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SYSTEMS ENGINEERING APPROACH TO GROUND COMBAT VEHICLE SURVIVABILITY IN URBAN OPERATIONS

by

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This thesis provides an overview of system survivability and discusses the conventional approach to GCV survivability. This thesis then uses a systems engineering approach to guide the subsequent study, which identifies likely threats to GCVs in an urban environment and discusses potential susceptibility reduction techniques and technologies that can counter the threats.

This thesis then develops a survivability assessment model (using Imagine That's ExtendSim), which quantifies the different survivability characteristics of a GCV and determines the sets of survivability characteristics to meet the defined survivability requirement. Finally, this thesis demonstrates the use of a decision-making methodology (multi-attribute decision-making) to manage the capability conflicts that arise between survivability and other key platform capabilities. Therefore, this author hopes to help military planners and engineers design more robust, holistic and balanced survivability solutions for GCVs, to provide more flexibility against different types of threats and threat scenarios.

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SYSTEMS ENGINEERING APPROACH TO GROUND COMBAT VEHICLE SURVIVABILITY IN URBAN OPERATIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

ACT	armored combat team
AFES	automatic fire extinguishing system
AFV	armored fighting vehicle
APC	armored personnel carrier
APFSDS	armor piercing, fin-stabilized, discarding sabot
APS	active protection system
ATGM	anti-tank guided missile
CIWS	close-in weapon system
CLOS	command line of sight
DARPA	Defense Advanced Research Projects Agency
DAS	defensive aid suite
DE	directed energy
DEAD	destruction of enemy air defense
DOD	Department of Defense
DRI	detect, recognize and identify
ECM	electronic countermeasures
EFP	explosively formed penetrator
ERA	explosive reactive armor
FCS	future combat system
GCV	ground combat vehicle
GPS	global positioning system
HEAT	high explosive anti-tank
HHQ	higher headquarters
HPM	high-powered microwave
ICV	infantry carrying vehicle
IED	improvised explosive device
IFV	infantry fighting vehicle
INS	inertial navigation system
IP	interception point
IR	infrared

KE	kinetic energy
LRF	laser rangefinder
LWD	laser warning device
M&S	modeling and simulation
MADM	multi-attribute decision making
MBT	main battle tank
MDD	minimum defeat distance
MEFP	multiple explosively formed penetrator
MRAP	mine resistant, ambush protected
NBC	nuclear, biological, chemical
NOE	nap-of-the-earth
NOLH	nearly orthogonal Latin hypercube
ODS	Operation Desert Storm
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
RAM	radar absorbing material
RCS	radar cross section
RF	radio frequency
RHA	rolled homogeneous armor
RPG	rocket propelled grenade
RWR	radar warning receiver
SAR	synthetic aperture radar
SEAD	suppression of enemy air defense
SRT	system reaction time
UAV	unmanned aerial vehicle

EXECUTIVE SUMMARY

Military planners expect ground combat vehicles (GCV) to fight primarily in head-on engagements over relatively open terrain. As such, engineers optimize the survivability systems for GCVs to provide the highest level of protection over the frontal arc of the vehicle. The conventional approach to GCV survivability focuses primarily on vulnerability reduction, which seeks to minimize the probability that enemy engagement kills a ground vehicle. Engineers primarily achieve vulnerability reduction on GCVs by using passive armor. While this survivability concept is suitable for traditional head-on engagements over relatively open terrain, it is insufficient to protect ground vehicles for urban combat, especially with the involvement of asymmetric elements. Urban combat is radically different from head-on engagements as threats can come from any direction in an urban environment, often with little or no warning. Therefore, optimizing protection in the frontal arc of a GCV only protects a small percentage of the vehicle against threats in an urban environment. Technologically and numerically superior armies suffered from unexpectedly high casualties and losses in recent urban conflicts such as Chechnya, Iraq, Afghanistan and Palestine, which bear testament to the insufficiency of the existing survivability concept for GCVs. The increasing gap between threat lethality and the proliferation of advanced anti-armor weaponry exacerbates this insufficiency.

The twin concepts of susceptibility and vulnerability define survivability in the survivability discipline. In order to protect GCVs sufficiently in urban operations, this author believes that military planners and engineers need to consider and incorporate susceptibility reduction, which seeks to prevent a hostile threat from hitting the system, upfront into the vehicle design. Engineers have utilized susceptibility reduction extensively for aircraft and ships over the years, and there are well-established susceptibility reduction techniques (threat warning and situational awareness, signature management, threat suppression, tactics and performance, noise jamming and deception and expendables) and technologies that are applicable to ground combat vehicles. This thesis discusses these susceptibility reduction techniques and technologies in detail and their applicability to GCVs.

This author also proposes a survivability assessment model (using ExtendSim) that one can use to determine the set of survivability characteristics that a GCV should have to meet defined threat scenarios and survivability requirements. The threat scenario is a single missile attack against a GCV in an urban environment from a distance of 100 m, and the probability that the missile attack kills a ground combat vehicle cannot exceed 5% (i.e., the probability of survival shall be at least 95%), at 95% confidence level. Unlike existing survivability models, the proposed model incorporates both vulnerability reduction and susceptibility reduction, particularly with the addition of hard-kill active protection system (APS) capability. Hard-kill APS is a key upcoming susceptibility reduction technology, and it uses physical countermeasures to intercept and destroy incoming threats before they hit the protected vehicle. The proposed model considers seven survivability characteristics or factors, namely P(active), P(detect), P(engage), P(hit), P(killed), APSP(hit) and APS minimum defeat distance (MDD). This author uses the nearly orthogonal Latin hypercube (NOLH) technique to generate 33 different design points for the factors and uses the ExtendSim simulation to determine which design points meet the defined survivability requirements. Based on the simulation results, this author uses linear regression analysis to identify the significant factors, to rank the significant factors in terms of their level of influence on the overall probability of survival and to develop a best-fit linear model that predicts the overall probability of survival. This author found that all the factors are significant, with MDD having the highest influence on the overall probability of survivability for the defined threat scenario. Leveraging the prior discussion on susceptibility reduction techniques and technologies, this author proposed different survivability architectures to meet the survivability characteristics, with each architecture resulting in varying trade-offs with other GCV capabilities (e.g., combat weight, passenger payload, ammunition capacity, mean time between failure). Finally, this author demonstrates the usage of a well-established systems engineering methodology known as multi-attribute decision-making (MADM) to manage the capability trade-offs and to facilitate decision on the most cost-effective survivability architecture to adopt for the defined threat scenario and survivability requirement. This author hopes that the improved model and decision-making methodology presented in this thesis helps military planners and engineers design more robust, holistic and balanced survivability solutions for GCVs in the future, to provide greater flexibility against different types of threats and threat scenarios.

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I. INTRODUCTION

A. BACKGROUND

Increasingly, strategists expect ground combat vehicles (GCV) to fight in urbanized terrain. Urban terrain offers significant advantages to a defender, especially if the defender is technologically inferior to the attacker. The close confines of urban terrain negate long-range firepower, degrade sensor capability and reduce the overall effectiveness of technologically advanced weapons systems. Urban terrain also offers many avenues of ambush and attack, which bogs down an attacker and results in high levels of attrition.

Ground combat vehicles, especially main battle tanks (MBT) and infantry fighting vehicles (IFV), are the mainstay of technologically superior armies. The combination of firepower, mobility and survivability allows such vehicles to dominate ground military operations. Military planners expect GCVs to fight in relatively open terrain, where threats come from the front. Therefore, engineers optimize the survivability for most GCVs to defend against frontal attacks. Figure 1 illustrates the differences between operating in open and urban terrains. The close confines of an urban environment, coupled with multiple avenues of ambush and attack, allow enemies to attack a GCV from any direction, which significantly complicates the survivability equation for the vehicle.

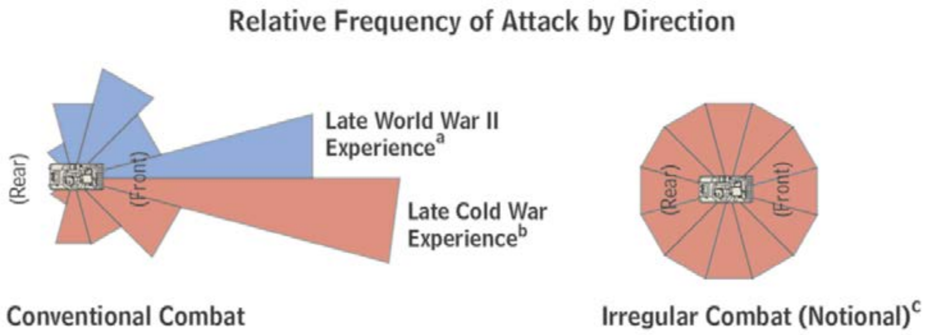

Figure 1. How Threat Direction Has Changed as Combat Evolved. Source: Kempinski and Murphy (2012).

The recent conflicts in the Middle East amply demonstrate the increased complication of GCV survivability due to urban operations. During the conflicts in Iraq and Afghanistan in the 2000s, U.S. ground forces found themselves in a similar position to the U.S. military aircraft community during the Vietnam conflict in Southeast Asia. The warfighters operated in a threat environment using vehicles not specifically designed to survive in that particular environment, resulting in high levels of vehicle kills and occupant casualties.

The U.S. forces primarily used GCVs such as the M1 Abrams MBT and the M2 Bradley IFV in the Afghanistan and Iraq conflicts. Military planners and engineers designed these vehicles back in the 1970s and 1980s (the Cold War period with the former Soviet Union) to function as integral components of a combined-arms force. Consequently, military planners and engineers designed these vehicles to fight a conventional, or symmetric, war between near peers, with a relatively well-defined battlefront and with sufficient knowledge of the location of enemy assets. This traditional concept of operations for GCVs and the associated survivability design of the vehicles proved to be correct when the United States launched Operation Desert Storm (ODS) against Iraq in 1991. The U.S. GCVs dominated the Iraqi forces in various engagements, leading to a swift conclusion of the land campaign in a mere 100 hours. As the United States did not intend to occupy Iraq, the troops and equipment departed for home quickly after the swift conclusion of the land campaign.

During the military operations in Iraq and Afghanistan in the 2000s, the U.S. forces used similar equipment with both the Iraqi and Afghan regimes being quickly defeated as well. The main difference between these operations and ODS was that unlike ODS, the U.S. forces did not depart from the theater of operations after defeating the regimes. Instead, the U.S. forces stayed behind and functioned as a stabilization force to facilitate the reconstruction of Iraq and Afghanistan. Consequently, the U.S. forces utilized the same GCVs to conduct operations against an asymmetric enemy that leveraged the constraints of an urban environment to make up for their technological and numerical inferiority. This new form of asymmetric urban operations is a radical departure from the original design requirements of the GCVs, which required GCVs to fight and survive conventional operations in relatively open terrain and against a near peer adversary. Unlike conventional engagements over relatively open terrain and with threats coming primarily from the front, the U.S. GCVs in Iraq and Afghanistan found themselves attacked from all directions, usually with little or no warning. The closed confines of the urban terrain also made maneuvering difficult and allowed enemies to channel the GCVs into designated killing zones. Engineers also designed the GCVs to protect occupants against ballistic projectiles primarily, with little emphasis on underbody threats such as mines and IEDs. The enemy exploited this by using mines and IEDs extensively against the GCVs. Since the ground combat vehicles operated in an environment that was different from the design requirements, it was not surprisingly that the U.S. forces suffered high levels of vehicle and personnel loss.

B. RESEARCH QUESTIONS

This thesis was guided by the following research questions:

1. How does one define system survivability?
2. How is system survivability implemented on ground combat vehicles traditionally?
3. How do urban operations affect the design of a ground combat vehicle?
4. What are the survivability techniques and technologies that one can use to enhance system survivability in urban operations?
5. How can one quantify the survivability characteristics of a GCV?

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II. WHAT IS SYSTEM SURVIVABILITY?

This chapter seeks to provide a basic overview on what constitutes system survivability and discusses the factors that affect system survivability. In the survivability discipline, "survivability is defined as the ability of a system to avoid and/or withstand a man-made hostile environment" (Ball 2003, 1). Thus, one determines survivability by analyzing two high-level factors, namely susceptibility and vulnerability. According to Ball, a susceptible system is one that is unable to avoid a hostile damage mechanism, while a vulnerable system is one that is unable to withstand a hostile damage mechanism (2003). Therefore, in order to improve system survivability, one can use different techniques to reduce the susceptibility (inability to avoid attack) and the vulnerability (inability to withstand the damage due to an attack) of the system.

A. SUSCEPTIBILITY

Ball explains that susceptibility is the inability of a ground vehicle to avoid an enemy's search, detection, and tracking elements, as well as the damage mechanisms associated with the enemy's weapon (2003). Therefore, the higher the probability that an enemy weapon detects, engages or hits a ground combat vehicle operating in a hostile man-made environment, the more susceptible is the vehicle. According to Ball, four main factors influence the susceptibility of a ground vehicle operating in a hostile man-made environment:

1. The quantity, quality and positioning of the enemy weapons (e.g., a large quantity of high performance anti-armor weapons and a large number of countermeasure-resistant IEDs that enemies deploy on roads that friendly forces use increase a ground vehicle's susceptibility).
2. The design choices that engineers incorporate into a ground combat vehicle (e.g., the use of quieter sub-systems such as electric engines and rubber tracks, active management of the vehicle's signature to reduce the probability that a hostile weapon detects, engages or hits the ground vehicle and improving maneuverability over cross-country terrain to avoid enemy forces reduce susceptibility).
3. The weapons and survivability equipment the ground vehicle carries to mitigate the effects of a hostile man-made environment (e.g., using long-

> range weapon systems such as missiles to kill or suppress hostile forces from afar, using a hard-kill active protection system (APS) to defeat incoming threats and using an on-board countermeasure device that detonates an IED's warhead before the vehicle comes within the range of the IED's fragment spray and blast zone reduce a vehicle's susceptibility).
>
> 4. The tactics that the ground vehicle employs (e.g., leveraging terrain features and silent watch to minimize the probability that a hostile weapon detects the ground vehicle, using C4ISR and situational awareness to avoid contact with the enemy forces, using large massed forces when attacking to overwhelm the enemy defenses and using convoy escorts to suppress any enemy waiting in ambush reduce susceptibility). (2003)

Susceptibility reflects the inability of a ground vehicle to avoid a man-made hostile environment and therefore, susceptibility reduction has the potential to improve the ability of a ground vehicle to survive in a man-made hostile environment (i.e., susceptibility is a capability gap that should be reduced). Ball proposes six susceptibility reduction techniques:

> (1) Threat Warning and Situational Awareness
>
> Threat warning and situational awareness systems provide early warning to the ground vehicle when a hostile weapon system targets the ground vehicle. Threat warning and situational awareness systems provide information such as threat direction and threat type. Early warning allows the ground vehicle to take immediate actions to disrupt the hostile targeting actions and ideally to prevent the deployment of the hostile weapon system. Examples include radar warning receivers (RWR) on aircraft, as well as laser warning devices (LWD) on ground vehicles. Having integrated situational awareness systems, such as battlefield management systems, also allows friendly forces to have real-time knowledge on the location of potential hostile forces and to take early action against those hostile forces.
>
> (2) Signature Reduction
>
> All systems emit certain signatures such as thermal, radar, acoustic and vibration that are detectable by appropriate sensors. Consequently, hostile weapon systems exploit these signatures to generate targeting and guidance solutions. Therefore, engineers use signature reduction to manage and reduce the signatures that a system emits, to minimize the probability of a threat detecting and engaging the system. A classic example is low-observable aircraft such as the F-117 Nighthawk and the F-22 Raptor, which placed significant emphasis on signature reduction,

particularly radar and thermal signatures, to maximize overall system survivability.

(3) Expendables

Operators can deploy expendables, which are non-reusable systems, to disrupt the targeting and guidance processes of a hostile weapon system, to minimize the probability of hit. Examples include using smoke and obscurants as well as flares and chaff to disrupt the guidance mechanisms for missiles.

(4) Threat Suppression

Military planners can use threat suppression to destroy or suppress hostile weapon systems, which prevents their employment against friendly forces. Good intelligence and situational awareness are key enablers for effective threat suppression. For example, long-range precision fire suppresses or destroys enemy air defenses before friendly aircraft enters the area of operations. Another example is using sensors and small arms fire to detect and suppress an enemy gunner firing a visually guided anti-tank missile. As the gunner needs to keep the targeting sight on the target in order to guide the missile to the target, suppressing or killing the gunner likely results in the missile missing the target.

(5) Tactics and Performance

Operators can use appropriate tactics to minimize the probability that a hostile weapon system detects and engages a friendly system. An example is low-level flying by helicopters. According to the dictionary of U.S. Army terms (1983, 109–110), low-level flying refers to "The operation of Army aircraft at optimum altitudes which afford cover and concealment from ground visual and electronic detection in order to exploit surprise to the fullest." Besides tactics, system performance is also important. For example, engineers usually design a ground combat vehicle to have good mobility performance, which allows the vehicle to exploit cross-country terrain effectively to bypass enemy forces and thus, proceed unimpeded to the final objective.

(6) Noise Jamming and Deception

This involves the use of electronic countermeasures (ECM) such as jammers and decoys. Noise jamming attempts to overload the hostile weapon system with multiple targets to confuse the system and to mask the actual target amid the jamming noise. Deceiving generates false targets that attempt to "seduce" a hostile weapon system away from the actual target. Noise jamming and deceiving only work against guided weapons and are not effective against unguided weapons (projectiles). Thus, if the

> threats are primarily unguided weapons, the expendables technique is more effective. (2003)

B. VULNERABILITY

Ball explains that vulnerability is the inability of a ground vehicle to withstand a man-made hostile environment (2003). Therefore, the higher the probability that a hostile weapon kills a friendly ground combat vehicle operating in a man-made hostile environment, the more vulnerable is the ground vehicle. According to Ball, three factors influence the vulnerability of a ground vehicle operating in a hostile man-made environment:

> 1. The characteristics of the enemy warhead damage mechanisms that hit the ground vehicle (e.g., increasing the velocity and mass of a kinetic energy projectile, increasing the number of projectiles that hit a ground vehicle by using a fragmentation warhead and using a larger explosive payload in a shaped charge warhead increase the vehicle's vulnerability).
> 2. The design choices that engineers incorporate into a ground combat vehicle (e.g., ensuring proper separation of highly flammable materials such as fuel and ammunition, protecting the engine compartment using armored steel, using mine-resistant seats to reduce the amount of force transmitted to the occupants when a mine or IED is detonated and using nonflammable hydraulic fluid reduce vulnerability).
> 3. The survivability and on-board repair equipment that mitigates the damage when a hostile weapon hits the ground vehicle (e.g., installing an automatic fire extinguishing system and providing equipment that allows operators to perform rapid and minor repairs on critical components reduce vulnerability). (2003)

Vulnerability reflects the inability of a ground vehicle to withstand a man-made hostile environment and therefore, vulnerability reduction has the potential to improve the ability of a ground combat vehicle to survive in a man-made hostile environment (i.e., vulnerability is a capability gap that should be reduced). A system is vulnerable primarily because its components are vulnerable (known as critical components) and thus, vulnerability reduction seeks to improve system survivability by reducing the probability that a hostile damage mechanism kills any of the critical components. Ball proposes six vulnerability reduction techniques:

(1) Component Redundancy (with Effective Separation)

Having redundant critical components reduces the probability of system kill if a hostile damage mechanism hits and kills one of the critical components. For example, engineers implemented two separate engines on the A-10 Warthog. Redundant components must have effective separation (either have physical separation or have armor in between), to minimize the probability that a hostile damage mechanism is able to kill all the redundant components at the same time. Component redundancy without effective separation enhances overall system reliability only, but not survivability.

(2) Component Location

In component location, engineers determine the optimal positioning of critical components to reduce the probability of a hostile damage mechanism hitting and killing a critical component. For example, engineers usually place engines at the rear of a ground vehicle in order to avoid threats, since most threats come from the frontal arc of the vehicle for conventional engagements.

(3) Active Damage Suppression

In active damage suppression, engineers use sensors to detect the impact of a damage mechanism, and the sensors automatically deploy countermeasures to minimize the effects of any damage. An example is the automatic fire extinguishing system (AFES), which uses fire wires to detect the presence of fires. The detection of fire automatically triggers the activation of the fire extinguishing system to put out the fire quickly.

(4) Passive Damage Suppression

Both active and passive damage suppression seek to minimize the effects of any damage caused by a hostile damage mechanism. The key difference between the two techniques is that passive damage suppression does not require the use of sensors to detect the impact of a damage mechanism. An example is self-sealing fuel tanks, where the interaction between the leaking fuel (due to a puncture) and the fuel tank material results in swelling of the fuel tank that seals the puncture.

(5) Component Shielding

In component shielding, engineers use armor materials to protect critical components from a hostile damage mechanism. Component shielding is prevalent on GCVs, in the form of heavy passive armor. The main drawback of component shielding is that the GCV can incur significant weight penalties due to the additional armor. The weight penalty limits the

> protected area of the ground vehicle. Engineers can use integrated armor, which involves building the armor into the structure of the GCV, to help minimize the weight penalty. Engineers can also use parasitic armor as an alternative, which involves adding armor to the GCV as external modules. While parasitic armor incurs more weight penalty compared to integrated armor, parasitic armor is typically easier and cheaper to replace and/or upgrade than integrated armor.
>
> (6) Component Elimination or Replacement
>
> Since a system is vulnerable because its "critical components are vulnerable" (Ball 2003, 14), one can eliminate or replace a critical component with a less vulnerable one to reduce overall system vulnerability. For example, one can replace the hydraulic turret drive systems onboard GCVs with electrical turret drive systems. A hydraulic turret drive releases high-pressure hydraulic fluids when hit by a damage mechanism, which results in catastrophic fires. One can use electric turret drives that do not require any high-pressure hydraulic fluids to eliminate this risk and reduce overall system vulnerability. (2003)

This chapter provided an overview on what constitutes system survivability (susceptibility and vulnerability) and presented the possible techniques that are applicable to reduce system susceptibility and vulnerability. The subsequent chapters discuss in further detail what constitutes a ground combat vehicle and the conventional approach to ground combat vehicle survivability.

III. GROUND COMBAT VEHICLES AND THEIR CAPABILITIES

Military planners require GCVs to engage and destroy enemy forces, to facilitate a swift conclusion of ground military operations. In order to fulfill this role, engineers typically design GCVs to be highly mobile, heavily armed and highly protected. Engineers mount a wide variety of weapons on GCVs, which range from small-caliber cannons (e.g., 20mm automatic cannon found on some IFVs) to large-caliber, high-velocity guns (e.g., 120mm gun on a MBT). Military planners may also require GCVs to have missile launchers to complement their gun system (e.g., the M2 Bradley IFV carries anti-armor missiles to allow the Bradley to engage MBTs). Military planners and engineers often refer to GCVs as armored fighting vehicles (AFV) because GCVs traditionally depend on heavy passive armor to survive. For mobility, engineers usually equip GCVs with tracked systems to allow the vehicles to move fast and maneuver quickly over both smooth roads and rough terrain (tracks have large surface area, which reduces ground pressure even for heavy AFVs). Nevertheless, engineers also utilize wheeled systems on GCVs, particularly those that operate primarily over relatively smooth cross-country and/or in urban areas. GCVs typically have a minimum of three crewmembers, namely a driver, a gunner and a vehicle commander. For GCVs such as MBTs and tank destroyers, military planners typically require the presence of a loader as the fourth crewmember, to handle the bulky ammunition for the large-caliber gun. Military planners and engineers generally classify GCVs into two categories: those that transport troops, such as armored personnel carriers (APC), infantry carrying vehicles (ICV), and IFVs; and those that do not, such as MBTs, tank destroyers and self-propelled artillery.

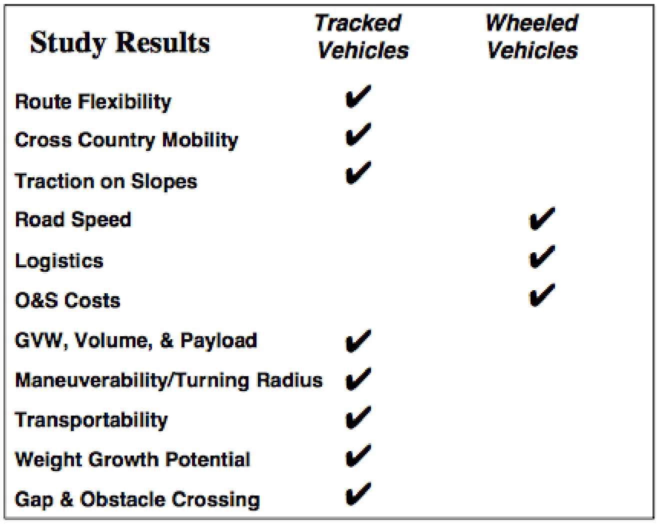
This author has worked on armored fighting vehicle programs for the past eight years. Based on this author’s experience, there are three main essential capabilities for a GCV, namely mobility, lethality and survivability.

A. MOBILITY

Military planners and engineers refer to mobility as the ability of a ground combat vehicle to move about freely in the designated operational environment to accomplish the operational objectives. According to Khalil and Hitchcock (1998), there are three levels of mobility, namely strategic, operational and tactical:

> Strategic mobility is the ability of the vehicle to move or be moved into the operational theatre. This implies that lighter and smaller vehicles have greater strategic mobility. Operational mobility is the ability of the vehicles to move by their own power at various speeds. Tactical mobility or battlefield mobility is the ability of the vehicle to move over various terrains and obstacles such as ditches, trenches and streams. The operational and tactical mobility requirements are extreme but necessary because the vehicle must be able to operate in various military environments. (2)

Military planners and engineers have to decide carefully on whether a ground combat vehicle adopts wheels or tracks for mobility, as the decision affects the operational capability of the vehicle. Based on this author's experience, combat vehicles generally adopt tracked systems, while tactical vehicles generally adopt wheeled systems. Nevertheless, this author wishes to highlight that there are exceptions to this general rule of thumb such as the Centuro tank destroyer, which is a wheeled vehicle. Military analysts and planners have performed many studies since 1985 in an attempt to answer "The Wheel Versus Track Dilemma." (Hornback 1998, 34) In his article, Hornback presents a summary of the "key advantages demonstrated by wheeled and tracked platforms based on thirty years of Army tests and studies" (34), as seen in Figure 2. Based on Figure 2, it is not surprising that military planners and engineers generally prefer tracked systems for combat vehicles, due to the superior cross-country and obstacle clearing capability. Nevertheless, Figure 2 also shows that wheeled systems are generally quieter and lighter, as well as easier and cheaper to maintain. Therefore, based on this author's experience, militaries are increasingly looking at wheeled systems, especially with the advent of urban operations and the continuing technological improvements in wheeled systems (e.g., tires that can be inflated or deflated to improve cross-country and obstacle clearing performance).



Study Results	*Tracked Vehicles*	*Wheeled Vehicles*
Route Flexibility	✔	
Cross Country Mobility	✔	
Traction on Slopes	✔	
Road Speed		✔
Logistics		✔
O&S Costs		✔
GVW, Volume, & Payload	✔	
Maneuverability/Turning Radius	✔	
Transportability	✔	
Weight Growth Potential	✔	
Gap & Obstacle Crossing	✔	

Figure 2. Different Advantages of Tracked and Wheeled Vehicles. Source: Hornback (1998, 34).

B. LETHALITY

Based on this author's experience, another essential capability for ground combat vehicles is the ability to engage and defeat the anticipated hostile threats in the operational environment. This author wishes to stress that lethality is dependent on both the weapon system performance as well as on the ability of the sensors onboard the ground combat vehicle to detect, recognize and identify (DRI) quickly and accurately potential targets. In order to minimize the amount of time that a GCV requires to DRI and engage a target, engineers typically equip ground vehicles with advanced sighting systems (both thermal and day sight) that are coupled to a fully stabilized fire control system, which allows the ground vehicle to accurately engage threats even on the move and under adverse weather conditions. Engineers equip ground vehicles with weapon systems that commensurate with the expected target sets for the ground vehicles. Therefore, engineers equip MBTs and tank destroyers with large-caliber, high-velocity guns as their target sets includes the most well protected targets (such as other MBTs and fortified enemy positions). On the other hand, engineers equip APCs, IFVs and ICVs with smaller caliber guns (typically ranging from 12.7mm to 40mm) because the main function of such vehicles is to transport troops and therefore, their target sets comprises primarily of less well protected targets such as other APCs/IFVs/ICVs, trucks and enemy soldiers.

C. SURVIVABILITY

Military planners and analysts generally view survivability as the most essential capability for a ground vehicle today. Defence iQ recently surveyed 205 senior executives and professionals within the armored vehicle domain, and the survey revealed that the top-ranked attribute or capability for armored vehicles was protection against ballistic and blast threats (Andrew and Richard 2015). According to the survey: "The message is clear: Protection, protection, protection. Almost half of respondents identified ballistic protection as a critical requirement while 58% viewed IED protection as the key attribute" (Andrew and Richard 2015, 13).

This author believes that it is not surprising for survivability to be the most important of the three essential capabilities, considering that survivability has the most direct correlation to overall mission cost effectiveness. A survivable vehicle has a higher probability of successfully completing a mission and returning safely. Military planners can then use the vehicle repeatedly for subsequent missions and thus, enhance the overall mission cost effectiveness. A survivable vehicle also results in fewer friendly casualties, which is a major political issue, as the recent conflicts in the Middle East amply demonstrate. To illustrate the importance of survivability, the U.S. Army had previously spent about US$45B (Tadjdeh 2012) on mine resistant ambush protected (MRAP) vehicles, which leverage primarily passive armor and vehicle shaping (e.g., V-shaped hull) to protect soldiers against mine and IED threats in the Middle East. To put the cost of the MRAP program into perspective, this author estimates that US$45B is sufficient for one to procure about 300 F-22 stealth fighters, which is the most advanced aircraft in the world today (according to the U.S. Air Force's 2011 budget estimates, the flyaway cost of an F-22 is about US$150M). In this author's opinion, due to the excessively high casualties in the conflicts, the U.S. Army had little choice but to make the huge investment on the MRAPs, even though the MRAPs have little utility as GCVs subsequently (due to their heavy weight and the corresponding lack of lethality and cross-country mobility).

In this author’s opinion, mobility, lethality and survivability are high-level capabilities that any ground vehicle must possess. Military planners and engineers then translate these high-level capabilities into various lower-level capabilities. Christopher Adams, a lecturer at the Naval Postgraduate School in Monterey, presented some of these lower-level capabilities in his lecture on combat survivability (see Table 1). In addition, this author wishes to highlight that incorporating different capabilities into a ground combat vehicle ultimately affects the overall cost-effectiveness of the vehicle, and military planners today regard cost-effectiveness as a key consideration for defense programs.

Table 1. Important Capabilities for GCVs. Source: Adams (2016).

Safe to operate and maintain	Secure and effective network communications	All-around situational awareness
Carry a large and/or heavy payload over a long distance without refueling	Provide effective and rapid protective and supporting fire day and night while stationary and moving—fire and maneuver	Effective communications between mounted and dismounted elements
Operate with few logistic and support requirements	Tolerable internal air and visibility environment	Operate with few crewmembers
Traverse most of the world’s roads, bridges, and tunnels	Self-recovery, towing, and towed capabilities	Quick, easy, and infrequent maintenance and repair
Tolerable ride	Easy deployment and transport	Quickly and accurately locate an enemy target
Adequate internal and external equipment stowage	Operate in extreme hot/cold/wet/dusty environments	Move and maneuver quickly, in tight places, and over rough and wet terrain
Precise navigation	Fuel efficient	Easy to produce, modular
Longevity	Reliable	Long mission endurance
Sufficient internal space for all	Carry and control unmanned systems	Easy to drive

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IV. GROUND COMBAT VEHICLE SURVIVABILITY

The previous chapter discussed what constitutes a ground combat vehicle and the key capabilities of a ground combat vehicle. Since military planners and analysts regard survivability as the most important capability of a ground vehicle, this chapter discusses the survivability approach for ground vehicles.

A. SURVIVABILITY ONION

Based on this author’s experience, military planners and engineers generally depict the survivability concept behind GCVs by using the “survivability onion” (see Figure 3). The first four layers of the onion deal with susceptibility reduction as they aim to prevent a hostile threat from hitting the vehicle (note the multiple use of the word “avoid”). The final two layers deal with vulnerability reduction, as they seek to prevent a hostile threat from killing the vehicle, after the threat hits the vehicle.

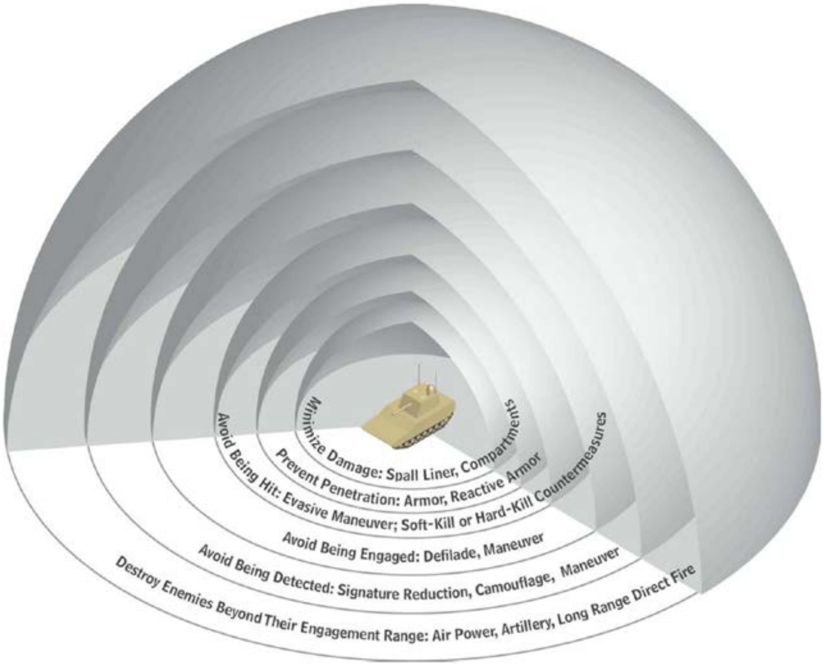

Figure 3. Different Layers of the Survivability Onion. Source: Kempinski and Murphy (2012).

1. Destroy Enemies Beyond Their Engagement Range

This is the outermost layer of the survivability onion. This author thinks that this layer links to the susceptibility reduction concepts of threat warning and situational awareness as well as threat suppression. Troops can use advanced long-range sensors and weaponry to detect and eliminate enemy threats before the threats can close in and engage friendly forces. According to Kempinski and Murphy (2012), military planners envisaged the now cancelled Future Combat Systems (FCS) to rely primarily on this outer layer of protection. Consequently, military planners hoped for the FCS vehicles to carry significantly lesser armor, making the vehicles lighter and more mobile. The U.S. Army previously touted this concept as "trading armor for situational awareness." Unfortunately, Kempinski and Murphy (2012) highlighted that the recent experiences in Iraq and Afghanistan demonstrated "it may be impossible to establish sufficient situational awareness to avoid many engagements" (21). This is especially true in an urban conflict scenario, where there are many places for threats to hide and to avoid detection (including posing as civilians) before performing surprise attacks on friendly forces.

2. Avoid Being Detected

This is the next layer of the survivability onion. This author thinks that this layer links to the susceptibility reduction concept of signature reduction. A GCV emits various signatures such as visual, thermal, radar, acoustic, vibrations and dust that are detectable by enemy sensors. Thus, engineers can reduce some or all of these detectable signatures to minimize the probability that a hostile threat detects the ground vehicles.

Engineers utilize signature reduction extensively on aircraft, particularly low-observable or "stealth" aircraft such as the F-117 and F-22. Based on this author's experience, however, while one can implement signature reduction on GCVs, it is more difficult due to the larger number of signatures that require managing, as compared to an aircraft. For example, it is particularly difficult for engineers to eliminate or minimize the dust trail that ground vehicles generate, especially in a hot and dry environment. Dust trails are not an issue for aircraft. In terms of radar signature, while one can use radar-absorbing material (RAM) to reduce the radar signature of a GCV, the material is expensive to procure and maintain. Coupled with the routine damage that ground vehicles sustain in their operational environments, especially urban, it can be prohibitively expensive for military planners to maintain and replace the RAM on a regular basis for ground vehicles. One can also shape a ground vehicle appropriately to attempt to minimize reflected radar energy, but this makes design and integration of armor on the vehicle more difficult.

3. Avoid Being Engaged

If a hostile threat detects the ground vehicle, the next layer is to prevent the threat from engaging the vehicle. This author thinks that this layer links to the susceptibility reduction concepts of tactics and performance. Operators can use natural or man-made obstacles to shield or mask their vehicles from enemy fire. Operators can also perform berm drills, which involve moving from a "hide position" to the berm to engage the enemy, and quickly returning to the "hide position" to avoid enemy counter fire (see Figure 4). In this author's opinion, the key limitation of these tactics is the requirement of large amounts of maneuver space and therefore, they are useful primarily for engagements over open terrain. Thus, it is more difficult for ground combat vehicles to execute such tactics in the confined constraints of an urban environment.

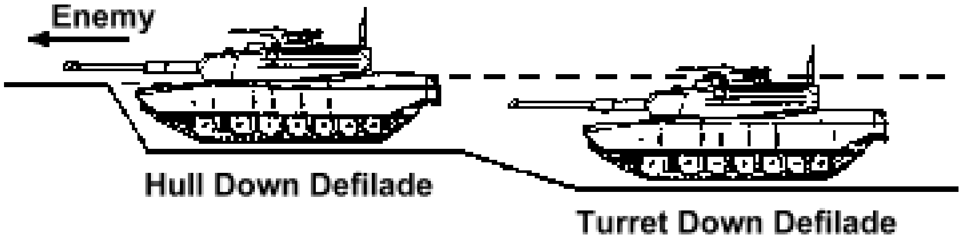

Figure 4. Illustration of the Berm Drill Tactic. Source: Cooke (2004).

4. If Engaged, Avoid Being Hit

If a hostile threat engages the vehicle, the next layer of the survivability onion is to prevent the incoming threat from hitting the vehicle. This author thinks that this layer links to the susceptibility reduction concepts of threat suppression, expendables, tactics and performance, as well as noise jamming and deception.

As in aircraft, a ground vehicle can utilize evasive maneuvers as a tactic to minimize the probability of hit. In order to be effective, this tactic requires sufficient maneuver space as well as good vehicle mobility characteristics, and therefore, it is more suitable for engagements over open terrain than urban terrain. In this author’s opinion, this tactic is also unlikely to be useful against modern, high-speed anti-armor threats such as supersonic missiles and kinetic energy penetrators.

Active protection is a relatively new and upcoming development in the field of hit avoidance. Dieter and Wagner (2009) classify active protection systems (APS) into soft-kill APS and hard-kill APS. This author thinks that soft-kill APS utilizes the susceptibility reduction concept of noise jamming and deception, while hard-kill APS utilizes the threat suppression concept. According to Dieter and Wagner, a key limitation of the soft-kill APS is that it is useful only useful against guided weapons, and engineers need to optimize the soft-kill APS to counter specific threats (2009). For example, one cannot use an infrared jammer to counter a radar-guided missile. Thus, Dieter and Wagner (2009) stress that soft-kill APS is not a “catch-all” system that one can use to defend against the entire spectrum of threats. Kempinski and Murphy (2012) highlights another key limitation of soft-kill APS, which is the jamming causes mutual interference with friendly electronic and communication systems. Soldiers encountered this issue when they employed broadband or barrage jamming in Iraq and Afghanistan to counter IEDs.

The hard-kill APS addresses the shortcomings of the soft-kill APS by using physical countermeasures to intercept and destroy incoming threats before they hit the vehicle. As such, the hard-kill APS is effective against a wide spectrum of threats, ranging from projectiles to guided weapons.

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5. If Hit, Withstand Penetration

The last two layers of the survivability onion deals with vulnerability reduction. If a hostile threat hits the ground vehicle, vulnerability reduction helps to mitigate the damage and increase the probability of survival. Engineers typically use physical armor to prevent a damage mechanism from penetrating the system and causing damage to internal critical components (such as the crew). Based on this author's experience, there are two main types of physical armor:

1. Passive armor seeks to minimize or prevent penetration of the damage mechanism by relying solely on the material properties of the armor. The earliest form of passive armor was armored steel, which became obsolete as threat lethality increased over the years. Engineers design modern passive armors to be composite in nature, meaning that they comprise of different layers of materials, such as armored steel, Kevlar and ceramics. The exact composition and layout of composite armors is highly classified and usually only a very select group of personnel knows the details of the armor.

2. Reactive armor relies on the detonation of a small explosive charge to disrupt or to deflect the damage mechanism. The most common reactive armor is the explosive reactive armor (ERA). Engineers design ERA specifically to disrupt the shaped charge jet found in high explosive anti-tank (HEAT) warheads. Figure 5 illustrates the working principle behind the ERA. The impact of a shaped charge jet generates sufficient energy to detonate the explosive liners, which causes the faceplates to expand in two opposite directions and thus, eroding and disrupting the shaped charge jet and reducing its penetrating power.

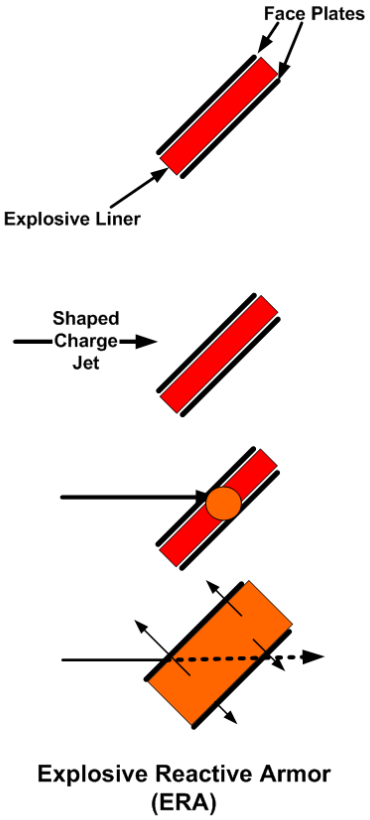

Figure 5. Working Principles Behind ERA. Source: Hebert (2005).

6. If Penetrated, Withstand Being Killed

Physical armor minimizes or prevents penetration by a damage mechanism, but it is still possible for a damage mechanism to cause critical damage to internal components without penetrating the armor. Engineers commonly refer to this effect as spalling, which is the ejection of “fragments, shards or splinters that detach from surfaces as a result of rapid deformation from pressure, expansion, a blow or explosion” (Erbil, Eksi and Bircan 2011, 1). Figure 6 illustrates the serious effects of spalling to critical components inside a ground vehicle, such as the crew. Based on this author’s experience, engineers typically install spall liners behind the physical armor of a ground vehicle to reduce the spray zone of the fragments, to reduce the probability of the ejected fragments hitting and killing critical components.

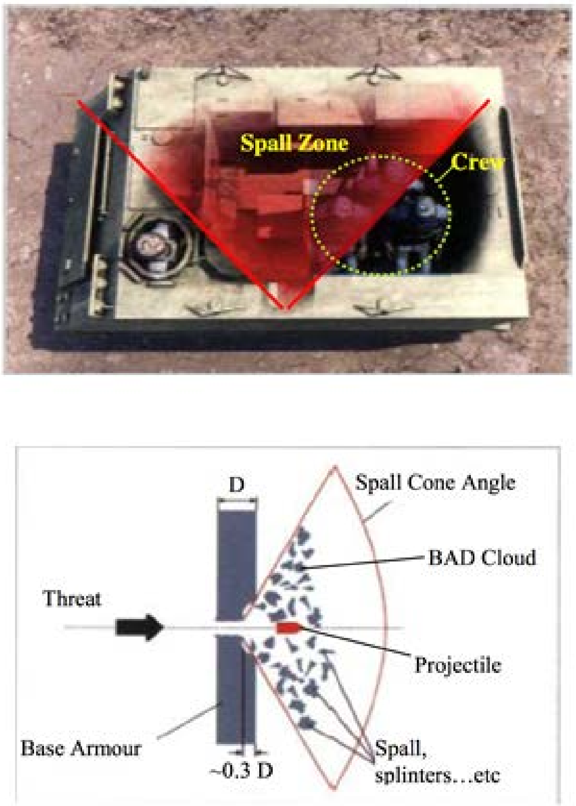

Figure 6. Spalling Inside a Vehicle. Source: Erbil, Eksi and Bircan (2011).

Besides using spall liners, engineers also use other survivability features on GCVs to minimize the probability of a kill when hit. One example is the replacement of hydraulic turret drives with electrical turret drives. When a damage mechanism impacts a hydraulic system, the leaking, high pressure hydraulic fluid usually results in internal fires. Engineers eliminate this hazard by replacing the hydraulic turret drives with electrical turret drives. Another example is the storage of ammunition in heavily armored compartments, equipped with blast-off panels. When a damage mechanism results in inadvertent detonation of the ammunition, the blast-off panels provide the detonation energy with a path of least resistance. This results in the detonation energy venting out of the vehicle through the blast-off panels, instead of into the vehicle.

B. CONVENTIONAL APPROACH TO GROUND COMBAT VEHICLE SURVIVABILITY

Military planners and engineers generally depend on passive armor to protect GCVs. The most common method used by engineers involves casting the vehicle structure out of a homogeneous material such as armored steel or aluminum. Engineers then add additional layers of material as needed to meet the survivability requirement. As such, engineers typically define the protection level of a vehicle by the equivalent thickness of rolled homogeneous armor (usually denoted by mm of RHA). In order to counter increases in threat lethality, engineers simply thickened the armor over the years, and this method was effective until the 1970s.

By the 1970s, there was widespread proliferation of highly capable anti-armor missiles and rockets utilizing shaped charge warheads. These weapons revolutionized anti-armor warfare due to their portability and effectiveness in penetrating homogenous materials, especially armored steel. Based on this author’s experience, early versions of shaped charge warheads can reliably penetrate more than 200 mm of armored steel, while modern versions can penetrate more than 1,000 mm of armored steel. Considering the relatively high density of armored steel, one can conclude that it was no longer feasible for engineers to continue adding additional armored steel to counter the increasingly lethal threats, as the weight penalty incurred severely compromises other platform capabilities. Since there was no acceptable armor solution then to counter the advanced shaped charge warheads, military planners and engineers deliberately designed some GCVs with less armor to make them lighter and more mobile and thus, decreasing the probability that shaped charge weapons can hit the vehicles. Examples include the German Leopard 1 MBT and the French AMX30 MBT, which prioritized mobility over armor protection.

As materials technology improved, engineers managed to design composite armor to replace homogenous armor. Based on this author’s experience, the main advantage of composite armor is better weight efficiency compared to traditional armored steel. This means that given the same armor thickness, composite armors have lower vulnerability compared to armored steel. Despite the good weight efficiencies of existing composite armors, equipping them still results in significant weight penalty on ground vehicles. The most well protected vehicles today are the MBTs and they already weigh upwards of 70,000kg even with advanced composite armor. Therefore, this author believes that GCVs have reached their realistic weight and size limits and short of a complete revolution in materials technology, it is not possible to continue adding more armor weight to counter future increases in threat lethality.

Military planners and engineers typically rely on reactive armor to protect lighter vehicles against modern threats. Engineers designed reactive armor to defeat shaped charge warheads. This means that reactive armor is ineffective against other threats such as kinetic energy (KE) penetrators. In addition, engineers also attempt to counter reactive armor by incorporating tandem shaped charge warheads into rockets and missiles. Tandem missiles and rockets have two warheads, namely a precursor warhead and a main warhead. The precursor warhead sits in front of the main warhead (hence the name “tandem”) and its purpose is to detonate the ERA, which clears the way for the main warhead to attack the vehicle. Nevertheless, the U.S., Israeli and Russian armies still widely deploy reactive armor as it is a relatively lightweight, low-cost and low-complexity solution compared to advanced composite armors (Kempinski and Murphy 2012).

Besides reactive armor, engineers can also equip lighter vehicles with slat or bar armor to protect them against shaped charge warheads (see Figure 7). According to Kempinski and Murphy, engineers optimize the spacing between the bars of the slat armor to counter specific threats (2012). This means that slat armor is only effective against specific threats and is ineffective against most other threats. In addition, based on this author’s experience, slat armor only provides variable protection, as the probability of defeating the threat is highly dependent on the angle of impact.

Figure 7. Slat Armor on a Stryker ICV. Source: Defense Update (2006).

V. URBAN OPERATIONS

This chapter seeks to provide an overview of urban operations and explains why urban operations are dominating current and future conflicts. This chapter also discusses the key challenges facing GCVs operating in urban environments and presents vignettes of actual urban conflicts to illustrate the challenges.

A. IMPETUS

The world is undergoing a period of rapid urbanization. Merriam-Webster defines urbanization as “The process by which towns and cities are formed, and become larger as more and more people begin living and working in central areas.” This is particularly evident in developing countries where people are rapidly moving from rural areas to cities to work and to live. In 2014, the United Nations (UN) provided some key statistics on world urbanization:

1. The UN estimates that 54% of the world’s population is currently living in urban areas. In comparison, only 30% of the world’s population was living in urban areas in 1950. The UN expects the percentage to increase to about 66% by 2060.
2. The most urbanized areas in the world today are North America (82%), Latin America (80%), the Caribbean (80%) and Europe (73%). Asia and Africa, on the other hand, only have 40% and 48% respectively of their populations living in urban areas. Urbanization will continue to increase across the globe, however, with Asia and Africa being the main drivers. By 2050, the UN expects the degree of urbanization in Africa and Asia to increase to 56% and 64%, respectively.
3. In terms of population growth, the UN expects world population to increase by 2.5 billion people by 2050, with the increase concentrated primarily in Asia and Africa (about 90%).

B. DESCRIPTION OF URBAN OPERATIONS

Against this backdrop of global urbanization and population growth, it is not surprising that military planners consider urban operations to form a major part of military operations today and in the future. According to the U.S. Army, urban operations are often full spectrum in nature, ranging from offensive and defensive operations to stability and support operations (see Figure 8). Offensive and defensive operations typically target both regular and irregular forces (insurgents), while stability and support operations (e.g., Iraq and Afghanistan) typically target irregular forces (after defeating the regular forces), with the ultimate aim of winning the support of the local populace.

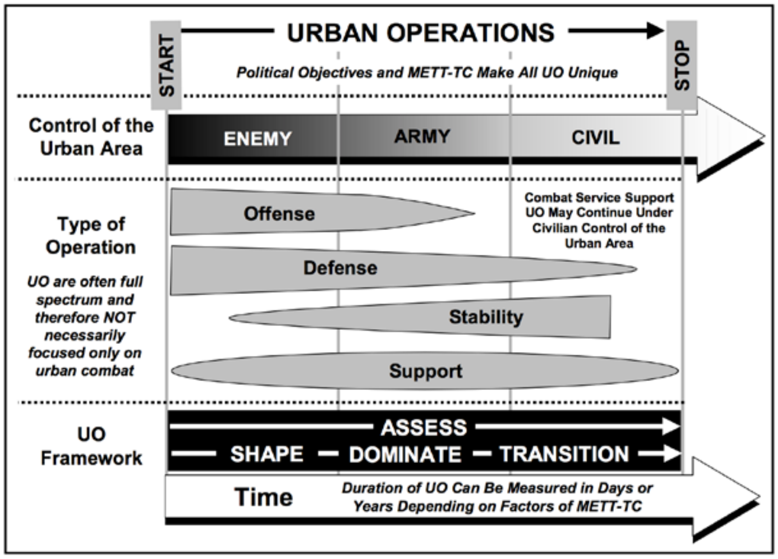

Figure 8. Full Spectrum Nature of Urban Operations. Source: U.S. Army (2006).

Urban operations are not new to military planners as, historically, urban areas have been central to military operations. In modern history, many battles occurred in urban areas, ranging from Stalingrad and Berlin during World War II, to Beirut, Chechnya, Iraq and Afghanistan in more recent times. Thus, with the increasing trend of global urbanization, planning for urban operations is critical to the execution and success of any military campaign.

The U.S. Army describes the urban environment as a multi-dimensional battlefield, which comprises various horizontal and vertical structures, as well as surfaces and sub-surfaces (see Figure 9). As is evident from Figure 9, enemy forces can attack from a multitude of directions, often with little or no warning. Based on this author’s experience, the key challenges facing GCVs operating in an urban environment include:

1. Lack of Situational Awareness

Unlike open terrain, where crewmembers operate primarily in the “hatch-out” mode for better situational awareness, crewmembers typically conduct urban operations from inside their vehicles. This is to counter enemy snipers who are lurking in an urban environment. The presence of multiple buildings in an urban environment results in obscured or poor all-round vision, which affects the ability of crewmembers to detect threats and respond accordingly. In addition, weapon systems and their corresponding sighting systems on ground vehicles today typically can only elevate up to 50°, which limits the vehicle’s ability to detect and engage targets that pop out from high-rise buildings. These limitations severely impair the ability of the crew to have coherent situational awareness in an urban environment.

Ground vehicles typically use electronic surveillance systems such as cameras and thermal imagers to help improve the situational awareness of the crewmembers in an urban environment. Unfortunately, the buildings and layout of an urban area significantly degrades the effectiveness of the electronic surveillance systems. For example, a small and well-positioned threat is able to stay concealed within buildings and structures, making it very difficult for electronic surveillance systems to detect the threat. As long as the threat stays concealed within the buildings or structures, it is largely immune to detection from overhead imaging assets (such as Unmanned Aerial Vehicles) and from ground-based imaging assets found on vehicles. Thus, the threat can creep up undetected and carry out surprise attacks on the ground vehicles from unexpected directions. Any significant volume of civilian movement within an urban environment also provides threats with a certain degree of camouflage and concealment, thus making detection difficult.

Since threat warning and situational awareness is a key susceptibility reduction technique, the lack of this in an urban environment increases the susceptibility of ground combat vehicles and reduces their survivability.

2. Increased Signature

The size and the acoustic and vibratory signatures of ground vehicles (especially armored vehicles) make concealing them nearly impossible. The large number of concealed surveillance sites in an urban environment also makes it very difficult for friendly forces to mask their movements. Enemy forces can easily see and hear an incoming ground force in advance before it reaches the urban area, thus allowing sufficient time for the enemy to prepare for the likely attack direction and to plan coordinated attacks against the incoming ground force. Enemy sensors can also easily acquire ground vehicles via other means such as detecting the radar and thermal signatures of the vehicles. Ground vehicles have substantial radar and thermal signatures due to their shape and geometry, as well as their need for large engines that generate a lot of heat (GCVs are very heavy and require large engines to provide the necessary mobility). Since signature reduction or management is a key susceptibility reduction technique, this increase in signature increases the susceptibility of ground combat vehicles and reduces their survivability.

3. Lack of Mobility

Depending on the layout of the urban environment, ground vehicles can encounter multiple choke points that impede their mobility when advancing toward the objective. Examples include weight loading of bridges, constrictions due to narrow roads and the general layout of road networks. The confined nature of an urban environment also makes maneuvering difficult, which limits the options that ground vehicles have in evading threats. Since tactics and performance (such as mobility performance) is a key susceptibility reduction technique, the lack of mobility and maneuverability in an urban environment increases the susceptibility of ground combat vehicles and reduces their survivability.

4. High Risk of Collateral Damage

Due to the close confines of an urban environment, military commanders may place restrictions on ground combat vehicles to minimize the probability of collateral damage as well as the risk to friendly forces. These restrictions can adversely affect the effectiveness of some susceptibility reduction techniques, which decreases the survivability of the ground combat vehicles. For example, military commanders may forbid the automatic deployment of smoke grenades to counter an incoming threat. This is because of the possibility of setting nearby structures on fire and the potential health hazards of the smoke to surrounding civilians and friendly soldiers. Military commanders can also impose restrictions on the use of hard-kill APS in an urban environment. Friendly troops tend to be in much closer proximity to the ground combat vehicles when operating in an urban environment. Therefore, the activation of an APS countermeasure to intercept an incoming threat has a high probability of injuring or killing nearby soldiers, as well as innocent civilians.

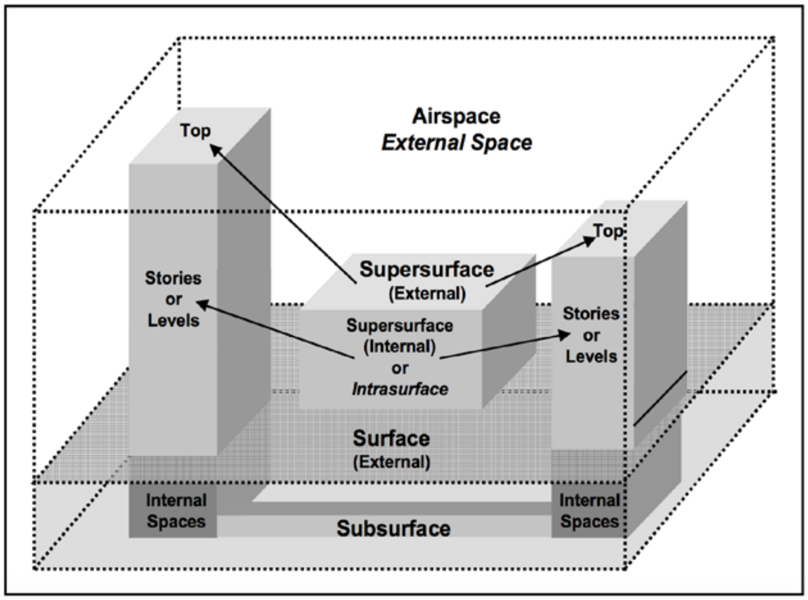

Figure 9. Depiction of an Urban Environment as a Multi-Dimensional Battlefield. Source: U.S. Army (2006).

C. VIGNETTES OF ACTUAL URBAN OPERATIONS

Due to the urban environment’s ability to mitigate numerical and technological disadvantages, it is not surprising that irregular forces favor urban combat. Examples from Chechnya and the West Bank illustrate the key challenges that all ground combat vehicles face when operating in an urban environment.

1. Battle of Grozny

Russia initiated this battle in 1994 to quell the ongoing civil war in Chechnya following the fall of the Soviet Union. The Russians first conducted heavy aerial and artillery bombardment of the city to eliminate any potential hiding spots for the Chechen separatists and to erode the separatists' will and means to fight by overwhelming them with superior technology. After this, Russia initiated a large-scale ground campaign, supported by armored vehicles and helicopter gunships, to take over the city. Compared to the separatists, Russia was technologically and numerically superior. Nevertheless, contrary to expectations, the Russians suffered greatly during the battle as the Chechen separatists were in prepared positions throughout the city and battled the Russian's mechanized forces with low-tech weapons such as RPGs to great success. According to Thomas (1999), the Russians greatly respected the RPGs employed by the separatists, due to the multiplicity of uses ranging from engaging troop formations as an area weapon, to a precision weapon fired directly at vehicles. Thomas also credits the tactical deployment of the Chechen separatists on multiple floors in the remnants of the buildings as a key strategy, as this allowed the Chechen separatists to engage Russian forces without themselves being targeted (1999). The separatists knew the elevation limits of the mounted sensors and weapon systems on the Russian vehicles, and they exploited this limitation to the maximum effect. Thomas also claims that the assimilation of commercially available equipment such as the cellphones enabled the separatists to maintain reliable communications (i.e., good threat warning and situational awareness) and to use the cellphones as a means of remote IED detonation (1999). Although the Russian forces eventually secured the city, the guerilla tactics employed by the Chechen separatists were overwhelmingly successful, and the separatists inflicted significant losses on the Russian forces in both man and materiel.

2. Operation Defensive Shield

The Israel Defense Force (IDF) conducted this operation in the West Bank region in 2002 where there was constant conflict between the local Palestinian populace and the IDF. The Palestinian insurgency posed serious challenges to the IDF due to the constant terror and guerilla elements employed within the villages and cities in the region. During the operation to reestablish IDF control over the major cities in the West Bank, the IDF found themselves in the midst of an urban battle. The operation was made more complicated when the insurgents started hiding them themselves among the local civilian population, which contributed significantly to the fog of war. The IDF decided to dispatch a joint deployment of ground vehicles and infantry troops to conduct house-to-house operations, instead of relying on heavy artillery and air strikes. This was necessary to minimize civilian casualties and any unnecessary collateral damages. Similar to the Russians in Chechnya, the highly trained and well-equipped IDF found itself maneuvering through a city that was extensively booby-trapped, and insurgents often attacked the IDF from multiple directions. Although the insurgents had only obsolete anti-tank weapons and grenades, they managed to impede the progress of the IDF by taking full advantage of the urban terrain to coordinate ambushes and by using IEDs. These asymmetric tactics in an urban setting largely negated the IDF’s technological and training advantages and skewed the battle favorably toward the insurgents.

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VI. SYSTEMS ENGINEERING APPROACH

The previous chapters provided an overview on system survivability and discussed the conventional approach to ground combat vehicle survivability. Due to increasing threat lethality and the prevalence of asymmetric urban operations, it is no longer possible for military planners and engineers to rely solely on the conventional survivability approach, which focuses on vulnerability reduction Thus, this thesis suggests for the exploration of alternative means to enhance survivability. A systems engineering approach facilitates this process. Systems engineering provides a structured and systemic methodology to understand and analyze customer needs, to develop the required system functionalities, to determine the system requirements and to guide the subsequent development, verification and validation process. According to Blanchard and Fabrycky (2003), Winston Royce developed the systems engineering Waterfall model in 1970 (see Figure 10). This author modified the Royce model to guide the systems engineering process for this thesis (see Figure 11). Even though this thesis focuses primarily on the survivability aspect of a ground combat vehicle, this author looks at the design of a ground combat vehicle in its entirety. This is because even though survivability is a key capability for ground combat vehicles, it is not a stand-alone capability. This means that enhancing the survivability of a ground vehicle often results in trade-offs to other key capabilities, and this thesis seeks to address the trade-offs as well.

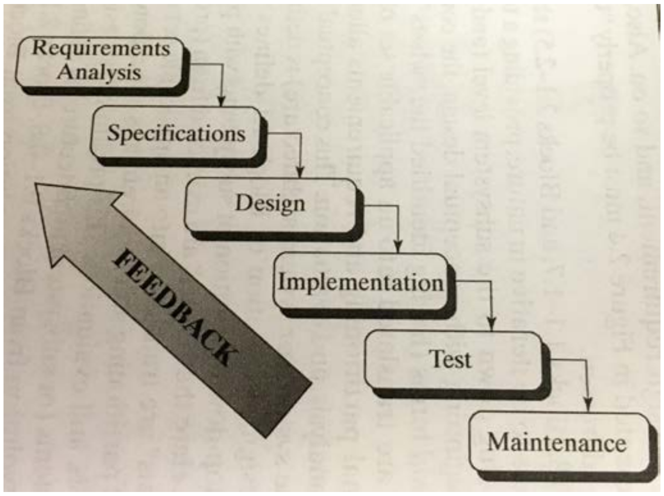


Figure 10. Systems Engineering Waterfall Model. Source: Blanchard and Fabrycky (2003).

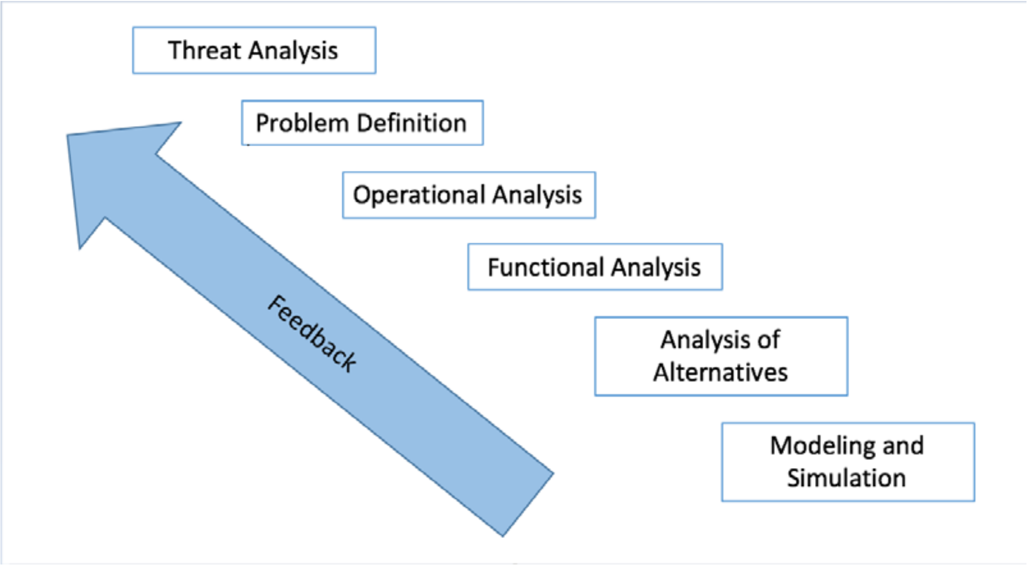


Figure 11. Modified Systems Engineering Waterfall Model.

A. THREAT ANALYSIS

A ground combat vehicle faces a myriad of threats in an urban environment. In order for engineers to devise suitable survivability systems, engineers first need to understand the types and characteristics of threats that the vehicle is facing. Chapter VII presents the threat analysis and assessment.

B. PROBLEM DEFINITION

Ground combat vehicles today lack survivability when operating in an urban environment. As demonstrated by recent conflicts, military planners and engineers can no longer rely solely on vulnerability reduction. Threats come from any direction in an urban environment, which means that it is no longer viable for engineers to optimize protection only in the vehicle frontal arc. In addition, while military planners and engineers can equip ground vehicles with advanced composite armor with good weight efficiencies, these armors still incur significant weight penalties on ground vehicles. Therefore, only the heaviest class of ground vehicles (i.e., MBTs) has sufficient weight budget to equip these armors. Nevertheless, based on this author’s experience, MBTs today already weigh upwards of 70,000kg, and it is not possible to continue adding more armor to counter increasingly lethal threats and threat scenarios. Therefore, military planners and engineers need to explore alternative means of enhancing ground combat vehicle survivability.

C. STAKEHOLDER ANALYSIS

Proper stakeholder management is critical to the success of any project. Stakeholder analysis seeks to identify the various parties that have a vested interest in the system, in order to determine and analyze their needs. More often than not, a system has multiple stakeholders and due to resource limitations, it is not feasible for one to devote equal attention to every single stakeholder. Thus, it is also important for one to be able to prioritize attention to stakeholders based on their level of interest, as well as their level of influence on the system. For the GCV, this thesis classifies the key stakeholders into five main categories. Table 2 describes the various goals and concerns of the key stakeholders.

1. Orchestrators and Regulators

This generally refers to government, regulatory bodies and policy makers who are responsible for the approval of budget, time scheduling and overall direction of the entire project. Orchestrators and Regulators also act as the executive decision body who can veto the project at any given time should there be a need.

2. Researchers and Developers

This is the group of people who perform the necessary engineering work to develop the GCV in accordance with the defined stakeholder needs and system requirements. This group includes the program management team, academia and defense contractors.

3. Opponents

This group of people is adversely affected by the success of the GCV. This group includes both the potential adversaries of the system and commercial competitors.

4. End Users

These are the actual operators of the GCV, and they are directly impacted by the success or failure of the system.

5. Others

This pertains to groups such as the public and the media who have an indirect interest in the system and can potentially result in a veto to the system should there be a critical mass of opposing sentiments. While the public does not have a direct influence on the GCV, the government needs to provide proper accounting of the GCV program to the public, due to the usage of taxpayer’s money. Similarly, the media can directly or indirectly influence the public’s perception of the system, which can result in widespread support or opposition to the system.

Table 2. Key Stakeholders with Their Goals and Concerns.

Category	Stakeholder	Goals	Concerns
Orchestrators and Regulators	Government	To maximize international political influence, by leveraging a strong military To ensure appropriate balance in governmental spending between military needs and other national needs	-Support from the general public -Will the new system be regarded as overly aggressive and result in adverse regional/ international repercussions -Is taxpayer money prudently spent on the system
Orchestrators and Regulators	Department of Defense (DOD)	To win any ground military operation, at minimal cost to both man and material	-Support from politicians and the general public -Budget sufficiency -Potential loss of credibility and public confidence should the system be delayed or cancelled.
End User	Army	To successfully execute ground military operations, as dictated by the DOD	-Budget sufficiency -Failure, delay or cancellation could result in a serious capability gap especially if conflicts arise. Deterrence capability would also be adversely impacted.
Researcher and Developer	Program Management Team	To develop and design a system that meets DOD's requirement, within cost and budget	-Technological feasibility and maturity -Availability of advanced technology, especially if need to be obtained from other countries -Cost, schedule, performance
Researcher and Developer	Defense Contractors	To develop and design a system that meets DOD's requirement, within cost and budget To make a profit To build a positive	-Market competition -Failure to meet budget, schedule and performance, resulting in financial losses and loss of credibility

Category	Stakeholder	Goals	Concerns
		reputation to facilitate subsequent business with other potential customers	
Others	Public/ Taxpayers	To ensure appropriate and prudent usage of taxpayer money	-Prudent usage of public monies -Failure, delay or cancellation would mean taxpayers money was wasted
Opponents	Adversary	To be able to defeat BLUE forces in any ground military operation	National security and political leverage compromised due to inferior capability to BLUE forces

This thesis then prioritizes the stakeholders based on the influence-interest matrix seen in Figure 12. The size of the bubbles indicates the relative influence of the stakeholders. Based on the location of the stakeholders in the matrix, this thesis proposes the following actions to manage the stakeholders:

a. High Influence, High Interest—Manage Closely

From the stakeholder analysis, it is clear that the Orchestrator and Regulator category has the most significant influence on the system. The government is the executive decision body with the prerogative to finance, support, influence or block the development of the GCV. The DOD provides high-level direction and provides the necessary funding for the program. Changes imposed by the government or DOD have an immediate and direct impact on the success of the program. Thus, it is critical for the program team to manage these two groups of key stakeholders closely.

b. High Influence, Low Interest—Engage Proactively, and Keep Contented

The public and media is in this category as they do not have any direct vested interest in the program. Despite this, it is important for the government to provide proper accounting to the public and media due to the involvement of taxpayer’s money. The public and media have high influence because their support or opposition to the program can directly sway the political support and funding for the program. Thus, it is important for the government to find ways to engage the public and media on a regular basis.

c. Low Influence, High Interest—Keep Informed of Decisions and Developments

The day-to-day Army operators of the GCV have a high interest in the success of the GCV as they are the ultimate end-users. It is important for the program team to keep the Army operators informed of the status of the program, to allow the operators to develop the necessary tactics, training and procedures (TTPs). In addition, operators also bring valuable operational inputs to the program.

d. Low Influence, Low Interest—Monitor and Be Aware of Developments

Potential adversaries fit into this category as they do not have a direct influence on the success of the GCV program. It is also not possible for the program team to directly influence or manage potential adversaries. It is important, however, for the program team to constantly monitor and be aware of changes to the capabilities of potential adversaries as these can potentially result in changes to the system requirements for the GCV.

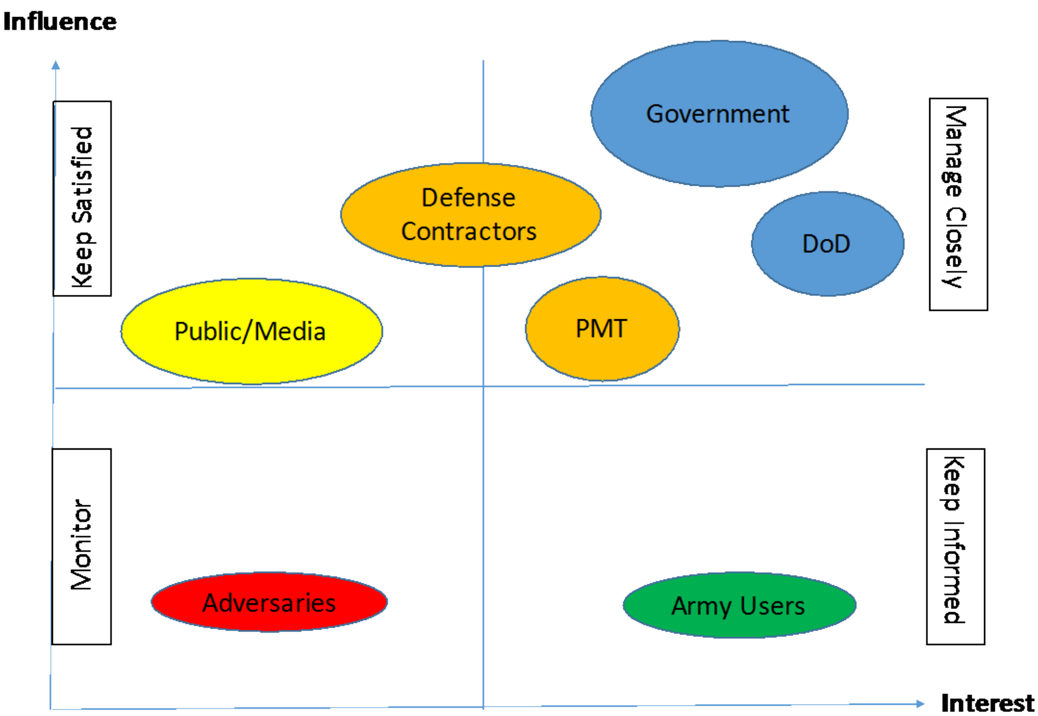


Figure 12. Stakeholder Influence-Interest Matrix.

D. EXTERNAL INTERACTIONS

In order for one to derive the requirements for the GCV, it is important for one to first identify the key external entities that interact with the GCV in the operational environment. This thesis uses a context diagram (see Figure 13) to achieve this purpose. One can see that the external entities that interact with the GCV directly affect the susceptibility and hence, the survivability of a GCV.

(1) Environment

This includes both weather and terrain. This is a one-way input into the GCV, as weather and terrain affects how the GCV operates. Using this author's home country as an example, the GCV needs to operate in a tropical wet climate and transverse cross-country terrain composed of mud, sand and clay. The GCV also needs to be able to overcome different kinds of slopes as well as obstacles and shallow water bodies. The GCV also needs to operate effectively in urban terrain. One can link environment to the susceptibility reduction technique of tactics and performance. If military planners and engineers do not design the GCV correctly for the operational environment, they will compromise the GCV's ability to operate and maneuver in the operational environment, which reduces the GCV's survivability.

(2) Threats

This includes both kinetic (projectile) and non-kinetic (rocket and missile) attacks, which are inputs into the GCV. When threats attack the GCV, they also give away their position, which is another input into the GCV. Correspondingly, once the GCV detects the threats, the GCV will proceed to engage and destroy the threats (output from the GCV). The threats directly affect the survivability measures that engineers need to design for the GCV.

(3) Tactical Unmanned Aerial Vehicle

This provides localized situational awareness to the GCV. Higher headquarters (HHQ) usually controls the unmanned aerial vehicle (UAV) and therefore, the GCV does not communicate directly with the UAV. Thus, the UAV only provides a one-way input (primarily real-time images and videos) to the GCV. One can link the tactical UAV to the susceptibility reduction technique of threat warning and situational awareness, as timely detection of threats allows the GCV to take appropriate actions to improve survivability.

(4) Global Positioning System

The global positioning system (GPS) provides one-way input (location data) to the GCV for navigational purposes. Most, if not all, military systems today rely on GPS as their primary source of navigational information. One can link GPS to the susceptibility reduction technique of threat warning and situational awareness. When GCVs are aware of their location, especially vis-a-vis the location of the enemy, the GCVs can employ appropriate actions to manage the enemy.

(5) Indirect Fire Support

Upon request from the GCVs, friendly artillery forces will provide indirect fire support to the GCVs. Thus, this is a two-way link between the GCV and the artillery forces. One can link indirect fire support to the susceptibility reduction technique of threat suppression. The ability to degrade enemy forces before they can engage the GCVs improves the survivability of the GCVs.

(6) Other Ground Assets

The GCV operates as part of an integrated combat team, which includes other platforms as well. Thus, the GCV needs to be in constant communications (two-way) with the other platforms to coordinate activities. One can link an integrated combat team to the susceptibility reduction technique of tactics and performance. An integrated combat team typically contains elements that complement one another. For example, MBTs are able to destroy high priority enemy targets like other MBTs and fortified positions to minimize the threats against the combat team. On the other hand, MBTs have relatively poor all-round situational awareness that enemy infantry can exploit to attack the MBTs. Thus, ICVs and IFVs protect MBTs from enemy infantry to allow the MBTs to focus on destroying the high priority targets. Such tactics improve mission effectiveness and overall GCV survivability.

(7) Headquarters

HHQ provides command and control (C&C) to the GCV, while the GCV provides status updates to HHQ. Thus, this is a two-way link. One can link HHQ to the susceptibility reduction technique of threat warning and situational awareness. HHQ possesses the larger strategic picture and provides the GCV with the latest intelligence and instructions to facilitate prosecution of the ground operation. One can also link HHQ indirectly to threat suppression as the HHQ can request for long-range precision fires to support the GCVs.

(8) Civilians

The GCV operates in an urban environment, meaning that it will encounter civilians. The presence and actions of civilians in the immediate area of operations is a one-way input to the GCV, which has an effect on how the GCV operates (assuming that military commanders wish to minimize collateral damage). Examples include tightening rules of engagement when civilians are around, as well as the increased difficulty in detecting insurgents who blend in with civilians. Therefore, the presence of civilians in an urban environment adversely affects the majority of the susceptibility reduction techniques.

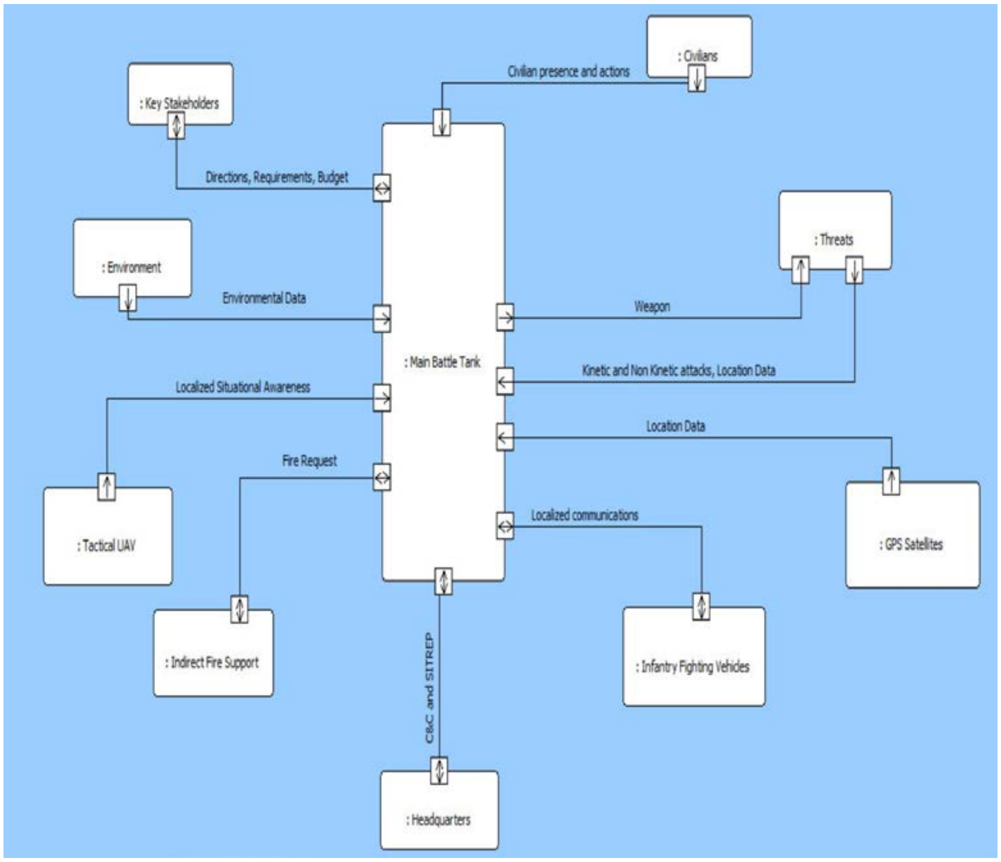


Figure 13. Context Diagram for the GCV, Using MBT as an Example.

E. OPERATIONAL ANALYSIS

Figure 14 illustrates the high-level concept of operations (CONOPS) or OV-1 for the GCV.

Before the GCVs can conduct any urban operations, the GCVs need to safely reach the urban objective first. Therefore, the first phase of the operation involves the GCVs moving out of the base camp as part of an armored combat team (ACT) and the

ACT maneuvering along the main axis (blue arrows) toward the objective. Overhead GPS provides the required navigational data to the ACT.

As the ACT moves toward the objective, UAVs are actively seeking out enemy forces ahead of the ACT. This improves the situational awareness of the ACT, which reduces the susceptibility of the ACT to enemy attacks. Upon the detection of enemy forces, the UAVs will alert both the ACT and HHQ, who can request artillery fire to destroy and/or attrite the enemy before the ACT arrives. This standoff suppression of enemy threats reduces the quantity of enemy forces that the ACT needs to be engage, which leads to improved survivability for the ACT.

Upon arriving at the urban objective, the GCVs first seek out and destroy high priority enemy assets such as MBTs and fortified positions using their long-range precision firepower. Besides the organic sensing capability of the GCVs, UAVs can also help to identify priority enemy assets for the GCVs to engage and destroy. Due to their superior protection capability, GCVs also act as the “hard-shield” for the ACT by drawing enemy fire away from the less protected elements of the ACT. All these activities maximize force preservation and facilitate the subsequent urban assault. Depending on the situation, GCVs can execute a variety of offensive maneuvers (e.g., envelopment, turning maneuver, penetration and frontal attack) to support the urban assault. For the envelopment and turning maneuver, GCVs utilize their mobility to quickly cut off key lines of communications and isolate the urban objective from any incoming reinforcements. For penetration and frontal attack, GCVs spearhead the assault and drive deep into the urban objective.

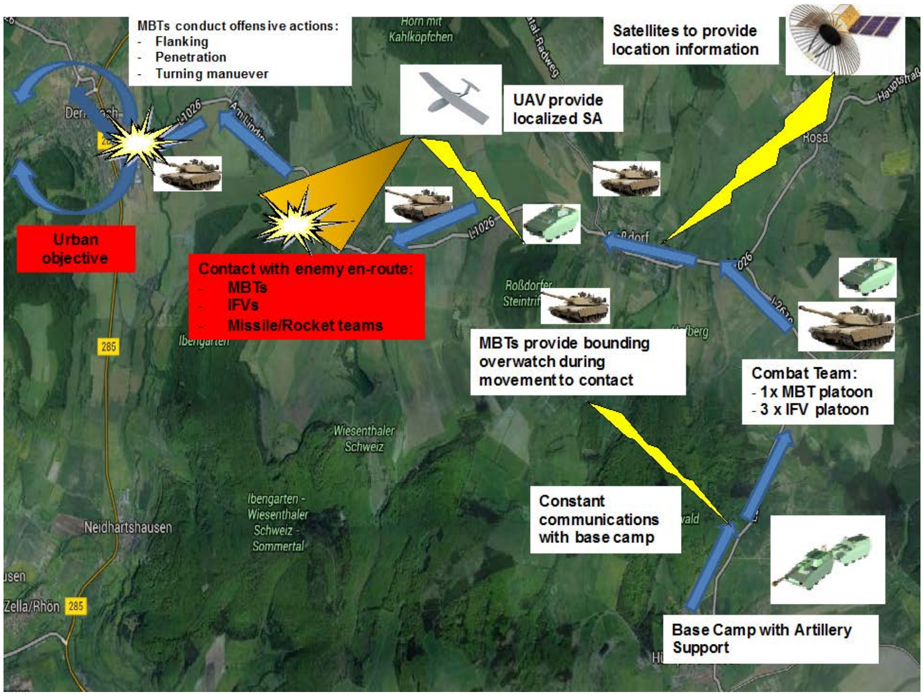


Figure 14. OV-1 for GCV Movement to Objective and Eventual Assault. Adapted from Google Maps (2016).

Based on the high-level CONOPS, one can determine the key operational activities that the GCV needs to conduct to achieve the mission objectives. One can depict these operational activities using an OV-5. Figure 15 shows the operational activities for the GCV mission presented using EFFBD, with the operational activities derived from the prior OV-1 description. There are three main threads in the OV-5, consisting of the main GCV mission, as well as the support from UAVs and friendly artillery forces for the main GCV mission.

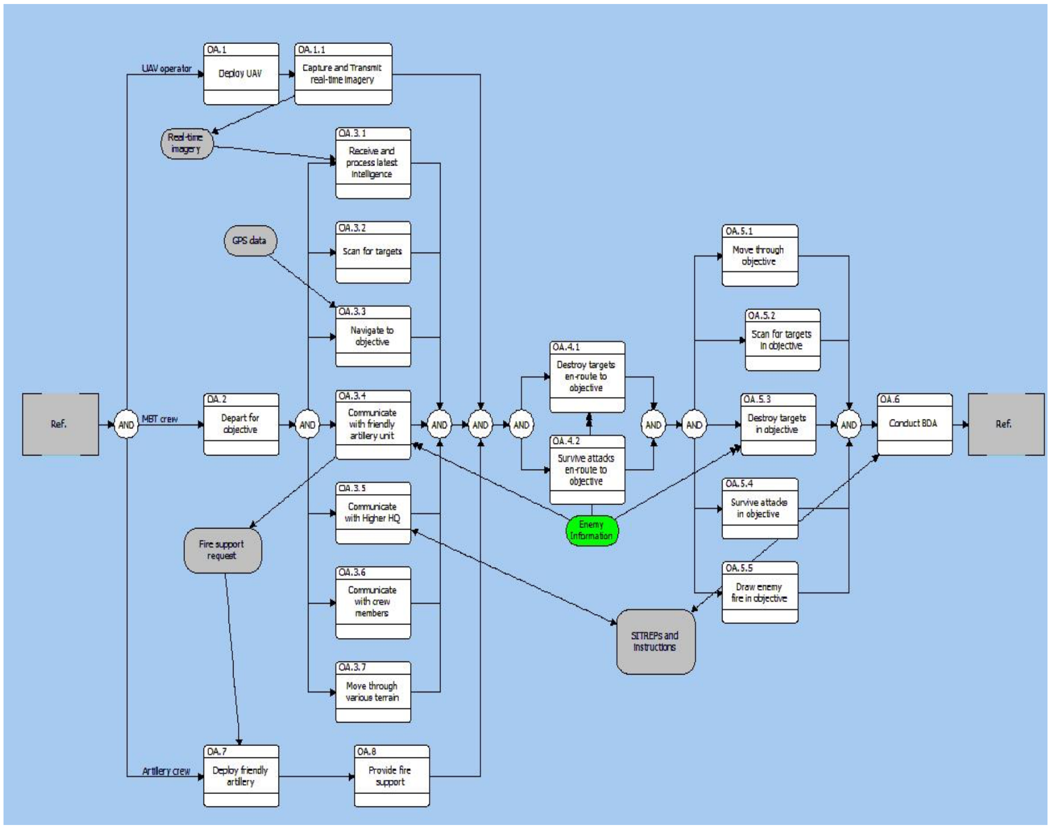


Figure 15. OV-5 for GCV Mission.

F. FUNCTIONAL ANALYSIS

SV-4 provides a graphical depiction of the system functional decomposition, which facilitates subsequent functional analysis. The SV-4 also facilitates the mapping of operational activities to the system functions.

Figure 16 shows the functional decomposition of the GCV. The GCV conducts offensive ground operations and achieves this through six main sub-functions, namely (1) to maneuver, (2) to communicate, (3) to provide situational awareness (SA), (4) to protect system and crew, (5) to engage enemy and (6) to provide battle damage and assessment (BDA). One can trace the six main sub-functions to the three high-level capabilities for a ground combat vehicle, namely lethality, survivability and mobility. This author further decomposes some of the sub-functions to achieve the necessary resolution to facilitate subsequent functional analysis. Figures 17 and 18 show the complete decomposition of the functions “to communicate” and “to maneuver” respectively. In order to coordinate activities, the GCV must be able to communicate with external air and ground assets as well as facilitate internal communications among the crewmembers. In order to maneuver to the objective, the GCV needs to be able to navigate itself as well as to move. In order to navigate, the GCV must receive location data, determine position based on the location data and minimize any navigational errors, which waste precious operational time. In order to move, the GCV must generate sufficient torque, speed and acceleration to ensure that it can overcome terrain and obstacles (both natural and man-made).

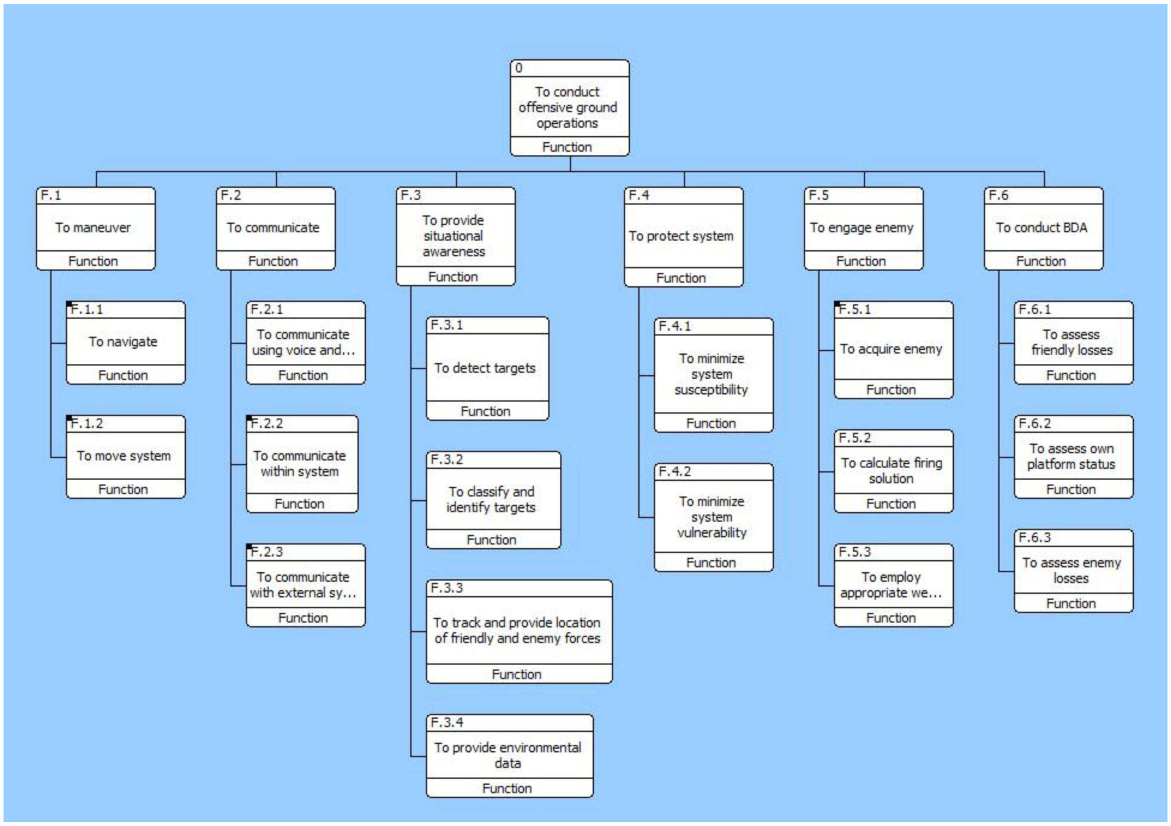


Figure 16. SV-4 for GCV.

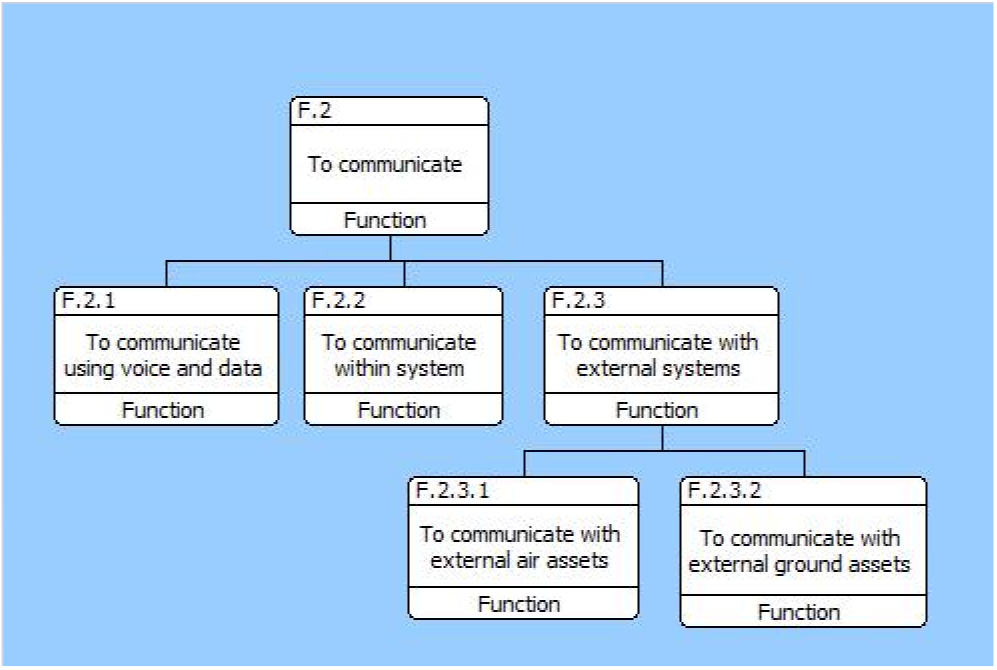


Figure 17. SV-4 Breakdown for “To Communicate.”

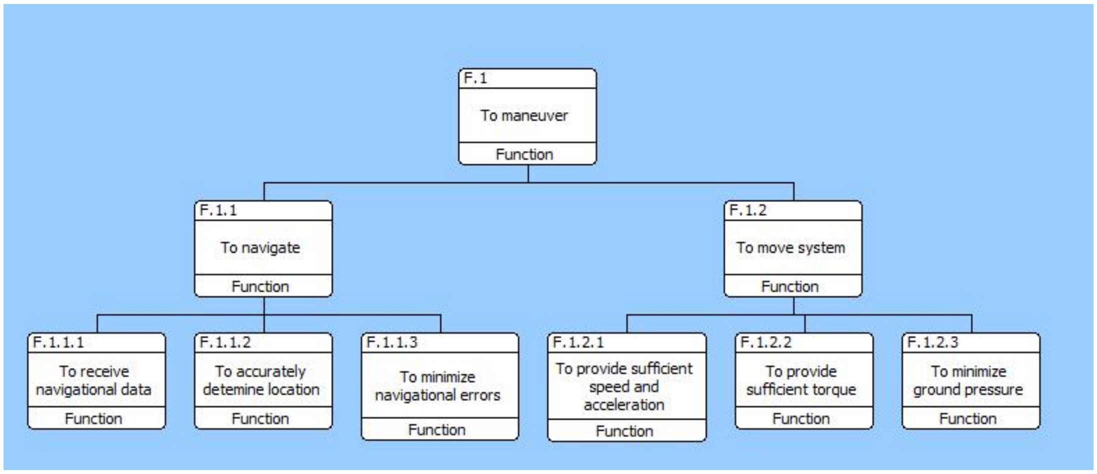
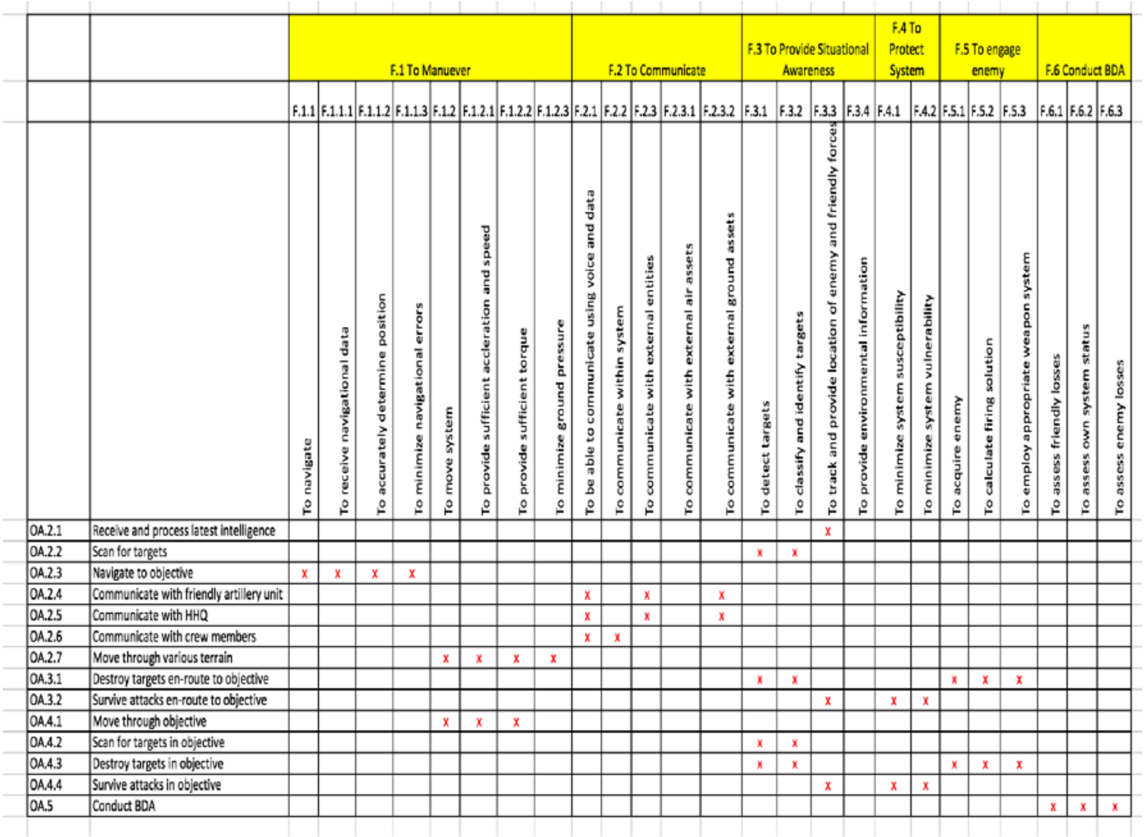


Figure 18. SV-4 Breakdown for “To Maneuver.”

As depicted in OV-5, the GCV needs to complete a series of operational activities in order to achieve mission success. Thus, it is important for this author to ensure that GCV’s system functions are able to perform the identified operational activities. This thesis achieves this by using the SV-5 (see Table 3), which maps operational activities to the GCV system functions (from the SV-4).

Table 3. SV-5 for GCV.



		F.1 To Manuever								F.2 To Communicate					F.3 To Provide Situational Awareness				F.4 To Protect System		F.5 To engage enemy			F.6 Conduct BDA		
		F.1.1	F.1.1.1	F.1.1.2	F.1.1.3	F.1.2	F.1.2.1	F.1.2.2	F.1.2.3	F.2.1	F.2.2	F.2.3	F.2.3.1	F.2.3.2	F.3.1	F.3.2	F.3.3	F.3.4	F.4.1	F.4.2	F.5.1	F.5.2	F.5.3	F.6.1	F.6.2	F.6.3
		To navigate	To receive navigational data	To accurately determine position	To minimize navigational errors	To move system	To provide sufficient accleration and speed	To provide sufficient torque	To minimize ground pressure	To be able to communicate using voice and data	To communicate within system	To communicate with external entities	To communicate with external air assets	To communicate with external ground assets	To detect targets	To classify and identify targets	To track and provide location of enemy and friendly forces	To provide environmental information	To minimize system susceptibility	To minimize system vulnerability	To acquire enemy	To calculate firing solution	To employ appropriate weapon system	To assess friendly losses	To assess own system status	To assess enemy losses
OA.2.1	Receive and process latest intelligence																x									
OA.2.2	Scan for targets														x	x										
OA.2.3	Navigate to objective	x	x	x	x																					
OA.2.4	Communicate with friendly artillery unit									x		x		x												
OA.2.5	Communicate with HHQ									x		x		x												
OA.2.6	Communicate with crew members									x	x															
OA.2.7	Move through various terrain					x	x	x	x																	
OA.3.1	Destroy targets en-route to objective														x	x					x	x	x			
OA.3.2	Survive attacks en-route to objective																x		x	x						
OA.4.1	Move through objective					x	x	x																		
OA.4.2	Scan for targets in objective														x	x										
OA.4.3	Destroy targets in objective														x	x					x	x	x			
OA.4.4	Survive attacks in objective																x		x	x						
OA.5	Conduct BDA																							x	x	x

G. ANALYSIS OF ALTERNATIVES

This section identifies and discusses the potential susceptibility reduction techniques and technologies that one can use to counter the threats that the threat analysis phase identified. Chapter VII discusses the threats as well as the potential alternatives to counter the threats.

H. MODELING AND SIMULATION

This section seeks to propose a model to quantify the various survivability characteristics of a ground combat vehicle taking into account both vulnerability and susceptibility reduction. It also demonstrates the use of a well-established decision-making methodology to address the various trade-offs in capabilities. Chapter VIII discusses the modeling and simulation for this thesis.

VII. THREAT ANALYSIS AND SUSCEPTIBILITY REDUCTION

Military planners expect a modern army to fight across a full spectrum of operations, ranging from low-intensity operations such as peacekeeping, to high-intensity operations against irregular and regular forces. Figure 19 illustrates the varying demands that different operations place on a GCV, with respect to the type and severity of the threats. Ball (2003) classifies the threats to a GCV into conventional and unconventional threats. According to Ball, engineers design conventional threats to attack relatively small targets, and they are not capable of causing destruction on a large scale (2003). Examples include guns, rockets, missiles and directed energy weapons. On the other hand, Ball explains that engineers design unconventional threats to function as weapons of mass destruction, which include nuclear, chemical and biological (NBC) weapons (2003). As the survivability requirements for conventional and unconventional threats are distinctly different, this thesis focuses only on conventional threats.

Figure 19. How Threat Severity Changes with Different Threat Scenarios. Source: Kempinski and Murphy (2012).

GCVs operating in urban environment face a multitude of threats, regardless of whether it is a low-intensity or high-intensity conflict. As the recent Middle East conflicts amply demonstrate, a skilled and determined enemy can utilize even obsolete weapons to great effect against advanced ground combat vehicles, especially in the confines of an urban environment. Since vulnerability reduction alone is no longer able to guarantee a reasonable level of survivability, this author believes that it is critical for military planners and engineers to explore alternative means of enhancing GCV survivability. Based on the survivability onion, this author believes that the only means to significantly improve GCV survivability is to leverage susceptibility reduction techniques, in addition to the existing vulnerability reduction techniques (i.e., designers and military planners need to embrace the survivability onion in its totality). The Defense Advanced Research Projects Agency's (DARPA) Ground X-Vehicle technology program (see Figure 20) amply illustrates the critical need to consider susceptibility reduction to counter future threats and threat scenarios. This author has been working on armored fighting vehicle programs since 2008, particularly in the area of threats and survivability. Therefore, this chapter uses contents from external sources, as well as from this author's previous work experiences.

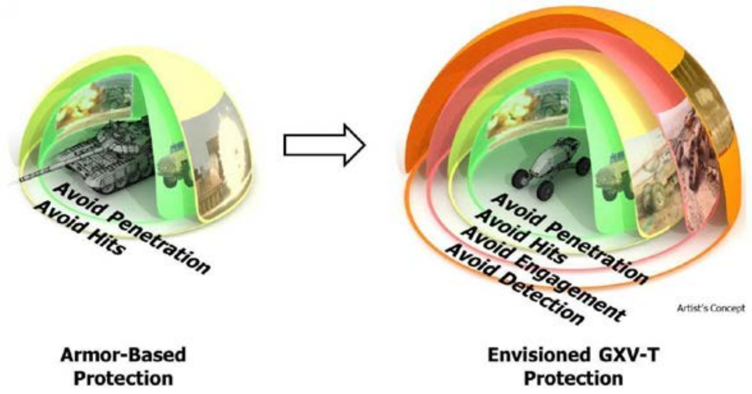


Figure 20. Illustration of DARPA's Ground X-Vehicle Program. Source: Lamothe (2014).

As per the modified systems engineering Waterfall process model, this thesis first identifies and analyzes the characteristics of the key threats encountered by ground vehicles during urban operations. After which, this thesis identifies and discusses the appropriate susceptibility reduction techniques that one can use to counter the threats. The six main susceptibility reduction techniques are (1) threat warning and situational awareness, (2) threat suppression, (3) signature management, (4) expendables, (5) noise jamming and deception and (6) tactics and performance. Finally, this thesis explores and discusses the potential technologies that can fulfil the susceptibility reduction requirements.

A. ROCKETS

As recent conflicts amply demonstrate, rockets are often the weapon-of-choice for urban engagements. This section provides a threat analysis on rockets and discusses the various susceptibility reduction techniques and technologies that one can use to counter rockets in an urban environment.

1. Threat Analysis

Rockets are short-range, unguided, fire-and-forget anti-armor weapons. Even though the precision and lethality of rockets are inferior compared to guided weapons, rockets are usually the weapon of choice for urban engagements. Based on this author's experience, the key reasons include:

1. Urban engagements are typically short to medium range (tens of meters to a few hundred meters). These ranges are well within the typical effective engagement ranges of rockets (about 200m to 300 m).
2. Rockets have short arming distances (about 15 m for a RPG-7), which allows an enemy to fire rockets very near to a friendly vehicle.
3. Rockets are generally smaller and lighter compared to missiles, which make it easier for a rocket carrying enemy to hide and to move around in an urban environment.
4. Rockets require minimal preparation to launch, unlike missiles that require an operator to set up the launcher and sensors. Thus, an enemy can simply pop up, fire a rocket, displace to another location and repeat the process.
5. Urban environment allows adversaries to target rockets at the weak spots of GCVs (sides, top and back), which are penetrable even by the smaller warheads on rockets.

6. Rockets are inherently cheaper to manufacture and therefore, much more readily available than missiles. Therefore, it is not surprisingly that insurgents and irregular forces favor rockets, especially the ubiquitous RPG-7.

Despite their relatively small size compared to missiles, military planners regard rockets as serious threats to GCVs because of their shaped charge warheads, similar to those found on the heavier missiles. Based on this author's experience, a shaped charge warhead typically consists of a concave metallic liner (usually copper), backed by high explosive. Upon detonation of the high explosive, the shockwave from the detonation compresses and squeezes the metallic liner into a long, thin jet, which can travel as fast as 10 km/s. The jet is very efficient at penetrating monolithic armored steel as long as the jet forms properly and maintains a coherent stream. Figure 21 shows a shaped charge warhead on an RPG-7, and Figure 22 shows how the jet formation of a shaped charge warhead varies with the cone angle. From Figure 22, one can see that as the cone angle increases, the jet eventually becomes a metallic slug known as an explosively formed penetrator (EFP), which is particularly deadly as an improvised explosive device. Kempinski and Murphy estimates that the penetration performance of modern shaped charge warheads is about "11 to 12 times the cone diameter." (2012, 49) This means that even for small (e.g., 40mm cone diameter) rockets, such rockets can already penetrate up to 480mm of armored steel. In addition to the effective shaped charge warheads, engineers typically design rockets to fly at velocities of around 200 m/s, meaning that for close-range engagements in an urban environment, it is highly unlikely for rockets to miss their target. Table 4 shows the U.S. Army Training and Doctrine Command's (TRADOC) estimates of the probability that a basic RPG-7 rocket can hit a fully exposed tank at various ranges. One can see that at close ranges of less than 100 m (a typical engagement distance for urban operations), the probability of hit is almost 100%.

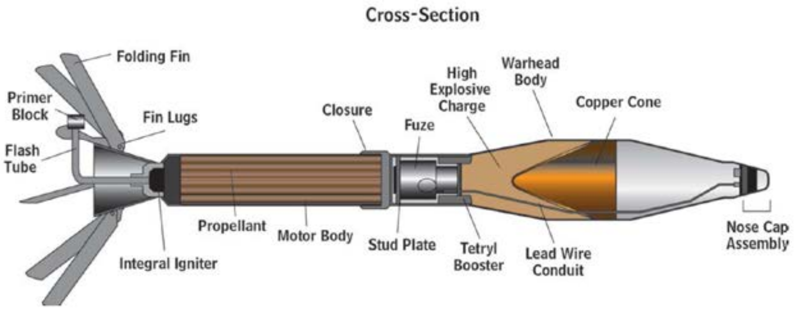


Figure 21. Cross-Section of RPG-7 Showing Shaped-Charge Warhead. Source: Kempinski and Murphy (2012).

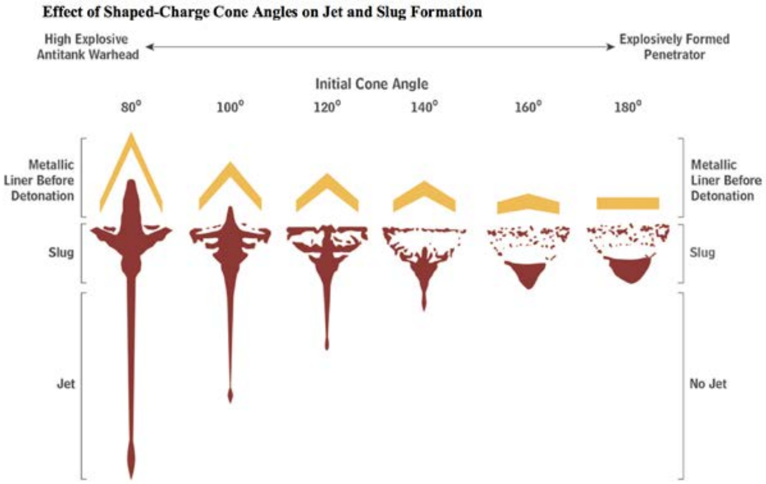


Figure 22. Effect of Cone Angle on Jet Formation. Source: Kempinski and Murphy (2012).

Table 4. Probability of Hit for an RPG-7 at Various Ranges. Adapted from U.S. Army TRADOC (1976).

Range	Probability of Hit
50 m	100%
100 m	92%
200 m	55%
300 m	25%
400 m	15%

Although engineers can use well-established solutions such as ERA or advanced composite armor to counter rockets with shaped charge warheads, these solutions incur significant weight penalties on a ground vehicle, despite continuous advancements in materials technology. In order to minimize the weight penalty on vehicles, military planners and engineers optimize the solutions to provide the highest level of protection from the most likely direction of attack. Since an enemy can attack a vehicle from any direction in an urban environment, it is clear that optimizing protection to a certain sector of a ground vehicle is not a viable solution. Figure 23 shows an insurgent popping up to fire a rocket from the roof of a building at a tank in the streets below, with the tank promptly destroyed by the rocket. Defense companies are also designing rockets to attack vehicles specifically at their weakest spot (such as the NLAW rocket from Saab), which is usually the top. It is difficult for one to attack ground vehicles from the top in conventional ground operations and therefore, military planners generally did not require engineers to up-armor the roofs of ground combat vehicles. With companies developing rockets such as the NLAW, it is now important for military planners and engineers to protect the roofs of ground vehicles as well.

Figure 23. Insurgent Destroying a Tank from a Roof. Source: YouTube (2013).

2. Susceptibility Reduction

a. Threat Suppression

This author believes that threat suppression is the key susceptibility reduction technique to counter rockets. Unlike guided weapons, rockets do not possess any sophisticated sensors and electronics that make them vulnerable against noise jamming and deception. In addition, due to the close engagement distances, there is very little time for a vehicle to react to a rocket attack in an urban environment. Thus, this author thinks that the only effective way to defend against rocket attacks in an urban environment is to use a hard-kill APS to intercept the rocket. .

According to Dieter and Wagner, a hard-kill APS consists of three main components, namely (1) sensors, (2) central processor and (3) countermeasures and the operating mode of the hard-kill APS typically consists of:

1. Detection, analysis and classification of incoming threat
2. Tracking of threat, estimate of threat hit point and decision whether to engage threat
3. Calculation of engagement profile and selection of appropriate countermeasure unit
4. Deployment of the selected countermeasure to degrade or destroy the incoming threat at the designated interception point (IP) (2009)

Figure 24 illustrates the operating sequence for a typical hard-kill APS. A hard-kill APS typically comprises multiple sensors to provide full 360° coverage in azimuth and at least 90° coverage in elevation (this can be likened to a dome covering a vehicle). The sensors (usually radar) detect and track the incoming threat and feedback the threat information (dimensions, velocity and flight path) to the central processor. The central processor then classifies the threat (missile, rocket or KE penetrator) and determines if the threat will hit the platform. If the central processor determines that the threat will miss the platform, no threat engagement will occur to preserve the limited quantity of countermeasures onboard. If the central processor determines that the threat will hit the platform, the central processor proceeds to calculate the engagement profile and selects the appropriate countermeasure to maximize the probability of intercepting the threat. Once ready, the central processor deploys the countermeasure(s) to degrade or destroy the incoming threat. According to Dieter and Wagner (2009), engineers typically utilize blast, fragmentation, “focused energy” or multiple explosively formed penetrators (MEFPs) as the damage mechanisms in the countermeasures.

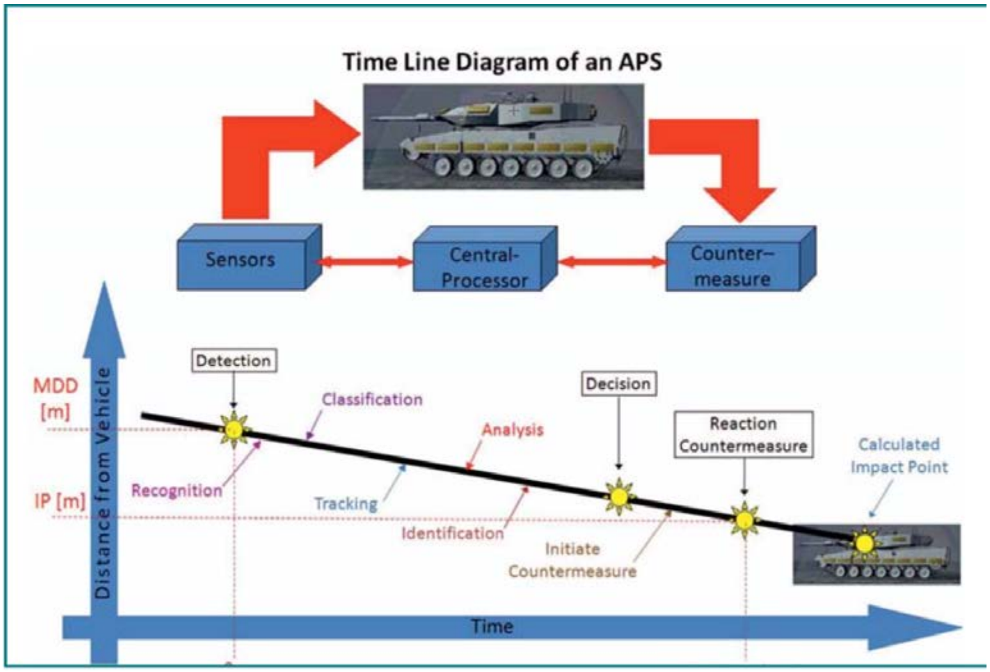


Figure 24. Typical Operational Sequence for a Hard-Kill APS. Source: Dieter and Wagner (2009).

According to Dieter and Wagner, one can differentiate hard-kill APS by their system reaction time (SRT), which refers to the total amount of time that the system requires to detect, identify and recognize an incoming threat, launch countermeasures and to intercept and destroy the incoming threat (2009). Table 5 shows how one can classify a hard-kill APS today, either as a microsecond system or as a millisecond system. Table 5 also shows that comparatively, a soft-kill APS has significantly longer SRT (measured in terms of seconds) compared to a hard-kill APS, which means that a soft-kill APS has limited effectiveness in an urban environment.

Table 5. SRT Classification for APS. Source: Dieter and Wagner (2009).

APS Category	SRT	SRT Classification
Hard Kill	less than 1000 μs	Microsecond System
	between 1 ms to 1000 ms	Millisecond System
Soft Kill	greater than 1 s	Second System

Besides the SRT, one can also differentiate hard-kill APS by their interception point (IP). Dieter and Wagner describe IP as the distance from the platform at which the countermeasure intercepts the incoming threat (2009). Table 6 shows the typical IPs that engineers use for hard-kill APS today. While operators will likely prefer the hard-kill APS to intercept an incoming threat as far away from the vehicle as possible, this author thinks that this likely requires the hard-kill APS to launch a physical projectile carrying the damage mechanism at the threat, which increases the overall SRT due to projectile flight time. Conversely, military planners can choose to intercept an incoming threat near to the platform, which allows engineers to use "focused energy" and MEFP countermeasures that travel significantly faster toward the incoming threat (based on this author's experience, MEFPs can travel up to 2,000m/s). Threat interception near the vehicle minimizes any countermeasure flight time and reduces the overall SRT, but increases the probability that the residual products of the interception hit the vehicle. In this author's opinion, another concern for intercepting threats far away is potential collateral damage against innocent civilians and property, especially in an urban environment. On the other hand, intercepting an incoming threat near to the platform contains the effects of the interception to within the immediate vicinity of the platform and thus, confines any collateral damage to a small area.

Table 6. IP Classification for Hard-Kill APS.
Source: Dieter and Wagner (2009).

	Interception Point (IP) Classification	Distance between IP and platform
1	Close-Range	less than 2 m
2	Medium-Range	2 m to 30 m
3	Far-Range	greater than 30 m

Engineers commonly use minimum defeat distance (MDD) as the key performance parameter for hard-kill APS. Dieter and Wagner refer to MDD as the distance within which the hard-kill APS is unable to react fast enough to counter an incoming threat (also known as the "dead-zone" for the hard-kill APS) (2009). For example, if the hard-kill APS has a MDD of 50 m, it cannot react to any threats that an enemy fires from within 50 m. According to Dieter and Wagner (2009), engineers can control MDD by defining the SRT and IP during system design (see equation for MDD). While it is not possible for one to control the incoming threat velocity, this author believes that the typical velocities for missiles, rockets and KE penetrators are well-known.

$$MDD = (SRT \times V) + IP$$

where MDD = minimum defeat distance

SRT = system reaction time

V = velocity of incoming threat

IP = interception point

Using the MDD equation, this author calculated the MDDs for different SRTs against rockets and missiles, assuming an IP of 5 m and typical velocities for rockets and missiles (see Table 7). Table 7 shows that microsecond SRT systems achieve MDD of less than 10 m, which in this author's opinion, means that such systems can respond fast enough to deal with most of the expected threats in an urban environment. For millisecond SRT systems, the calculated MDD for missiles and rockets is at least 105 m, which in this author's opinion, may be an issue in an urban environment. Based on this author's experience, engineers design anti-tank rockets and missiles to have typical safe arming distances of less than 100 m (e.g., RPG-7 has an arming distance of only about 15 m). Coupled with the close confines of an urban environment, adversaries can easily sneak up and attack ground vehicles from distances well within the MDD of some millisecond SRT systems.

Table 7. MDD for Different SRT Systems against Rockets and Missiles.

		Minimum Defeat Distance (m)			
Threat type	Threat velocity(m/s)	1000 ms reaction time system	500 ms reaction time system	1000 μs reaction time system	500 μs reaction time system
Anti-tank rocket	200	205	105	5.2	5.1
Anti-tank missile	300	305	155	5.3	5.15

TROPHY is the only known operationally fielded hard-kill APS today, and the IDF uses it on the Merkava IV MBT. According to the Zitun, TROPHY achieved its first operational success in March 2011 when it successfully intercepted an incoming RPG-29 rocket (2012). During the 2014 Gaza conflict, military commentators reported that TROPHY made dozens of successful interceptions against advanced missiles such as the Kornet and Metis, as well as rockets such as the RPG-7 and RPG-29, resulting in zero hits to tanks equipped with the system.

Dieter and Wagner (2009) classify TROPHY as a millisecond SRT system, with SRT of 300 to 350 ms and IP of 10 to 30 m. Figure 25 shows that TROPHY has four radars around the vehicle to provide a complete coverage dome around the vehicle. There are also two countermeasure launchers and two auto-reloaders, one on each side of the vehicle.

Figure 25. TROPHY on Merkava IV, showing Radar, Countermeasure and Auto-Reloader. Source: Rafael (2010).

This author believes that the TROPHY system is relatively simple and consists of only a few components, which potentially reduces the integration effort required. In addition, having fewer components also reduces the logistics burden for the system (i.e., system reliability, installation, removal and maintenance time, spares), as well as reduces the vulnerable area of the TROPHY system. This author thinks that reducing the vulnerable area is very important as it reduces the probability that a hostile damage mechanism can hit and disable the TROPHY system. Nevertheless, the main trade-off for this kind of centralized architecture is the relatively long SRT of about 300–350 ms, which in this author’s opinion, is due to the fact that (1) the system needs to mechanically rotate the countermeasure to face the incoming threat and (2) the system needs to re-load the countermeasure mechanically after each shot.

Besides TROPHY, other companies are also developing their own hard-kill APS. Examples include the IRON CURTAIN from Artis and the AMAP-ADS from Rheinmetall. This thesis highlights these two systems in particular because they are well-developed (though not known to be operationally fielded) and more importantly, they utilize a distributed architecture, unlike the centralized architecture of TROPHY.

Figure 26 shows the AMAP-ADS. One can see that unlike TROPHY, the AMAP-ADS has multiple sensors and countermeasures arranged in a ring around the platform.

This author suggests that this ring-like distribution of sensors and countermeasures is the defining characteristic of distributed architecture systems. As there are no known rotating components on the system, each sensor and countermeasure has its own fixed field-of-view/field-of-attack (Rheinmetall 2013). Another key difference between the AMAP-ADS and TROPHY is the IP. Unlike TROPHY that has IP of 10 m to 30 m, engineers designed the AMAP-ADS to intercept a threat 2 m from the platform (Rheinmetall 2013). In addition to a short IP, engineers also designed some systems such as the IRON CURTAIN to intercept a threat from the top, using "directed energy" instead of explosive projectiles. From Figure 27, one can see that these design decisions help direct most of the energy and collateral damage from the threat interception downwards and in the immediate vicinity of the platform, thus helping to minimize collateral damage. Nevertheless, from Figure 27, one can also easily visualize the potential risks to the crew sitting inside the vehicle when IRON CURTAIN intercepts a threat so close to the vehicle.

Figure 26. AMAP-ADS System Installed on a Tactical Wheeled Vehicle. Source: Eshel (2011a).

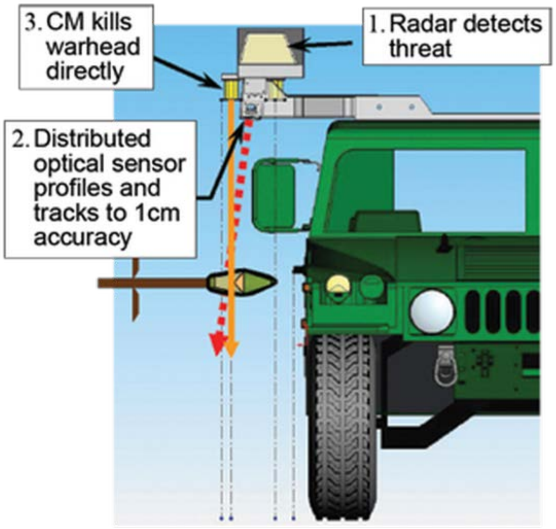


Figure 27. Downwards Interception of a Threat by IRON CURTAIN. Source: Rutherford (2009).

This author believes that the key advantage of a distributed architecture is the very fast SRT. According to Rheinmetall (2013), the AMAP-ADS has SRT in the region of about 600 μs, which is 500 times faster than TROPHY's SRT of about 300 ms. The IRON CURTAIN has a similar design architecture to the AMAPS-ADS, and this author expects it to have a similar SRT to the AMAP-ADS. This author attributes the fast SRT of a microsecond APS to the distributed architecture, whereby all the sensors and countermeasures have fixed sectors, meaning that there is no need for any mechanical movement (unlike TROPHY that requires mechanical steering and reloading of countermeasures). In addition, one can see from the MDD equation that having a short IP directly reduces the MDD for a hard-kill APS. Microsecond SRT systems have very short MDD (ideal for urban operations), which is almost independent of the incoming threat velocity (see Table 7). As such, this author believes that a distributed architecture hard-kill APS is likely to have a higher potential of defeating high-velocity threats such as kinetic energy penetrators, compared to a centralized architecture system.

Although a distributed architecture system has very fast SRT and very short MDD, it is not without trade-offs. One key disadvantage is the distribution of multiple sensors and countermeasures around the vehicle to provide full and overlapping coverage. If one compares Figures 25 and 26, it is evident that a distributed architecture system like the AMAP-ADS has more than 30 components, compared to only about 10 for a centralized architecture system like the TROPHY. This means that the distributed architecture system is likely more expensive than a centralized architecture system. The large quantity of components with their corresponding wires and connection points also means that it can be more difficult for engineers to integrate distributed architecture systems onto vehicles and this also results in a heavier logistics burden downstream (i.e., system reliability, installation, removal and maintenance time, spares). Due to the large quantity of components distributed around the ground vehicle, this author also thinks that the overall vulnerable area of a distributed architecture system is significantly greater than a centralized architecture system. This increases the probability that a hostile damage mechanism can hit and disable a hard-kill APS that uses distributed architecture. Finally, while engineers can design microsecond hard-kill APS to minimize collateral damage by intercepting the threats close to the vehicle, this can result in a higher probability of residual penetration (due to the remnants from the interception), especially from kinetic energy penetrators.

B. MISSILES AND SMART BOMBS

Recent conflicts generally pitted ill-equipped insurgent forces against technologically and numerically superior regular forces. As such, it is not surprising that advanced weapons such as missiles and smart bombs are not as prevalent in the recent conflicts compared to rockets. Nevertheless, future urban conflicts can involve near-peer forces, and one can expect extensive use of missiles and smart bombs in those conflicts. As such, this section provides a threat analysis on missiles and rockets and discusses the various susceptibility techniques and technologies that one can use to counter them.

1. Threat Analysis

Besides rockets, hostile forces can also attack GCVs by using a variety of guided weapons such as missiles and smart bombs. Due to the presence of guidance and tracking mechanisms on such weapons, their inherent accuracy is much greater than ballistic projectiles such as rockets. In addition to their higher accuracy, based on this author’s experience, guided weapons typically have higher velocities (typically 300–400 m/s for missiles vis-a-vis about 250 m/s for rockets), longer engagement distances (a few kilometers for missiles vs less than one kilometer for rockets) and more lethal warheads compared to rockets. Based on this author’s experience, these advantages allow one to fire guided weapons outside the typical effective weapon engagement ranges for GCVs (about 1.5 km for IFV cannon and about 3 km for MBT main gun), which makes it difficult for GCVs to engage and suppress potential threats before they deploy their guided weapons.

An operator must first detect a target and determine the target location before launching a missile or smart bomb at the target. The operator can obtain this information from sensors on-board surveillance aircraft/drone or from a forward observer on the ground. When the missile or smart bomb is sufficiently close to the target (terminal phase of the engagement), the weapon utilizes its onboard seekers to home in on the target, usually either via the infrared (IR) radiation generated by the target or via laser or radio-frequency (RF) waves reflected from the target. Based on this author’s experience, engineers can implement three main types of seekers on guided weapons, namely (1) active homing seekers, (2) semi-active homing seekers and (3) passive homing seekers. Based on this author’s experiences, missiles can employ all three seeker types, while smart bombs typically employ semi-active homing seekers and passive homing seekers.

Based on this author’s experience, active homing missiles typically rely on Radio Frequency (RF) waves to home in on a target. The missile carries an onboard transmitter to generate and transmit the RF waves, which reflect off a target. The receiver on the missile then detects the reflected RF waves, which allows the missile to determine the target location and to correct its flight path to intercept the target. This author believes that a key advantage of active homing missiles is their fire-and-forget capability, which allows the shooting platform to escape immediately after launching the missile, or to engage another target. Based on this author’s experience, engineers currently design active homing missiles primarily for the air-domain and the ship-domain, and there are no known active homing missiles designed to engage GCVs specifically. In this author’s opinion, this is probably because of the high cost for engineers to integrate RF transceivers (which are expended every time one launches the missiles) on the missiles, vis-a-vis the cost of a GCV (compared to a much more expensive aircraft or ship). Thus, engineers typically use semi-active homing seekers or passive homing seekers on anti-GCV missiles.

Based on this author’s experience, the key difference between active homing and semi-active homing is that for the latter, the transmitter is on an external source and not onboard the missile itself. The external source transmits the energy, and the receiver on a semi-active homing missile detects the reflected energy (see Figure 28). The external source can be a radar onboard an airborne platform (e.g., the millimeter wave radar on the Apache attack helicopter) or a forward ground observer using a laser designator. The external source needs to illuminate the target constantly to guide the missile to the target and thus, semi-active homing missiles do not have a fire-and-forget capability. Examples of semi-active homing missiles include the AGM-114L HELLFIRE (using millimeter wave radar) and the LAHAT (using laser).

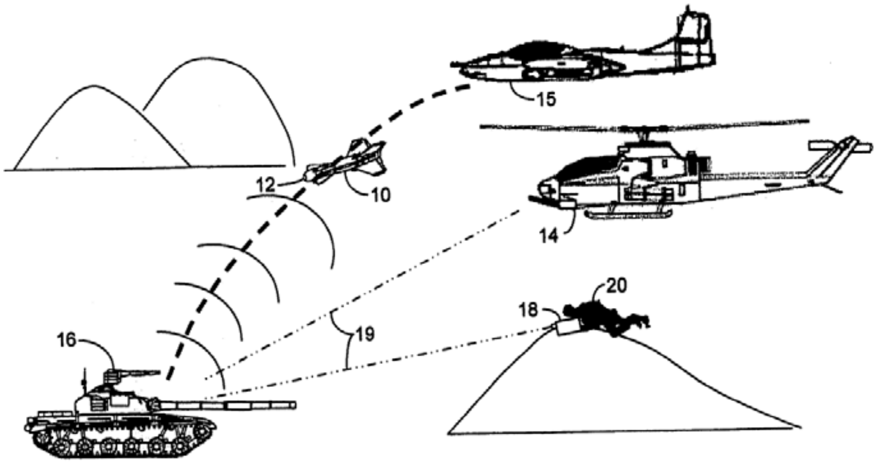


Figure 28. Semi-Active Homing Concept. Source: Hartman and Griffin (2007).

Based on this author’s experience, a key disadvantage of active and semi-active homing missiles is that they rely on reflected energies to home in on the target. If the target has appropriate sensors to detect the incident energies, the sensors can provide the target with early warning of impending attack and can potentially reveal the location of the hostile threat. Passive homing missiles can circumvent this disadvantage as they do not require any external source of illumination of the target. Engineers design passive homing missiles to detect and track the electromagnetic (EM) radiation that targets emit. Since all bodies or gases above absolute zero temperature emit EM radiation, IR seekers can pick out targets as long as there is sufficient temperature difference between the target and the environment. Another added advantage of passive homing missiles is the fire-and-forget capability. Once the missile locks on to the target's IR signature, it can independently track and guide itself to the target. An example is the U.S. Army's Javelin missile, which uses an imaging IR seeker to track and destroy a target without any additional guidance from the gunner.

Besides homing missiles, adversaries can also use command line of sight (CLOS) missiles to attack GCVs. Based on this author's experience, CLOS missiles are more prevalent in ground operations compared to homing missiles. For CLOS missiles, a gunner needs to guide the missile optically to the target, which necessitates that the gunner keeps the optical sight on the target until impact. Thus, CLOS missiles also lack fire-and-forget capability. CLOS missile systems typically have a sighting device on the launcher, which calculates the angular difference between the missile flight path and the target and generates command signals to minimize the angular difference. CLOS missile systems usually transmit the command signals to the missile via wires trailing behind the missile or via RF signals. See Figure 29 for an illustration of CLOS guidance. Since CLOS missiles rely on optical guidance, the target will not have early warning of attack, similar to passive homing missiles. Nevertheless, one can expect CLOS missiles to be less complex and cheaper compared to homing missiles, but with trade-offs in accuracy (due to human tracking error involved) and range (due to the length of wire required). An example of a CLOS missile is the U.S. Army's Tube-Launched, Optically-Guided, Wire-Tracked (TOW) missile.

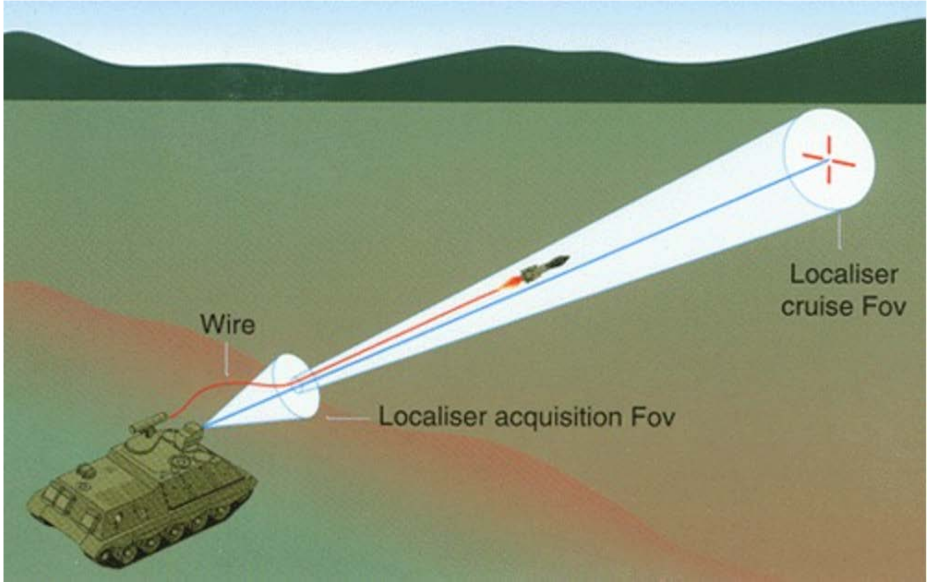


Figure 29. Command Line of Sight Guidance. Source: Army-Technology (2016).

Besides missiles, smart bombs also utilize similar principles to home in on their targets. One example is the Paveway series of laser-guided bombs that the U.S. military uses for precision strikes. These bombs have a semi-active laser seeker that detects reflected laser energy from a target and homes in on the target using the reflected laser energy. Another example is the CBU-105 Sensor Fuzed weapon (SFW), which is a 1,000 pound guided Cluster Bomb Unit (CBU). According to Defencyclopedia (2015), the SFW contains 40 projectiles or “skeets.” The “skeets” rely on passive homing IR seekers to detect the thermal signatures of ground vehicles before engaging them by firing EFPs through their roofs. Considering the lethality of EFPs, the thin roof armor of most GCVs and the number of “skeets” per CBU-105, it is certainly possible for an adversary to degrade or destroy an entire column of GCVs by using just a few CBU-105 units. Currently, only select nations can afford advanced weapons such as laser-guided bombs and the CBU-105, but it is conceivable for engineers or even technologically savvy insurgents to integrate the technologies in such weapons (such as the sensor) into “cheap” weapons (e.g., rockets and mortars) in the future and use them as precision swarm weapons.

2. Susceptibility Reduction

Missiles and smart bombs have higher inherent accuracies and kill probabilities compared to rockets due to their complex targeting and guidance mechanisms. Nevertheless, this author believes that having such capabilities also makes it easier for one to defeat guided weapons. Compared to unguided rockets that have no complex targeting and guidance mechanisms, one can use more susceptibility reduction techniques to defeat missiles and smart bombs, which include threat warning and situational awareness, signature reduction, expendables, threat suppression and noise jamming and deception.

a. Threat Warning and Situational Awareness

Based on this author's experience, most GCVs today lack an integrated defensive aid system (DAS) to warn the crew of potential incoming attacks, and to generate automatically a response to minimize the probability of engagement or probability of hit. Anti-GCV missiles and smart bombs today predominantly rely on semi-active homing guidance, and laser is the most common method to guide a weapon onto the target. Thus, this author thinks that it is critical for military planners and engineers to equip GCVs with early warning systems to detect hostile "lasing," so that the GCV can take appropriate counter-measures to improve survivability. Figure 30 shows that a DAS composes of three main components, namely (1) sensor, (2) central processor and (3) countermeasures. The sensor provides warning of potential threat as well threat location. The DAS processor processes the threat information and displays it to the crew via the man-machine interface. In addition, the DAS processor also sends the threat information to the battlefield management system to alert other friendly forces, which permits subsequent prosecution of the target. Finally, depending on the settings, the DAS processor can also automatically deploy the necessary countermeasures to minimize the probability of engagement and hit.

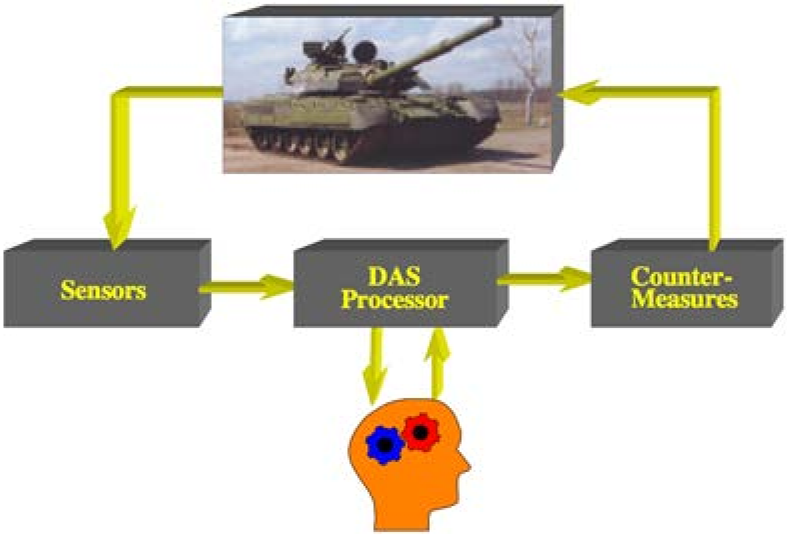


Figure 30. Basic Concept of a DAS. Source: Fournier (2012).

Against laser designators, engineers typically use a laser warning device (LWD) to provide early warning of hostile "lasing." An example of this is the Goodrich AN/AVR-2, which receives, processes and displays threat information resulting from illumination by laser designators and laser rangefinders from all directions. As the sensor is capable of detecting the direction of the laser source, this author believes that engineers should integrate the information into a ground vehicle's weapon system. Upon threat detection, engineers can program the sensor to slew a weapon or jammer to the approximate location of the threat and attempt to disrupt the laser designation process (threat suppression). The DAS can also cue the deployment of expendables such as smoke and aerosols to mask the ground vehicle from the hostile laser energy. These actions can increase the probability of the missile missing the target.

b. Signature Reduction

An operator needs to detect and locate a target first before the operator can launch a guided weapon at the target. One can detect a GCV by using different sensors such as optical, radar, electro-optic or infrared. Therefore, signature reduction seeks to negate the effectiveness of these sensors in detecting the GCVs. Even if the sensors manage to detect and engage a GCV, signature reduction helps to reduce the ability of the missiles and smart bombs to home in on the GCV and therefore, increase the probability of miss. This author believes that signature reduction is an important countermeasure against attacks by swarms of “cheap” smart weapons in the future. Once an enemy deploys such swarm weapons (e.g., smart bomblets), it is not feasible or possible for the GCV to shoot down all of the weapons. Thus, signature reduction plays a significant role in reducing the probability that such weapons can detect, engage or hit the ground vehicle. Based on this author’s experience, signature reduction in the thermal region is particularly important for ground vehicles as passive homing weapons predominantly use IR guidance. While radar-guided weapons are not as prevalent as IR guided weapons currently, many airborne sensors use radar (such as synthetic aperture radar) to detect ground vehicles. In addition, this author believes that the main reasons for the current lack of radar-guided weapons against GCVs are cost and the signal clutter when operating radars in a ground environment, particularly in urban settings. As radar technology continues to evolve, this author expects the cost-effectiveness and performance of radar-guided missiles in ground urban operations to improve and therefore, it may become feasible for militaries to employ such missiles against GCVs extensively in the near future.

ADAPTIV from BAE Systems is a unique active camouflage system that can mask the thermal signature of ground vehicles. According to Eshel, ADAPTIV makes use of modules that can individually cool down or heat up to create different thermal patterns (2011b). This allows ADAPTIV to mimic the surrounding temperature and thus, reduce the thermal contrast between the vehicle and its surroundings. As IR seekers require thermal contrast to detect targets, decreasing thermal contrast reduces the probability that an IR sensor or missile can detect, engage or hit a ground vehicle. Eshel (2011b) also mentions that the ADAPTIV system can create specific thermal signatures that military planners can use for vehicle identification, which reduces the chance of friendly fire (fratricide) and indirectly improves the survivability of a ground vehicle. Figure 31 shows the ADAPTIV system and illustrates its capability to blend in with the surrounding, as well as mimic different vehicle thermal signatures.

Figure 31. ADAPTIV Thermal Camouflage System. Source: Eshel (2011b).

While the ADAPTIV system has significant potential in the area of thermal signature management, this author believes that there are trade-offs. These include the need for engineers to provision additional power to operate the system, the additional costs that military planners incur to maintain the system (especially in ground urban operations) and the potential difficulties that engineers face to integrate ADAPTIV with vehicular passive armor. There are other operationally available solutions on the market today that can provide passive reduction in thermal signatures. A well-known example is the Barracuda Mobile Camouflage System (MCS) from the Swedish company Saab, which is an operationally proven system (see Figure 32). In this author’s opinions, the key advantages of a “net” system such as the MCS over ADAPTIV include lower life-cycle cost, no power requirement from the vehicle as well as the ability to reduce the internal temperature of the vehicle, which is critical especially in hot climates. Nevertheless, this author expects active systems such as ADAPTIV to provide better signature reduction performance against IR sensors, as active systems seek to mask a vehicle’s thermal signature, unlike a passive system, which merely seeks to reduce a vehicle’s thermal signature.

Figure 32. Barracuda MCS. Source: Saab (2014).

Besides reducing thermal signature, this author thinks that it is also important for military planners and engineers to reduce vehicular radar signature as well. This is because radar technology and cost-effectiveness will continue to improve, and it will be viable for militaries to employ radar-guided missiles against GCVs in the future. In February 2016, researchers at the Raytheon-UMass Lowell Research Institute (RURI) developed a novel ink technology. According to Raytheon (2016), this technology is a special ferroelectric nano-ink that can generate different electromagnetic frequencies depending on the voltage that one applies to the ink. In addition, one can also spray or "print" the ink onto any surface using an aerosol jet, which can then function as radio antennas or radar arrays (see Figure 33). In this author's opinion, a key military application for this new ink is its potential to revolutionize how engineers can protect platforms against radar. According to Majumdar, engineers optimize stealth technology today to defeat high-frequency radars and not low-frequency radars, which is because low-frequency radars are currently not good at discerning targets, especially in a cluttered environment (2014). Nevertheless, Majumdar cautions that this situation will change eventually as radar and processing technology improves, which can allow even low-frequency radars to accurately and precisely discern targets (2014). This poses a clear threat to the existing stealth technology, which engineers optimize to defeat high-frequency radar.

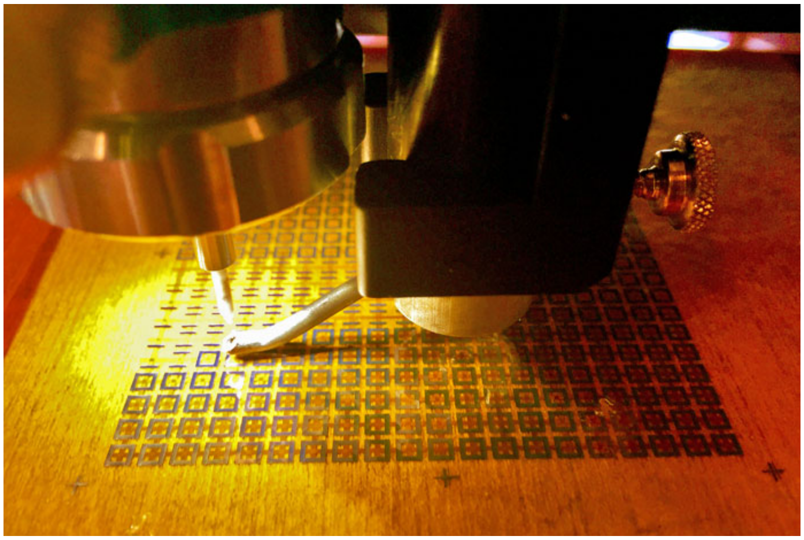


Figure 33. An Aerosol Jet Applying Electric Ink at the RURI. Source: Raytheon (2016).

In this author's opinion, the new printable ink technology is a potential solution to the issue of high-performance, low-frequency radars. As one can tune the ink's electromagnetic frequency by varying the amount of voltage that one applies to the ink, the ink can potentially generate a wide spectrum of radar frequencies. Depending on the frequency of the hostile radar, one can tune the ink to generate an appropriate counter-frequency to negate the hostile radar wave through destructive interference. Therefore, the tunable ink can reduce the amount of reflected EM energy that the hostile radar receives, which reduces the probability that the hostile radar detects the protected platform. In other words, the new ink technology can potentially create an "invisibility cloak" around the protected platform that significantly reduces the radar signature of the platform against both low-frequency and high-frequency radars. In addition, since one can print the ink onto any surface, engineers will not need to cater excessive space for the printed radar antennae, which facilitates integration of the printed radar antennae onto compact platforms such as a ground combat vehicle.

Besides reducing thermal and radar signatures, this author thinks that it is also important for military planners and engineers to reduce a GCV’s signature to laser designators. One can achieve this by using special materials and paint to attenuate the amount of reflected laser energy. In 2010, a team from Yale University proposed an interesting concept known as Coherent Perfect Absorber (CPA) or “anti-laser,” and the team demonstrated a working prototype of the “anti-laser” in 2011. The anti-laser device consists of a specially designed optical cavity, which traps incident laser light and forces the light to bounce repeatedly within the optical cavity to dissipate the laser energy as heat. Results indicated that for a specific laser wavelength, the anti-laser device absorbed 99.4% of the incident laser light (BBC 2011). If engineers can implement such a technology on ground vehicles, engineers can potentially reduce a GCV’s susceptibility to laser-based threats such as laser designators and laser rangefinders.

Aircraft and ships are the primary military platforms today that incorporate significant amounts of signature reduction technologies. Based on this author’s experience, no military is currently fielding GCVs with significant signature reduction technologies in their design. Nevertheless, Poland and BAE Systems are attempting to buck the trend by jointly developing a prototype tank known as the PL-01 (see Figure 34). The PL-01 attempts to minimize infrared signature by using the ADAPTIV system from BAE Systems. The PL-01 also attempts to reduce radar signature by adopting smooth contour shapes (GCVs today are typically “boxy” looking) that help minimize reflected radar energies. Engineers also reduced the number of potential radar scatter points on the PL-01. For example, engineers recessed the smoke grenade launchers at the vehicle rear, instead of mounting them outside the PL-01, like most ground vehicles today. These measures help to reduce the PL-01’s radar, thermal and visual signatures and thus, reduce the probability that a hostile threat can detect, engage or hit the PL-01.

Figure 34. Futuristic PL-01 Concept Tank. Source: Military-Today (2016).

c. Expendables

One major component of a DAS is the countermeasure suite to reduce the probability that an incoming threat hits the vehicle. In air combat, fighter pilots typically expend onboard chaff or flares to deceive hostile seekers for a limited period while they maneuver away from the seeker-tracking window. Engineers also use this method to defend ground vehicles against laser and IR guided weapons. Smoke and aerosols are generally quite effective against such weapons. Based on this author’s experience, smoke and aerosols typically consist of a cloud of small particles. When an electromagnetic wave (laser in this case) strikes the cloud, the cloud can absorb, scatter and/or transmit the laser energy. The main purpose of the cloud of particles is to scatter and attenuate the laser energy, to minimize the amount of laser energy that the ground vehicle reflects back to the hostile receiver. Without receiving a sufficient return signal, the hostile threat is unable to detect, engage or hit the ground vehicle. The ability of smoke and aerosols to scatter and attenuate laser energy depends on the type of particles and the particle size, vis-a-vis the expected laser wavelength. Therefore, it is important for engineers to optimize smoke and aerosols systems for the expected laser wavelengths. Based on this author’s experience, multispectral smoke is increasingly popular today because they are effective against electromagnetic radiation with frequencies ranging from about 1µm to 10µm. This is because battlefield laser rangefinders and designators typically operate around the 1µm band, while thermal imagers and seekers typically operate in the 3µm to 5µm band, or the 8µm to 12µm band.

d. Noise Jamming and Deception

Missiles and smart bombs are susceptible to noise jamming and deception as one can attempt to interfere with the electronics inside these guided weapons, which increases the probability that the weapon misses the intended target. According to Ball, noise jamming seeks to overwhelm a seeker by generating large numbers of false targets and hiding the true target among the false targets, while deception seeks to “seduce” a hostile seeker away from the intended target by presenting false target information to the hostile seeker (2003). An example is the AN/AAQ-24 system that seeks to protect fixed and rotary wing aircraft from IR missiles by jamming the missiles with a high-intensity laser. In this author’s opinion, engineers can adapt and integrate such jammers onto ground combat vehicles to reduce their susceptibility to IR missiles, and engineers can do so with a significantly lower weight penalty compared to passive armor. In addition, as long as the vehicle provides sufficient power to the jammer, the jammer can protect the vehicle from repeated attacks by IR missiles, unlike passive armor and hard-kill APS, which have limited multi-hit capability (due to structural integrity of the armor and limited ammunition for the hard-kill APS). The main disadvantage of jammers is that they are only effective against the specific threats which engineers designed the jammer to defeat. Using the AN/AAQ-24 as an example, it is only effective against IR guided missiles and not radar or laser-guided missiles. Jammers are also ineffective against ballistic projectiles that have no electronics for the jammers to act against. Since ground combat vehicles face ballistic threats and non-ballistic threats, this author believes that jammers by themselves cannot satisfy the survivability requirements of a ground vehicle, especially in an urban environment.

C. KINETIC ENERGY PENETRATORS

Kinetic energy (KE) penetrators are not prevalent in recent conflicts for the same reasons as missiles and smart bombs. Nevertheless, one can expect widespread use of KE penetrators in any future ground conflicts that involve near-peer forces. As such, this section provides a threat analysis on KE penetrators and discusses the various susceptibility techniques and technologies that one can use to counter KE penetrators.

1. Threat Analysis

Military planners typically use KE penetrators, particularly the armor-piercing fin stabilized discarding sabot (APFSDS), to defeat heavily armored GCVs such as main battle tanks. KE penetrators like the APFSDS are efficient at penetrating heavy armor due to the penetrator mass (typically five to 10kg) and the penetrator velocity (up to 2,000 m/s). Based on this author's experience, the length to diameter or L/D ratio of a penetrator also has significant effect on the penetrating capability of a KE penetrator. In general, the larger the L/D ratio, the better the penetrating capability of the penetrator. This explains why modern APFSDS penetrators resemble medieval arrows. Therefore, in order to counter increasingly advanced composite armor, engineers typically try to increase penetrator mass, L/D ratio and/or penetrator velocity.

The impact of a KE penetrator on armor generates behind-armor-debris (BAD) inside the vehicle. BAD comprises of both the fragments from spalling (ejection of material from the back face of the armor), as well as the remnants of the penetrator that perforates into the vehicle interior. BAD is the primary killing mechanism for KE penetrators, as the fragments can seriously injure or kill anybody behind the armor, as well as cause significant damage to equipment inside the vehicle. The most effective KE penetrators are APFSDS fired from large caliber guns, as large caliber guns generate the high muzzle velocities that penetrators require. Both MBTs and tank-destroyers use large-caliber, high-velocity guns. Based on this author's experience, modern APFSDS penetrators have maximum effective range of about 3,000 m. Due to the high velocity of the penetrator, it takes the penetrator only about 2 s to hit the target, even at the maximum effective engagement range. In an urban environment, the typical engagement distance is short and if a hostile threat fires an APFSDS penetrator at a ground vehicle, it is highly likely for the penetrator to hit and kill the ground vehicle.

While APFSDS penetrators are very effective in penetrating heavy armor, they are not without disadvantages and constraints. In order to penetrate heavy armor, APFSDS penetrators need to travel at high velocities of up to 2,000 m/s. Only large-caliber, high-velocity guns such as those found on MBTs and tank destroyers can generate such high energies. Due to the confines of an urban environment, it is not easy for an adversary to hide MBTs and tank destroyers in the urban environment. In addition, due to the large size of the ammunition, MBTs and tank-destroyers can only carry a limited quantity of rounds (about 40 on average), which are usually a mix of High Explosive rounds (general purpose) and APFSDS (armor killing). Therefore, in order to destroy the maximum number of targets, MBTs and tank destroyers need to have a high first round hit probability. MBTs and tank destroyers achieve this by providing accurate target range data to the onboard fire control computer, which uses the range data (plus other information) to calculate the optimal ballistic solution for firing.

2. Susceptibility Reduction

This author thinks that military planners and engineers can employ susceptibility techniques such as threat suppression, threat warning and situational awareness, noise jamming and deception and expendables to reduce a GCV’s susceptibility against KE penetrators. MBTs and tank destroyers typically use laser rangefinders to obtain accurate target range data. Laser rangefinders use similar technology to laser designators, which this thesis had discussed in the previous section. Therefore, some of the techniques and technologies that one uses to counter laser designators can also apply to laser rangefinders.

a. Threat Suppression

It is difficult for an enemy to hide MBTs and tank destroyers in an urban environment. Thus, good intelligence and reconnaissance operations prior to an assault can determine the locations of some of these weapons. Military commanders can then use precision fires to destroy the threats before they can engage friendly forces. If military commanders have air superiority, airborne assets and sensors can also provide persistent surveillance during the urban assault mission. Besides providing aerial surveillance, airborne platforms can also engage any hostile MBTs or tank destroyers that the enemy deploys against the friendly ground forces.

If a hostile MBT or tank destroyer fires a KE penetrator at a ground vehicle, the vehicle has very little time to react to the incoming threat. Therefore, this author believes that a hard-kill APS provides the best chance of survival for the ground vehicle. This thesis discussed hard-kill APS in detail under the section on rockets, but there are differences between defeating a high-velocity KE penetrator and a much slower missile or rocket. As this author discussed previously, MDD is a crucial performance parameter for a hard-kill APS. This author used the MDD formula to calculate the MDD for different hard-kill APS systems against KE penetrators. Table 8 shows that hard-kill APS with fast SRT (microseconds) have generally no issues reacting to KE penetrators because of their relatively short MDD. For hard-kill APS with slower SRT (milliseconds), there can be instances whereby a hostile threat fires a KE penetrator from within their MDD (especially in urban environments), which essentially negates the effectiveness of the hard-kill APS. If one compared Tables 7 and 8, one can see that the MDD for microsecond SRT systems is largely independent of threat velocity (MDD increases slightly from 5 m to 27 m when threat velocity increases from 200 m/s to 2000 m/s). On the other hand, one can also see that threat velocity greatly affects the MDD for millisecond SRT systems (MDD increases from 200m to 2,000 m when threat velocity increases from 200 m/s to 2,000 m/s).

Table 8. MDD for Different SRT Systems against KE Penetrators.

	Minimum Defeat Distance (m)			
Threat velocity (m/s)	1000 ms reaction time system	500 ms reaction time system	1000 μs reaction time system	500 μs reaction time system
1,500	1,525 m	775 m	26.5 m	25.75 m
2,000	2,025 m	1,025 m	27 m	26 m

Currently, there is no known operational hard-kill APS that can defeat KE penetrators. This is because rockets and missiles largely dominate the recent conflicts, particularly those in the Middle East. Therefore, it is not surprising that military planners and engineers steer the development of hard-kill APS toward defeating rockets and missiles. Nevertheless, the now-cancelled IRON FIST system from Israeli Military Industries (IMI) (see Figure 35) had the potential to defeat KE penetrators. According to IMI (2016), engineers designed the IRON FIST countermeasure to detonate as it passes by a KE penetrator. The radial blast from the detonation de-stabilizes the penetrator and causes it to either miss the target vehicle completely or to impact the target vehicle at a non-optimal angle (significantly reduces penetration power). This author mentioned previously that engineers can improve the penetrating capability of an APFSDS penetrator by increasing the L/D ratio. In this author’s opinion, this actually makes it easier for hard-kill APS such as the IRON FIST to defeat the penetrator as the larger the L/D ratio, the easier it is for a countermeasure to destabilize the penetrator in flight and cause the penetrator to tumble.

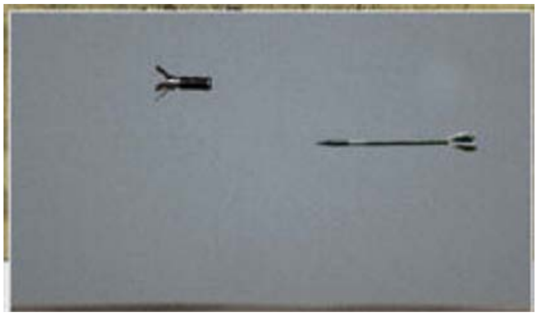


Figure 35. Iron Fist Interceptor Approaching a APFSDS.
Source: Israeli Military Industries (2016).

b. Threat Warning and Expendables

MBTs and tank destroyers require accurate range data to achieve a high first round hit probability, and they usually rely on laser rangefinders to do this. This thesis had previously discussed about the threat warning and expendables techniques and technologies that one can use to counter laser designators. One can employ the same techniques and technologies to counter laser rangefinders.

c. Noise Jamming and Deception

While ground vehicles can use expendables such as smoke and aerosols to defeat battlefield lasers, this author believes that smoke and aerosols are effective against laser designators but are not as effective against laser rangefinders. Based on this author’s experience, modern laser rangefinders usually only require a couple of pulses at most to accurately determine target range. Considering the fact that smoke and aerosol clouds require a few seconds to form completely (this duration can be longer due to environmental conditions, especially wind), vis-a-vis the time (measured in milliseconds) that the hostile laser signal requires to travel to the target and back to the receiver, the cloud is unlikely to attenuate the laser energy sufficiently to prevent the hostile MBT or tank destroyer from obtaining an accurate range reading. Therefore, this author believes that engineers need to explore other susceptibility reduction means such as noise jamming and deception to degrade hostile laser rangefinder performance. The “anti-laser” system that this author discussed previously is a potential solution to this issue.

Besides using the “anti-laser” system, engineers can attempt to deceive a hostile laser rangefinder by transmitting a false laser echo back to the hostile receiver. This results in incorrect range information and in an incorrect ballistic solution, thus reducing the probability of hit. While there is research into such a spoofing system, there is little open source information available. Magnit Ltd claimed in 2006 that the Ukrainian Army is using a laser-spoofing system (known as the F-3 LRF Deceptor) developed by the company. According to Defense-Update (2006), the F-3 LRF Deceptor is effective against lasers with wavelength of 1.06 μm, can result in target miss distance of up to 400 m and can increase target engagement time by as much as 15 to 20 s.

Germany previously developed a simple laser deception system that does not contain any complex electronics, unlike a laser-spoofing device (Wei 2007). According to Wei, engineers placed multiple converging lenses around a vehicle, and used an optical fiber delay line to connect the lenses together (2007). Wei further explains that when laser energy impinges on the vehicle, the lenses collect the laser energy and routes the laser energy through the optical fiber delay line and out through a reflector (2007). This process artificially changes the time for the laser energy to return to the hostile receiver, which results in incorrect range data. While this appears to be a simple and feasible concept, this author thinks that the fragility of the lenses can affect the robustness of the system in ground operations, which limits the actual operational utility of the system. Nevertheless, in this author's opinion, one can circumvent the limitation by using multiple small lenses instead of a few large lenses, to minimize performance degradation due to lens damage (similar to the concept behind LED lamps), or by relying on technological advancements to improve the robustness of the lens.

D. IMPROVISED EXPLOSIVE DEVICES

Improvised explosive devices (IED) are among the most common weapon that insurgents used in recent conflicts. This is because insurgents know that engineers designed the existing ground combat vehicles to survive ballistic projectiles primarily and not underbody threats such as mines and IEDs. In fact, one can consider IEDs as being synonymous with asymmetric warfare. The IED threat was so severe in the recent conflicts that the U.S. Army invested US$45B to develop and build MRAP vehicles to protect troops, even though the vehicles had little utility as ground combat vehicles. Thus, it is important for one to understand IEDs and to be aware of the susceptibility reduction techniques and technologies that one can use to counter IEDs.

1. Threat Analysis

The relative ease of obtaining the required raw materials and setting up IEDs allowed insurgents and militants to employ them to devastating effects against technologically and numerically superior forces. According to Freudenrich, IEDs typically employ three main damage mechanisms, namely blast, fragmentation and penetration (2008).

a. Blast

With the proliferation of arms from conventional sources, it is easy for insurgents to obtain high-energy explosives to make IEDs with significant blast effects. The blast effect is dependent on the type and quantity of explosive that one uses to make the IED. The primary killing mechanism in blast IEDs is the overpressure on a target that is near the point of detonation. The blast overpressure causes material strain due to the supersonic blast waves and the overpressure can propagate beyond the armor, which causes spalling within the interior of the vehicle. Besides causing spalling, the blast overpressure can also cause internal injuries to humans, such as failure of internal organs and traumatic brain injuries. While blast IEDs are dangerous, they are only effective if the intended targets are near to the point of detonation. This is because blast overpressure and energy decreases rapidly with distance from the point of detonation.

b. Fragmentation

Insurgents often create fragmentation IEDs by using existing artillery and mortar shells, whose design incorporates the fragmentation damage mechanism. Insurgents can also enhance the effects of fragmentation by including additional fragmentation-generating objects such as nails, metal shavings or ball bearings inside the IED. Due to the mass and velocity of the individual fragments, it is not difficult for fragments to penetrate lightly armored regions of vehicles and body armor, to cause serious injuries or even death. Nevertheless, fragmentation IEDs are generally ineffective against more heavily armored vehicles.

c. Penetration

Insurgents create penetration IEDs by incorporating metal liners into the IEDs, which results in the formation of EFPs upon detonation. Based on this author’s experience, EFPs are relatively heavy and can travel over 2,000 m/s, meaning that they essentially function as KE penetrators. Unlike fragmentation and blast IEDs, EFPs are capable of traveling long distances and penetrating heavy armor. In addition, due to the relatively small amount of explosive charge required to form EFPs, it is easier for an insurgent to conceal an EFP IED, compared to blast and fragmentation IEDs. Therefore, it is not surprisingly that military planners often regard EFP IEDs as the deadliest form of IED.

2. Components of an IED

Although IEDs differ in design depending on the intended target and the damage mechanism, they share a common set of components that include (1) initiating system, (2) casing, (3) power source and (4) the main charge (Department of Homeland Security 2016). By examining the components of an IED and the chain of activities leading up to detonation, one can identify appropriate susceptibility reduction techniques.

a. Initiating System

The initiating system triggers detonation of an IED. A target can trigger an IED detonation by activating a tripwire or by stepping on the IED. Insurgents can also detonate an IED remotely, by using a simple hard wire or by using wireless means such as a RF signals or IR signals.

b. Casing

The purpose of the casing is to conceal the IED and to generate additional fragmentation effects. In the recent Middle East conflicts, insurgents have used a wide variety of innocuous looking objects such as cans, boxes, plastic bags and even animal carcasses to conceal IEDs.

c. Power Source

Most IEDs require an internal or external power source to trigger detonation. Batteries are the most common power source for IEDs, and battery sizes can range from small flashlight alkaline batteries to large car batteries (for detonation of vehicle borne IEDs). It is also possible for insurgents to power IEDs by linking them to the local power supply in a house or office.

d. Main Charge

Insurgents generally prefer to use military-grade explosives as the main charge because these explosives are relatively easy to obtain (especially in a war-zone), are ready to use and have high detonation energies. Insurgents can also “daisy-chain” military explosives together (such as artillery shells) to take out even the heaviest vehicles like MBTs. Even if military explosives are not available, insurgents are often able to convert commercial products such as fertilizers into ammonium nitrate fuel oil (ANFO), which is a form of commercial high explosive.

3. Susceptibility Reduction

Due to the tight constraints with operating in an urban environment, many engagements are in close contact or proximity, and are often limited to line of sight engagements. This author thinks that one can use threat warning and situational awareness, noise jamming and deception and threat suppression to counter IEDs.

a. Threat Warning and Situational Awareness

In this author’s opinion, the first line of defense against IEDs is the ability of friendly forces to detect and understand any threat in the vicinity, as this allows one to take appropriate response to counter the IEDs before enemies can deploy them. As it is easy for an enemy to conceal IEDs, this author believes that engineers need to integrate different sensor technologies on a single platform to provide a high probability of detecting IEDs. While optical and radar sensors are prevalent in the field of IED detection, it is also important for engineers to leverage non-visual means such as atomic emission spectroscopy. This is because of the ease in concealing IEDs. According to Freudenrich, atomic emission spectroscopy can detect traces of explosive content within a 30 m radius (2008). The Israel Aerospace Industries (IAI) is developing an integrated counter IED suite known as the Counter IED & Mine Suite (CIMS). According to Eshel (2014c), the CIMS fuses information collected from various sensor suites onboard the CIMS vehicle to enable operators to detect different types of threats both above and underground. The CIMS can also apply follow-on responses to neutralize any IED threats that will endanger friendly forces. The CIMS uses a variety of sensors, including synthetic aperture radar (SAR), optical detection systems, ground penetrating radar and magnetic detectors, to detect accurately, recognize and map any IED threats.

While integrated detection systems such as the CIMS can provide effective warning to friendly forces, this author believes that such systems only provide just-in-time warning of potential IED threats. If one detects IEDs well in advance of the arrival of friendly forces, this further reduces the IED threat. One can achieve this by employing systems that provide persistent surveillance of the areas that friendly forces need to pass through. Analysts can then process the captured imageries and compare them with previous ones to detect anomalies or changes in the environment, which can indicate the presence of IEDs. Airborne systems such as the Persistent Threat Detection System from Lockheed Martin (see Figure 36) are the most suitable for such a role. Besides performing an anti-IED role through persistent surveillance, it is conceivable for military planners to use persistent airborne systems to perform other critical battlefield roles such as functioning as a centralized communications hub to integrate and disseminate information to friendly units in the area. This can help to mitigate the inherent communications problem in urban areas due to buildings and clutter, which enhances the overall situation awareness for friendly forces in the area.

Figure 36. Persistent Surveillance System. Source: Lockheed Martin (2016).

b. Noise Jamming and Deception

As recent conflicts amply demonstrate, insurgents prefer to initiate an IED through remote means such as using a cell phone. It is relatively easy and cheap for insurgents to obtain such a wireless initiator, and cell phones allow insurgents to detonate IEDs in relative safety from a considerable distance away. While the ideal solution is for friendly forces to disable the IED at its source, either by removing the remote activation trigger (usually an insurgent with a cell phone) or by neutralizing the IED itself, it is often not possible for one to do so due to constraints such as the wide search area, time, resources and the relative ease of hiding an IED. As such, the next best solution is for one to prevent the insurgent from remotely detonating the IED. In order to achieve this, one can use area jammers that target several specific bands of wireless frequencies and attempt to saturate and overpower the frequencies to prevent detonation signals from reaching the remote trigger of the IED. U.S. and coalition forces used such jammers successfully during the recent Middle East conflicts, but they also discovered that the jammers indiscriminately disrupted the use of RF devices for friendly forces such as communications systems (Kempinski and Murphy 2012). Besides indiscriminate jamming, another disadvantage of jammers is that they can only jam IEDs as long as the jammers are in the immediate vicinity of the IEDs. Once the jammers leave the area, insurgents can still remotely detonate the IEDs to attack other friendly targets that do not have jammer support. Finally, these jammers are only effective against IEDs that rely on RF signals for detonation, and they will not work against other detonation triggers, such as tripwires, IR, pressure and contact.

c. Threat Suppression

Since it is not always possible for one to detect an IED threat before friendly forces enter an operational area, military planners often use area jammers to prevent the remote detonation of IEDs that rely on RF for initiation, thus suppressing the IED threat. While such jammers are effective, jamming is not a “catch-all” solution for IEDs and have their own set of trade-offs.

Engineers can consider directed energy (DE) systems, such as those using high powered microwave (HPM) to address the shortcomings of RF-based IED jammers. According to Diehl, HPM works by using electromagnetic energy to induce currents in electronic circuits (2013). Most IEDs have some form of electronics in them, such as cables, connections and circuit boards, and these components act as antennas to receive the EM energy from HPM systems. Since electronic circuits normally operate with supply voltages ranging from 1V to 5V, HPM systems are capable of inducing voltages much higher than these values within the IEDs (Diehl 2013). This can potentially overload and burn the IED’s circuitry and thus, permanently disable the IEDs, unlike the temporary disabling of IEDs by a RF jammer (see Figure 37). Therefore, HPM systems are more effective in neutralizing a wider spectrum of IEDs than RF jammers. Since HPM systems can permanently disable IEDs, one needs fewer numbers of HPM-equipped vehicles to protect a convoy of friendly forces. This author thinks that positioning one or two HPM-equipped vehicles at the front of a friendly convoy is sufficient to provide IED protection to the convoy. In contrast, one often needs multiple RF-jammer equipped vehicles to protect the entire convoy, especially if the convoy is large. Since RF jamming is only temporary, one needs to distribute multiple jammer vehicles throughout the convoy to ensure that there are no coverage gaps in the jamming. Figure 38 shows a HPM-equipped vehicle.

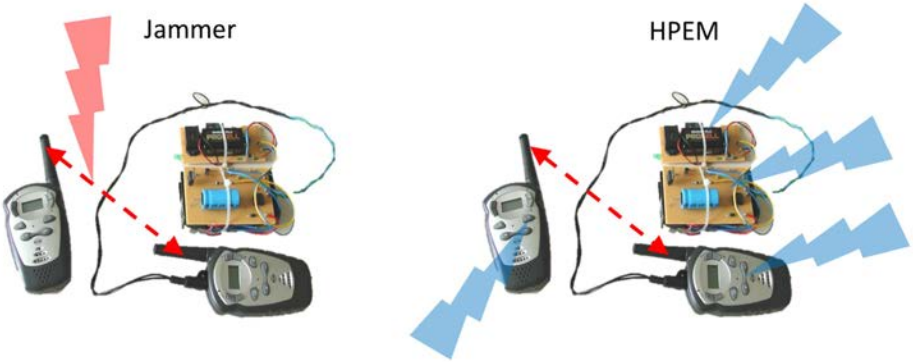


Figure 37. Key Difference Between Jammers and HPM. Source: Diehl (2013).

Figure 38. HPM System Mounted at the Front of a GCV. Source: Diehl (2013).

This chapter identified and analyzed the key threats that GCVs face in an urban environment, which include rockets, missiles, KE penetrators and IEDs. This section then proposed and discussed appropriate susceptibility reduction techniques and technologies that one can use to counter the threats. In the subsequent chapters, this thesis will use the susceptibility reduction techniques and technologies to develop survivability architectures to fulfill the various survivability characteristics (determined using modeling and simulation) that a GCV needs to have to meet defined threat scenarios and survivability requirements.

VIII. PROPOSED METHODOLOGY TO PERFORM SYSTEM-LEVEL ASSESSMENT FOR A GCV

Many factors affect the overall survivability of a ground combat vehicle. The traditional survivability approach for ground vehicles focuses primarily on the two inner most layers of the survivability onion (vulnerability reduction). Based on this author’s experience, most survivability models are not available over open-sources due to the sensitive nature of survivability. Known survivability assessment tools today such as the Modular UNIX-based Vulnerability Estimation Suite (MUVES) and the BRL-CAD, focus primarily on vulnerability reduction. This author was unable to find any detailed information on MUVES and BRL-CAD from open sources, but available descriptions of the tools indicate that they focus primarily on ballistic vulnerability and not susceptibility. This focus on vulnerability is not surprising because of the conventional approach to ground combat vehicle survivability, which focuses on vulnerability reduction. Due to the advent of asymmetric and urban warfare, vulnerability reduction is no longer sufficient for ground vehicles, and military planners and engineers need to leverage susceptibility reduction to increase the probability that a ground vehicle survives in an asymmetric and urban operational environment. With many more factors to consider in the overall survivability design of a ground vehicle, there must be a way for one to quantify the different factors and to view their interactions in determining the overall survivability of the vehicle. This means that for a certain survivability requirement, one can likely find different possible combination of factors to meet the requirement. Hence, the first section of this chapter proposes a model to perform survivability assessment, taking into account both susceptibility and vulnerability reduction.

The second section of this chapter addresses the natural capability conflicts that arise between survivability and other key GCV capabilities. This section then demonstrates how one can use decision-making methodologies to manage the conflicts and trade-offs to help decision-makers determine the most cost-effective set of survivability characteristics to meet a defined survivability requirement. This author hopes that the model and the decision-making methodology presented in this chapter helps military planners and engineers design more robust and holistic survivability solutions for ground combat vehicles, to deal with a wider spectrum of threats and threat scenarios.

Survivability is a highly sensitive topic, with minimal information available via open-sources. Therefore, this author made certain assumptions to derive the data used in the model and simulations. This author wishes to emphasize that the data used does not represent the characteristics of any particular ground vehicle in use today.

A. SIMULATING SURVIVABILITY

1. Probability Tree Diagram

An often used procedure for estimating a vehicle's survivability is a probability tree diagram, such as the one-on-one probability tree diagram shown in Figure 39, where a pair of branches represents the outcome of each phase of the scenario. Christopher Adams, a lecturer at the Naval Postgraduate School, Monterey, presented the probability tree diagram in his lecture on combat survivability. According to Ball, the main purpose of a probability tree diagram is to highlight the different phases of an engagement scenario and to depict the possible outcomes for each of the phases, as well as the corresponding probabilities for each of the outcomes (2003). Ball also explains that one can use the probability tree diagram to illustrate improvements in the survivability of a ground vehicle through the use of various survivability enhancement features, such as adding a hard-kill APS or incorporating signature reduction features (2003). Figure 39 shows that the one-on-one probability tree progresses in a top-down manner. Each phase of the engagement scenario has two mutually exclusive outcomes, and a numbered node represents the start of a phase (from 0 to 4). The next node at the end of an arrow represents the end of a phase. On the left side of each node, one can see a description for that particular phase of the engagement scenario. For example, the first phase (search phase), lies between nodes (0) and (1) of the tree diagram, and one can find a description of that phase to the left of the node (exposure avoidance).

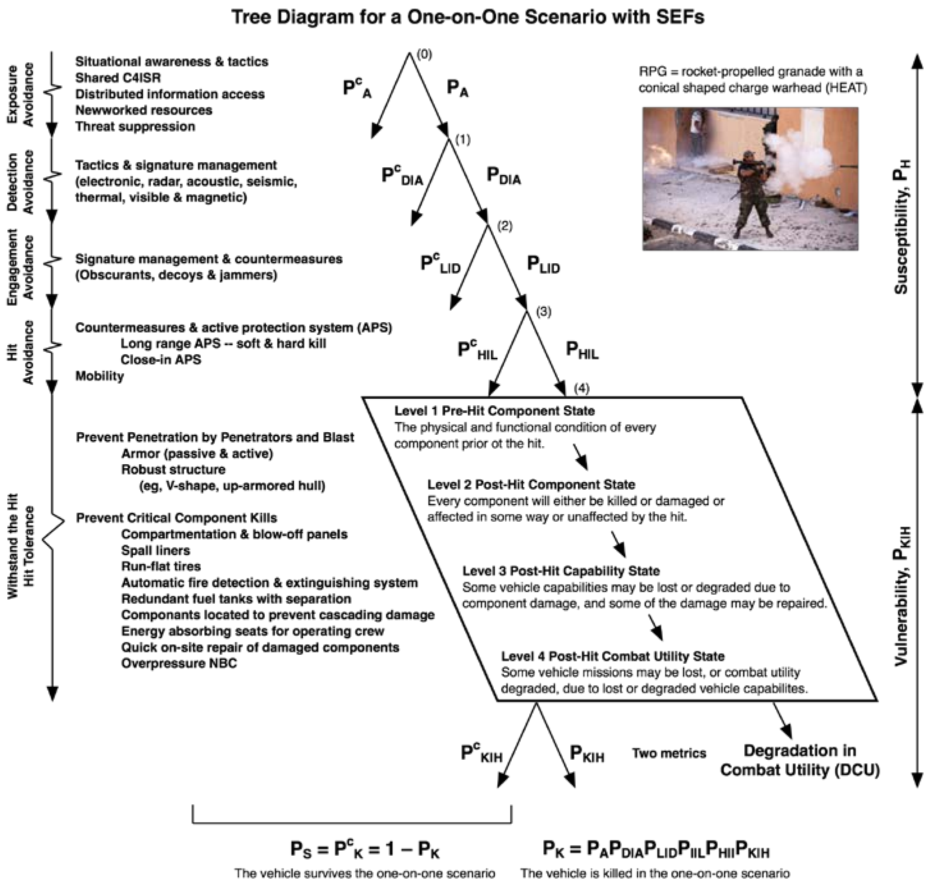


Figure 39. Tree Diagram for the One-on-One Scenario. Source: Adams (2016).

According to Ball (2003), a ground vehicle will be “hit only when each of the first four susceptibility phases has a successful outcome. The likelihood or probability that each susceptibility phase will have a successful outcome at some time during the scenario, given that the preceding phases were successful, can be estimated with a conditional probability.” (12) Ball uses probabilities to measure the likelihood of success for each of the four susceptibility phases:

1. P_A is the probability that a hostile weapon system is in the vicinity of the GCV, is actively scanning for ground vehicles and is ready to engage any ground vehicles that enter the defended area.

2. $P_{D|A}$ is the conditional probability that a hostile weapon system detects the GCV, given that the hostile weapon system is actively scanning for the ground vehicle.

3. $P_{L|D}$ is the conditional probability that a hostile weapon system launches a projectile or missile to engage the GCV, given that the hostile weapon system is active and has detected the ground vehicle. Before the hostile weapon system can engage the GCV, it must first obtain the appropriate fire control solution.

4. $P_{H|L}$ is the conditional probability that the projectile or missile hits the GCV, given that the hostile weapon system has launched the projectile or missile at the ground vehicle (2003).

Considering all of the possible susceptibility events in Figure 39, one sees that the only event that results in a hit of the vehicle is the one that proceeds down the right side of the probability tree. All of the other possible events (i.e., the left side of the probability tree) result in a vehicle surviving the encounter (the complement events), as the hostile threat is unable to hit the vehicle. Consequently, one can refer to all of the right side, downwards-pointing arrows, as the kill chain. If one breaks any of the chain links, (i.e., proceed along the left side of the probability tree for any of the engagement phases), this means that the hostile weapon is unable to achieve success in that particular phase of the engagement and therefore, the vehicle survives the encounter. Thus, one can calculate the probability that a threat hits the vehicle or P(Hit) in the one-on-one scenario by multiplying all four probabilities in the susceptibility phase (i.e., $P_A P_{D|A} P_{L|D} P_{H|L}$). One can then calculate the probability that a threat kills a ground combat vehicle, which is simply the product of P(Hit) and P(Killed given hit). P(Hit) represents the susceptibility of the ground vehicle, while P(Killed give hit) represents the vulnerability of the ground vehicle.

2. Model Description

This thesis uses ExtendSim to develop the model, which leverages the one-on-one probability tree diagram. According to Law (2015), ExtendSim is a graphics-based simulation, whereby “a model is constructed by selecting blocks from libraries (such as Item, Value, Plotter), placing the blocks at appropriate locations in the model window, connecting the blocks to indicate the flow of entities (or values) through the system, and then detailing the blocks using dialog boxes.” (198) For the purpose of simulation, this thesis assumes that the survivability requirement is to ensure no more than 5%

probability that a missile attack kills a ground combat vehicle, at 95% confidence level (CL). An increasingly common threat scenario in an urban environment is one whereby an enemy launches a missile relatively close to the GCV. A one-on-one scenario is common in urban engagements because the majority of anti-GCV missiles are either semi-active homing or CLOS, which requires an operator to guide the missile to the target. Therefore, the operator can only engage one GCV each time. Based on this author's experience, it is also not a common tactic to fire multiple missiles at a single GCV at the same time, especially when there are other GCVs for one to engage in the immediate area. While rockets are still predominantly the main threats to ground vehicles in an urban environment, advanced missiles are increasingly prevalent in recent conflicts. In the ongoing Syrian conflict for example, Stratfor reported that insurgents possess large quantities of advanced ATGMs from Russia, Europe, and the United States, and the insurgents are using them to deadly effect (Stratfor 2015). Since ATGMs typically have arming distances of around 50m, this thesis uses an engagement distance of 100m in the model, which is reasonable due to the constrained nature of an urban environment. This thesis also uses the key parameters shown in Table 9, which are derived from the probability tree diagram and represent the survivability characteristics of a ground combat vehicle.

Table 9. Key Parameters Used in the Model.

Parameters	Description
Probability of Active	This represents the probability that a hostile threat is present in the area of operations and is actively seeking out the ground combat vehicle.
Probability of Detection	Given that there is an active hostile threat actively seeking out the ground vehicle, this parameter represents the likelihood that the hostile threat detects the ground vehicle.
Probability of Launch (or Engage)	Given that hostile threat has detected the ground vehicle, this parameter represents the likelihood that the hostile threat is able to obtain a firing solution to launch a missile at the ground vehicle.
Probability of Hit	Given that the hostile threat has launched a missile, this parameter represents the probability that the missile can be successfully guided to hit the ground vehicle.
Probability of Kill	Given that the missile hits the ground vehicle, this parameter represents the probability that the ground vehicle is killed.

Figure 40 shows the basic ExtendSim model, which details the key building blocks.

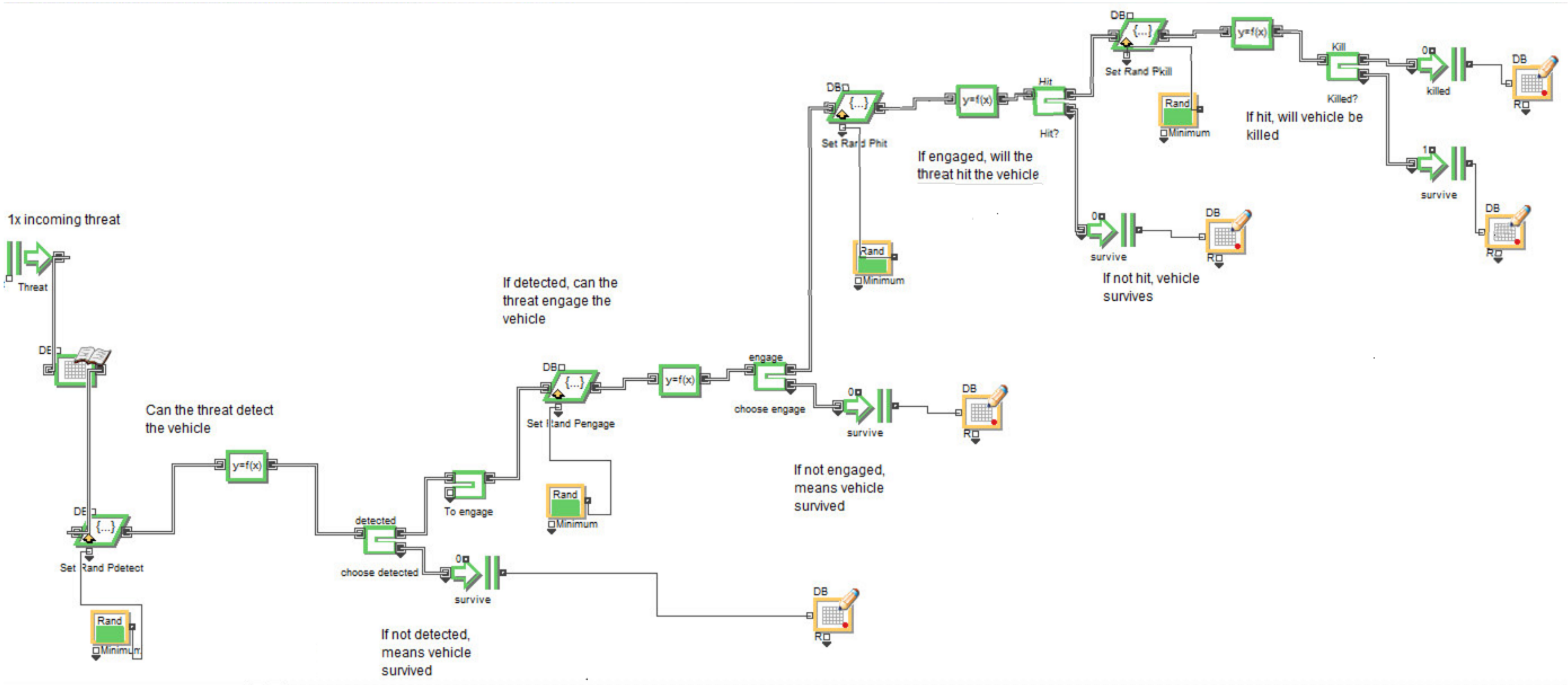


Figure 40. Basic ExtendSim Model.

1. <u>Create block</u>. This block creates a single missile threat to the vehicle. The block represents the start point of the simulation, which proceeds from left to right

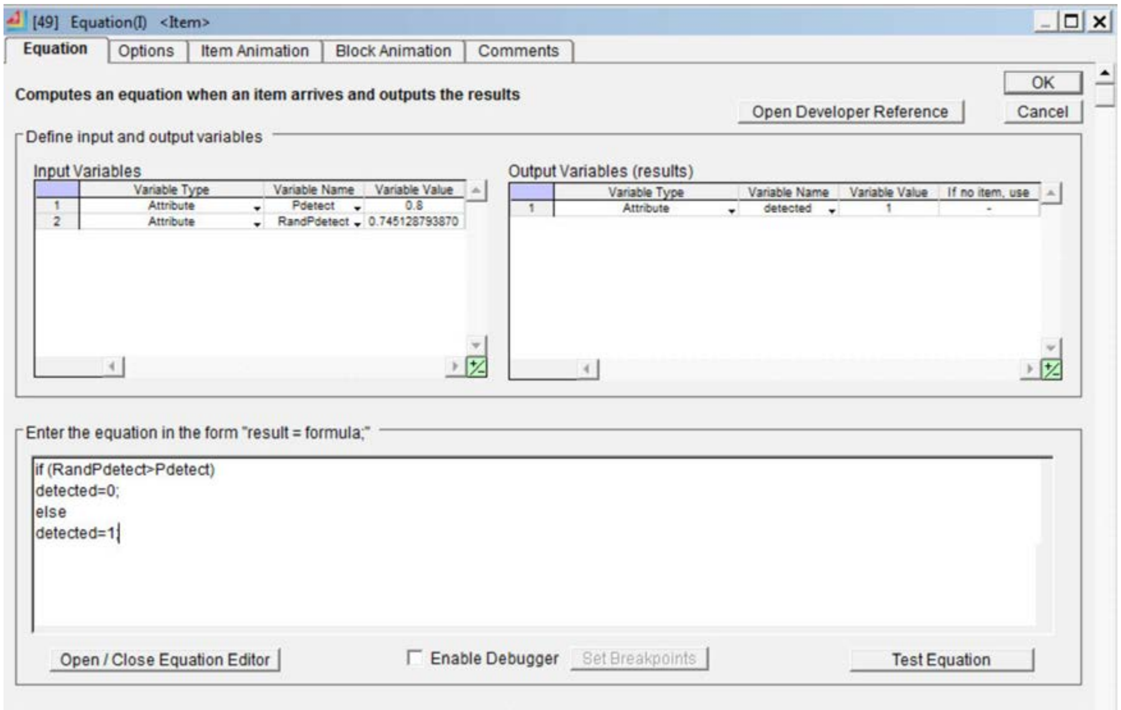
2. <u>Read block</u>. This block reads the various probabilities (described in Table 9) from the input database into the model.

3. <u>RAND block</u>. This block generates random numbers from 0 to 1 using a uniform distribution, which is fed into the equation block. This block creates uncertainty in the survivability simulation.

4. <u>Equation block</u>. Using an IF statement, the equation block compares the generated random number with the appropriate probability from the database. If the random number is less than or equal to the corresponding probability, the equation block generates an output of "1," which means that the threat has detected, engaged, hit or killed the GCV. If not, the equation block returns a "0," which means that the vehicle survived the engagement, as the threat was unable to detect, engage, hit or kill the vehicle. For example, Figure 41 shows the equation block for detection. As one can see, the randomly generated number (0.745) is smaller than the detection probability of 0.8, thus the equation block returns a "1," meaning that the threat has detected the vehicle.

5. <u>Select block</u>. Depending on the output from the equation block ("1" or "0"), the select block determines the next course of action for the simulation. Using detection as an example, if the threat is unable to detect the vehicle (returns a "0"), the vehicle survives and the select block routes the simulation to the "Survive" exit block. If the threat detects the vehicle (returns a "1"), then the select block routes the simulation to the next phase, which determines whether the threat can engage the vehicle.

6. <u>Write block</u>. This block captures the outcome of each simulation and writes it into the output database. One can analyze the output database to determine the overall probability of survival for the ground vehicle and to perform statistical analysis such as regression analysis.



Computes an equation when an item arrives and outputs the results

Input Variables

	Variable Type	Variable Name	Variable Value
1	Attribute	Pdetect	0.8
2	Attribute	RandPdetect	0.745128793870

Output Variables (results)

	Variable Type	Variable Name	Variable Value	If no item, use
1	Attribute	detected	1	-

```
if (RandPdetect>Pdetect)
detected=0;
else
detected=1
```

Figure 41. Equation Block Used to Determine if GCV Was Detected.

3. Model Verification

Before one uses the model to perform detailed survivability assessment, it is important for one to verify that the model is correctly set up. This thesis does this by comparing the simulation results to the back-of-envelope (BOE) results using the probability tree diagram. Table 10 shows the values of the key parameters that this author used for the simulation and the BOE calculation. This author ran the simulation five times, and Table 11 compares the simulation results with the BOE results. One can see that both sets of results are similar, meaning that this author set up the model correctly. Therefore, the next step is to use the ExtendSim model to perform survivability assessment.

Table 10. Values Used for Model Verification.

Probability of Active	1.0
Probability of Detection	0.8
Probability of Launch	0.7
Probability of Hit	0.8
Probability of Kill	0.6

Table 11. Comparison of Simulated Results and BOE Results.

	Simulation		BOE	
Run Number	P(Survive)	P(Killed)	P(Survive)	P(Killed)
1	74.8%	25.2%	73.1%	26.9%
2	74.8%	25.2%		
3	73.6%	26.4%		
4	71.6%	28.4%		
5	72.8%	27.2%		

4. Using Model to Perform Survivability Assessment

As military planners and engineers move toward incorporating susceptibility reduction into the ground vehicle survivability concept, one can use the ExtendSim model to determine the appropriate sets of survivability characteristics (represented by the various probabilities in this case) that a ground combat vehicle needs to have in order to fulfill the survivability requirement for the given threat scenario. Previously, due to the focus on vulnerability reduction, military planners and engineers are typically only concerned with the probability that a missile kills a ground vehicle, given that the missile hits the ground vehicle.

a. Incorporating Hard-Kill APS into the Model

Hard-kill APS is a key upcoming susceptibility reduction technology that uses physical countermeasures to intercept incoming threats to prevent them from hitting the protected ground vehicle. Therefore, this author proposes to include hard-kill APS into the survivability assessment. Figure 42 shows the addition of the hard-kill APS branch into the ExtendSim model, which is in between the vehicle engagement phase and the vehicle-hit phase. The addition of the APS branch introduces two new parameters, namely minimum defeat distance (MDD) and APSP(hit), into the model. This brings the total number of parameters that one can use in the survivability assessment to seven. For a detailed discussion on hard-kill APS, please refer to Chapter VII.

1. Minimum defeat distance (MDD) is a key performance parameter for a hard-APS. MDD represents the dead-zone of an APS-equipped ground vehicle. This means that if an enemy fires a rocket or missile within the dead-zone, the hard-kill APS is unable to react fast enough to the threat. In the revised ExtendSim model, if the incoming threat is within the APS's MDD (meaning APS is unable to engage the threat), the select block routes the simulation to the branch that determines whether the threat can hit and kill the vehicle. If the threat is outside the APS's MDD (meaning the APS is able to engage the threat), the select block routes the simulation to the branch that determines if the APS can destroy the threat (based on the APSP(hit)). If the APS manages to destroy the threat, the simulation ends with the vehicle survival. If not, the select block routes the simulation to the branch that determines whether the threat can hit and kill the vehicle.

2. APSP(hit) refers to the probability that the hard-kill APS is able to detect, classify, intercept and defeat an incoming threat. Therefore, APSP(hit) is another key performance parameter for a hard-kill APS.

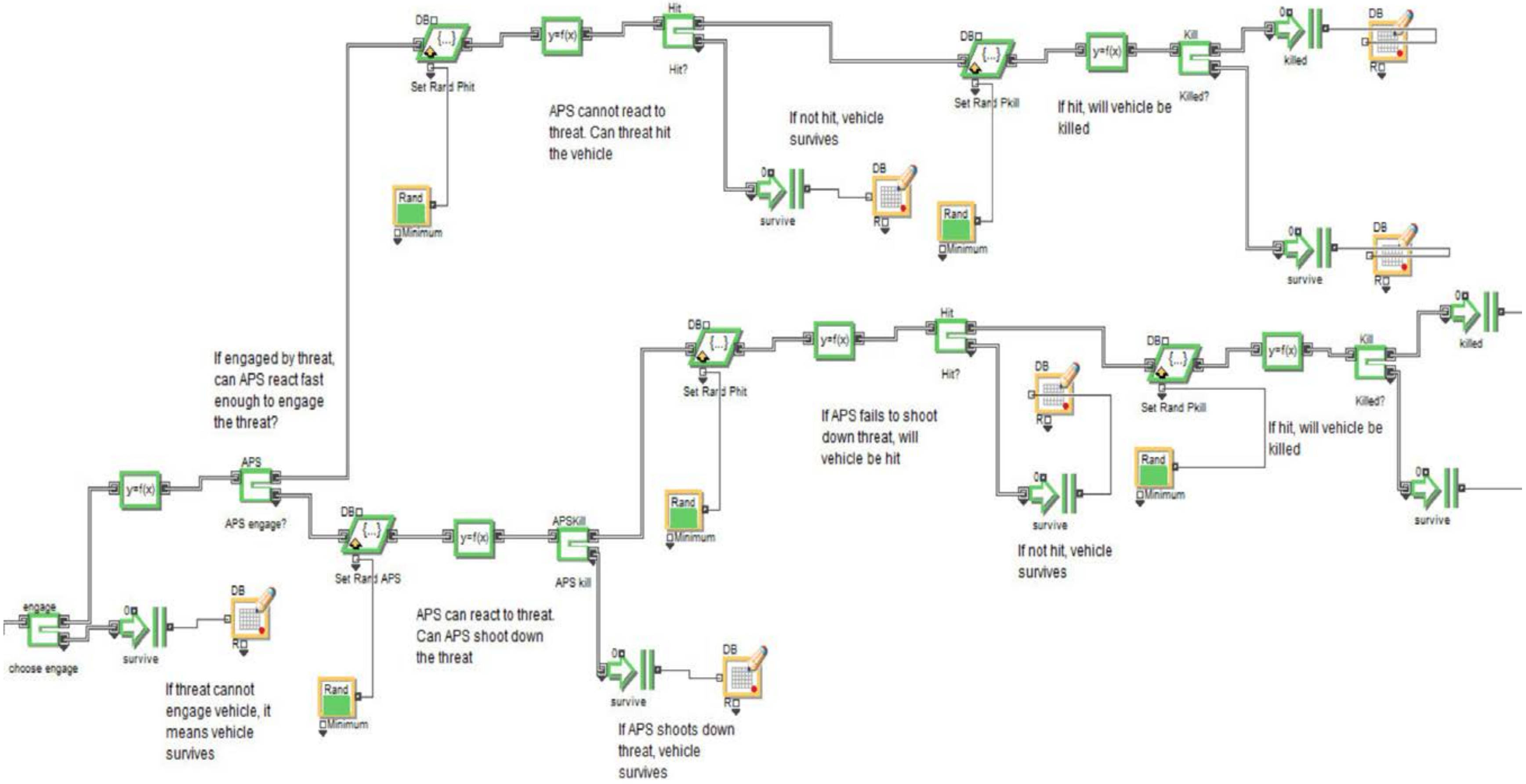
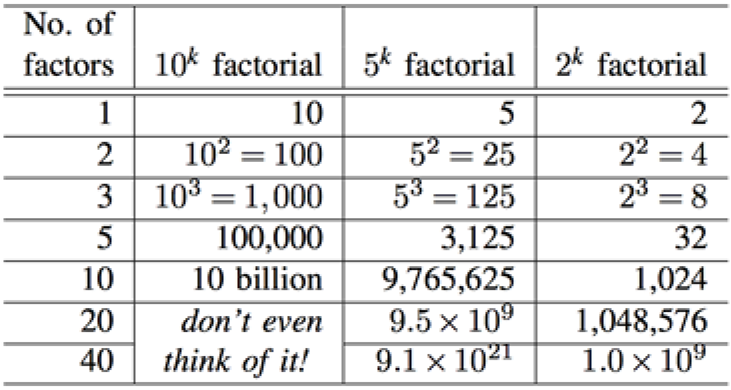


Figure 42. Addition of APS Branch to the ExtendSim Model

b. Nearly Orthogonal Latin Hypercubes (NOLH) Design

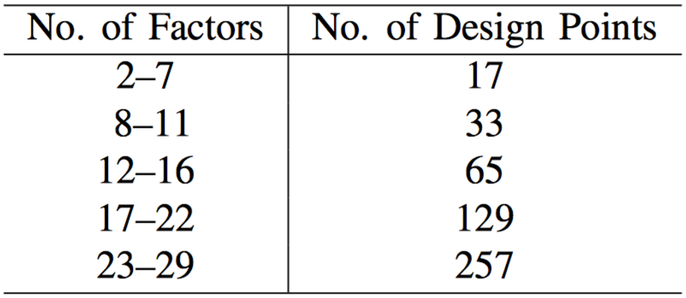
The parameters or factors in Table 10 represent the survivability characteristics of a ground combat vehicle, whose values and interactions affect overall system survivability. One can use different experimental designs to explore the design space for the parameters, to determine possible combinations of parameters that can meet a survivability requirement. According to Sanchez (2006), factorial designs of the form m^k, where m refers to the number of levels and k refers to the number of factors, are popular experimental designs because they are relatively easy to construct and explain. While factorial designs have good space-filling properties (especially with larger m), which facilitates a detailed study of how the various factors affect system performance, Sanchez claims that factorial designs are in fact “not good experimental designs for more than a handful of factors because of their massive data requirements.” (52) Figure 43 illustrates how data requirements for factorial designs change exponentially as m and k change, which supports Sanchez’s claim.



No. of factors	10^k factorial	5^k factorial	2^k factorial
1	10	5	2
2	$10^2 = 100$	$5^2 = 25$	$2^2 = 4$
3	$10^3 = 1{,}000$	$5^3 = 125$	$2^3 = 8$
5	100,000	3,125	32
10	10 billion	9,765,625	1,024
20	*don’t even think of it!*	9.5×10^9	1,048,576
40		9.1×10^{21}	1.0×10^9

Figure 43. Data Requirements for Factorial Designs. Source: Sanchez (2006).

In order to mitigate the issue of large data requirements, Sanchez (2006) proposes the Latin hypercubes (LH) methodology as an alternative to the factorial design. According to Sanchez, “LH sampling provides a flexible way of constructing efficient designs for quantitative factors. They have some of the space-filling properties of factorial designs with fine grids, but require orders of magnitude less sampling.” (52) For example, a two-factor, 11-level factorial design generates 121 design points (11^2). If one uses LH design, one only requires 11 design points to perform an adequate assessment on the effects that the factors have on system performance (Sanchez 2006). It is evident that LH sampling is useful as the number of factors (k) increases. For small to moderate number of factors however, Cioppa and Lucas proposes the nearly orthogonal Latin hypercubes (NOLH) methodology (Sanchez 2006). The NOLH methodology generates different number of design points depending on the value of k. Figure 44 shows the number of design points for $k \leq 29$.



No. of Factors	No. of Design Points
2–7	17
8–11	33
12–16	65
17–22	129
23–29	257

Figure 44. Data Requirements for Nearly Orthogonal Latin Hypercube Designs. Source: Sanchez (2006).

Based on the seven factors in the revised ExtendSim model and the criteria in Figure 44, 17 design points are sufficient for the analysis. Nevertheless, this author decided to use 33 design points instead (for 8 to 11 factors) because orthogonality of the NOLH design improves as the number of design points increases (Tng 2014). Another key reason is the small range between the low and high values for most of the factors, which means that increasing the number of design points improves the resolution of the analysis. In order to generate the design points, one needs to first define the low and high values for each parameter or factor. This thesis uses the low and high values seen in Table 12 to generate the design points. One should note that the survivability characteristics of any military platform is highly sensitive information and not available via open sources. Thus, this author chose the values in Table 12 based on certain assumptions, and the values do not represent any particular system in use today.

1. P(active) refers to the probability that a hostile sensor is actively looking for ground vehicles. An urban environment provides multiple concealed surveillance sites for hostile forces and therefore, it is reasonable to assume that hostile forces are constantly monitoring and looking for ground vehicles in an urban environment (i.e., P(active)=1)). Since P(active) is equal to one, there was no need to include P(active) inside the design factors and ExtendSim model. As such, the model only needs to consider six factors instead of seven.

2. It is easy for a hostile force to detect ground combat vehicles in an urban environment due to their large size and the many signatures that a ground vehicle emits, primarily acoustic, vibration and thermal signatures. Thus, this thesis chose a large lower bound value of 0.7.

3. For probability of engage and probability of hit, this thesis chose smaller low bound values. This is because there are many techniques and technologies that one can use to minimize these two probabilities. For example, if a sensor warns a ground vehicle of hostile “lasing” actions, the vehicle can attempt to suppress the enemy who is performing the lasing, and this minimizes the probability that the enemy can launch a laser guided missile at the vehicle. Similarly, for probability of hit, one can use smoke, aerosols and jammers to minimize the probability that an enemy can successfully guide the missile to hit the vehicle.

4. For probability of kill, this thesis chose a relatively large lower bound value of 0.6. This is because an urban environment allows enemies to attack ground vehicles at their weakest spots, such as the sides, the rear or the roof. Since military planners and engineers design existing ground vehicles to survive head-on engagements over relatively open terrain, the vehicles have the heaviest armor at the front. On the other hand, military planners and engineers usually protect the vehicle’s side, top and rear against lighter rockets and small and medium caliber projectiles only. Thus, a ground vehicle is largely vulnerable to missile attacks, especially in urban environment.

5. According to Dieter and Wagner (2009), the MDD for hard-kill APS against anti-armor missiles can range from as low as 10m to greater than 100m. Thus, this thesis chose 10m and 200m for the low and high values respectively.

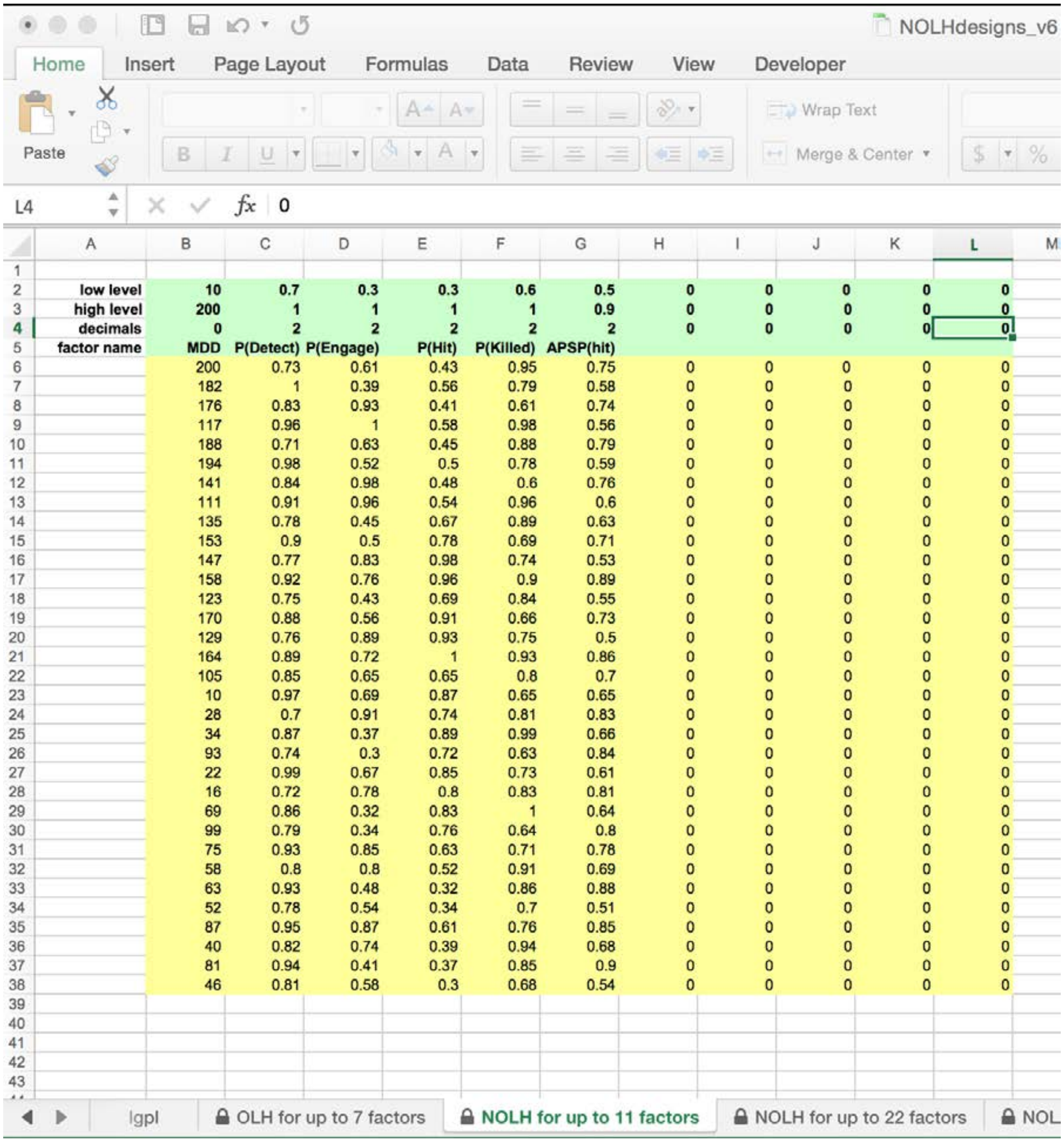
6. This thesis chose an average value of 0.5 as the lower bound for APSP(hit), as it is unlikely for engineers to deliberately design a low performance APS. For the upper bound, it is not realistic in this author’s opinion to expect the hard-kill APS to perform perfectly all the time. Thus, an upper bound of 0.9 was chosen. According to Thompson (2012), the success rate for the Israeli IRON DOME system, which uses physical

> interceptors to shoot down rockets, mortars and artillery shells, has a success rate of about 90%.

Table 12. Low and High Values for Design Factors.

Design Factor	Low Value	High Value
Probability of Detection	0.7	1
Probability of Launch (or engage)	0.3	1
Probability of Hit	0.3	1
Probability of Kill	0.6	1
MDD	10	200
APSP(hit)	0.5	0.9

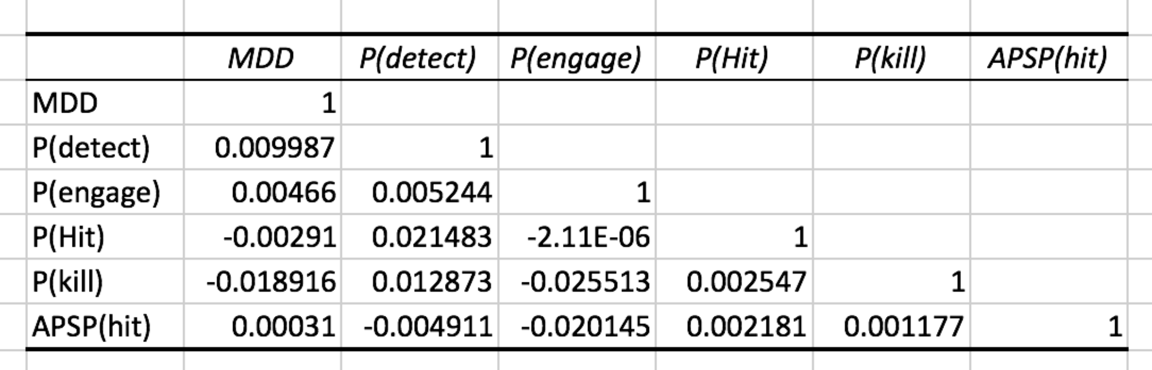
Based on the low and high levels, this author generated 33 design points using the NOLH spreadsheet that one can download from the website of the Seed Center for Data Farming, Naval Postgraduate School (see Figure 45). The “decimal” row in the spreadsheet controls the number of decimal places for each design point. This author used two decimal places for the probabilities as there was only a small range between the low and high values. On the other hand, this author did not use decimal places for MDD as the range between the low and high values was large.



	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	**low level**	**10**	**0.7**	**0.3**	**0.3**	**0.6**	**0.5**	**0**	**0**	**0**	**0**	**0**
3	**high level**	**200**	**1**	**1**	**1**	**1**	**0.9**	**0**	**0**	**0**	**0**	**0**
4	**decimals**	**0**	**2**	**2**	**2**	**2**	**2**	**0**	**0**	**0**	**0**	**0**
5	**factor name**	**MDD**	**P(Detect)**	**P(Engage)**	**P(Hit)**	**P(Killed)**	**APSP(hit)**					
6		200	0.73	0.61	0.43	0.95	0.75	0	0	0	0	0
7		182	1	0.39	0.56	0.79	0.58	0	0	0	0	0
8		176	0.83	0.93	0.41	0.61	0.74	0	0	0	0	0
9		117	0.96	1	0.58	0.98	0.56	0	0	0	0	0
10		188	0.71	0.63	0.45	0.88	0.79	0	0	0	0	0
11		194	0.98	0.52	0.5	0.78	0.59	0	0	0	0	0
12		141	0.84	0.98	0.48	0.6	0.76	0	0	0	0	0
13		111	0.91	0.96	0.54	0.96	0.6	0	0	0	0	0
14		135	0.78	0.45	0.67	0.89	0.63	0	0	0	0	0
15		153	0.9	0.5	0.78	0.69	0.71	0	0	0	0	0
16		147	0.77	0.83	0.98	0.74	0.53	0	0	0	0	0
17		158	0.92	0.76	0.96	0.9	0.89	0	0	0	0	0
18		123	0.75	0.43	0.69	0.84	0.55	0	0	0	0	0
19		170	0.88	0.56	0.91	0.66	0.73	0	0	0	0	0
20		129	0.76	0.89	0.93	0.75	0.5	0	0	0	0	0
21		164	0.89	0.72	1	0.93	0.86	0	0	0	0	0
22		105	0.85	0.65	0.65	0.8	0.7	0	0	0	0	0
23		10	0.97	0.69	0.87	0.65	0.65	0	0	0	0	0
24		28	0.7	0.91	0.74	0.81	0.83	0	0	0	0	0
25		34	0.87	0.37	0.89	0.99	0.66	0	0	0	0	0
26		93	0.74	0.3	0.72	0.63	0.84	0	0	0	0	0
27		22	0.99	0.67	0.85	0.73	0.61	0	0	0	0	0
28		16	0.72	0.78	0.8	0.83	0.81	0	0	0	0	0
29		69	0.86	0.32	0.83	1	0.64	0	0	0	0	0
30		99	0.79	0.34	0.76	0.64	0.8	0	0	0	0	0
31		75	0.93	0.85	0.63	0.71	0.78	0	0	0	0	0
32		58	0.8	0.8	0.52	0.91	0.69	0	0	0	0	0
33		63	0.93	0.48	0.32	0.86	0.88	0	0	0	0	0
34		52	0.78	0.54	0.34	0.7	0.51	0	0	0	0	0
35		87	0.95	0.87	0.61	0.76	0.85	0	0	0	0	0
36		40	0.82	0.74	0.39	0.94	0.68	0	0	0	0	0
37		81	0.94	0.41	0.37	0.85	0.9	0	0	0	0	0
38		46	0.81	0.58	0.3	0.68	0.54	0	0	0	0	0

Figure 45. Generated NOLH Design Points for Simulation.

Before using the generated design points for survivability analysis, this author verified that the design points have sufficient orthogonality and good space-filling properties. According to Tng (2014), orthogonality “means that the design points are independent, and the results of one design point will not be dependent on the other design points.” (54) Tng (2014) determines the degree of orthogonality by the level of correlation between two factors, and the closer the pairwise correlation value is to zero, the better the degree of orthogonality. While it is usually not possible to have zero pairwise correlation values between factors, Tng mentions that based on his discussion with Professor Thomas W. Lucas (Naval Postgraduate School), correlation values less than +/- 0.05 are sufficient to demonstrate independence between the design points (2014). This thesis generated a correlation matrix for the six factors using the correlation function in the analysis toolpack of Microsoft Excel, with the results shown in Figure 46. The correlation matrix shows that the pairwise correlation values between the six factors all fall within the +/- 0.05 guideline, which means that there is sufficient independence and orthogonality between the factors. One can assess the space-filling properties of the design points by looking at the scatterplot matrix of the design points. Using the JMP Pro 12 software, this thesis generated the scatterplot matrix for the design points (see Figure 47). One can see from the scatterplot matrix that there is no abnormally large empty space for any of the factors and therefore, one can conclude that the generated design points have good space-filling properties. Since this thesis has verified that the design points have sufficient orthogonality and good space-filling properties, the next step is to use the 33 generated design points for survivability analysis.



	MDD	*P(detect)*	*P(engage)*	*P(Hit)*	*P(kill)*	*APSP(hit)*
MDD	1					
P(detect)	0.009987	1				
P(engage)	0.00466	0.005244	1			
P(Hit)	-0.00291	0.021483	-2.11E-06	1		
P(kill)	-0.018916	0.012873	-0.025513	0.002547	1	
APSP(hit)	0.00031	-0.004911	-0.020145	0.002181	0.001177	1

Figure 46. Correlation Matrix for the Design Factors.

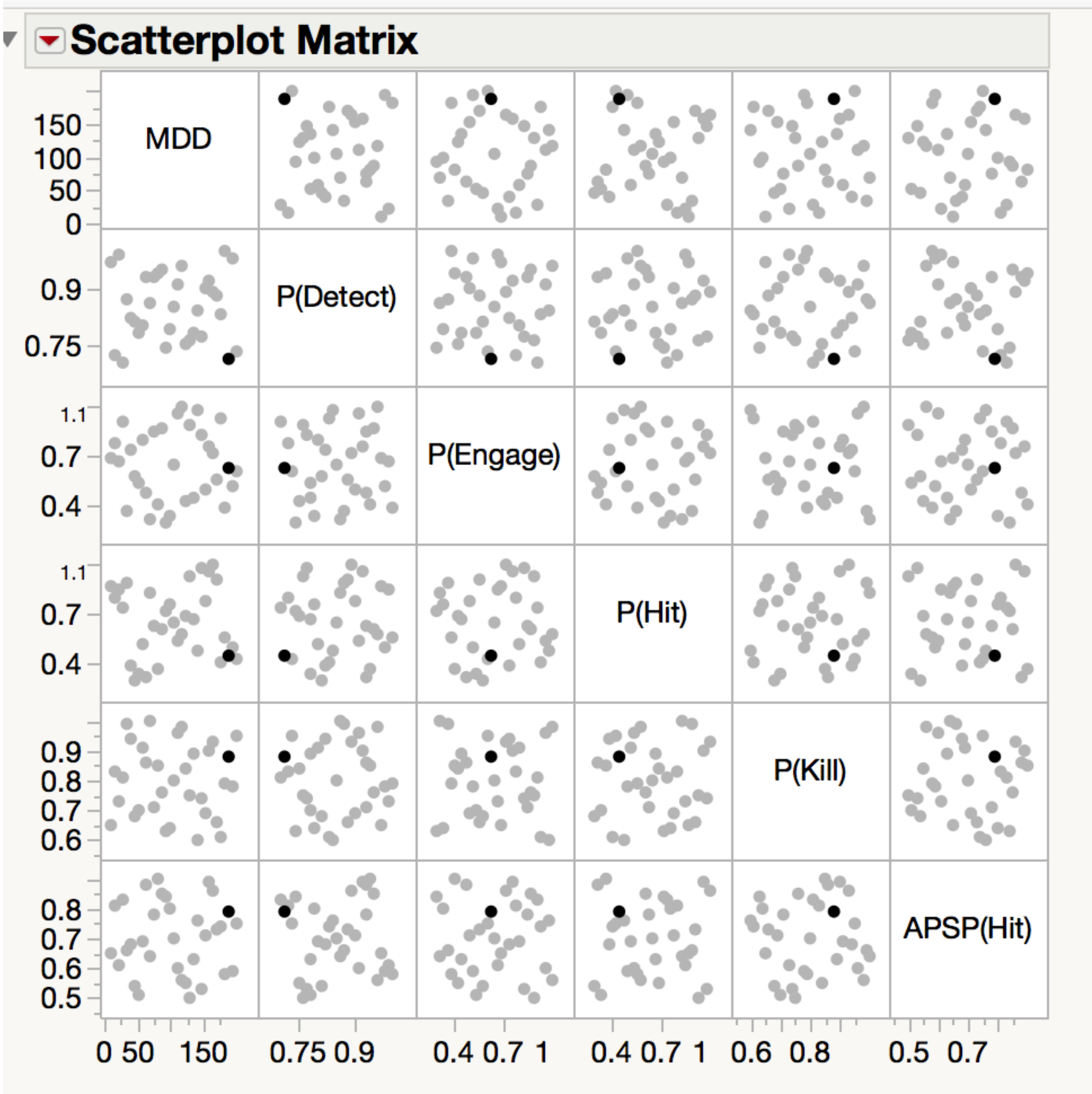
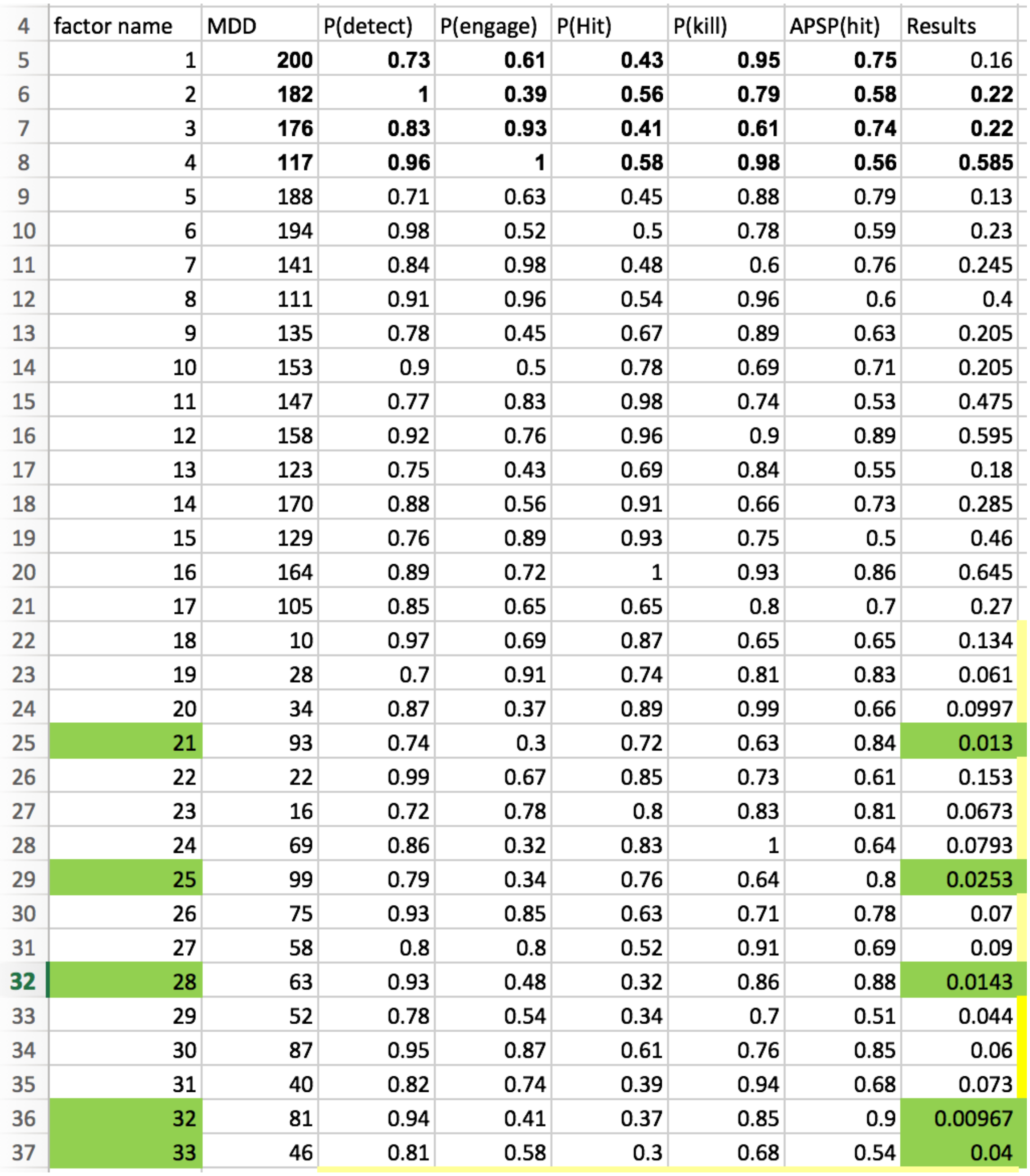


Figure 47. Scatterplot Matrix for the Design Factors.

5. Simulation Results

This thesis simulated each of the 33 generated design points 200 times in ExtendSim to determine if they meet the 95% survivability requirement. Figure 48 shows the outcome of the simulations, and one can see that only five out of the 33 design points meet the 95% survivability requirement (namely design points #21, 25, 28, 32 and 33). This thesis then calculated a 95% upper bound CI for each of the five design points to ensure that they meet the 95% survivability requirement (see Table 13). This author chose an upper bound CI because the survivability requirement is that the probability of a missile killing the ground vehicle cannot exceed 5%.



4	factor name	MDD	P(detect)	P(engage)	P(Hit)	P(kill)	APSP(hit)	Results
5	1	**200**	**0.73**	**0.61**	**0.43**	**0.95**	**0.75**	0.16
6	2	**182**	**1**	**0.39**	**0.56**	**0.79**	**0.58**	**0.22**
7	3	**176**	**0.83**	**0.93**	**0.41**	**0.61**	**0.74**	**0.22**
8	4	**117**	**0.96**	**1**	**0.58**	**0.98**	**0.56**	**0.585**
9	5	188	0.71	0.63	0.45	0.88	0.79	0.13
10	6	194	0.98	0.52	0.5	0.78	0.59	0.23
11	7	141	0.84	0.98	0.48	0.6	0.76	0.245
12	8	111	0.91	0.96	0.54	0.96	0.6	0.4
13	9	135	0.78	0.45	0.67	0.89	0.63	0.205
14	10	153	0.9	0.5	0.78	0.69	0.71	0.205
15	11	147	0.77	0.83	0.98	0.74	0.53	0.475
16	12	158	0.92	0.76	0.96	0.9	0.89	0.595
17	13	123	0.75	0.43	0.69	0.84	0.55	0.18
18	14	170	0.88	0.56	0.91	0.66	0.73	0.285
19	15	129	0.76	0.89	0.93	0.75	0.5	0.46
20	16	164	0.89	0.72	1	0.93	0.86	0.645
21	17	105	0.85	0.65	0.65	0.8	0.7	0.27
22	18	10	0.97	0.69	0.87	0.65	0.65	0.134
23	19	28	0.7	0.91	0.74	0.81	0.83	0.061
24	20	34	0.87	0.37	0.89	0.99	0.66	0.0997
25	21	93	0.74	0.3	0.72	0.63	0.84	0.013
26	22	22	0.99	0.67	0.85	0.73	0.61	0.153
27	23	16	0.72	0.78	0.8	0.83	0.81	0.0673
28	24	69	0.86	0.32	0.83	1	0.64	0.0793
29	25	99	0.79	0.34	0.76	0.64	0.8	0.0253
30	26	75	0.93	0.85	0.63	0.71	0.78	0.07
31	27	58	0.8	0.8	0.52	0.91	0.69	0.09
32	28	63	0.93	0.48	0.32	0.86	0.88	0.0143
33	29	52	0.78	0.54	0.34	0.7	0.51	0.044
34	30	87	0.95	0.87	0.61	0.76	0.85	0.06
35	31	40	0.82	0.74	0.39	0.94	0.68	0.073
36	32	81	0.94	0.41	0.37	0.85	0.9	0.00967
37	33	46	0.81	0.58	0.3	0.68	0.54	0.04

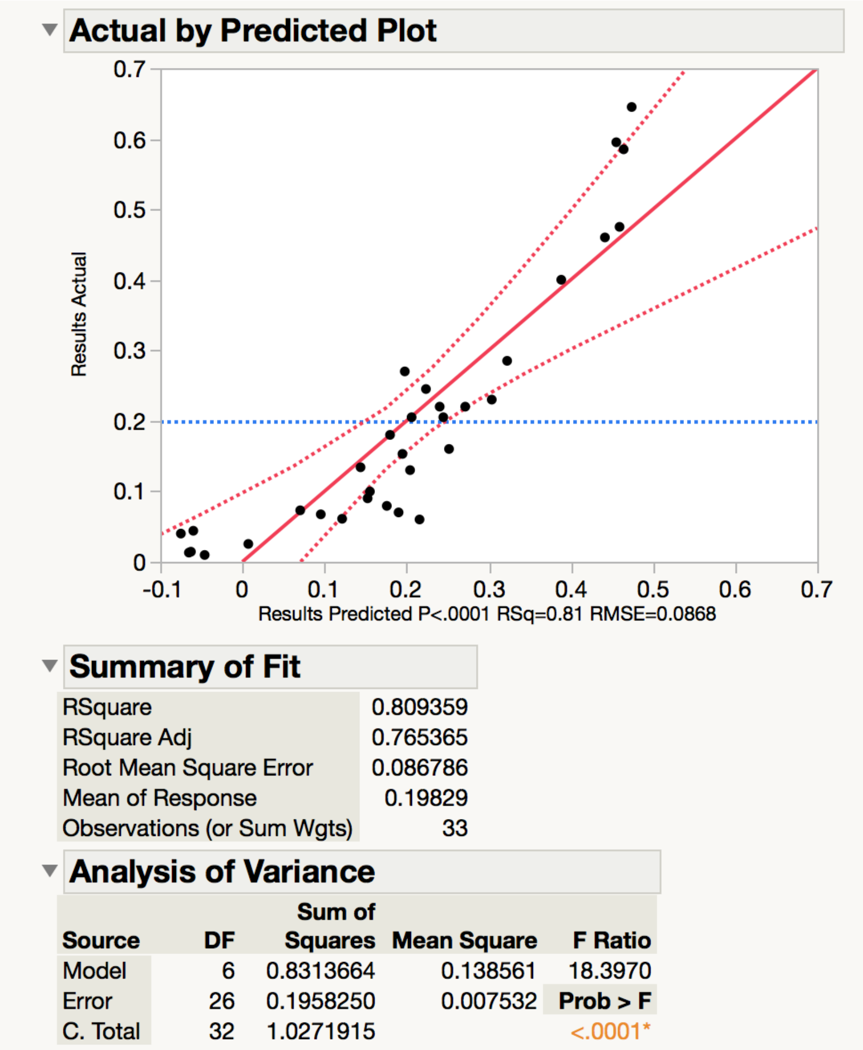
Figure 48. Simulation Outcomes for the 33 Design Points.

Table 13. 95% Upper Bound CI for Design Points That Meet Requirement.

Design Point #	95% Upper Bound CI for the Probability of Being Killed by a Missile
21	Mean: 0.013 (1.3%) Upper bound: 0.0161 (1.61%)
25	Mean: 0.0253 (2.53%) Upper bound: 0.0293 (2.93%)
28	Mean: 0.0143 (1.43%) Upper bound: 0.0183 (1.83%)
32	Mean: 0.00967 (0.967%) Upper bound: 0.0119 (1.19%)
33	Mean: 0.04 (4%) Upper bound: 0.0463 (4.63%)

6. Regression Analysis and Model Fitting

Based on the simulation results for all 33 design points, this thesis then performed regression analysis to determine a best-fit linear expression that predicts how the overall probability of survival changes with the six different factors. Using the Fit Model function in JMP Pro 12, this thesis generated an Actual by Predicted Plot (see Figure 49), which shows how well the predicted linear model fits the simulated data. The solid line in Figure 49 represents the predicted linear model, while the two dotted lines on top and beneath the solid line represents the upper and lower boundaries of the model respectively. The dots represent the individual simulated data and the more dots that fall within the lower and upper bounds, the better the fit of the predicted linear model. One can see that majority of the data points fit within the two boundaries. Figure 49 also shows the R^2 value of the fit, which has a relatively large value of 0.809. This means that the predicted linear model is able to account for 80.9% of the variation in the overall probability that a missile attack kills the ground combat vehicle. Finally, Figure 49 also shows the analysis of variance (ANOVA) results for the regression analysis. One can see that the p-value from ANOVA is extremely small (less than 0.0001). A small p-value means that one can reject the null hypothesis, which states that none of the six factors has any significant impact on the overall probability that a missile attack kills the ground combat vehicle. In other words, this means that there is at least one factor that has a significant impact on the overall probability that a missile attack kills the ground combat vehicle.



Summary of Fit

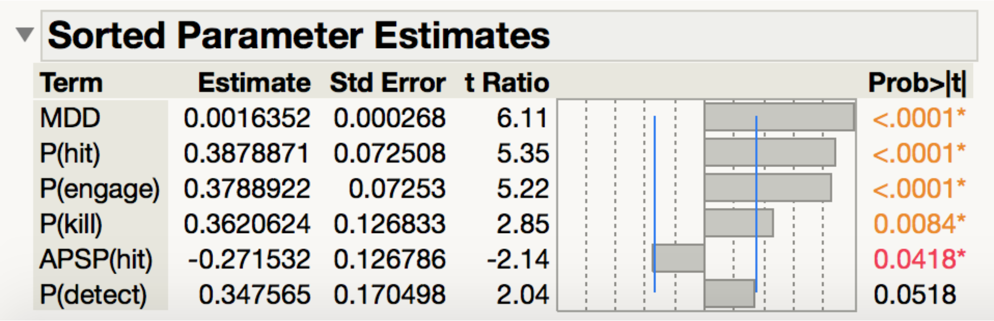
RSquare	0.809359
RSquare Adj	0.765365
Root Mean Square Error	0.086786
Mean of Response	0.19829
Observations (or Sum Wgts)	33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	0.8313664	0.138561	18.3970
Error	26	0.1958250	0.007532	Prob > F
C. Total	32	1.0271915		<.0001*

Figure 49. Actual by Predicted Plot and Regression Analysis Results.

The regression analysis functionality in JMP Pro 12 can rank the factors according to the amount of effect each factor has on the overall probability that a missile attack kills the ground combat vehicle. This is shown in Figure 50. One can see that MDD of the hard-kill APS has the greatest effect on the ground combat vehicle's overall probability of survival. This author expected this as a hard-kill APS seeks to destroy an incoming threat before the threat hits the protected vehicle, and MDD determines whether the hard-kill APS is able to react fast enough to an incoming threat. This means that the shorter the MDD, the more suitable is the hard-kill APS for urban operations, due to the typically short engagement distances in urban operations. P(detect) has a p-value of 0.0518, which is slightly higher than the chosen significance level of 0.05. Strictly speaking, this means that the p-value lies in the rejection region, and there is not enough statistical evidence to reject the null hypothesis that P(detect) has no significant effect on the overall probability of survival. Nevertheless, this author chose to retain P(detect) as a significant factor as the p-value is very close to the 0.05 threshold. Figure 50 also shows the predicted coefficients for each of the factors in the best-fit linear model. With the exception of APSP(hit), all the coefficients are positive. This means that the larger the values of those factors, the higher the probability that a missile can kill the ground combat vehicle. Conversely, for APSP(hit), the higher the value, the lower the probability that a missile can kill the ground combat vehicle. This makes sense because a higher APSP(hit) means a higher probability that the APS can successfully intercept an incoming missile.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
MDD	0.0016352	0.000268	6.11	<.0001*
P(hit)	0.3878871	0.072508	5.35	<.0001*
P(engage)	0.3788922	0.07253	5.22	<.0001*
P(kill)	0.3620624	0.126833	2.85	0.0084*
APSP(hit)	-0.271532	0.126786	-2.14	0.0418*
P(detect)	0.347565	0.170498	2.04	0.0518

Figure 50. Ranking of Factors According to Their Effect on Overall P(Killed).

One can potentially fulfil each of the five design points by combining different susceptibility reduction techniques and technologies (discussed in detail under Chapter VII). This thesis treats each combination of susceptibility reduction techniques and technologies as a survivability architecture. Therefore, each survivability architecture can result in differing trade-offs with other important ground combat vehicle capabilities. The subsequent sections of this chapter discuss about capability trade-offs and demonstrate how one can use decision-making methodologies to manage the capability conflicts and trade-offs to determine the most cost-effective survivability architecture.

B. CONFLICT BETWEEN SURVIVABILITY AND OTHER KEY GCV CAPABILITIES

This thesis mentioned previously that survivability is only one of the three essential capabilities of a ground combat vehicle, with the other two essential capabilities being mobility and lethality. Table 1 in Chapter III presented important capabilities for any ground combat vehicle, which one can trace back to the three essential capabilities of survivability, mobility and lethality. While the capabilities in Table 1 are important, it is not technically possible or economically feasible for engineers to achieve all of them in the design of a ground combat vehicle, due to the natural conflict that exists between the capabilities. For example, consider the conflict between the "carry a large and/or heavy payload over a long distance" capability and the "easy deployment and transport" capability. In order to fulfil the former, engineers need to increase the size of a ground vehicle to accommodate the payload and the additional fuel that the vehicle requires for long distance movement. If there is a need to protect the payload (e.g., soldiers in the case of IFVs, ICVs and APCs), engineers need to incorporate additional armor into the ground vehicles, which results in further weight increase to the vehicles. The significantly larger and heavier ground vehicle may then be unable to fulfil the capability of "easy deployment and transport," as it can be difficult to fit the vehicle inside a cargo transport plane, especially smaller planes such as the C-130 Hercules. The size and weight increase of the ground vehicle also adversely affects the "fuel efficient" capability. Therefore, this author regards the design of ground combat vehicles as a zero sum game between the three main high-level attributes of mobility, lethality and survivability.

According to Bochenek (2007), the U.S. Army uses a simple, three degree of freedom trade-space construct known as "The Iron Triangle" to address the dilemma between mobility, lethality and survivability. The U.S. Army classifies ground vehicle capabilities into one of the three primary categories of Payload, Performance and Protection, and each side of the Iron Triangle represents one of these three primary capability categories, as shown in Figure 51. Therefore, the main purpose of the Iron

Triangle is to illustrate the conflicts between the three capabilities categories of Payload, Performance and Protection and to emphasize the importance of a proper balance between them. Therefore, military planners and engineers need to be aware of the various trade-offs when designing a ground vehicle and strive to achieve a proper balance between all of the capabilities.

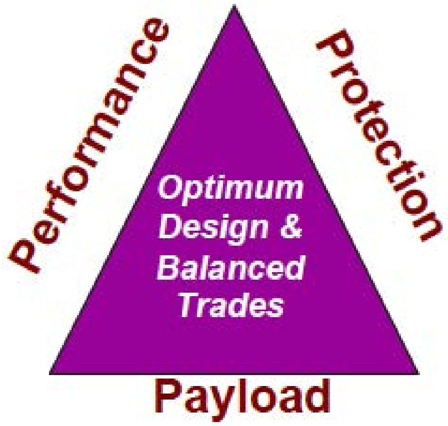


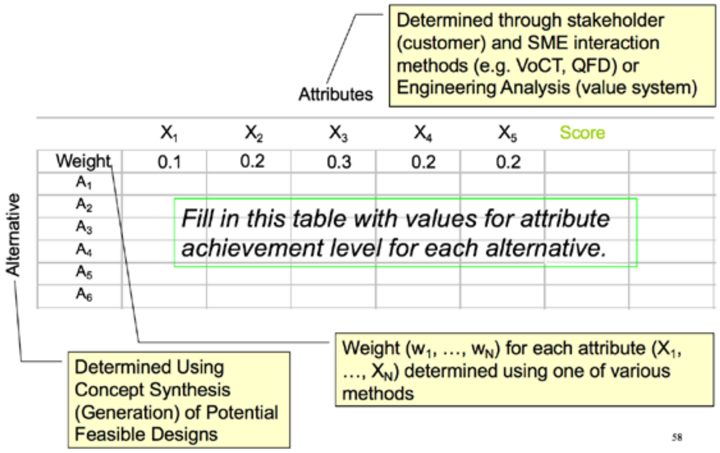
Figure 51. The Iron Triangle Construct Used by the U.S. Army. Source: Bochenek (2007).

C. USING MULTI-ATTRIBUTE DECISION MAKING TO MANAGE CONFLICT BETWEEN SURVIVABILITY AND OTHER KEY CAPABILITIES

The key to a successful ground combat vehicle design is in achieving proper balance between the different conflicting capabilities. While the ExtendSim modeling allows one to determine potential survivability characteristics for a ground combat vehicle to meet a survivability requirement, the model does not account for the resultant trade-offs with other key capabilities. Thus, when one performs system-level assessment of a ground combat vehicle, it is important to have a methodology to identify the various trade-offs and to present them in an appropriate manner to the key stakeholders for decision making. In the SE process, there are many methods that one can use for trade-off analysis and decision making. Such methods include “ranking, elimination, weighting and rating.” (Blanchard and Fabrycky 2011, 187) Since there are multiple, conflicting factors in the overall design of a ground combat vehicle, one can use a well-established

SE methodology known as multi-attribute decision-making (MADM) to facilitate the decision making process. Gregory Miller, a lecturer at the Naval Postgraduate School in Monterey, presented a typical MADM decision table during his lecture on Systems Architecting and Design (see Figure 52). One can see that there are five main components to the decision table for MADM:

1. The left-hand column of the table shows the architecturally different alternatives that can fulfill the system requirements.
2. Attributes are the key factors that one uses to assess the overall system performance.
3. Each attribute has a weight reflecting the relative importance or priority of that attribute in the overall system-level assessment.
4. Each alternative has performance value scores for every attribute, which reflects how well the alternative performs for that attribute
5. The final score for each alternative is a weighted sum-product between the attribute weightages and the performance values achieved for each alternative.



Determined through stakeholder (customer) and SME interaction methods (e.g. VoCT, QFD) or Engineering Analysis (value system)

Fill in this table with values for attribute achievement level for each alternative.

Weight (w_1, …, w_N) for each attribute (X_1, …, X_N) determined using one of various methods

Determined Using Concept Synthesis (Generation) of Potential Feasible Designs

Figure 52. Typical Decision Table Used in MADM. Source: Miller (2016).

1. Key Attributes

Based on this author’s experience, Table 14 shows key attributes that stakeholders are typically concerned with during the design of a new ground combat vehicle, which are also similar to the capabilities that this thesis presented in Table 1 of Chapter III. The attributes in Table 14 are for illustration purpose only and one needs to determine the actual attributes with the key stakeholders as early as possible in the program. One can see that while survivability is a key attribute for the GCV, military planners and engineers need to balance survivability at a system level with other key attributes as well. For example, engineers can improve survivability by adding heavier armor to the GCV, but this degrades other factors such as passenger payload and fuel efficiency, which has adverse repercussions for the ability of the GCV to complete its mission. Engineers can also improve survivability by using active signature management, jamming or hard-kill APS, but this degrades other attributes such as TRL and power requirement.

Table 14. Key Attributes Used for System-Level Assessment of the GCV.

Attributes	Rationale
Passenger payload	A larger payload means that more soldiers can be transported into the operational area.
Combat weight	Lower combat weight improves mobility and transportability of the ground vehicle.
Fuel efficiency	High fuel efficiency reduces logistics burden.
Survivability	Affects overall mission cost-effectiveness of a system
Technology readiness level (TRL)	This is a measure of when the system can be matured and deployed operationally in the field.
Power requirement	Lower power requirement will reduce electrical loading and can free up more space for other components, particularly for future upgrades.
Mean time between failure (MTBF)	Higher MTBF means greater operational availability of the ground vehicle and also reduces logistics burden, particularly in maintenance and spare parts.
Quantity of ammunition	More ammunition means that the ground vehicle is able to engage and destroy more targets, which increases the firepower and lethality of the vehicle.
Vehicle dead-zone	The vehicle dead-zone represents the area around the vehicle, within which the vehicle has no time to react to a threat. For the purpose of this analysis, the vehicle dead-zone is measured by MDD.

2. Architectural Alternatives

The ExtendSim simulation determined five design points or design permutations that can meet the 95% survivability requirement. Using the susceptibility reduction technologies that this thesis discussed previously, one can derive different survivability architectures to fulfil the survivability characteristics of the five design points. Table 15 shows an example of the different survivability architectures that one can derive from the various susceptibility reduction technologies.

Table 15. Potential Survivability Architectures for the Design Points.

Design Points	Survivability Architectural Description
21 and 25	- electric or hybrid-electric engines - active signature reduction and stealth technology - heavy armor (reduced mobility and agility) - standard smoke and aerosol - hard-kill APS - situational awareness system - threat warning system coupled to threat suppression system
28/32	- diesel engine - mobile camouflage net - active jamming only - lightweight armor with good agility - hard-kill APS - situational awareness system - threat warning system
33	- gas turbine engine - active jamming in addition to smoke and aerosols - medium weight armor with average agility - hard-kill APS - threat warning system

The different survivability architectures in Table 15 will affect other ground combat vehicle capabilities in varying ways. One can quantify these capabilities trade-offs by using the key attributes in Table 14, which then allows one to perform quantitative comparison between the different architectural alternatives (see Table 16). Using design points 21 and 28 as an example, one can see that design point 21 has a significantly greater weight compared to design point 28, which is due to the heavier armor. This can mean that design point 21 has better survivability, but at the expense of lower passenger payload due to overall weight constraints, as well as lower mean time between failure (MTBF) due to the heavier wear and tear on components. Similar to ExtendSim simulation presented earlier, one should note that the numbers used in Table 16 are for illustration purpose only, and the numbers are not intended to represent any particular ground combat vehicle in use today. This author then normalized the performance figures in Table 16, with the highest performing alternative given a value of one (see Table 17). This facilitates the MADM assessment subsequently.

Table 16. Raw Performance Figures for Each Alternative.

Design Points		21	25	28	32	33
Factors	Objective					
Passenger payload (kg)	Max	600	850	1500	1200	1000
Weight (tons)	Min	60	55	40	45	50
Fuel efficiency (m/liter)	Max	300	200	600	500	400
Probability of being killed	Min	0.0161	0.0293	0.0183	0.0119	0.0463
TRL	Max	3	3	7	7	8
MTBF	Max	200	250	400	450	350
Power (kW)	Min	20	18	15	11	10
Ammunition capacity	Max	200	250	400	350	300
Vehicle dead-zone (m)	Min	93	99	63	81	46

Table 17. Normalized Performance Figures for Each Alternative.

Design Points		21	25	28	32	33
Factors	Objective					
Passenger payload (kg)	Max	0.4	0.567	1	0.8	0.667
Weight (tons)	Min	0.667	0.727	1	0.889	0.8
Fuel efficiency (m/liter)	Max	0.5	0.333	1	0.833	0.667
Probability of being killed	Min	0.739	0.406	0.65	1	0.257
TRL	Max	0.375	0.375	0.875	0.875	1
MTBF	Max	0.444	0.556	0.889	1	0.778
Power (kW)	Min	0.5	0.556	0.883	0.909	1
Ammunition capacity	Max	0.5	0.625	1	0.875	0.75
Vehicle dead-zone (m)	Min	0.495	0.464	0.73	0.568	1

3. Swing Weight Matrix and Values

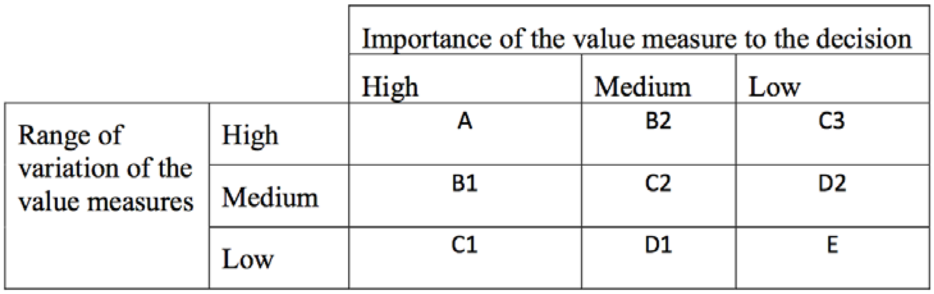
After one has identified and quantified the key attributes, one needs to assign weightages to the attributes. Engineers can use different methods to assign weightages to attributes, and for this thesis, this author used the swing weight matrix method that Parnell and Trainor proposed during the INCOSE International Symposium held in Singapore in 2009. Parnell and Trainor (2009) provided the following description of the Swing Weight Matrix in their paper:

> The key concept of the swing weight matrix is to define what we mean in the decision context by the importance and range of variation for the value measures. The idea of the swing weight matrix is straightforward. A measure that is very important to the decision should be weighted higher than a measure that is less important. A measure that differentiates between alternatives, that is, a measure in which value measure ranges vary significantly, is weighted more than a measure that does not differentiate between alternatives. The first step is to create a matrix in which the top defines the value measure importance and the left side represents the range of value measure variation. The levels of importance and variation should be thought of as constructed scales that have sufficient clarity to allow the stakeholders to uniquely place every value measure in one of the cells. A measure that is very important to the decision and has a large variation in its scale would go in the upper left of the matrix (cell labeled A). A value measure that has low importance and

has small variation in its scale goes in the lower right of the matrix (cell labeled E). (5)

Consistency Rules. Since many individuals may participate in the assessment of weights, it is important to ensure consistency of the weights assigned. It is easy to understand that a very important measure with a high variation in its range (A) should be weighted more than a very important measure with a medium variation in its range (B1). It is harder to trade off the weights between a very important measure with a low variation in its range (C1) and an important measure with a high variation in its range (B2). Weights should descend in magnitude as we move on the diagonal from the top left to the bottom right of the swing weight matrix. Multiple measures can be placed in the same cell with the same or different weights. If we let the letters represent the diagonals in the matrix A, B, C, D, and E; A is the highest weighted cell, B is the next highest weighted diagonal, then C, then D, and then E. (6)

Any measure in cell A must be weighted greater than measures in all other cells. Any measure in cell B1 must be weighted greater than measures in cells C1, C2, D1, D2, and E. Any measure in cell B2 must be weighted greater than measures in cells C2, C3, D1, D2, and E. Any measure in cell C1 must be weighted greater than measures in cells D1 and E. Any measure in cell C2 must be weighted greater than measures in cells D1, D2, and E. Any measure in cell C3 must be weighted greater than measures in cells D2 and E. Any measure in cell D1 must be weighted greater than measures in cell E. Any measure in cell D2 must be weighted greater than measures in cell E. No other strict relationships hold. (6) Figure 53 shows a sample swing weight matrix.



		Importance of the value measure to the decision		
		High	Medium	Low
Range of variation of the value measures	High	A	B2	C3
	Medium	B1	C2	D2
	Low	C1	D1	E

Figure 53. Elements of a Swing Weight Matrix. Source: Parnell and Trainor (2009, 5).

This author determined the weightages for the attributes in Table 14 by leveraging the swing weight matrix methodology. This author first calculated the variation range for each set of attribute values and then classified the variations as low, medium or high. One can calculate variation range by dividing the difference between the maximum and the minimum values by the average value. Using passenger payload as an example, the maximum, minimum and average values are 1500, 600 and 1030 respectively, which yields a variation range of 0.874. Table 18 shows the variation ranges for all the attributes and the classification of the variation ranges.

Table 18. Variation for Each Attribute.

Attributes	Variation	Classification (High, Medium or Low)
Passenger payload	0.874	High
Weight	0.4	Low
Fuel efficiency	1	High
Probability of being killed	1.41	High
TRL	0.893	High
MTBF	0.758	Med
Power requirement	0.676	Med
Ammunition capacity	0.667	Med
Vehicle dead-zone	0.694	Med

Based on the variation range and the importance or priority for each of the attributes, this author sorted the attributes into a swing weight matrix. One should note that there is subjectivity involved in assigning the importance or priority of the attributes and hence, one should always do this in consultation with the key stakeholders to minimize the probability of conflicts occurring subsequently. The issue of subjectivity is not unique to the swing weight matrix and also occurs in other decision-making methodologies such as the analytic hierarchy process (AHP). It is also important for one to adhere to the consistency rules when assigning values to the swing weight matrix. After completing the swing weight matrix, this author used the formula provided by Parnell and Trainor to normalize the swing weights into measure weights. Tables 19 and 20 show the swing weight matrix and the normalized measure weights for all the attributes respectively.

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i}$$

where f_i = Un-normalized swing weight for attribute i

w_i = Normalized swing weight or measure weight for attribute i

Table 19. Swing Weight Matrix for the Attributes.

	Importance of value measure		
Variation in range	High	Medium	Low
High	P (being killed) (20)	Passenger payload (13) TRL (15)	Fuel efficiency (10)
Medium	Ammunition capacity (17)	MTBF (9) Vehicle dead-zone (11)	Power requirement (5)
Low	Weight (8)		

Table 20. Normalized Measure Weight for Each Attribute.

Attributes	Swing Weight	Measure Weight
Passenger payload	13	0.12
Weight	8	0.0741
Fuel efficiency	10	0.0926
Probability of being killed	20	0.185
TRL	15	0.139
MTBF	9	0.0833
Power requirement	5	0.0463
Ammunition capacity	17	0.157
Vehicle dead-zone	11	0.102

D. MADM AND COST COMPARISON

After determining the swing weights, this author then calculated the weighted score for each of the architectural alternatives, using the decision matrix in Table 21. The normalized measure weights for each attribute are in the top row, below which are the normalized performance values for each of the alternatives. This author computed the final weighted score for each alternative by taking the sum-product of the measure weights and the normalized performance values. One can see from Table 21 that design point 28 has the highest benefit score of 0.873 and design point 21 has the lowest benefit score of 0.522. This means that from a purely system performance point of view, design point 28 is the best overall performer. Nevertheless, one also needs to consider the cost-effectiveness of the various alternatives before deciding on the alternative to adopt, as the best performing alternative may not be the most cost-effective and vice versa.

Table 21. Final Weighted Score for Each Alternative.

	Passenger Payload	Weight	Fuel efficiency	Probability of being killed	TRL	MTBF	Power Requirement	Ammunition capacity	Dead-zone	Score
Measure Weights	*0.12*	*0.0741*	*0.0926*	*0.185*	*0.139*	*0.0833*	*0.0463*	*0.157*	0.102	
Design Points										
21	0.4	0.667	0.5	0.739	0.375	0.444	0.5	0.5	0.495	0.522
25	0.567	0.727	0.333	0.406	0.375	0.556	0.556	0.625	0.464	0.498
28	1	1	1	0.65	0.875	0.889	0.833	1	0.73	0.873
32	0.8	0.889	0.833	1	0.875	1	0.090	0.875	0.568	0.867
33	0.667	0.8	0.667	0.257	1	0.778	1	0.75	1	0.719

In order to determine which survivability architectural alternative is the most cost effective, this author made certain cost assumptions to determine the cost required to implement each of the alternatives. Similar to survivability information, the costs to implement survivability features are usually not available in open source and thus, the assumptions and numbers are for illustration purposes only:

1. This thesis assumed that a GCV cost about US$10M and survivability-related features constitute 30% (US$3M of the cost). P(detect), P(engage), P(hit) and P(Kill) each constituted US$0.75M to the overall survivability cost.
2. This thesis adjusted the individual survivability costs in proportion to how their corresponding probability changes. For example, if P(engage) reduced by 20% (an improvement), the additional cost to implement this enhancement to P(engage) was US$0.15M (20% of US$0.75M).
3. For APS, this thesis assumed a baseline model for comparison that cost US$1.5M, with MDD of 50m and APSP(hit) of 0.8. This thesis assumed that APSP(hit) constituted US$0.75M to the overall APS cost. For APSP(hit), this thesis adjusted the cost in proportion to the change in APSP(hit). For MDD, this author used the assumptions shown in Table 22. For example, for an alternative APS with MDD of 100m and APSP(hit) of 0.7, this author estimate that it would cost US$1.3M (0.65 + 0.875*0.75) to implement, as compared to US$1.5M for the baseline APS system.

Table 22. Assumed Relationship Between MDD and Cost.

MDD	Cost to implement (US$M)
< 25 m	1
Between 25 m and 75 m	0.75
Between 75 m and 125 m	0.65
Between 125 m and 175 m	0.55
Greater than 175 m	0.45

Based on the cost assumptions, this thesis computed the cost to implement the various alternatives and the final benefit-cost ratios (see Table 23). This thesis also plotted the cost-efficiency frontier for the alternatives (see Figure 54). Based on the benefit-cost ratios and cost-efficiency frontier, one can see that design point 32 is the most cost-effective, even though it is neither the cheapest nor does it has the highest-weighted score (benefit). When plotting the cost efficiency frontier, it is important for one to ensure that both axes start at zero. This prevents distortion of the plotted data points, which can lead to incorrect conclusions.

Table 23. Benefit-Cost Ratio for the Design Points.

Design Points	Weighted Score (Benefit)	Cost ($M)	Benefit-Cost Ratio
21	0.522	2.12	0.246
25	0.497	1.96	0.254
28	0.873	2.14	0.408
32	0.867	2.06	0.421
33	0.719	2.05	0.351

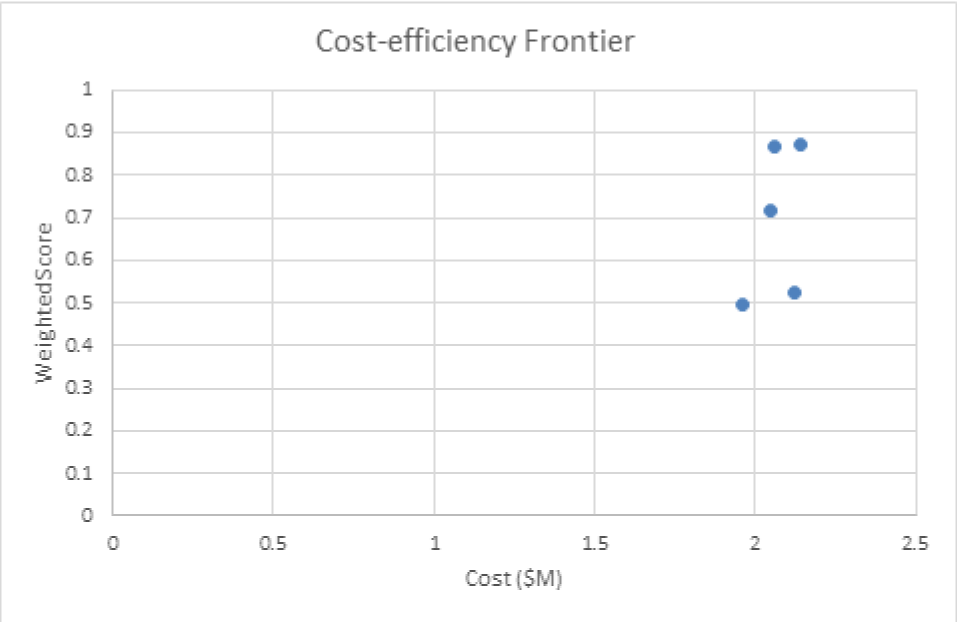


Figure 54. Cost-efficiency Frontier for the Different Alternatives.

The first portion of this chapter developed a working model (using ExtendSim) based on the existing one-on-one probability tree diagram, and this author improved the model by incorporating hard-kill APS, which is a key upcoming susceptibility reduction technology. Based on the defined threat scenario and survivability requirement, this author used the NOLH technique to generate 33 design points. This author performed simulation on the design points and determined that only five out of 33 design points can meet the survivability requirement. This author then performed regression analysis on the simulated data and determined that all six factors are significant to the overall survival probability for the ground vehicle, with MDD having the highest level of influence on the survival probability. The regression analysis also allowed this author to determine a best-fit linear model that one can use to predict survivability performance.

The second portion of this chapter discussed about the natural capability conflicts between survivability and other key GCV capabilities. In order to manage the capability conflicts, this author demonstrated how one can use a decision-making methodology such as MADM to address the capability trade-offs between survivability and other key GCV capabilities. This facilitated the subsequent decision-making process to help decision-makers choose the most cost-effective survivability architecture to fulfill a certain survivability requirement.

IX. CONCLUSION

Military planners and engineers designed the majority of GCVs today for the Cold War scenario, which assumes head-on combat between near-peer forces, over relatively open terrain. The survivability of ground combat vehicles traditionally relies on vulnerability reduction through the use of advanced passive armor that engineers optimize over the frontal arc of a vehicle. Due to the rapid growth in global urbanization, military planners now expect the next generation of ground warfare to be urban in nature, which can also involve both symmetric and asymmetric elements. Recent conflicts in the Middle East amply demonstrated the survivability shortcomings of existing combat vehicles. While passive armor continues to improve in performance and weight efficiency and continues to be an important element in the survivability equation, it is no longer possible for military planners and engineers to rely solely on vulnerability reduction. This is due to the increasing gap between threat lethality and capability of passive armor, the change in threat scenario from relatively open terrain to the closed confines of an urban environment and the proliferation of advanced anti-armor weapons. Thus, it is important for military planners and engineers to consider and incorporate susceptibility reduction techniques and technologies upfront in the design of a combat vehicle.

The thesis identified and analyzed the key threats that ground combat vehicles will encounter in urban operations, which include rockets, missiles and smart bombs, kinetic energy penetrators and mines and IEDs. Based on the threat analysis, this thesis then proposed and discussed appropriate susceptibility reduction techniques and technologies that one can use to counter the threats.

Subsequently, the thesis proposed a survivability assessment model based on the one-on-one probability tree diagram, but with the added improvement of incorporating a hard-kill APS, which is a key upcoming susceptibility reduction technique. The proposed survivability model performs the following functions to facilitate survivability assessment:

1. Quantify the survivability characteristics of a ground combat vehicle, using the factors P(active), P(detect), P(engage), P(hit) and P(kill). Due to the incorporation of hard-kill APS, the improved survivability model incorporates two additional factors, namely MDD and APSP(hit).

2. Generates different sets of survivability characteristics (known as design points) using the NOLH methodology. The NOLH methodology is a design-of-experiment (DOE) technique for a small number of factors, as is the case for this thesis.

3. Simulates the survivability of the ground combat vehicle using the generated sets of design points to determine which sets of design points meet the survivability requirement

Based on the defined threat scenario and assumptions made, five out of 33 design points were able to fulfill the survivability requirement. This thesis then performed linear regression, which showed that MDD is the most significant factor affecting overall ground combat vehicle survivability. The linear regression analysis also allowed this author to determine a best-fit linear model that one can use to predict survivability performance.

Leveraging the earlier discussion on susceptibility reduction techniques and technologies, this thesis proposed different survivability architectures to fulfill the five design points. Each survivability architecture resulted in trade-offs with other capability areas of a ground combat vehicle, due to the natural conflicts between the three essential capabilities of a ground combat vehicle, namely survivability, mobility and lethality. In order to address the conflicts and to facilitate decision making on the most cost-effective survivability architecture, the thesis demonstrated the use of a decision-making methodology known as MADM. The MADM methodology used normalized swing weights (or measure weights) to determine the overall benefit score (or weighted score) for each survivability architecture, based on a set of key attributes that one can use to perform system-level assessment of a ground combat vehicle. Finally, this thesis calculated the assumed cost for each survivability architecture and determined the most cost-effective architecture by plotting a cost-efficiency frontier for all the architectures.

This author hopes that the improved model and the decision-making methodology in this thesis help military planners and engineers design more robust, holistic and balanced survivability solutions for ground combat vehicles in the future, to provide more flexibility against different types of threats and threat scenarios.

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