a non-oblique hull. This research will encourage engineers/designers to evaluate the protective capabilities of the LAVs while considering ergonomic aspects. On the contrary, the V-shaped hull geometry's main drawback is that it reduces the LAV's interior space and increases its mass. Therefore, a new geometric shape was presented as an optimal design concept. It provided increased penetration resistance and effective space occupancy without affecting weight. Considering specific user populations (Ethiopian army personnel) in this study, we proposed well-suited space occupancy for a wide range (5^{th}p to 95^{th}p) of military users. The methodology used to analyse the optimal parameters can be used to set the standard when developing the conceptual design of LAVs.

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He has supervised the overall research work presented in the current paper by providing ideas and guidance in conducting the experiments and writing the manuscript in a systematic way.