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BALANCING DURABILITY AND DEPLOYABILITY: ENHANCED SITUATIONAL AWARENESS (ESA) FOR NON-COMBAT TACTICAL VEHICLES

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ABSTRACT

The persistent rate of accidents and fatalities involving legacy tactical military vehicles underscores a critical need for Enhanced Situational Awareness (ESA) technologies. However, the prohibitive cost and lengthy development cycles associated with full MIL-STD ruggedization often prevent these safety systems from reaching the in-service non-combat vehicles with limited driver visibility. This paper suggests a strategic shift in procurement policy: The adoption of relaxed ruggedization standards for vehicles operating in non-combat, administrative, and training roles. By deriving requirements from high-stress commercial sectors—such as heavy mining, steel production, and NASCAR racing—the military can utilize electronics designed for "extreme industrial" rather than "battlefield" environments. The principal objectives of this relaxation is cost reduction, lowering the barrier to entry and increasing the likelihood of ESA deployment across the legacy fleet. Furthermore, this approach aligns with Modular Open Systems Approach (MOSA) principles by enabling the integration of non-proprietary commercial devices. Utilizing these accessible technologies on legacy platforms creates a real-world testbed to evaluate technological advances rapidly. These insights can then inform and accelerate the development of future MIL-STD systems for combat vehicles, effectively shortening the traditional development life cycle while prioritizing the immediate enhanced protection of service member lives.

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1. INTRODUCTION

The development of Enhanced Situational Awareness (ESA) for tactical military vehicles is currently guided by the imperative to create safer, more survivable vehicles that can operate effectively with "closed hatches" in high-threat environments. Central to this evolution is the integration of AI-assisted hazard detection, which automates the classification and prioritization of threats—ranging from dismounted combatants to drone swarms—to reduce the cognitive load on crews.

It is important to enable non-combat tactical vehicles with some of the capabilities of these top-tier ESA systems for the safety of the drivers, passengers and personnel in their vicinity.

In a 10-year period 2010-2019 the Army and Marine Corps reported 3,753 non-combat accidents involving tactical vehicles (tanks and trucks). These incidents represent a significant portion of non-combat training fatalities, often exceeding combat-related deaths in certain years. [1]

While the High Mobility Multipurpose Wheeled Vehicle (HMMWV) was involved in the highest total number of incidents, specialized armored vehicles like the Stryker, LAV, and MRAP actually had higher accident rates when adjusted for their total numbers in the inventory. Safety data indicates that rollovers account for 63% of fatalities despite being only 25% of total accidents. For heavy armored vehicles like the M1 Abrams and M2 Bradley, rollovers are particularly dangerous due to their high center of gravity and extreme weight, which can crush the vehicle's turret or hull during a flip. [2]

For armored vehicles, limited external visibility (often called "restricted situational awareness") is a known engineering constraint, but it is not always the decisive factor in accidents. Surprisingly, most fatal training accidents occur during daylight hours on regular roads or established training paths, rather than in low-visibility nighttime and off-road conditions. Human factors—including driver inattentiveness, lack of training, and supervisor lapses—are cited in 83% to 86% of all accidents. Research on armored vehicle operators suggests that up to 70% of accidents are associated with low situational awareness, but this is often driven by cognitive overload (managing complex digital systems and communications) rather than just physical sightlines. [3]

Unfortunately, the cost of military ESA systems makes the outfitting of legacy fleet of thousands of vehicles infeasible despite the critical need. One of the main drivers of the cost is the requirement for MIL-STD ruggedization. While typical commercial off-the-shelf (COTS) sensors, processors and monitors could not survive the conditions extant in tactical military vehicles there are special commercial applications in which electronic devices must endure harsh environments, such as heavy mining, power generation, steel and metal processing, and car racing (NASCAR). We will refer to the various testing and specification standards for these special-purpose commercial applications as the SPECOM-STD as we consider alternatives to the full MIL-STD.

Tactical vehicles in non-combat roles such as administrative and training will not be exposed to all the conditions or the time duration experienced in combat. In the following sections we will compare SPECOM-STD with MIL-STD noting where some requirements may be relaxed enough to make non-combat role ESA feasible.

A Modular Open Systems Approach is essential to achieve a level of affordability that results in broad adoption and installation onto legacy vehicles as the cost of proprietary high-end SA systems cannot be justified non-combat vehicles.

Adherence to a MOSA compliance standard also increases the likelihood of updates as the technology advances in sensors processors and software. The resulting shorter development cycle offers an early testbed for emerging technology.

2. COMPARING STANDARDS

There are a lot of unsubstantiated claims about the resilience and survivability associated with commercial products. As noted by Ben Sharfi, CEO of GMS Computing Engines, "All too often, COTS vendors who aren't knowledgeable or serious about the defense market slap the word "rugged" on a system and declare it ready for military service." [4]

In this paper we are comparing the levels and types of testing required for special purpose sensors and electronics for applications in extreme environments with the MIL-STD for combat ready tactical vehicles. The two key attributes of ruggedization for military vehicles are heat transfer and ruggedization. Standard COTS products fall short of these requirements, however there are special commercial applications in which electronic devices must endure harsh environments, such as heavy mining, power generation, steel and metal processing, and car racing (NASCAR). We will refer to the various testing and specifications for these special-purpose commercial applications as the SPECOM-STD as we consider an alternative standard lacking some of the most extreme requirements of the full MIL-STD but still adequate for tactical vehicles in a non-combat role.

2.1. Shock and Vibration

Shock and vibration are quantified by measuring the magnitude frequency and duration of various levels of mechanical stress. Shock is expressed as G-force (g) usually representing peak acceleration coupled with pulse duration in milliseconds and the wave shape (i.e. the acceleration-time history for how the G-force builds up and drops off on impact).

Typical SPECOM-STD calls for a half-sine wave shape representative of a car hitting a "soft" wall [NASCAR] or a piece of industrial equipment being dropped onto a cushioning mat [warehousing and logistics]. Other SPECOM-STDs can close the gap with military requirements (e.g. heavy off-road construction and mining). In these environments, electronic control units, sensor and rugged displays are subjected to forces that mirror MIL-STD 810H (specifically Method 514.8 for vibrations and 516.8 for shock. [MIL-STD shock tests use a sawtooth wave shape to mimic a military vehicle being struck by a high-velocity projectile. Some industrial specifications also require sawtooth shock tests. [5]

In compliance with MIL-SDT 810 Method 522 the hardware used in military tactical vehicles rated for combat operations must survive ballistic shock and near-miss explosions that can exceed 300g up to 1,000,000g for short periods (< 180 milliseconds). This requirement only applies to certain hardware. Most military devices such as computer laptops and radios are tested under the less stringent conditions of mechanical shock (Method 516) equivalent to a 4-foot drop test (26g to 75g).

Vibration tests are more complex since they are usually measured as Root Mean Square acceleration (Grms) for random vibrations, or as peak-to-peak displacement for low-frequency sine vibration. See Figure 1. These measurements are quantified in Power Spectral Density (PSD) plots mapping the

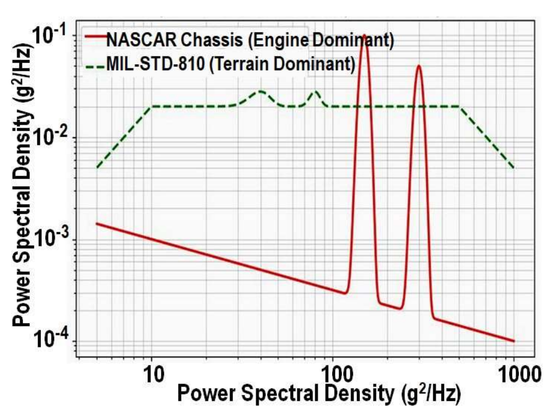

Figure 1: Comparison of Power Spectral Density NASCAR vs MIL-STD

vibration energy across a range of frequencies designed to expose resonant frequencies potentially damaging to device structures or electronics.

This example illustrates that the testing is not simply a matter of magnitude of force but is specific to the particular types of forces anticipated for each application. The purpose of MIL-STD-810 shock testing, or Method 516.8, is to assess a system's resilience to physical impact in handling, transportation and service environments, according to the standard's latest revision. In the context of MIL-STD-810, shock refers to mechanical, rather than electric, shock. A MIL-STD-810 shock test, therefore, assesses the structural and functional effects of mechanical shock impact on a system. [6]

Shock testing also assesses a system's fragility level. This ultimately helps with creating protective packaging, stowage and mounting configurations, which ensures the system's physical and functional integrity. In addition, shock testing is used to assess the strength of devices that are at risk of being involved in a crash and experiencing breakage or ejection as a result.

SPECOM-STD shock testing encountered in commercial applications can be similar to MIL-STD except for the highest levels. For example, MIL-STD 810H Method 516.8 is a reasonable match to the shock tests for manufacturing applications as its purpose is to evaluate the physical and functional performance of materiel likely to be exposed to mechanically induced shocks generally limited to a frequency range not to exceed 10,000 Hz, and a duration of not more than 1.0 second. This MIL-STD omits effects of pyrotechnic device initiation, ballistic impacts, and high-pressure wave impacts from gun fire.

In addition to matching commercial and military specifications, the methods of dissipating the energy of shock and vibration used by NASCAR or in industrial applications are different than those used for military-grade damping commercial ruggedization can be modified to better withstand the conditions encountered in military tactical vehicles. For example, rubber grommets can be replaced with military grade wire rope isolators, camera and processor mounting brackets can be filled with tungsten or steel micro-spheres (non-obstructive particle damping), or the constrained layer damping (see MIL-P-23653) can be applied to printed circuit boards or camera housing.

2.2. Temperature Specifications

Operation of sensors, processors, and displays through a range of extreme temperatures not only depends of the equipment itself but how heat dissipation is managed. The core difference lies in the type and application of the thermal sink available. For example, NASCAR uses high-velocity air passing through low drag NACA/NASA ducts directed through aluminum pin-fin heat sinks attached to cool boxes holding the temperature sensitive equipment. [8]

Some industrial applications rely on fanless conduction cooling by making the entire chassis as an aluminum finned heat sink. Thick thermal Gap Pads may also be used to thermally connect a processor to the outer casing.

For military tactical equipment cold plate/liquid cooling and very large copper-core heat sinks may be used since there is less concern for the added weight. The vibration wire mounts and damping particles are also thermally conductive thus serving multiple purposes.

2.3. EM Tolerance

For non-combat roles, including training, the ability of electronic systems to function in the presence of electronic interference is less critical than for combat vehicles. First, operating in a contested environment is under the control of the training supervisor and or test missions.

Also, in combat, a loss of function due to electromagnet interference (EMI) can lead to mission failure, even loss of life. In training, an EM-related failure is generally a nuisance, allowing for a passive coping strategy, at worst, resulting in delays or the need for adjustments.

From the point of view of EM emissions, combat vehicles must minimize their electromagnetic footprint to avoid detection and targeting by the adversary. Training vehicles do not face the same threats eliminating the need for an EM emission control (EMCON) MIL-STD.

One difference worth noting is the requirement for electrically and thermally conductive gaskets and seals. In military applications the seal must provide IP protection (see below) as well as EMC shielding.

Finally, enabling a tactical vehicle with high EM tolerance adds significant cost and weight, which is often not justified for legacy vehicles in a non-combat role.

While it's not a critical issue, EM tolerance is not completely ignored in the specifications of special industrial and racecar electronics. For NASCAR, EM tolerance is regulated by automotive standards such as CISPR 25, which requires extremely low on-board noise levels (down to 18 dB μV/m) to ensure camera signals do not interfere with critical engine control units or telemetry with the racing team. Industrial equipment follows FCC/CE or CISPR 35 guidelines as well. For high-interference environments such as near motors or solar plants, the ECU-1051 gateways may be used to provide superior radiated immunity against external surges.

2.4. Ingress Protection (IP) Methods

Methods of Ingress Protection (IP) between SPECOM-STD and MIL-STD go well beyond blocking water and dust set by IP67. IP concerns vary according the specific chemicals and the levels of kinetic energy of the contaminants. The primary threats for NASCAR are hot oil, tire debris, and high-pressure spray cleaning.

With respect to chemical contaminants, fuel vapors can degrade standard seals. In industrial applications sawdust, metal shavings and other fine particulates are the primary concern as well as various caustic washdown chemicals. The golden trio for military IP is fine (talcum-like) sand, mud, and fuel/decontaminants for cleaning. For combat vehicles there is the additional issue of surviving Chemical, Biological, Radiological, and Nuclear (CRBN) chemicals.

The primary difference between SPECOM-STD and MIL-STD with respect to kinetic IP is high-wind-speed sand and dust that can erode seals and fog glass lenses. Otherwise the requirements for both are similar for high-pressure jets and high-temperature sprays for cleaning.

2.5. Issues of Latency

A major contributor to the cost of an ESA system is the management of latency. Generally speaking, latency is the time delay between the occurrence of an event and its detection or presentation to an observer. While there is no single military specification for glass-to-glass latency, there are a number of design criteria standards and human factors research sources that specify upper limits to the magnitude of latency allowed in military equipment used by a human operator.

A person's reaction time can vary between 120ms and 250ms but the effect of latency on human performance occurs well below these times. A driver's performance is measurably degraded for visual delays above 80ms. In rough terrain, the human vestibular system detects the difference between what the eye is seeing and the body is feeling for delays as small as 20ms. An exact specification of a latency limit for video displays. However, since the presentation by Paul DiZio and James R. Lackner at the RTO HFM Workshop on "The Capability of Virtual Reality to Meet Military Requirements" in 1997 [9], their results have been verified for viewing video displays while traveling across rough terrain and for helmet mounted displays (HMDs) in general, *"We found that above delays of 40ms motion sickness and postural instability are evoked minutes after head movement begin."* These results are referenced in a number of research articles and military specifications such as STANAG 4697 – PLEVID: Platform Extended Video Standard as a part of the NATO Generic Vehicle Architecture (NGVA) agreement from 2016. We will use 40ms as the baseline glass-to-glass latency requirement for cost and performance comparisons. Below this level the human observer finds the monitor display scene essentially indistinguishable from a real-time direct view.

2.6. Comparison Summary

Reviewing Figure 2 we compare MIL-STD specifications with selected SPECOM-STD specifications for Temperature, Shock, Vibration, and EM Tolerance. These should be considered only an exemplar of the types of testing for special purpose commercial equipment that could be adapted to tactical military vehicles in a non-combat role.

The upper limit on temperature in NASCAR and Special Industrial within a few degrees of the MIL-STD. The shock tolerance ranges of SPECOM-STD overlap MIL-STD ranges. Special Industrial vibration requirements actually exceed those for military combat vehicles.

The MIL-STD for EM Tolerance is tested across a broader frequency range and a shorter distance from the source or detector but otherwise are comparable.

The argument for relaxing the MIL-STD requirements for tactical vehicles used in training aligns with the MOSA mandated strategy to accelerate the development and deployment of technological advances. This is particularly true for enhanced situational awareness systems on legacy vehicles.

The loss of function of an ESA system in combat can be catastrophic while in training it becomes a maintenance event. Since training environments have built-in safety buffers, the Consequence of Failure (CoF) is significantly lower. The practical argument is, accepting a lower mean-time between failure (MTBF) in exchange for an order-of-magnitude reduction in system cost is reasonable, particularly when the alternative is a lack of ESA entirely.

In addition to providing essential experience to soldiers, the use of commercially available systems in training exercises can become a testing ground for advances in technology. Tactical electronics evolves faster than the vehicles they sit on. Strict MIL-STD-810 testing for extreme thermal, shock or ballistic vibration can double the development time. By using ruggedized commercial standards for recently developed equipment in training, the Army can field the most recent advances in sensors, processors, and situational awareness software in a year or two rather than a decade. This type of early feedback from soldiers can more efficiently inform the

Feature	NASCAR On-Board	Special Industrial	MIL-STD
Standard	SAE J1455	IEC 60068-2 / MIL-STD-810	MIL-STD-810H
Ambient Operating Temp	Up to 140°F (60°C) in cockpit	-40°F to 158°F (-40°C to 70°C)	-60°F to 160°F (-51°C to 71°C)
Max CPU Temp	throttles at 185°F - 203°F (85°C - 95°C)	sustains 212°F (100°C) (Xeon/Atom)	sustains 221°F+ (105°C+) (Tactical)
Shock Tolerance	crash survivability (~50G / 11ms)	20G (Standard) to 50G (Custom)	40G to 75G (Method 516)
Vibration	High-freq mechanical (Engine)	2G to 5G (IEC 60068-2-6)	4.7 Grms+ (Method 514)
EM Tolerance	CISPR 25 / ISO 11452	CISPR 35 / FCC Class A/B	MIL-STD-461G

Figure 2: Comparison of Special Commercial and Military Ruggedization Standards

longer development life cycles for full combat capable ESA systems.

The less stressful two-week training rotation compared to a year-long combat deployment makes the use of SPEC-COM level equipment a reasonable choice. In addition, while the operations in rough terrain during exercises at training sites such as Ft. Moore, the duration of extreme stress and range of temperatures is reduced. Relaxed specifications can be tailored to the specific climatic cycles rather than demanding they meet the maximum extreme hot/cold cycles required for global deployment, resulting in a significant cost reduction.

3. LEVELS OF ESA

This section explores low-cost alternatives to the high-end, combat-rated 360° Enhanced Situational Awareness (ESA) and targeting systems currently in development. Our focus is on providing ruggedized ESA tailored for tactical vehicles in training and administrative roles. The level of ruggedization of all components is at the Special-industrial-commercial (SPEC-COM) level previously discussed.

The rollout begins with a day-only driver's system featuring moderate ruggedization and a strict 40ms latency ceiling. We then incrementally add AI-driven hazard detection, threat warnings, and night vision, ensuring each phase maintains high reliability and low cost. To support rapid development and future-proofing, all designs adhere to Modular Open Systems Approach (MOSA) principles for seamless interoperability and component upgrades. In the following descriptions, reference to specific devices is not to be considered an endorsement, but rather examples of commercially available products that meet the performance levels and have verifiable data on ruggedization test results.

3.1. Level 1: Driver View Day Only

For the Level 1 baseline we are choosing an analog video camera (e.g. the Opticom CC02-V) with a 60-fps video rate (which is its only contribution to latency of approximately 16ms). A camera of this type scans and outputs each frame of the image line-by-line, so there is no frame buffer or encoding stage. This video output is passed into one of the channels of a dual-input analog distribution amplifier (e.g. the Extron Video Amplifier MDA 2V EQ). The reason for using the dual-input amplifier anticipates the addition of a FLIR/thermal video camera in the next ESA level. The output of the video amplifier can be passed to a compatible ruggedized analog monitor. The total latency for such a system would be less than 25ms. The total cost for this Level 1 ESA is under $1,000.

3.2. Level 2: Driver View Day-Night

Driver View Day/Night – For this Level 2 ESA system, a thermal video camera (e.g. the Teledyne PathFindIR II) is added with its video signal being passed into the dual-input video amplifier. The amplified output is then passed to a ruggedized video signal blending OSD controller (e.g. the Advanced Micro Peripherals (AMP) VAC2000). This device accepts the two analog video signals to perform Alpha-blending allowing the viewer to see through the thermal layer onto the visible layer. For tactical vehicle training a ruggedized monitor is recommended (e.g. the NAV-TV LCD or Ultra 7). The cost for this level is jumps to around $4,000 mainly due to the addition of a thermal camera. In addition, the thermal camera adds about 30ms latency pushing the total up to a little less than 50ms. Faster thermal cameras (e.g. direct-to-CRT or Workswell WIRIS or FLIR boson) are slightly faster but higher cost and less suited to operation on ground vehicles.

3.3. Level 3: AI Assisted ESA

AI Enhanced Situational Awareness – In Level 3 the analog visible and thermal video signals are tapped from the dual video amplifier and digitized for machine vision processing. An efficient way to perform this frame grabbing function is to use an industrial Edge AI Gateway equipped with a multi-channel analog capture card (e.g. the Magewell Eco Capture Dual CVBS).

There are a number of ruggedized, fanless AI platforms using high-performance NVIDIA Jetson AGX Xavier edge processors specifically design for vehicle-mounted machine vision. The digitization and Direct Memory Access (DMA) process adds around 30ms of latency.

The object detection and visible/thermal fused hazard detection can be based on a combination of YOLO trained AI recognition and geometric/kinematic analysis. The output of this processing can be tagging and compositing of hazard on the driver display (using the VAC2000 overlay controller), audible tones, or Generic Vehicle Architecture (GVA) compliant alerts. Figure 3 shows a diagram of a generic Level 3 ESA system. The speed of the analog real-time (essentially zero lag) video streams are not affected by the digitization process (solid green arrows). The digitized video frames are directed to the AI processor for hazard assessment and alert logic generation (dashed blue arrows). This processing can exceed the 40ms latency limit, taking a few frames of video for kinematic analysis. However, this delay is still insignificant compared to driver

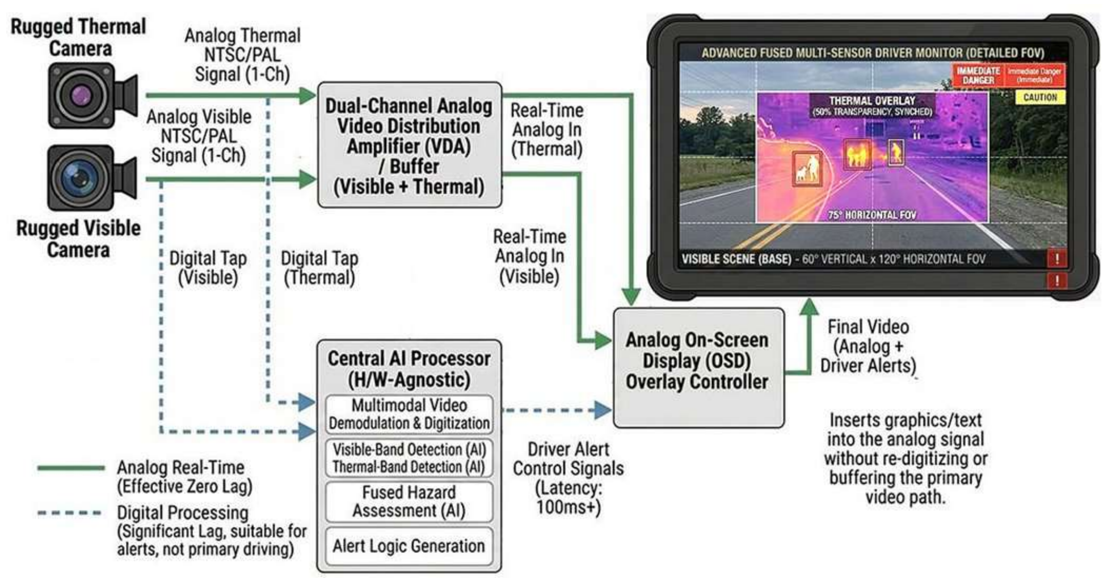

Figure 3: Example of Low-Cost Low Latency AI Assisted ESA

reaction times and particularly vehicle maneuverability. Those alerts that are displayed on the driver's monitor as composite symbols are combined with the direct view video stream 2 or 3 frames behind real-time and have no effect on the near zero lag (glass-to-glass latency) afforded the driver. [10]

In tactical military vehicle programs, Tera Operations Per Second (TOPS) requirements for edge AI cards vary based on the complexity of the situational awareness (SA) task, ranging from basic object recognition to high-end autonomous navigation. Modern systems typically demand between 20 and 275+ TOPS per module to process high-resolution, multi-sensor video feeds in real-time. As an example, the current performance tiers for Jetson tactical edge AI include the levels shown in Figure 4. The Jetson series cards run Linux and are frequently integrated into systems that meet MOSA standards.

Application Type Required	Performance (Estimated)	Common Hardware Examples
Basic Threat Detection	10–30 TOPS	Hailo-8 Jetson Nano
Autonomous Driving	40–100 TOPS	Jetson Orin NX, Rockchip RK3588
Multi-Sensor Fusion 360° SA	200+ TOPS	Jetson AGX Orin, Hailo-8 Century

Figure 4: Example AI Edge Cards

4. RECOMMENDATIONS

We recommend that a separate standard for tactical vehicles acting in a non-combat role be established based on special industrial commercial ruggedization SPECOM-STD to promote the cost-feasible implementation of enhanced situational awareness and hazard alert system on legacy vehicles. The argument for relaxing MIL-STD requirement for ESA systems (i.e. cameras, processors, and displays) on administrative and training vehicles centers on a risk-adjusted reliability. If a system isn't "mission critical" for the safe operation of the vehicle, over-engineering it for a training environment creates unnecessary prohibitive cost, resulting in no ESA being provided at all.

The 2021 Government Accountability Office report states, "The Army and Marine Corps reported 3,753 tactical vehicle accidents from non-combat scenarios and 123 resulting military deaths for fiscal years 2010 through 2019..." [11] This report concludes the Army and Marine Corps have not developed a well-defined process to fully train their tactical vehicle drivers in off-road terrain or night driving. Further, the implementation of risk management practices, (e.g. requirements for seat belts, securing potential projectiles inside passenger compartments and following speed limits) is left to first-line supervisors such as vehicle commanders. This ad hoc approach to safety issues amplifies the need for improved driver awareness.

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