Automotive Ground Vehicles' Resilience to HEMP Attack: An Emergency Management Mitigation Plan

Julian A. LoRusso,[1,2] Mariama Yakubu,[3] Wayne Sandford,[4] Jeffrey Treistman,[5] Ed Goldberg,[6] and Matt Van Benschoten[7]

[1] Senior Engineer, Roush Industries, Inc.; Hazard Mitigation Reservist, FEMA

[2] Corresponding author, jlorusso1@outlook.com

[3] Lecturer, University of New Haven, Fire Sciences & Emergency Management Department

[4] Lecturer and Program Director, University of New Haven, Fire Sciences and Emergency Management (ret)

[5] Assistant Professor, University of New Haven, National Security Department

[6] Manager, Eversource, Inc., Business Continuity, Disaster Recovery and Threat Assessment (ret)

[7] Vice President, Roush Industries, Inc., Advanced Engineering

[*see Author Capsule Bios below*]

Abstract

United States exposure to attack from a nuclear weapon of mass destruction (WMD) optimized to generate a high-altitude electromagnetic pulse (HEMP) is a concern in national security forums. Such an attack could lead to widespread damage to the electrical components of many critical infrastructures. The purpose of this study was to develop a framework to better understand the hazard risks from a HEMP attack on non-military (non-MIL), "electronics-heavy" automotive ground vehicles that could inform an effective emergency management response and recovery plan. A hybrid emergency management and engineering hazards risk analysis utilizing a Failure Modes and Effects Analysis (FMEA) format helped visualize the critical vehicle electronics subsystems and components, and their respective potential failure modes. A design of experiments test plan was developed to quantify the risks, and to develop a pathway to validate cost-effective mitigation countermeasures based on present-day best practices for HEMP hardening. The proposed emergency management plan emphasized strategic implementation of HEMP mitigation countermeasures to support continuity in emergency services and delivery of community lifelines to the public. The results of this study will serve as a foundation for future HEMP projects with

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automotive ground vehicles that will support the FEMA National Preparedness Goal, Presidential Executive Order 13865, and the recent FY2020 National Defense Authorization Act (NDAA) legislation. The methodologies can also apply to other critical infrastructure segments.

Introduction

An electromagnetic pulse (EMP) can be generated by a human source such as a nuclear weapon, a natural hazard event such as a solar flare, or an Intentional Electromagnetic Interference (IEMI) weapon, all with varying degrees of damage potential to critical infrastructure components and sub-systems. The deployment of a HEMP-optimized nuclear weapon is one form of a WMD Chemical, Biological, Radiological, or Nuclear (CBRN) attack most likely perpetrated by a state actor due to the complex technology required, and less likely by a terrorist organization. When deployed in space 30–400 km above the earth, catastrophic damage could be incurred in the electronics components on the ground over a wide geographic area without the thermal, kinetic impact, and radioactive contamination effects of close-to-ground level explosions (Radasky 2010; Ostrich and Kumar, 2017).

The reports by the national EMP Commission (2008) and Schneider (2007) presented comprehensive reviews of the potential damage by an optimized EMP nuclear device to various sectors of the critical infrastructure in the U.S. Reports by Pry (2017) and Popik et al. (2017) delineated the capabilities of technology-capable state actors and associated attack scenarios. The InfraGard (2020) National Disaster Resilience Council report presented a comprehensive analysis of the impact to critical infrastructure components in the U.S. from a HEMP attack or geomagnetic disturbance (GMD) event along with a range of strategies to achieve critical infrastructure resilience. Savage, Gilbert and Radasky (2010) discussed the vulnerability effects due to HEMP, portable Intentional Electromagnetic Interference (IEMI) devices, and Geomagnetic Storms with substantive mitigation concepts presented to improve

EMP resiliency. Executive Order 13865 (White House 2019) and corresponding FY2020 NDAA (2019) legislation called on the nation to find ways to strengthen its critical infrastructure from an EMP strike. The threat assessment matrix presented in Table 1 shows the potential impact a HEMP attack could have on critical infrastructure in the U.S. as compared to a geomagnetic disturbance (GMD) for reference, which produces similar effects as the E3 component of the HEMP waveform.

Table 1. HEMP and GMD Threats to Critical Infrastructure

(from information presented in similar tables, Ostrich and Kumar (2017), InfraGard (2020))

Attribute	EMP	GMD
Tactical Warning	None	20 to 45 minutes
Risks on equipment	E1: Telecommunications (cellular, celluar, satellite); micro-processor and micro-electronics equipment; electric power generation, transmission and distribution systems; critical infrastructure control systems; automotive vehicle controls, sensors and actuators E2: Power lines, telecommunications tower components, transformers E3: Transformers, relays, long transmission lines, generator step-up transformers	E3: same as EMP E3 damage
Footprint	Regional to continental, depending upon the weapon characteristics, height of burst, number deployed	Regional to worldwide, depending upon GMD event
Variability	Impact varies due to size of weapon (Kt), level of HEMP optimization, height of burst, radial distance from ground zero, geographic location (earth's magnetic field interactions)	Intensity increases near large bodies of water & higher latitudes. Some events observed in southern latitudes

These references support the need for an investigation into the HEMP vulnerability for modern automotive ground vehicles, a significant unknown in national security forums as well as current emergency management response and recovery plans. A new pathway was needed to define the HEMP-induced hazard risks for "electronics-heavy" automotive ground vehicles leading to validation of cost-effective mitigation measures that could be implemented nationwide to ensure that emergency management plans from a HEMP attack are effective. Specific goals for this study aimed at improving the understanding of HEMP risks and mitigation countermeasure options were:

- Develop methodologies to better understand the critical components and sub-systems vulnerable to a HEMP attack for modern electronics-heavy transportation sector automotive ground vehicles.
- Develop test plans to quantify critical component and sub-system failure modes, and to validate the effectiveness of potential mitigation design actions.
- Develop an affordable implementation plan for mitigation design upgrades and repair scenarios that can be deployed nationwide.
- Illustrate how proposed actions will enable an effective emergency management plan following a HEMP attack to restore emergency services and community lifelines to the public.

The accomplishment of these goals are intended to assist researchers, government agencies, and industry partners to develop future projects and plans to increase the resilience of automotive ground vehicles to a HEMP attack. The same methodology can be applied to other critical infrastructures to enable more effective emergency management responses.

HEMP National Security Threat

The understanding of HEMP effects from high altitude nuclear weapon detonations began in the 1960s from tests conducted by the United States and the former Soviet Union (Savage et. Al. 2010; NCC 2019). In 1962, the Starfish Prime HEMP test was conducted by the United States through the detonation of a 1.4MT device at 400 km altitude HOB generating a ~14Kv/m electromagnetic pulse at Johnson Island, about 900 miles west of Oahu, Hawaii. Fuses were damaged in ~300 streetlights in Oahu, telephone service microwave equipment was impaired, some car ignition systems failed, and burglar alarms were activated. Damage also occurred to a microwave telecom system, high frequency radio communications were disrupted, and an "artificial radiation belt of trapped electrons" damaged satellites caused by degraded solar panels. The Soviet Union also conducted HEMP tests in 1962. A 300 kT nuclear weapon was deployed at 290 km HOB. Back-up diesel generators, and overhead power and communications lines were damaged including the puncture of high voltage transmission lines, damage to power supplies, damage to electric grid safety devices, and malfunction of radio equipment.

More recently, significant concern in security forums has centered on the national security risk of state actors developing SuperHEMP weapons with capabilities and deployment scenarios that could threaten national security (e.g., Pry (2017), Schneider (2007), Albert (2019)). Technologies required for HEMP weapon development and deployment methods are within the capabilities of state actors with nuclear WMD arsenals. Weapon deployment techniques include long- or short-range missiles, satellite deployment systems, meteorological balloons, or jet airliners placed on zoom-climb trajectories. Although—for multiple reasons—it is less likely that a terrorist organization could deploy a nuclear weapon, national security forums conclude that an EMP attack from a terrorist organization is possible, particularly if a multi-site coordinated attack were to occur on targeted critical infrastructure installations (Radasky et al. 2010; Pry 2017).

Emergency Management Response and Recovery

In the composite, these and other credible threats prompt the need for a comprehensive risk assessment analysis, and a HEMP-specific hazard mitigation plan for automotive ground vehicles. This would facilitate effective emergency management response and recovery consistent with capabilities present in other national disaster scenarios. The FEMA National Response Framework (FEMA 2019) describes stabilization of community lifelines through the Emergency Support Functions (ESFs) as a primary objective following a national disaster to minimize threats to public health, safety, the economy, and national security. Figure 1 identifies the seven community lifelines that are essential to restore in the response and recovery period if disrupted by a national disaster. All of these are supported by automotive ground vehicles. If disruptions following a HEMP event prove to be significant for automotive vehicles, 911 emergency services, and timely stabilization of community lifelines supported by commercial and personal ground vehicles could be compromised leading to significant casualties and economic loss. Consistent with FEMA (2019), and Baker and Volandt (2018), community lifelines are interdependent and vulnerable to cascading failures such as the interdependency of electric power on communications systems, and fuel supply chains supporting automotive transportation sector vehicles.

(from FEMA National Response Framework (FEMA 2019))

Figure 1. Community Lifelines for Incident Stabilization

What is understood from the FEMA National Response Framework (2019) is that in the event of a major national disaster, tools are in place to stabilize community lifelines in a reasonable timeframe. This will require all critical infrastructure segments to be resilient to a HEMP or GMD disturbance. Response effectiveness to a HEMP attack will depend on the hazard risk severity to the critical infrastructure as well as mitigation measures implemented prior to such an attack. Presently there are no hazard mitigation plans for non-military automotive vehicles in response to HEMP attack. Assuming that damage risks are significant, and that mitigation upgrades could be designed and validation tested, two extreme scenarios are presented in Table 2 for mitigation measure application, and the subsequent impact on the response and recovery periods. The "mitigation measures applied" scenario, *the goal*, shows how HEMP resilient vehicles support the 3 phases of incident response with a timely restoration of the vehicle infrastructure and with minimum casualties. The "no mitigation measures applied" scenario (present status), shows that the impacts of a HEMP attack could be significant for emergency, delivery, utility, personal, and work vehicles. Such impairment would lead to long-term interruptions to community lifelines with the possibility of massive casualties and economic loss.

A functional National Incident Management System (NIMS, FEMA 2017)) is deployed in response to any national disaster or catastrophe. This assumes that a "Mitigation Measures Applied" scenario is implemented prior to the disaster. The NIMS Incident Command System (ICS) following any national disaster event operates in a multi-jurisdiction Unified Command mode requiring functional ground vehicles for Emergency Support Functions (ESFs) as described in FEMA (2019). This requires a minimum strategic investment for ground vehicles within critical infrastructures for an effective HEMP emergency response, as well as for emergency management and public use. The lack of data to quantify the vulnerability level needing to be addressed for a national HEMP mitigation strategy imposes significant risk.

Table 2. Disaster Response and Recovery Extreme HEMP Scenarios

Impact of HEMP Mitigation Measures During Response and Recovery**

Scenario	Short Term *(days)*	Intermediate *(weeks – months)*	Long Term *(months – years)*
1) Mitigation Measures Applied *(the goal)*	• Most emergency, delivery, utility & personal vehicles functional. • Damaged personal vehicles transported for repairs. • Lifeline supplies delivered to distribution sites	• Emergency services restored. • Personal vehicles repaired. • Lifeline supplies available.	• Transportation vehicle infrastructure restored. • Minimal casualties.
2) No Mitigation Measures Applied *(present status)*	• Numerous emergency, delivery, utility, & personal vehicles • Lifeline supplies in short supply	• Shortage of repair shops & spare parts for repairs. • Lifeline supplies begin to be exhausted. • Massive casualties possible	• Lifeline supplies in short supply. • Military resources limited due to national defense needs. • Massive casualties possible

*** Assumes the effect of HEMP on automotive ground vehicles is significant*

What is Needed to Close the Gaps

The diagram presented in Figure 2 *(p-diagram)* illustrates "existing measures" in the critical infrastructure to restore community lifelines in response to the "understood disaster scenarios." The "HEMP threat" to critical infrastructure is incremental to understood scenarios requiring "new measures" for mitigation action. This would assure that resilient critical infrastructure can restore community lifelines in a reasonable time to minimize casualties and economic loss. Resilient critical infrastructure would also support continuity of government in enabling the Department of Defense to conduct their mission in protecting the country from a HEMP attack (Stuckenberg et al. 2019).

To close the gaps for automotive ground vehicles for the HEMP threat, analysis was needed to identify the vulnerable components and sub-systems followed by identification of cost- effective mitigation upgrade measures. A test plan was needed to generate data to quantity the risks with current unmodified vehicles and to validate the effectiveness of the proposed mitigation countermeasures. Once new data are available, subsequent update or creation of engineering standards will capture lessons learned, and be implemented through regulatory requirements, or voluntary measures among the automotive OEMs. For vehicles that have not applied the mitigation upgrades, advanced logistics plans are needed for the repair shops and the supply chain to address repair of existing unmodified production vehicles assuming repairs could be completed in a reasonable time frame in the context of a supportive national strategy.

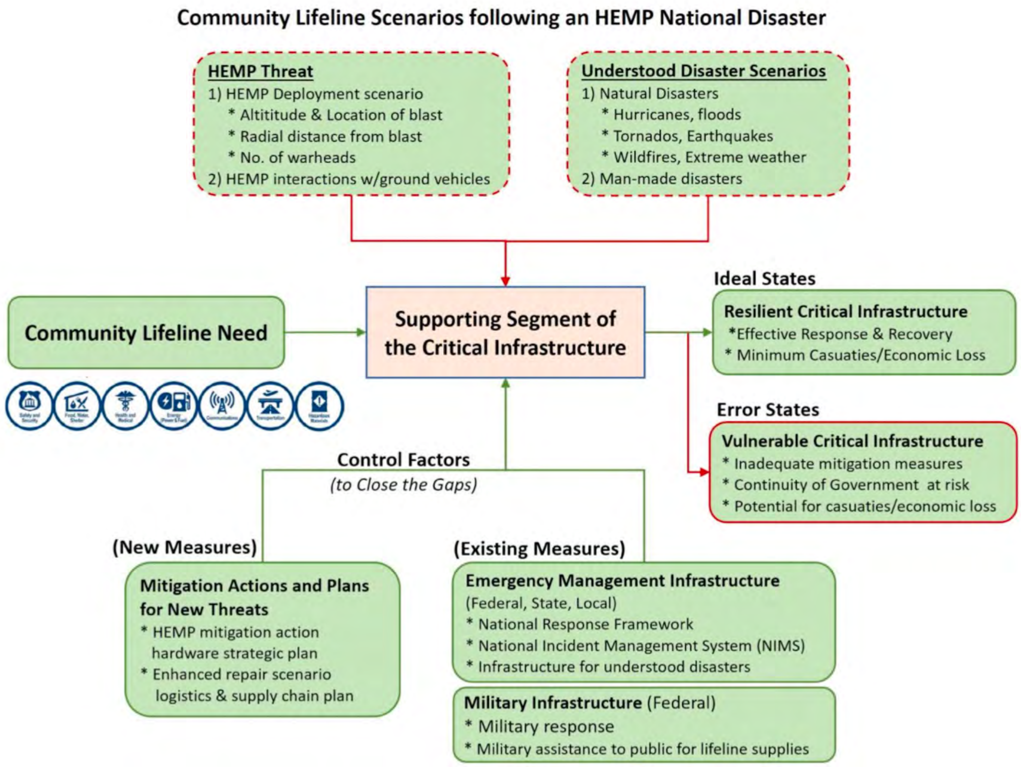


Figure 2. What's Needed to Close the Gaps
(*Incremental HEMP threat requires new measures*)

Methodology

Modern transportation sector ground vehicles make extensive use of electronic actuators, sensors and microprocessors for engine and transmission controls, and auxiliary controllers for climate control, electronic steering, vehicle entry and security interlock systems. More recently, introduction of electric vehicles (EVs) and autonomous vehicles (AV) have further increased microprocessor-based control systems, all vulnerable to a HEMP event. Testing a modern automotive vehicle for vulnerability to a HEMP disturbance with this level of electronics has never been conducted, and, consequently, testing is required to prioritize the risks and to validate potential mitigation countermeasures. A methodology was needed to help visualize the critical components and potential failure modes from a HEMP event in automotive ground vehicles, and to inform the proposed test plan and mitigation design proposal strategy.

Vehicle HEMP Mitigation Scenarios

Two mitigation pathways shown in Figure 3 were envisioned to address resilience of automotive ground vehicles to a HEMP event: a "Modified" Vehicle path to design and implement upgrades for increased HEMP resilience; and an "As-Built" Vehicle path to define logistics requirements for repair of damaged vehicles in a reasonable time. The "As-Built" Vehicle plan would likely require Defense Production Act (DPA) measures to accelerate repair of vehicles, and to address supply chain issues if damage to vehicles was extensive.

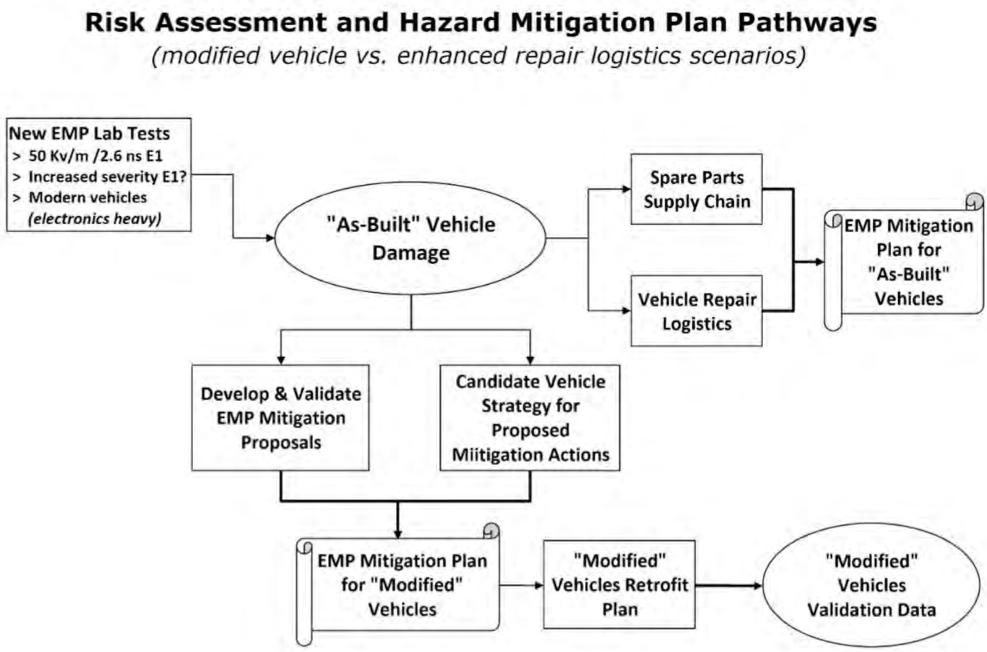


Figure 3. Mitigation Pathways to Improve Transportation Vehicle Resilience to HEMP

Table 3 describes the transportation mix for ground vehicles, their role in an emergency response, what HEMP risk assessment testing would be required, some plausible mitigation strategies, and potential consequences for inaction. The proposed mitigation strategies support the minimum that would be required to restore community lifelines and emergency services to the public following a HEMP event. Mitigation upgrades would be applied to select vehicles such as police and first responder cars and trucks, medium/heavy duty trucks responsible for delivery of lifeline supplies to the public, and utility and communications system bucket-truck repair vehicles. Once the risks and mitigation upgrades are understood, automotive original equipment manufacturers (OEMs) and cross-industry technical organizations (SAE, IEEE) could facilitate the incorporation of resilience measures into future vehicle designs if incremental cost to the customer is minimized. For Fire and EMS vehicles, a class of medium-heavy duty trucks, trade-studies should compare mitigation actions applied to the fire engines and EMS vehicles (Laracy, 2012), or alternatively, to the garages where the vehicles reside prior to deployment per MIL-STD-188-125-1/2(2005) and/or IEC-TS-61000-5-10 (2017) technical standards. Non-combat military vehicles with increased use of current off the shelf (COTS) microprocessor-based electronics components would also require a HEMP risk assessment and mitigation plan.

Table 3. Vehicle Mitigation Proposed Scenarios

Testing Requirements and Mitigation Strategy To Achieve HEMP Resilience
(proposed scenarios)

Vehicle Class	Sub-Class	Role in Response	Risk Assessment Testing	Mitigation Strategy*
Passenger cars/ Cross-Overs & Light Trucks	Police Vehicles	Law enforcement & 911 response	1) Base vehicle 2) Communication Equipment	1) Base vehicle upgrades 2) Upgrades for communications equipment
	Personal vehicles	Lifeline supplies, personal travel, work vehicles	Base vehicle	1) Select vehicle upgrades (voluntary) 2) Enhanced repair logistics via DPA
	EMS Vehicles	Medical 911 response	1) Base vehicle 2) Communication/Life Support Equipment	1a) Base vehicle upgrades 1b) Upgrades for communications/life support equipment
				2) Harden facilities/garages where EMS vehicles reside
Medium/Heavy-Duty Trucks	Deliery & long-haul tractor vehicles	Delivery of lifeline supplies to distrubtion centers	Base vehicle	1) Upgrades to select vehicles to support response/recovery 2) Enhanced repair logistics via DPA
	Fire Engines	Fire, Hazmat, Medical 911 Response	1) Base vehicle 2) Communication/Life Support Equipment	1a) Base vehicle upgrades 1b) Upgrades for communications/life support equipment
				2) Harden facilities/garages where Fire engine resposne vehicles reside
Non-Combat MIL vehicles	Vehicles with commercial hardware	Military missions and emergency response	1) Base vehicle 2) Support equipment	1) Base vehicle upgrades 2) MIL support equipment

* Consequences of inaction: *Role in response compromized / not be able to be achieved*

Component/Sub-System Visualization and Potential Failure Modes

The Interface Chart presented in Figure 4 for vehicle controls and propulsion systems was the first step in visualizing the vulnerable electrical components exposed to a HEMP event. The satellite elements surrounding the "Vehicle Controls and Propulsion System" represent the key components and subsystems for engine and transmission controls. For the engine, this included the Electronics Control Unit (ECU), wiring harness, ignition components, throttle, fuel injector actuators, valvetrain control actuators, and sensors for data input to the ECU. The transmission had a similar suite of actuators and sensors for gear shift and lock-up clutch controls. The vehicle has sensors and additional microprocessors for climate controls, dashboard displays, safety systems, and security interlock. The vehicle body materials, e.g., steel, composites, or aluminum will affect the level of attenuation of the E1 pulse as coupled to the electrical components from the external environment. A similar breakdown is needed in a follow-up study for hybrid vehicles, electric vehicles, and vehicles with autonomous drive controls.

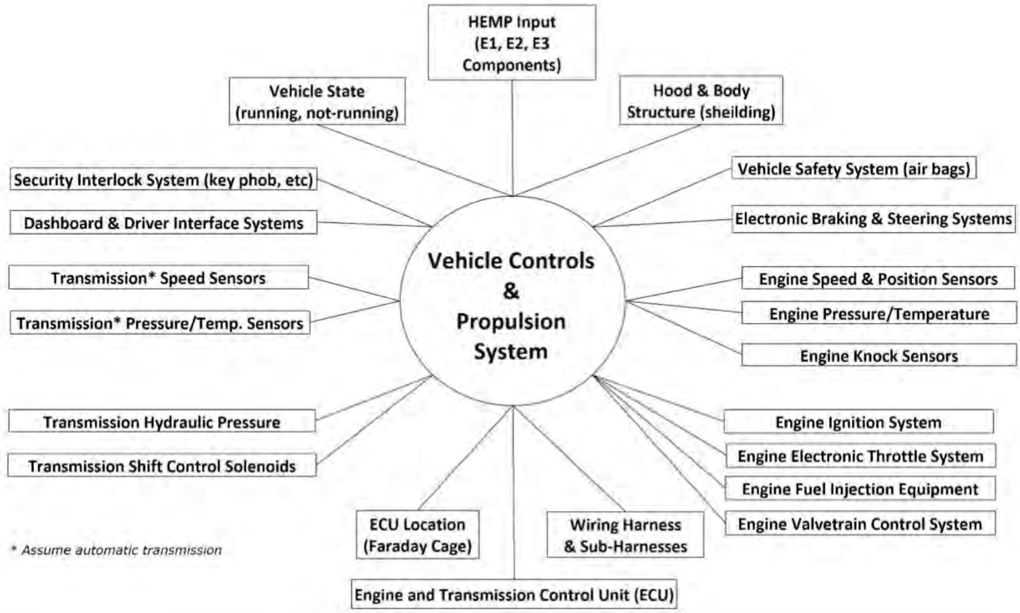


Figure 4. Vehicle Controls and Propulsion System EMP Interface Chart

Of particular interest for HEMP vulnerability is the engine control unit (ECU) which is utilized for engine and transmission controls, adaptive speed control, and numerous other vehicle functions. Internal to the ECU, the microprocessor, memory, analog-to-digital (A/D) converters, digital-to-analog (D/A) converters, signal conditioning circuitry, and numerous power MOSFETs (metal oxide field effect transistors) exist collectively for program software instructions, sensor signal conditioning, electronic throttle motor control, and control of numerous actuators such as ignition coils, fuel injectors, engine and transmission control solenoids, and emissions control valves (Ribbens 2017). Unique components for emergency vehicles would require special consideration, e.g., communications equipment for Police vehicles, and life-support equipment for Fire and EMS emergency vehicles.

The Boundary Diagram presented in Figure 5 helps illustrate the path from the HEMP energy source, e.g., a nuclear blast, to the vehicle under-hood subsystem components. The upper left source diagram shows the burst at high altitude, 30–400 km above the earth where gamma radiation is transformed into an electromagnetic pulse interacting by coupling to vulnerable critical infrastructure electronics components on the ground including automotive vehicles. The effect of the burst is directed downwards from the location of the detonation and propagates outward radially at distances determined by the height of the blast (HOB), the strength of the weapon, and how well it's optimized for HEMP. The HEMP waveform at the lower left describes the fundamental E1, E2, E3 characteristic components with the ~ 0.9 to 2.6 ns short duration E1 pulse the concern for automotive vehicle electronics components. The vulnerable sub-systems and components impacted by the HEMP environment are configured like that shown in the wiring harness illustrations on the right based on the actual vehicle wiring harness diagrams (Ford 2014).

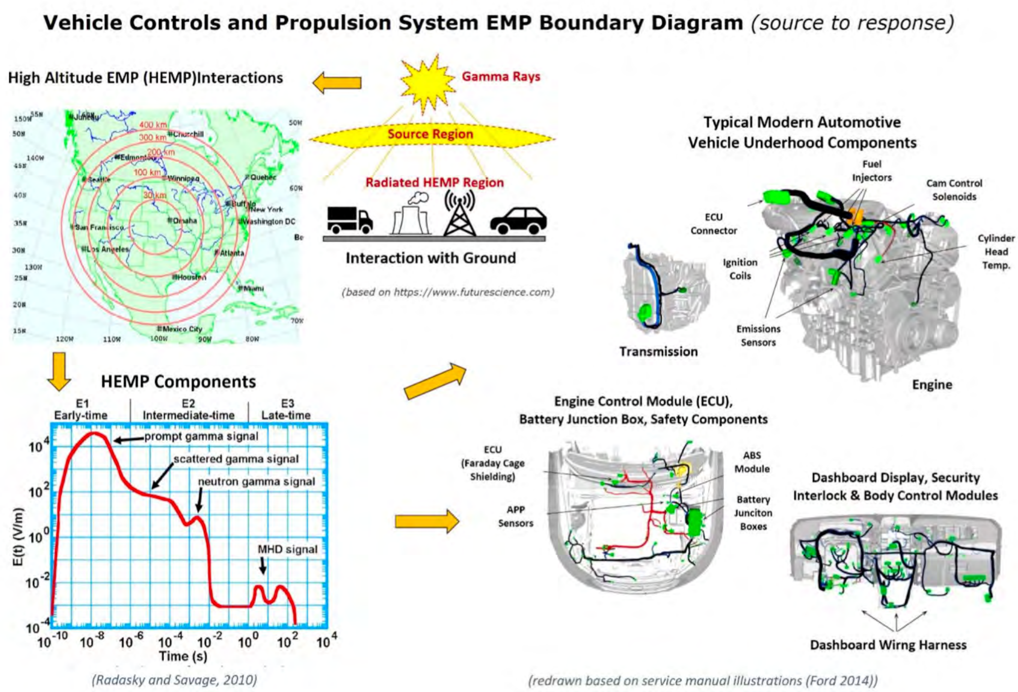


Figure 5. HEMP Boundary Diagram: *Path from HEMP Source to End-Systems and Components*

Applying the discussion of coupling from Savage, Gilbert and Radasky (2010) to the vehicle wiring diagrams shown in Figure 5, the interaction of the HEMP pulse to the vehicle electronics components is hypothesized as follows. The HEMP environment outside the vehicle is attenuated by the vehicle body structure constructed of steel (good), or aluminum/composite materials (not as good), the aperture openings (e.g., front grill, underbody openings), and varying Faraday-cage attenuation features for critical components like the ECU. The resultant electromagnetic pulse is then coupled to the conductors inside the vehicle wiring harness segments via electric/capacitive and magnetic/inductive coupling. For capacitive coupling, the EMP electric field rearranges electric charges on the conductors causing charge movements (currents) and voltages. For magnetic/inductive coupling, the high frequency wave coupled to the wiring harness section conductors cause a voltage spike rise depending upon which way the EM wave is propagating and the E & H field polarization. An E1 radiated electromagnetic field of 50 Kv/m imposed on a 0.5 m section of wiring harness, unshielded and unattenuated, could impose a 25K voltage pulse for a ~2-5 nanosecond time-period. Since all actuators and drive motors have two conductors for supply and return power, and sensors commonly have three conductors for excitation voltage and signal return, the voltage spikes imposed on these conductors could be partially balanced depending on the difference in supply and return conductor lengths for the sensor or actuator.

The results of the Interface Chart and Boundary Diagram analyses informed the initial summary of HEMP vulnerable components presented in Table 4, and the corresponding list of potential HEMP induced failure modes presented in Table 5. Since all actuators and sensors are connected similarly to either the ECU or other auxiliary microprocessors via the wiring harness,

HEMP E1 spikes could reach the input of the ECU, and due to numerous internal paths to ground, failure to the internal ECU components could result. This was an important hypothesis for mitigation design proposals.

Although it's logical to assume the engine and transmission components would be most vulnerable to HEMP, the "Dashboard Display & Body Functional Components" such as the security interlock system, safety systems for braking and electronic steering, and other autonomous vehicle functions could also be vulnerable. Experience in testing competitive vehicle engines and powertrain systems has many times shown the entire dashboard needed to be installed in the test room because of the security interlock system to the ECU. This implies that HEMP damage to the security interlock system could cause a "no-start" condition for the vehicle.

Table 4. HEMP Vulnerable Components

(Examples for IC Engine Powered Vehicles)

- Electronics Control Unit (ECU)
    - Microprocessor, memory instructions
    - Analog -to-Digital (A/D) & digital-to-analog (D/A) converters
    - Power MOSFETs for actuator controls
    - H-Bridge MOSETs for DC motor controls
    - Sensor excitation and signal conditioning circuits
- Actuators (with electromagnetic coils or piezoelectric actuators)
    - Electronic throttle drive motor
    - Fuel injectors
    - Ignition coils (port/direct injection, gasoline vs. diesel)
    - Engine/transmission hydraulic control solenoids
- Sensors
    - Traditional - Temperature, pressure sensors, air flow
    - Speed sensors - crank/ cam position
    - Engine knock sensors
    - SENT Protocol, SAE J2716, sensors (TI (2010))
- Security inter-lock systems, dashboard displays
- Exhaust emission systems monitors and sensors
- Numerous Microprocessors, ~30-100 for a modern vehicle
- Anti-lock braking (ABS), electric braking systems
- Electronic steering, driver assist lane keeping, adaptive cruise

Table 5. HEMP Potential Component / Sub-System Failure Mode

Potential Failure Modes Caused by Voltage/Current Surge from HEMP Environment

- Software and hardware interrupts requiring ECU restart or CPU memory reflash (soft failures)
- Internal ECU MOSFET (used to control all actuators) failures (hard failures)
- Actuator component failures, electromagnetic coil burn-out
- Wiring harness shorting due to over-current
- Sensor failures
    - Traditional sensors -- signal conditioning hardware or sensor failures
    - SENT Protocol (SAE J2716) sensors
- Security inter-lock system, dashboard display system, body control module (micro-processor interrupts)
- Failures in vehicle safety systems such as electric steering, electric braking, anti-lock braking, adaptive cruise control systems

Mitigation Proposals

Historical Approaches

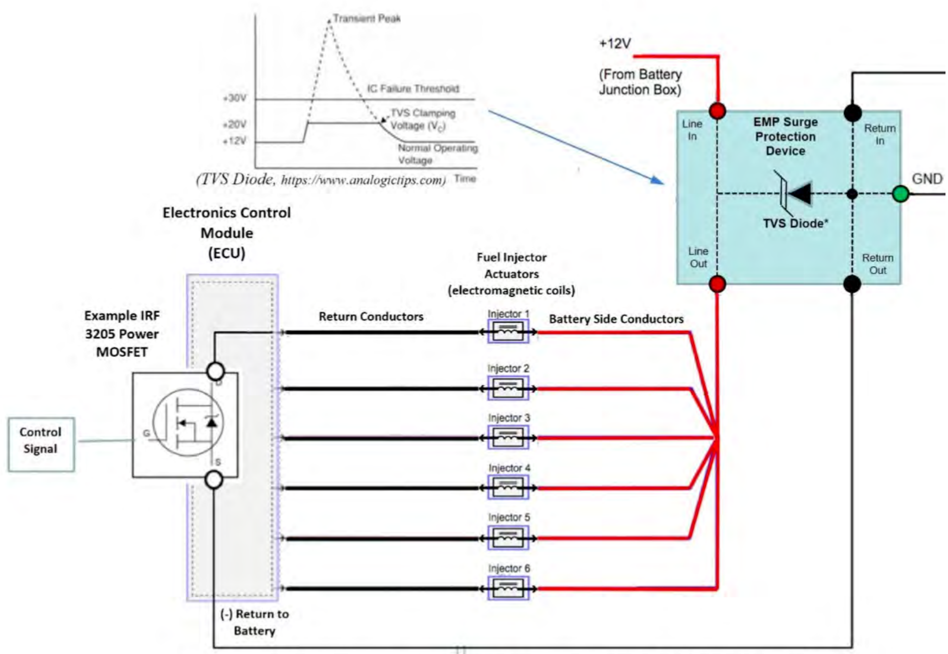
HEMP mitigation actions applied to facilities and military vehicles are well known and documented in MIL-STD-125-1/2 (2005), MIL-STD-464C (2010), and International ElectroTechnical Commission (IEC) Subcommittee (SC) 77C published standards for HEMP and IEMI (Radasky and Savage 2010). These standards provide HEMP resilience via Faraday cage shielded electronics components, shielded cables, and bounding metallic structures to a single point ground, aperture treatments, and conductor treatments via electrical bonds, isolators filters and voltage suppression devices. The IEC TS 61000-5-10 (2017) and MIL-STD-188-125-1 provide a useful reference for protecting the garages where EMS or fire engine vehicles reside as an alternative to the more costly hardening of the vehicles themselves. In automotive ground vehicles, some of these principles are applied; otherwise, electromagnetic interference and electromagnetic compatibility standards (EMI/EMC) would not be achievable due to noise interference from the high voltage ignition system or external vehicle noise sources.

Proposed Mitigation Designs

Baseline technologies applied for EMI/EMC, some common to the MIL and IEC standards, will provide a starting point for HEMP protection. Unlike combat vehicles, most automotive ground vehicles could allow for some level of interrupt from a HEMP event with possible exceptions for emergency vehicles. A plausible National strategy would be to maximize a sufficient level of resilience to allow a response and recovery period to be completed within a reasonable time following a HEMP disaster, similarly to known natural disasters.

A cost-effective HEMP mitigation concept is a transient voltage suppression (TVS) device applied to the 12 or 24V power source. The fast-response TVS device would trigger passively, creating a shunt (short) to ground during a HEMP event reducing the magnitude of the voltage spike seen by the ECU and the under-hood electronics components to a safe level. If the concept is validated experimentally, TVS devices could serve as a high-value, low-cost mitigation option with little disruption to the under-hood electronics components.

In Figure 6, the TVS surge protection concept is shown connected externally to the wiring harness between the positive to negative terminal of the battery and the ECU/vehicle chassis ground return. The chassis ground is a floating ground; hence, during a HEMP event, a voltage potential would exist between the chassis ground and earth ground. TVS devices are marketed commercially by EMP Shield (2020) and Transtector (2020) incorporating Metal Oxide Varistor (MOVs), Silicon Avalanche Suppressor Diode (SASDs), or Gas Discharge Tube (GDTs) suppression concepts with varying cost, rise-time, and E1 peak amplitude protection. TVS devices could be implemented as low-volume after-market conversions for police and emergency vehicles, select medium-duty/heavy-duty delivery vehicles, and selected or interested passenger car and truck customers. Once the function and design configurations are understood, large volume production for future OEM vehicles could be considered.



(Injector Circuit Example, re-drawn illustration from service manual information, (Ford 2014))

Figure 6. Power Source EMP Surge Protection, Concept to Protect Vehicle Electronics

In the event that additional HEMP power surge protection is required, selective application of filters, inductive choke ferrites, and additional surge protection hardware could also be used. The complexity of the electronics in a modern transportation sector vehicle would require a mitigation solution that avoids disruption to the wiring harness assembly for validation testing and small volume production. This could be accomplished by an interface module installed between the wiring harness connector(s) and the vehicle firewall connector for the ECU. Inside the interface module, additional filters, ferrite inductive chokes, surge protectors could be installed per requirements identified during HEMP testing. The interface module and additional harness sections could employ a Faraday Cage enclosure and shielding concepts per the IEC or MIL standards.

Prioritized Risk Analysis

The HEMP functional diagram for the "Vehicle Controls & Propulsion System" presented in Figure 7, commonly called a "p-diagram," was used to inform the risk analysis Failure Modes Effects Analysis (FMEA) worksheet, the test plan parameter definitions, and the mitigation design options for HEMP resilience. The "Input" representing "Driver Demand" would define vehicle states coincident with the HEMP event, e.g., vehicle entry and start-up, idle, drive-away to reach a required destination, and safe shutdown and exit from the vehicle.

The output "Ideal States" imply the vehicle fulfills driver demands, robust to the influence of the "noise factors," e.g., the HEMP event, and associated variability factors. The "Error States" imply the vehicle failed to deliver the driver demands with anomalies such as vehicle entry not possible due to issues w/security system, vehicle will not start, vehicle not running/runs erratically, or vehicle safety systems malfunction. The "Control Factors" describe the mitigation countermeasures, some inherent to the base vehicle design for EMI/EMC mitigation, and the incremental design features for HEMP resilience. It is well known that design and validation of a vehicle for EMI/EMC standards provide a foundation for HEMP resilience measures due to actions taken for enclosures (Faraday cage), shielding, grounding, and use of ferrite chokes for noise suppression. The lowest cost incremental mitigation concepts include the transient voltage suppression (TVS) devices, chokes and filters, and implementation of incremental filters within an interface module without disruption to the parent vehicle wiring harness. Higher cost incremental options, hopefully not required, would involve re-design of the wiring harness, sensor/actuator/processor design changes, or aperture treatments.

The error states from the p-diagram become the potential failure modes for the Failure Modes and Effects Analysis (FMEA) worksheet, a reliability analysis sheet introduced by the U.S. Military in the 1940s and widely used in engineering for product design and validation test planning (U.S. Army 2006). A similar analysis has also been applied for emergency management hazard risk assessment

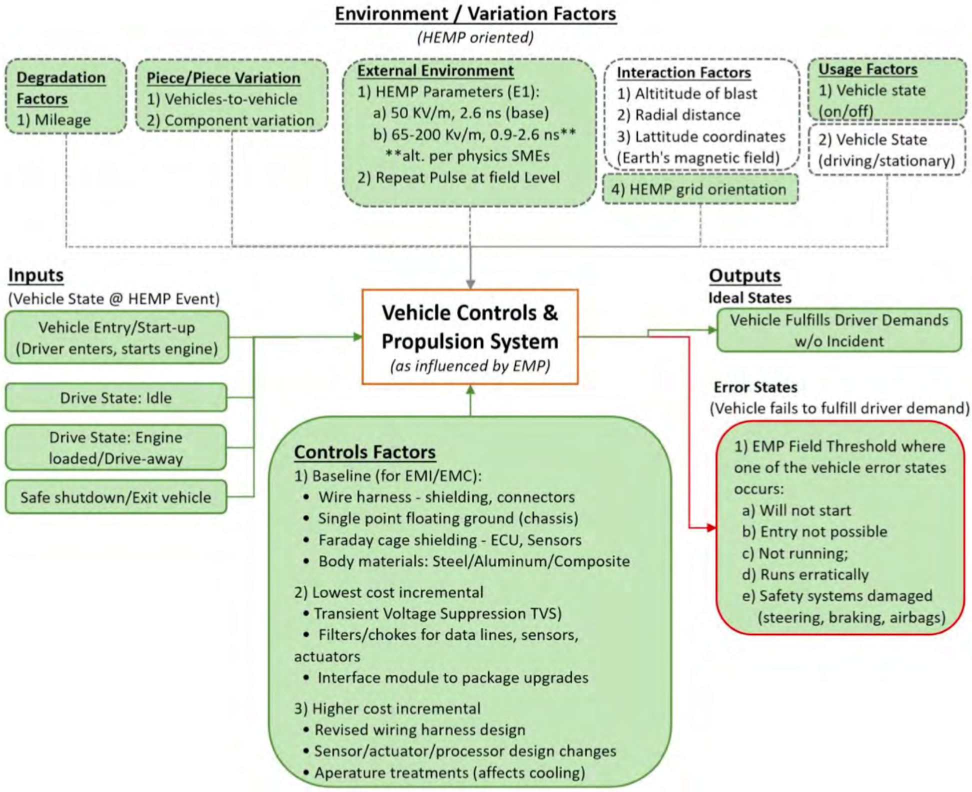


Figure 7. HEMP Functional Diagram for Test Planning *(p-diagram)*

Table 6. Failure Modes and Effects Analysis (FMEA) for Example HEMP Failure Modes

Failure Modes and Effects Analysis (FMEA)
(HEMP Example, Automotive Ground Vehicles)
Prepared By: Jules LoRusso | Rev. 12/02/2021

<<<< Based on severe damage assumption (Pry 2017) >>>>

					Priority Risk Index (PRI)							Adjusted PRI					
System / *Component* / Function	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes of Failure	Current Control Methods / Comments	Probability	Impact	Spatial	Warning	Duration	PRI Index	Recommended Action(s)	Probability	Impact	Spatial	Warning	Duration	PRI Index
Engine System / ***Engine Control Unit (ECU) /*** Control Engine Speed and Load per Driver Demand	Software Interrupt. Vehicle requires re-start	Vehicle coasts to stop. Vehicle driveable after re-start.	EMP Voltage surge caused software interrupt.	Existing ECU protections for EMI/EMC	3	1	3	4	1	2.30	None. Same PRI metrics.	3	1	3	4	1	2.30
	Hardware Interrrupt ECU requires re-flash at dealership	Vehicle coasts to stop. Vehicle not driveable	EMP voltage surge caused memory loss in ECU	Requires dealership to re-program ECU	3	3	3	4	3	3.10	Enhanced logistics to increase repair shop capacity (DPA applied)	3	1	3	4	1	2.30
											Mitigation actions implemented, TVS devices, filters.	2	1	2	4	1	1.80
	Hardware Failure. ECU requires re-build or replacement	Vehicle coasts to stop. Vehicle not driveable.	EMP voltage surge damaged internal ECU components	None. ECU requires replacement. Likely supply chain & repair shop capacity issues.	3	3	4	4	4	3.40	Enhanced logistics to increase repair shop capacity (DPA applied)	3	1	4	4	3	2.70
											Mitigation actions implemented, TVS devices, filters.	2	1	2	4	2	1.90
Engine System / ***Throttle Position Sensor (TPS), SENT Protocol, SAE J2716 /*** Twin redundant, angular position to ECU	TPS Sensor failed, does not provide feedback signal to ECU	Vehicle not driveable. Electronic throttle body must be replaced.	EMP voltage surge caused over-voltage to excitation circuits.	SENT protocol sensors are more robust to EMI	4	3	4	4	3	3.60	Enhanced logistics to increase repair shop capacity (DPA applied)	3	1	3	4	1	2.30
											Mitigation actions implemented, TVS devices, filters.	2	1	2	4	2	1.90

PRI Index = [(PROBABILITY x .30) + (IMPACT x .30) + (SPATIAL EXTENT x .20) + (WARNING TIME x .10) + (DURATION x .10)] analysis described by Stamatis (2019). The worksheet presented in Table 6 utilizes a hybrid engineering-emergency management format for documenting potential failure modes, consequences of the failure, potential causes, current control methods, and a unique emergency management Priority Risk Index (PRI) metrics system to quantify the risks and recommended countermeasures. Four example failure modes are documented in the worksheet. The PRI metrics explained in New Hanover (2010) utilized 5 factors with a formula to create a composite PRI index risk factor. The factors are *Probability*, *Impact, Spatial Extent, Warning Time*, and *Duration*. The worksheet shows the PRI risk index prior to application of the mitigation actions, and the adjusted PRI index after the mitigation actions are applied. Once the test program commences and real failure mode data are obtained, the FMEA worksheet method will provide a pathway for prioritizing and implementing the design upgrades to support an effective emergency management mitigation plan in response to a HEMP event.

Logistics – Logistical In-Depth Analysis (LiDA)

The second mitigation scenario presented in Figure 3 relied on logistics with repairs of "unmodified vehicles" in the dealerships and service garages, addressing ramp-up needs for service technicians, and dealing with supply chain issues due to shortage of replacement parts.

The "Logistical In-Depth Analysis (LiDA)" introduced by Austin (2017) was used to analyze the logistics in repairs of automotive vehicles that have not implemented HEMP resilience upgrades, and are described in detail by the parent study (LoRusso 2020).The analysis considered the following logistical factors: procurement and cost; transportation to point of receipt; staffing and equipment; storage requests; distribution and transportation requests; security and site control; safety issues; de-mobilization requirements; and other requirements. For each of the logistical requirements, documentation was provided for: the method of obtaining the resource; training to support that logistical factor; and are other logistical factors needed to support the higher-level requirement.

The methodology was used for a hypothetical HEMP attack addressing the logistical requirement "Repair of Vehicles at Dealership or Service Garages." This analysis yielded a significant incremental list of requirements that extended well beyond the simple list of vehicles and requirements presented in Table 3 from inspection of the FEMA emergency response documentation. Factors addressing the surge in vehicle repairs in repair shops has never been addressed, including how to transport the damaged vehicles to garages, addressing the need to train additional service technicians, and dealing with supply chain part deficits such as ECUs with significant microprocessor and semi-conductor chip content. The need to implement the Presidential Defense Production Act (DPA) to facilitate and enhanced repair scenario for HEMP damaged vehicles would also be required.

Verification and Validation Test Plan

A verification and validation (V&V) test plan will first determine if a vehicle conforms to codes and standards for HEMP resilience, the verification step—and then generate test data to confirm a new design action is effective for HEMP resilience, the validation step. Codes and standards would be generated in technical organizations such as SAE and IEEE based on the data and lessons learned from HEMP testing. The proposed test plan to complement the risk assessment analysis was developed for two vehicle groups supporting delivery of community lifeline supplies to the public:

- Cars/Crossovers and light trucks representing personal transportation, work, and emergency vehicles.
- Medium-duty (MD) and heavy-duty (HD) trucks representing delivery and transport vehicles, utility repair vehicles, and 911 response vehicles.

The plan addressed the gaps with the historic test data:

- Significant increase in electronics content since the 1982-2003 MY vehicles were tested in 2004 by the EMP Commission (2008).
- Peak E1 levels for optimized HEMP weapons could exceed the MIL-STD-125-1/2
- (2005) and DOE-EMP (2021) 50 Kv/m levels with faster rise times as discussed by Wilson (2008), Giri and Prather (2013), Pry (2017). It is recognized the E1 recommendations from these references need to be reconciled with the recent DOEEMP (2021) recommended HEMP waveforms which state the original MIL-STD-464C, 50 Kv/m, 2.6 nanosecond rise time E1 levels are acceptable for benchmark design sign-off testing.

Comments on 2004 EMP Commission Tests

The EMP Commission (2008) conducted vehicle tests on a range of passenger cars, pickups and tractor-style trucks providing a baseline for risk analysis, and the proposed path forward for this study. Thirty-seven passenger cars between 1982 and 2002MY with simulated HEMP environments up to 50 KV/m were tested with engine-on vs. engine-off operational states. The most serious effects observed were cars in the running state (engines on) causing the vehicles to glide to a stop requiring re-start, and in one vehicle, the dashboard system was damaged requiring repair. Most vehicles exhibited malfunctions considered a nuisance such as blinking dashboard lights, all of which could be likely repaired in a dealership repair bay. Similar tests were conducted on eighteen trucks ranging from gasoline powered pickups to large diesel-powered tractors, model years 1991 to 2003. Three of the truck engines stopped, two were re-started successfully, and one needed to be towed to a garage for repair. Ten of the trucks exhibited minor temporary responses. Five trucks did not exhibit any anomalous response up to 50 KV/m.

The data from the 1982-2003 model year vehicles were significant even though many additions in electronics content occurred for present *electronics-heavy* automotive ground vehicles. For the 2000-2003MY range of vehicles tested, all gasoline engine powered vehicles incorporated sequential electronic fuel injection and electronic ignition, and significant use of emissions control equipment requiring various sensors, actuators, and electronic motor drives. The fact that damage observed was very modest given the magnitude of the EMP pulse suggests that there was significant faraday cage attenuation of the HEMP pulse from the external environment to the vehicle under-hood electronics, likely implemented for EMI/EMC protection. It may also imply that although a voltage spike was imposed on the wiring harness, the nature of how the conductors are arranged in-route to actuators and sensors could lead to a balancing effect for applied voltage, or dissipation effects with the internal coils for the actuators. The requirement to re-start following the simulated HEMP event implied that an interrupt occurred in the ECU. These observations support the proposed mitigation strategy utilizing TVS devices and selective filters all without major tear-up to the under-hood wiring system.

Testing

Test Labs

To support the HEMP test plan proposals, a survey of available test labs was conducted and presented in the parent study (LoRusso 2020). For simulated HEMP testing, the White Sands Missile Range (WSMR), the Patuxent River Test Lab, and the Advanced Fusion Systems test lab in Connecticut can accommodate a large-format full vehicle simulated HEMP test. The Elite, Keystone Compliance, Dayton Brown and NTS test labs are private labs which can accommodate component bench-top and medium-format HEMP testing with options to upgrade for a full vehicle system level test. All labs can test to the MIL-461-G (2015) or IEC-61000-4-25 technical standards. Sandia National Labs and EPRI also have HEMP test capabilities. All labs conducted full vehicle EMI/EMC testing in an anechoic chamber.

Based on the lab interviews, costs per shift (test day) ranged from $2500 to $10,000/shift except for Pax River which is more costly to accommodate full aircraft and naval vessel testing. For planning purposes, this cost range was used since—once a procedure is established for the proposed multi-vehicle tests—the process will be sufficiently repetitive, supporting a lower-mid range cost estimate. Test preparation and oversight costs were also considered for vehicle instrumentation, test procedure development, test oversight at the labs, data analysis, and report creation, which were assumed to be similar to the test lab costs. For the test plan and procedure to be discussed, it's safe to assume one vehicle test per shift until experience is gained in executing the procedures. At least 5 shifts should be allowed for initial test setup and procedure validation.

Design of Experiments Test Plans

The proposed simulated HEMP test plan utilized a core design of experiments (DOEx) multi-vehicle test matrix to allow the main effects and interaction effects from the parameters of interest to be quantified. Once the interaction effects are understood, a supplemental set of vehicle tests could be conducted at worst-case test conditions to measure the varying simulated HEMP sensitivities, or to evaluate proposed mitigation hardware upgrades.

Table 7. Test Plan Independent Variables for Cars/Crossovers and Light Trucks (x-factors)

DOEx Test Plan Independent Variables (x-Factors)

(Levels, implementation means, rationale for testing)

Factor	Name	Levels	Implementation	Rationale
X1	Vehicle Type	X1.1) Crossover/Hybrid	Toyota Priius, Ford Edge, Chevy Volt	• Present and future vehicles for personal transportation, government support vehicles
		X1.2) SUV	Ford Explorer, Chevy Tahoe, Chevy Suburban, Dodge Durango	• Police vehicles o Tests with parent OEM vehicles o Incremental tests w/communications equipment
		X1.3) Pickup-Aluminum Body	Ford F150	• Personal transporation & work vehicle (PTWV) • Less attenuation of E1 w/aluminum body
		X1.4) Pickup-Steel Body	Chevy Silverado, Dodge Ram, Toyota Tahoe	• PFWV • More attenuation of E1 w/steel body structure
X2	HEMP E1 Field	X2.1) 50 Kv/m, 2.6 ns rise time	Equipment specified by RS-105 Test procedure (MIL-STD-461-G)	• Benchmark waveform specified in DOE-EMP (2021), MIL-STD-461-G (2015) RS105, IEC-61000-4-25. • Benchmark levels, "must-pass" sign-off test
		X2.2) 65-200 Kv/m, 0.9 to 2.6 ns rise time	Possibly different test equipment from HEMP generator for R-105.	• Multiple references, optimized EMP weapons, E1 > 50 Kv/m o Giri and Prather (2013), 65 Kv/m @ 0.9 ns o Wilson (2008), Pry (2017)), E1 max ~200 Kv/m *(Needs discussion w/HEMP physics SMEs. May not be reqd. due to DOE-EMP (2021) recommendations)*
X3	Orientation	X3.1) Parallel to E1 HEMP grid	Per illustration in Table 8, vehicle oriented on test pad relative to grid.	• Affects wiring harness-HEMP interactions • 0, +/-30 variation provides additional orientation info w/repeat pulse data.
		X3.2) Orthoganal to E1 HEMP grid		
		Secondary x- factors		
X4	Body Material	X4.1) Aluminum Body	F150 has aluminum body	• Less E1 attenuation for Aluminum body. • Composites further reduces E1 attenuation.
		X4.2) Steel body	Chevy Silverado, Dodge Ram, Toyota Tundra all have steel body	• Increased E1 attenuation for steel body
x5	E1 Repeat Pulses	X5.1) 1st pulse	0 deg orientation in test chamber relative to paralllel or orthogonal orientation (see Table 8)	• Measure of repeatabilty with small changes in orientation. • Repeat E1 pulses simulates multiple warhead attack scenarios well known from the Cold War era.
		X5.2) 2nd pulse	+30 deg offset for repeat pulse test	
		X5.3) 3rd pulse	-30 deg offset for repeat pulse test	

Two design of experiments test plans are proposed, the first for Cars/Crossovers and Light Trucks, and the second for Medium-duty Delivery and Heavy-Duty Commercial Trucks. In Table 7**,** the x-factors recommended for first DOEx test plan are presented along with the rationale for the levels during HEMP testing. This test group would represent personal transportation, work vehicles, and select police/emergency vehicles. In Table 8, these factors are incorporated into the DOEx test plan and once executed, the data will provide the following information:

- A means of measuring the main effects described by the x-factors.
- A means of quantifying the interactions, e.g., is the response to E1 level more significant when the body structure is aluminum vs. steel due to attenuation effects.
- A measure of repeatability and reproducibility along with information on vehicle orientation relative to the simulated HEMP generator.

Table 8. Design of Experiments (DOEx) Test Plan Proposal: Cars/Crossovers & Light Trucks

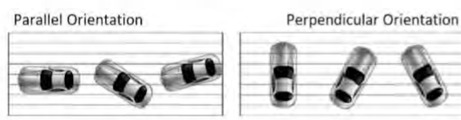
Simulated HEMP Design of Experiments (DOEx) Test Plan

(Passenger Car/Crossover & Light Trucks)

x-factors

Run No.	Vehicle[1]	Simulated HEMP Peak E1 Level[2,3] (KV/m)	Simulated HEMP 10-90% Rise Time[2,3] (ns)	Vehicle Orientation[4]
1	SUV	50	2.6	Perpendicular
2	Pickup-Alum	65/max	0.9-2.6	Perpendicular
3	Pickup-Alum	50	2.6	Perpendicular
4	PassCar/Crossover	50	2.6	Perpendicular
5	Pickup-Alum	65/max	0.9-2.6	Parallel
6	Pickup-Steel	50	2.6	Perpendicular
7	Pickup-Steel	65/max	0.9-2.6	Parallel
8	PassCar/Crossover	50	2.6	Parallel
9	Pickup-Steel	50	2.6	Parallel
10	SUV	65/max	0.9-2.6	Perpendicular
11	Pickup-Steel	65/max	0.9-2.6	Perpendicular
12	PassCar/Crossover	65/max	0.9-2.6	Parallel
13	SUV	50	2.6	Parallel
14	Pickup-Alum	50	2.6	Parallel
15	PassCar/Crossover	65/max	0.9-2.6	Perpendicular
16	SUV	65/max	0.9-2.6	Parallel

	Proposed Test Sequence Per Run No. Configuration**
1	Install vehicle; setup instrumentation; diagnostics
2	a) HEMP Pulse generator set to **10%** of peak E1 setting
	b) EMP test w/engine off
	c) EMP test w/engine on, 3 repeat tests
3	Repeat at **20%** of desired E1 peak setting
4	Repeat at **50%** of desired E1 peak setting
5	Repeat at max**%** of desired E1 peak setting
**	For steps 2 - 5, run detailed vehicle diagnostics w/drive evaluations



Notes:

(1) Design of Experiments x-factors described in detail in Table 7

Given the projected costs/test for the laboratory and support engineering, such a plan was estimated at ~$100,000-$250,000 for lab costs to run the tests, and likely a similar $100,000-$250,000 amount for test planning, data analysis, and final report out. The cost estimate for purchase of the vehicles was ~$450,000 assuming 2-year pre-owned vehicles purchased. These costs based on the parent study (LoRusso 2020) provide an idea of test costs that must be refined at time of testing.

A DOEx test plan was also created for Medium-duty (MD) and Heavy-duty (HD) trucks representing vehicles for emergency services, delivery of lifeline supplies to the public, critical infrastructure repair services, and public transportation. The x-factors were identical to the factors presented in Table 7 for cars/crossovers and light trucks, with 3 different classes of truck style vehicles (the X1 factor):

- *Delivery Van* (e.g., Ford Transit, Chevy Express, GMC Savanna, Mercedes Sprinter, Dodge Ram), vehicles used for local deliveries, work vehicles, and are typically gasoline or diesel engine powered.
- *Medium Duty Delivery/School Bus* (e.g., International, Blue Bird), vehicles used for school buses, local box trucks, and importantly for a HEMP emergency response, utility repair "bucket" trucks, and are typically gasoline or diesel engine powered.
- *Heavy Duty Over-the-Road Tractor* (e.g., International, Kenworth, Volvo, Mercedes), vehicles used for transport of supplies to the public to restore community lifelines, which are typically diesel engine powered.

Since the truck DOEx test matrix utilized only 3 vehicle types, the proposed test plan was reduced to a 12-run matrix, similarly to that presented in Table 8. All MD and HD trucks have significant diesel IC engine content with similar "electronics heavy" content; hence, vulnerable to a HEMP event like the car/cross-over and light truck vehicle mix. The proposed test procedures were identical to the car/light truck procedures. The test chamber must accommodate a much larger vehicle with sufficient surrounding area for drive evaluations. Since there were less vehicles run in the truck test matrix, 12 vs. 16, estimated costs for lab time and engineering support for MD and HD trucks were slightly less than projections generated for cars and light trucks, with procurement estimated cost of ~$650,000 for purchase of 2-year-old vehicles. The special handling for running larger format vehicles in the test labs, e.g., over the road tractor style vehicles would require an additional cost analysis.

Cost Estimates for HEMP Mitigation Upgrades

Cost estimates were created for a targeted implementation of HEMP vehicle upgrades to support emergency services and delivery of lifeline supplies to the public considering the number of police vehicles, emergency vehicles and deliver vehicles in the U.S. (LoRusso (2020). Nonrecurring costs were estimated in the range of $5-10 M for testing and prototype development costs for mitigation upgrades, subject to refinement once a formal development program is initiated. Assuming an initial estimated upgrade cost range for a short-term mitigation solution, e.g., $500-$3000 for parts and ~$500 for labor, a preliminary nationwide implementation for HEMP mitigation upgrades was projected at ~$2 billion to $3 billion based on estimates for the number of police vehicles, EMS vehicles and MD/HD delivery vehicles required to deliver lifeline supplies and emergency services to the public following a HEMP event.

Even if these costs were adjusted by a factor of 5, nationwide implementation would still be far less than typical costs for a regional disaster hurricane Katrina and Superstorm Sandy, with costs of ~$170 billion and $74 billion, respectively. Initially HEMP mitigation upgrades can be applied to select vehicles to achieve the desired level of preparedness for emergency management response and recovery efforts short-erm. Longer term, providing that HEMP mitigation design upgrades are cost-effective, the automotive OEMs can consider implementing these actions in future model year vehicles, particularly if this becomes a regulatory requirement or a cross-industry cooperative agreement. Cost estimates for the repair of "unmodified" vehicles via the enhanced logistics analysis would be the subject of a future study.

Discussion

From a national security and emergency management perspective, no disaster has occurred approximating the substantial effects of a HEMP attack. Substantial vulnerability exists across the nation's critical infrastructure segments to such an event. A HEMP attack could lead to massive casualties and economic loss without proper mitigation measures applied, assuming the impact on the critical infrastructure is significant. Executive Order 13865 (White House 2019) stated "the Federal Government must foster sustainable, efficient, and cost-effective approaches to improving the Nation's resilience to the effects of EMPs." For automotive ground vehicles, data are needed to quantify the hazard risks for current "electronics heavy" production vehicles, and to validate the effectiveness of cost-effective mitigation measures. Strategic implementation of cost-effective HEMP countermeasures that can be implemented nationwide for automotive vehicles that will build critical infrastructure resilience to enable emergency management response and recovery plans to be effective. Once the mitigation countermeasures have been validated, appropriate engineering standards can be developed in collaboration with technical organizations to serve as a reference for legislation calling for a particular level of resilience for the given vehicle application. The goal would be to have a V&V process that can first verify a design compliant with codes and engineering standards enabling HEMP resilience, and second, to conduct standardized tests to validate proposed design upgrades for production sign-off. The same approach outlined in this report can be applied to remaining categories of critical infrastructure. Policy makers can use these concepts to implement critical infrastructure resilience best practices.

Conclusions

The national security threat from a HEMP attack—and related emergency management response and recovery—vulnerabilities prompted the need for a comprehensive risk assessment analysis, and a HEMP-specific hazard mitigation plan for automotive ground vehicles. A methodology was developed to assess the hazard risks for vehicles using a hybrid emergency management and engineering assessment method for failure modes analysis and risk prioritization. A comprehensive design of experiments (DOEx) test plan was developed for passenger car/crossovers, light trucks, and medium/heavy-duty trucks to generate data supporting an emergency management hazards risk analysis for modern-day transportation sector vehicles. Preliminary mitigation countermeasure proposals were developed to improve HEMP resilience. A plan was developed on how the resilience measures for automotive ground vehicles can be strategically implemented to assure continuity of community lifelines following a HEMP attack. An enhanced logistics system for repair of unmodified vehicles impacted by a HEMP event was discussed. Cost estimates were created for risk assessment testing, validation testing of mitigation upgrades, and strategic implementation of mitigation upgrades nationwide. Integrating these concepts into emergency management mitigation plans will help assure community lifelines and emergency services can be delivered to the public following a HEMP attack, minimizing hardship to the public, casualties, and economic loss.

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Acronyms and Abbreviations

DOEx	Design of Experiments (testing terminology)
E1	1st part of Electromagnetic Pulse Waveform
E2	2nd part of Electromagnetic Pulse Waveform
E3	3rd part of Electromagnetic Pulse Waveform
ECU	Electronics Control Unit – microprocessor for vehicle controls
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMP	Electromagnetic pulse
EMS	Emergency Medical Services
FEMA	Federal Emergency Management Association (part of DHS)

FMEA	Failure Modes and Effects Analysis
GMD	Geomagnetic Disturbance
HEMP	High Altitude Electromagnetic Pulse (used interchangeably with EMP)
HOB	Height of Burst for nuclear weapon generating electromagnetic pulse
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kv	Kilovolt (e.g., 50 Kv = 50,000 volts)
MIL	U.S. Military (in reference to military vehicles and facilities hardened for EMP)
MIL STD	U.S. Military (in reference to military technical standards)
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
MOV	Metal Oxide Varistor
MY	Vehicle Model Year
NCC	National Coordinating Center for Communications
NDAA	National Defense Authorization Act
Non-MIL	Non-Military (in reference to transportation sector vehicles)
ns	Nano-second, (0.000,000,001 seconds)
OEM	Original Equipment Manufacturer (e.g., Ford, GM, FCA, Toyota, etc.)
p-diagram	Parameter diagram used for reliability analysis
PRI	Priority Risk Index (emergency management metric used for FMEA risk analysis)
SAE	Society of Automotive Engineers
TVS	Transient Voltage Suppression (HEMP surge protection device)
V&V	Verification and Validation (related to test plan for design sign-off)
WMD	Weapon(s) of mass destruction

Author Capsule Bios

Julian A. LoRusso is a Senior Engineer for Roush Industries and a FEMA 406 Hazard Mitigation reservist serving the public in disaster response, recovery, and mitigation planning. He spent 30 years at Ford Motor Company and 12 years at Roush Industries, Inc. He holds a BS ME degree from Purdue, an MS ME from MIT, a MS in EE Control Systems from Wayne State, and an MS in Emergency Management from the University New Haven. He is a professional engineer (PE), a member of the IAEM, ACP, IEEE, SAE, and AIAA. At Ford, key accomplishments included combustion research with automotive engine emissions, design and development of advanced-concept engine control systems, and product engineering performance, durability, and calibration testing. He is trained as a Six Sigma Black belt involved in problem solving for critical warranty issues. He was a leader of Ford's worldwide engine test procedure committee. He originally joined Roush to help build their diesel engine design and development capabilities. He was lead technical specialist for a H2-O2 fueled internal combustion engine and auxiliary power generation system designed for space flight, partially funded by NASA, which included design and oversight of hazardous fuel testing at two rocket propulsion labs. He is presently Testing Work Group leader for the InfraGard National Disaster Resilience Council (NDRC).

Dr. Mariama Yakubu (Mariama) earned her Ph.D. in Emergency Management from North Dakota State University, M.A. in International and Development Economics from University of San Francisco, and B.A., First Class Honors, in Sociology and Information Studies from University of Ghana. Her research interests include Business Continuity and Crisis Management, Supply Chain Uncertainties, Individuals and Household Disaster Recovery, and Emergency Management Higher Education Curriculum Development. She applies both qualitative and quantitative research methodologies in her research, leading to her co-authoring articles and a book chapter in peer review journals such as International Journal of Mass Emergencies and Disaster, Journal of Homeland Security and Emergency Management, and Journal of Management and Sustainability. Previously, she had worked with both academic and non-academic institutions such as Concordia College (Minnesota), North Dakota State University—Agribusiness Department, Quinnipiac University, National Disaster Management Organization (NADMO-Ghana), Social Security and National Insurance Trust (SSNIT-Ghana), and the Electoral Commission of Ghana. Currently, Mariama is a lecturer and coordinator of the Homeland Security and Emergency Management Program in the University of New Haven's Fire Science and Emergency Management Department.

Wayne Sandford is former director of the Emergency Management program of the Fire Science and Emergency Management Department at the University of New

Haven Henry C. Lee College of Criminal Justice and Forensic Sciences. Wayne has earned his M.A. from Sacred Heart University, a B.S. from The University of New Haven, an A.S. from Waterbury State Technical College, and an A.S. from Hartford State Technical College, 1971. He is former Deputy Commissioner of Emergency Management and Homeland Security for the State of Connecticut, and a former Fire Chief for the East Haven Fire Department. As founder of the Emergency Management Department at the University of New Haven, Mr. Sandford taught classes in Emergency Management, Holistic Disaster Recovery, Emergency Scene Operations, Fire Hydraulics, Fire Prevention, Building Construction, Issues in Public Safety Professional Responsibility, and Issues in Public Safety Management.

Dr. Jeffrey Treistman is an Assistant Professor of National Security at the University of New Haven's Henry C. Lee College of Criminal Justice and Forensic Sciences. He was a Research Assistant at the Institute of National Security and Counterterrorism. He also served as a consultant to the Department of Defense's Africa Command (AFRICOM) and was a Policy Advisor for the Department of State in Iraq. Dr. Treistman currently is an editorial board member of the journal *Studies in Conflict & Terrorism*. His research interests focus on military policy, international relations, asymmetric war, and terrorism. Dr. Treistman earned his PhD in International Relations & Public Policy from Syracuse University, an M.A. in Economics from Syracuse University, a MPP in International & Global Affairs from Harvard University, and a BA in History from the University of Colorado.

Dr. Ed Goldberg recently retired as Manager of Business Continuity, Disaster Recovery and Threat Assessment at Eversource Energy (formerly Northeast Utilities) in New Britain, CT. He holds a PhD in Management and Organizational Leadership from the University of Phoenix, a Post-Graduate Certificate from Rensselaer Polytechnical Institute, an MBA in Computer and Information Science from the University of New Haven, and a BS in Electrical Engineering from the University of New Haven. He is an FBI New Haven Citizens Academy graduate, and a Licensed Professional Engineer in the State of CT. He has expert-level knowledge in business continuity, threat assessment and disaster recovery, and is an experienced IT manager. While at Eversource, he worked for Northeast Utilities Millstone Nuclear Power Station as IT Supervisor and Senior Manager. He also served on as Faculty at Capella University School of Business and Technology for its PhD IT Management programs. He was IT Manager/Senior Manager at Northeast Utilities & Dominion at Millstone Nuclear Power Station and Electrical Engineering Manager at NAPCO, a division of Thermo Electron. He is a member of InfraGard, presently serving as President and Energy Sector Chief for its Connecticut chapter. He was Chapter President of the Connecticut Chapter of the Association of Continuity Professionals (ACP) and served as Director of Association of Contingency Planners and on the National Board of Directors for ACP.

Matt Van Benschoten is Vice President, Advanced Engineering at Roush Industries, where he has served for 28 years. He leads engineering teams with the Mobility, Space, Aerospace, Marine, Defense, and Government business segments. He received his BS ME from GMI Engineering & Management Institute, Kettering University. Prior to leading the Roush Advanced Engineering organization, he had powertrain and propulsion systems design, engineering, simulation, test, and development responsibilities. This included the specification development, design, installation, and commissioning of several high degree of freedom test environments for developing and validating modern vehicle powertrain/propulsion systems. He spent over a decade at Roush managing vehicle Controls and Calibration engineering, delivering several high-feature and high-performance vehicle programs for automotive OEMs in the North American market. He is a member of SAE, ASME, and AIAA.

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