Recent Trends of Electromagnetic Pulse Mean for Denied Vehicular Access Application or Vehicle Immobilization

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Abstract – **This paper reviews and provides insights into current trends in the methods used by researchers and companies to develop and invent the denied vehicular access application. There are three types of electromagnetic pulses (EMPs) sources that may be used to stop vehicles: High Altitude Electromagnetic Pulse (HEMP), Ultra-Wideband (UWB), and High Power Microwave (HPM). The current trends in system development are reviewed from three perspectives, namely company-government cooperation, current commercial products, and pattern invention. In general, the average effective distance range for stopping vehicles using S- or L-frequency bands is between 3 m and 200 m. In fact, the effective distance also depends on the peak power of electromagnetic waves ranging from 7 W to 4 GW generated by the system. In addition, the design challenges of the denied vehicular access system are discussed.**

Keywords – **EMP, HEMP, UWB, HPM, Peak power.**

I. Introduction

Law enforcement members today face problems in carrying out their essential duties. Certain drivers disobey law enforcement officers' orders to halt their vehicles. This occurs when drivers engage in criminal activity as the authorities set up roadblocks and pursue offenders. The emigration authorities also experience this situation in carrying out tasks at the border. As a result, many researchers and companies have developed equipment or methods that can be used to deny vehicular access applications, especially stop vehicles, without involving injuries to drivers and the general public. Conventional methods often used, such as roadblocks using barricades, patrol cars, nets, bars on public roads, are dangerous actions to officers and the public. Even pursuing offenders at high speeds can cause damage to public property, even endangering the lives of citizens.

Various methods are used to stop the car in addition to conventional methods. Electromagnetic Pulses (EMP) signal can disable and disrupt the electronic component in the targeted vehicle, especially the engine control unit (ECU), which is the main heart of the car. The method is one non-lethal solution to stopping the vehicle. Therefore, Section 3 will address research conducted by researchers and companies that demonstrate the effectiveness of EMP in stopping cars. Any disturbance to the operation of the control unit will trigger the engine to stop. ECU is an electronically integrated device, like a digital computer, which reads signals from various sensors on various car components and controls different critical units depending on that information. The microcontroller chip and the erasable programmable read-only memory (EPROM) or Flash memory chip are essential components of the ECU [1]. The EMP effect makes discrete electronic components, integrated circuits (microchips) and microprocessors vulnerable to failure [2].

This paper will provide insights into current trends in methods used by researchers and companies in developing methods to stop the vehicle by using electromagnetic means.

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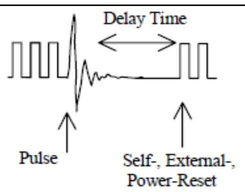
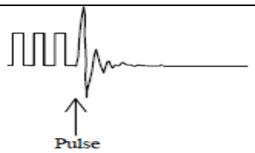
II. Susceptibility of the Electronic Component to the Electromagnetic Environment

An EMP is a temporary electromagnetic disturbance or energy released in a short burst. An EMP can be generated by three different means, namely High Altitude Electromagnetic Pulse (HEMP) from a nuclear warhead detonation, Ultra-Wideband (UWB) from UWB communication, and High Power Microwave (HPM) from devices generating high peak microwave power [3]. All electronic equipment under sufficient electromagnetic radiation is susceptible to malfunctions and permanent damage [4]. EMP has high voltage and current transient effects that may contribute to the irregular reaction of an electronic device in terms of physical damage and upset [5]. Electronic equipment can be damaged by EMP coupling through either the front or back door [4], [6].

Kim *et al.*, 2004 [7] show that power levels greater than +10 dBm and frequencies between 1 and 20 GHz affect individual metal oxide semiconductor field-effect transistors (MOSFET). The effect results in a loss of switching power, amplification saturation and linearity, DC null drainage offset currents, and a significant reduction in breakdown voltages [7]. The damaging effect and degrading mechanism of MOSFETs caused by EMP have been investigated [8], where the unit is thermally compromised and thus fails or burns out.

Camp *et al.*, 2002 [9] studied transistor-transistor logic (TTL) and CMOS technology on EMP and UWB. While the levels of destruction for TTL and CMOS devices are comparable, TTL devices remain irreversible. To explain the multiple failure results, the Breaking Failure Rates (BFR) and the Destruction Failure Rate (DFR), as seen in Table 1, are used. Electronic components on the chip, such as diodes or transistors, were affected by flashover impact at low field strength. EMP may cause further damage to chip wires and other components if their amplitude is increased by around 50%. Increased amplitude also contributes to further destruction of the bond wire and various elements and on-chip wire destruction. Gurevich, 2016 [2] discuss the susceptibility of the discrete electronic component, integral circuit (microstrip), and processor to the electromagnetic environment.

TABLE 1
FAILURE RATE [9]

Breakdown	Destruction
	
BFR = $\frac{No.of\ Breaksdown}{No.of\ Pulses}$	DFR = $\frac{No.of\ Destructions}{No.of\ Pulses}$

Nitsch *et al*., 2003 [10] showed that the susceptibility levels of the microprocessor boards are about 100 V/m and a few kV/m, using HPM and UWB signal sources, respectively. In addition, the impact of electromagnetic interference (EMI) on digital electronics, mainly the timer used to monitor the spark plug series of the vehicle, has been investigated [11]. The calculation results showed a good relation of +20 dBm at 3 GHz to the timer terminals to interrupt the process. Digital circuits with reduced bias voltage become less resistant against EMI. Przesmycki and Wnuk, 2018 investigated the vulnerability of information technology (IT) equipment, such as PCs, notebooks, HDDs, SD cards, MMC cards, and Wi-Fi routers, to the HPM pulse. It demonstrates that IT equipment has immunity levels ranging from 30 kV/m to 320 kV/m [12]. Pulse amplitude of damaging electrical field for different parts of a PC has also been studied [2]. EMI effects on Field Programmable Gate Array (FPGA) have also been studied [13], [14].

III. The Invention of the Stopping Vehicles System in an Electromagnetic Pulse Environment

A. Cooperation in Developing Stopping Vehicles System

Eureka Aerospace was awarded a contract by the US National Institute of Justice (NIJ) to develop a lightweight single-frequency high-power electromagnetic device (HPEMS) [15]. HPEMS are the systems for immobilizing a vehicle that uses microwave radiation to damage or disable the vehicle's electronic control module and a microprocessor, which regulates the engine's critical functions. Stopping ships, protecting high-value properties, and neutralising improvised explosive devices (IEDs) are some of the other purposes of HPEMS [16]. The system is comprised of a rapid charge power source capable of delivering up to 100 pulses per second at a voltage of 640 kV, and the energy of EM fields is 20 kV/50m through a 16-stage Marx generator. At a distance of 30 feet, the system has been shown to transmit approximately 60 kV/m from the antenna. A single radiated blast is used to “bury’’ a 1999 Honda Accord engine. At frequencies from 350 MHz to 1.35 GHz, the device works up to a distance of 200 m and weighs around 104 kg [15], [17-19].

Fiore Industries Inc developed the Electromagnetic Weapon System (EMWS) for engine stoppers. The National Institute of Justice is funding the development of EMWS [20]. The EMWS has a remote control and a pulse repetition frequency of 8 kHz, and it can generate 2.4 kW of power with a pulse width of 30 µsec. The EMWS routes several pulse amplifiers to their corresponding antenna components. The EM field was released using a 24-element antenna in front of a Ford F350 pickup truck with a minimum gain of 23 dB. The test was conducted in 2 phases, namely, the first phase of the susceptibility testing was carried out in idle and dynamic conditions with the vehicles. The chase scenarios and dynamic conditions were used in the second phase of the test. The engine of the tested car was halted at 20 to 60 feet while illuminated from the front, driver, and passenger/rear sides, respectively, and at various car speeds during the susceptibility test [20].

In 2005, Joint Non-Lethal Weapons Directorate (JNLWD) from US Armed Forces was funded for developing a multifrequency Radio-Frequency (RF) Vehicle Stopper (RFVS). The technology and capability to stop vehicles and vessels are being developed in partnership with L3 Electron Devices, United States [19], [21]. The system is primarily built for army security and is intended to be used on entry points, checkpoints, roadblocks, or by mobile patrols. RFVS system based on HPM weapon uses multiple HPM frequencies to increase the system's performance. High-power magnetron tubes are used to produce powerful RF bursts that interact with a car's electronics. Forty-two personal vehicles (cars, small trucks, buses, and SUVs) and three heavy trucks (dump trucks and tractors) were tested, and the effective capability was higher than 80% [21].

The SAVELEC (safe control of non-cooperative vehicles using electromagnetic means) initiative was started by the European Commission in 2016. The method relies on using electromagnetic devices to block the normal functioning of the vehicle's electronic components. The SAVELEC system uses a high-power generator with field strengths ranging from 500 V/m to 25 kV/m at 15 m and a frequency range of 1 to 2.5 GHz [22].

B. Commercial Stopping Vehicles System

Diehl Defense GmbH & Co. developed HPEMcarStop, HPEMcheckPoint, and HPEMcase. High Power Electromagnetics (HPEM) pulse is at the heart of the technology [23]. To stop moving trucks, cars, and motorcycles, the HPEMcarStop (Fig. 1) function can be used. At a center frequency of 350 MHz, HPEMcarStop has a target distance of 3 to 15 m, a maximum burst length of 180 seconds, and a maximum peak radiated power of 4 GW. Meanwhile, HPEMcheckPoint (Fig. 2) has the same features as HPEMcarStop, which incorporates a powerful HPEM source on a trailer for static operation [23].

Fig. 1. HPEMcarStop [23]

Fig. 2. HPEMcheckPoint [23]

Fig. 3. HPEMcase [23]

As shown in Fig. 3, the HPEMcase is optimized to disable electronic equipment for special forces operations. The HPEMcase has a maximum power of up to 365 MW and a total explosive length of up to 60 seconds at a center frequency of 350 MHz [23]. HPEMcase is also used as an EMP source in-field testing to determine the impacts of an EMP pulse on vehicle testing [24], [25].

Three RF Safe Stop products are available from Teledyne e2v [26], [27]. The RF Safe Stop employed a radio frequency energy system to disable the engine management system of land vehicles and marine vessels, bringing them to a safe stop at a safe distance. First, as shown in Fig. 4, RF Safe Stop (Land) fits into a four-wheel drive (4WD) car. It uses one 1 m^2 antenna and has a stopping distance of 50 m. Second, RF Safe Stop (Sea) system can be used for port security, coastal policing, and anti-piracy operations. RF Safe Stop (Sea) is a modular system that allows reconfiguration to suit the platform. It uses an antenna size of 1 m^2 and has a stopping distance of 50 m. Third, RF Safe Stop Lite (Sea) with the same application as RF Safe Stop (Sea) but is different in terms of stopping distance (120 m), antenna size (1.5 m × 0.75 m), and weight (156 kg) [26], [27].

Fig. 4. RF Safe Stop (Land) [26]

C. The Invention Stopping Vehicles System

In recent decades, several invention strategies for stopping or immobilising vehicles using various methods have emerged [28–31]. The disrupter circuit was invented by Haste [28] and placed on or near a stopped car to deactivate the engine management control system. The disrupter circuit will generate the electromagnetic signal that will disable the electronic component in the target vehicle.

Elson, 2014 [29] used a database to evaluate a vehicle's specific parameters such as frequency modulation (FM), amplitude modulation (AM), and pulse repetition rate until modulated microwave radiation is transferred to the target vehicle. The microwave signal is transmitted with a helical antenna having a gain of 20 to 25 dB. The total power to deactivate the vehicle is less than 10 Watts.

Kaufman *et al*., 2015 [30] use RF tones to scan VHF/UHF signals from the internal combustion engine of a target vehicle. The processor automatically uses an engine information database to pick the best interference signal to interrupt the target vehicle's engine type or fuel system by the established RF signature. Engine operating characteristics for any vehicle can be stored in the database. It has been discovered that most ECUs are susceptible to attacks on frequencies in the VHF and UHF bands. The transmitter incorporates a power combination GaN amplifier capable of providing continuous-wave power of 170 kW for ECU disruption at around 100 m and approximately 17 W for 10 m. It is also suitable for vehicle checkpoints such as border crossings where the vehicle's antenna array is set up [30].

Stimson, Guy, and Hicks, 2018 [31] give a full description of the concept of a modulated signal package transmitted with an antenna in a single burst of RF energy to disrupt a vehicle engine. The signal package comprises pulses grouped in sets of one to 20 pulses. The system employs a magnetron to transform electrical input pulses into RF output pulses emitted via the antenna. The magnetron operates at 3 GHz and has a narrow bandwidth, with a 5 MW output power. Tests were conducted using a system verified against a sample of 23 vehicle types from 14 different manufacturers. The system interferes with the target car's engine management system, causing the vehicle to a complete stop with an 80% success rate [31]. The summary of the invention strategies for stopping vehicles system is shown in Table 2. Meanwhile, Table 3 summarises the development and invention strategies for stopping the vehicles system.

TABLE 2
SUMMARY OF THE INVENTION STRATEGIES FOR STOPPING VEHICLES SYSTEM FROM 2010 TO 2018

Assignee	Year	Descriptions	Features
Nil [28]	2010	The electromagnetic signal from the disrupter circuit disable electronic equipment, particularly the engine management control system.	It may be incorporated with a global positioning system (GPS) to track the suspect vehicle.
Fiore Industries Inc [29]	2014	Transmit modulated microwave radiation after the database analyses the parameter from a specific target vehicle.	▪ Weight – 90 kg. ▪ Peak power – 5 kW. ▪ Carrier frequency – 1.1 to 1.6 GHz. ▪ Antenna gain - 20 to 25 dB from a helical antenna. ▪ The total power to deactivate the vehicle is less than 10 W.
Raytheon Company [30]	2015	Use RF tones to scan the VHF/UHF signal from the internal combustion engine target vehicle.	▪ ECU disruption-CW power of 170 kW at a distance of about 100 m. ▪ ECU disruption-CW power of 17 W about 10 m.
E2V Technology (UK) Limited [31]	2018	The modulated signal package will be transmitted in a single burst of RF energy using an antenna to disrupt the vehicle engine. The signal package comprises pulses grouped in sets of one to 20 pulses.	▪ Peak power within the range of 1 MW to 5 MW. ▪ Operating frequency – 3 GHz and narrow bandwidth. ▪ Pulse width -100 ns to 10µs. ▪ Pulse repetition frequency – 50 Hz to 2 kHz.

TABLE 3
SUMMARY OF DEVELOPMENT AND INVENTION STRATEGIES FOR STOPPING VEHICLE SYSTEMS

Development /Invention	Weight [kg]	Operation	Frequency	Peak power	Effective range	Antenna/ Gain
Eureka Aerospace [15]	104	Microwave and RF Technology	350 MHz to 1.35 GHz	_	200 m	_
Fiore Industries Inc [20]	_	_	_	2.4 kW	6 m to 18 m	Array 24 element (23 dB)
JNLWD and L3 Electron Devices [21]	_	HPM	_	_	_	Dish
European Commission [22]	_	EMP and HPM	1 to 2.5 GHz	_	15 m	_
Diehl Defense GmbH & Co. - HPEMcarStop [23]	_	High power electromagnetics	350 MHz (Centre Freq)	4 GW	3 m to 15 m	_
Diehl Defense GmbH & Co.- HPEMcase [23]	28	High power electromagnetics	350 MHz (Centre Freq)	365 MW	_	_
Teledyne e2v [26]	350	Microwave	1 to 4 GHz	_	50 m	Array
Thomas E. Haste, [28]	_	EMP	_	_	_	_
Fiore Industries Inc [29]	90	Microwave	1.1 to 1.6 GHz	5 kW	N/A	Helical (20 to 25 dB)
Raytheon Company [30]	_	RF Technology	N/A	170 kW 17 W	100 m 10 m	_
E2V Technology (UK) Limited [31]	_	Microwave and RF Technology	3 GHz	1 MW to 5 MW	_	_

IV. CHALLENGES

There are several challenges in the development and invention of the electromagnetic mean for denied vehicle application that need to be considered:

a) Standards for vehicle equipment's electromagnetic immunity must be established throughout the design process. A 5 volt supply voltage, for example, is often used to power electronic circuits [23]. EMP has been shown to have a damaging effect on semiconductors and microprocessor boards [4], [8], [32–34]. The effective distance of EMP propagation to the target circuit board determines the impact of EMP. However, because each chip manufacturer has different standards and specifications, the chips' quality must also be considered.
b) The health issues of drivers and the public should be taken seriously when the EMP is implemented in the public environment. The radiated signal from the EMP system should conform to the electromagnetic radiofrequency zone of human exposure from 100 kHz to a few GHz [35], [36]. Two different scenarios have been considered [37] to evaluate the exposure of the human body to the HPM plane [38], [39] as well as understand the effective level of the electric field to the human body. However, Raman, 2018 [40] found no significant health risks in the harmful impacts of microwave radiation. The adverse effects of electromagnetic radiation are enhanced through enhanced electromagnetic spectrum sensitivity.
c) Study the automotive EMI/EMC legislation and regulation to better understand the EMC threshold for every car manufacturer [22], [41].
d) The EMP system size is one of the essential factors in its design. Power supply, electromagnetic energy source, and antenna are the main factors that affect the size of the system. In fact, the EMP system should be compact, easy to install, and portable.
e) Antenna selection affects the effective distance of the emitted electromagnetic waves to the target. Moreover, the antenna beam angle and gain are usually considered to guide the electromagnetic waves towards the target. Different incident directions of the antenna will give different coupling processes [42].

V. CONCLUSION

The development and invention strategies discussed can be used by law enforcement to stop cars involved in criminal activity. Development in resolving problems using conventional methods can help reduce the risk of injury to law enforcement and the general public as well as the criminals involved. Considering the susceptibility of electronic equipment in modern vehicles today to EMP, especially the ECU, gives researchers and companies an advantage for developing and producing products that can be used for a specific purpose. From Table 3, the average effective range of stopping a vehicle is between 3 and 200 m (depending on the speed of the target vehicle) for frequencies in S and L bands. The effective range depends on the equipment's peak power (17 W to 4 GW) and the technology or technique used by researchers and companies, especially in modulating signals.

However, the effectiveness of each development and invention depends on the effective distance to the target vehicle, the exposure time to the radiated signal, and the influence of vehicle orientation and engine speed. Every development and invention have its advantage, respectively. The challenges discussed above should be taken into account in determining the system design. Developments or inventions for stop cars must comply with automotive technology standards for electromagnetic immunity, especially for requirements for electromagnetic compatibility (EMC).

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