Safe maintenance of high voltage electrical vehicles (HVEVs)

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Abstract: In the framework of the Sustainable Development Goals in a world scale, certain strategic decisions have been made that will affect the Environmental, Social and Governance affairs and extend deep into our everyday life. One of these decisions is the adoption of electro-kinesis in vehicles instead of the internal combustion engines. Health & Safety is the science of prevention; hence, managing change is the core of its objectives. This impressive technological change entails hazards that result in risks that have thus far not been readily assessed under the EU's extreme pressure of achieving an economy with net-zero greenhouse gas emissions by 2050 the contribution of commercial transportation being a serious challenge.
On the other hand, the thus far experience has shown that the use, repair and maintenance of high-voltage electrical vehicles, which use electricity as their main power drive, present special risks not only for the automotive industry maintenance technicians but for the road assistance personnel as well, since the technology is extremely new so there is not sufficient historical incident data.
This paper will present a generic approach risk assessment on the hazards of electric vehicles that are mainly driven by high-voltage DC batteries, the thus far EU requirements of repair shops, the fire protection and environmental challenges of the exposed professionals including road assistance personnel and provide recommendations for further safety technical as well as organizational measures to be adopted.
This work should be considered more of a discussion paper having the ambition to draw the attention of the scientific as well as business community on the safety mitigation measures that must be developed and integrated throughout the electrical vehicle's supply chain and lifecycle.

1. Introduction

In the framework of the Sustainable Development Goals (SDG) in a world scale, certain strategic decisions have been made that will affect the Environmental, Social and Governance (ESG) affairs and extend deep into our everyday life.
One of these decisions is the adoption of electro-kinesis in vehicles instead of the internal combustion engines. This impressive technological change entails hazards that result in risks that have thus far not been readily assessed under the EU's extreme pressure of achieving an economy with net-zero greenhouse gas emissions by 2050 the contribution of commercial transportation being a serious challenge.
Health & Safety is the science of prevention; hence, managing change is the core of its objectives and since this change has reached our doorstep, the Occupational Safety & Health Science must examine the relevant issues arising for all involved parties namely vehicle industries that must deliver a safe product, maintenance professionals that must preserve its longevity and usability, consumers that must enjoy the product safely and the political entities that must provide the relevant resources, either legal or technical or emergency to minimize the new and emerging risks entailed in any new endeavour.
So, this paper is more of a discussion paper whose objective is to stir up the interest in full-electrical vehicle safety for mainly maintenance personnel and provide a first approach review of what is already specified, identify the existing gaps and provide direction and guidance on the issue still pending but that have to be immediately addressed prior to experiencing a large-scale disaster.
In this way, the author has the strong conviction to have contributed to the SDG3 by "ensuring healthy lives and promote well-being for all at all ages" including maintenance personnel as well as users, SDG4 by "ensuring inclusive and equitable quality education and promote lifelong learning opportunities for all" on the new and emerging risks of this technology and SDG7 "guarantee access to affordable, safe, sustainable and modern energy for all" that will be hopefully be the case of electrokinesis.

Symbols/Oznake			
I	- electric current flowing through a conductor, A		**Subscripts/Indeksi**
V	- voltage across the conductor or between the two traction battery poles, V	b	- reference to human body
R	- conductor resistance, Ω	t	- reference to touch potential between two body parts
P	- traction battery power, W	max	- maximum quantity
	Greek letters/Grčka slova		
Ω	- Ohm, the unit of electrical impedance measurement		

2. Hazard recognition and Analysis

2.1. Electrical hazards

An a priori clarification must be made regarding this chapter as well as its further analysis to avoid confusion. This work refers only to all-electric vehicles, namely vehicles whose main driving power is provided by electric motors which are fed by battery trains; it does not examine hybrid vehicles whose electric motors are used as alternative power supply to move the vehicle.

In the regulation CEC-100 [1] and [2], governing the safety specifications for all-electrical vehicles, "*High Voltage*" means the classification of an electric component or circuit, if its working voltage is > 60 V and ≤ 1500 V DC or > 30 V and ≤ 1000 V AC root mean square (rms).

We can thus derive the conclusion an all-electric vehicle is considered a High Voltage Electrical Vehicle (HVEV) since its power train exceeds the abovementioned limits.

Since we are going to analyze the hazards of the HVEVs, electrocution is the most probable incident scenario we are going to begin with not excluding other scenarios but of inferior probability and severity.

The first point we must consider is that in the occupational contemporary reality the direct current (DC) is harmless, since most risk analyses, assessments and mitigation measures are consumed with the alternating current (AC) application hazards. It is true that AC currents entail higher risk since their alternating characteristics intervene with the heart's pulsation. Also, it is experimentally proven that the human body has higher threshold endurance to the DC current consequences affecting the body tissue and loss of muscular control due to contraction [3]. Yet, DC current is just as hazardous as the AC current under the power-output conditions of a HVEV, which ranges from 400-800 VDC.

In any case, the exposure to a voltage difference causes the electric current to flow through the human body causing either:

- an electric shock, which is a bodily stimulation when electrical energy flows through the human tissue when the latter comes in contact with a live conductor, or
- an arc flash/ arc blast injury due to instant high temperature, >0,01sec and >15.000**°C,** shockwave exposure, caused by a short circuit between two live conductors too close in proximity allowing a fault current to be created to bridge the gap between them through ionization of the ambient air

It is well known that, in spite of the fact that there must be a voltage difference to create a current flow, it the current magnitude that is hazardous to the human body creating blood electrolysis, burns and organ malfunction (pulmonary and/ or heart defibrillation).

In order to calculate the current flowing through any structure that becomes under potential (voltage difference); in the case of a DC power source the structure is considered to provide resistance when we we use Ohms's Law as per equation (1):

$$I=V/R, \qquad (1)$$

that, in case of the human body, it is adjusted as follows:

$$I_b=V_t/R_b. \qquad (2)$$

in which:

I_b = Electric Current flowing through a human body

V_c= Voltage measured across the human body (touch potential)

R_b= Body Resistance

In spite of the fact that the R_b value is variable depending on the electrical current path, the skin thickness and moisture, the surface contact area and other factors, we can use a reference value of 2000Ω for 200V DC to 1000Ω for 700VDC [3]. Assuming also a 1sec time duration of current flow through the body, the threshold value to a DC current is 150mA DC.

Applying Ohm's Law of equation (2) for personnel or users that may accidentally be exposed to DC touch potential of a HVEV, we may make some rough calculations. Their traction battery pole voltage to which the body may be exposed to a touch potential is V_b =400–800 V. Considering that a HVEV traction battery energy output is between 24–100 kWh, and by considering a 4-hour battery autonomy (full-power operation), a HVEV's traction Battery Power is P=6–25 kW or 6.000–25.000 W, hence the current output produced is:

$$I_{max} = (P/V_b) = 10\text{-}60\ A \quad (3)$$

Applying the same formula (2) in this case and for 400V, which is the best case, the corresponding resistance is R_b=1000Ω [3], which yields an electrocution current of 400mA way above the 150mA limit.

2.2. Magnetic field exposure

This voltage is high enough to produce magnetic fields that can also cause problems to maintenance personnel that wear pacemakers or other implants that are sensitive to magnetic fields.

2.3. Fire and explosion hazards

HVEVs power trains use "Open type traction batteries" which means a liquid type battery requiring refilling with water and generating hydrogen gas released to the atmosphere [2].

That in turn means that, during maintenance, the most flammable gas is released that may reach explosive conditions.

Also, the electrode metal, Lithium, may overheat, self-ignite and explode under conditions that have not been meticulously investigated yet [4]. The electrolytes contained, are toxic and their vapors may ignite or explode as well [5].

Extinguishing such a fire requires only specialized knowledge and equipment that even fire fighters do not possess yet.

The only extinguishing media is water in ample quantities usually 4-32 m^3 to cool down the vehicle to a temperature less than 70°C, which is considered a safe temperature limit [6].

2.4. Hazardous chemicals exposure hazards

The electrolytes contained in the power trains are toxic as well as corrosive. Exposure to fumes may cause short or long term diseases, not to mention the damage to the environment in case of spillage.

Maintenance will have to keep a stock of power trains or batteries, either for maintenance or for disposal; these Battery Storage Areas will contain large quantities of electrolytes and will include charging stations, so they will create hazardous emissions of hydrogen and electrolyte fumes creating additional exposure hazards to maintenance technicians in the area.

3. Safety Measures for HVEV Maintenance Personnel

3.1. Preventing electrocution [1] and [7]

The HVEV maintenance area must be dedicated and constructed for this purpose only; internal combustion vehicles may be serviced in this area but not vice-versa; when a HVEV vehicle replaces an internal combustion vehicle the area must be previously cleaned thoroughly.

To avoid electrocution hazards, cables for high voltage buses which are not located within enclosures shall be identified by having an outer covering with the colour orange.

Additionally, all Rechargeable Electrical Energy Storage Systems (REESS) must bear a yellow-background electrical shock hazard sign, as in Figure 1.

Figure 1. Marking of HV equipment

Additional signs must be placed, on top of the HVEV, near the steering wheel, on the windshield and below the hood when it is open.

Electrically 1000V-rated insulated tools must also be purchased and used by maintenance technicians.

Personal Protective Equipment (PPE) should be provided and used by maintenance technicians including electrically insulated safety boots, 1000V electrician gloves, insulating aprons, masks and respirators, face shields, goggles or glasses but also arc flash coveralls.

Local or small-enterprise maintenance shops areas are sometimes accessible to clients, which are certainly unaware of the seriousness of the hazards involved during their HVEV service. Hence, maintenance area access must be strictly prohibited to all unauthorized personnel, including colleagues that are not certified HVEV technicians as will be discussed in the following.

Additionally, each vehicle must be maintained in a dedicated area with impermeable and incompatible to the electrolytes industrial flooring and fenced by poles and the appropriate safety signs as shown in figure 3.

Figure 3. Example of a HVEVs maintenance area that is isolated and demarcated

3.2. Preventing magnetic field exposure

Without violating the provisions and mandates of GDPR, each HVEV Maintenance employer must have issued a fit-to-the job certificate for all technicians that will be executing HVEV maintenance tasks in close proximity with live HV DC or AC components by an Occupational Health Doctor, to get the necessary health clearance. This certificate has to be renewed every two years or less in case of technician health deterioration.

3.3. Fire safety measures

Spontaneous fire is quite rare in HVEVs, but not improbable; the issue is that these fires cannot be extinguished by conventional fire extinguishers, since they are initiated at the hermetically closed power trains. The only effective extinguishing medium is water but in quantities that are unavailable in conventional maintenance shops as the water supply requirements are quite demanding as described in paragraph 2.3 above.

Also, the fire-fighting techniques can only be applied by professionals with the appropriate training and using special PPE and equipment. A typical HVEV fire may last for more than one hour before it is effectively extinguished [6].

Therefore, HVEV Maintenance Shops must have direct access to traffic routes that can be easily reached by the Fire Brigade vehicles.

Consequently, the measures of the Maintenance Shop must be focused on prevention of electrical fires and explosions, which means that the HVEV maintenance area must be kept clean and tidy, smoking and open flames must be strictly prohibited, flammable and combustible materials must be kept to a minimum for the daily tasks, waste bins must be non-combustible and bear pedestal–operated lids, the waste must be frequently removed and the hot work permit system must be applied, among other requirements.

It is also strongly recommended that a Fire Safety Study is conducted in order to specify the appropriate passive fire safety measures like fire compartmentation to avoid fire spreading and the use of non-combustible structural materials. Fire alarm and suppression systems like smoke detectors, sprinklers, fire pumps and water hoses are also strongly recommended.

Where applicable a Fire Safety Permit must be obtained as per the local regulations.

Additional measures may include the use of fireproof isolation curtains and possibly a minimum of $20m^3$ water tank feeding a dedicated to the purpose fire pump.

Battery Storage Areas, must be assessed for explosion risks by developing an “Explosion Protection Document” as per the ATEX Directive [8] and, if necessary install EX-rated equipment.

Another issue to consider is that more probable are fires that happen when a HVEV presented a failure that rendered it inoperable or after a collision with the same result.

In this case, the Hellenic legislation requires that an Outdoor Quarantine Area is available for each Maintenance Shop as per figure 3, or else such an area may be leased from a Road Assistance Company.

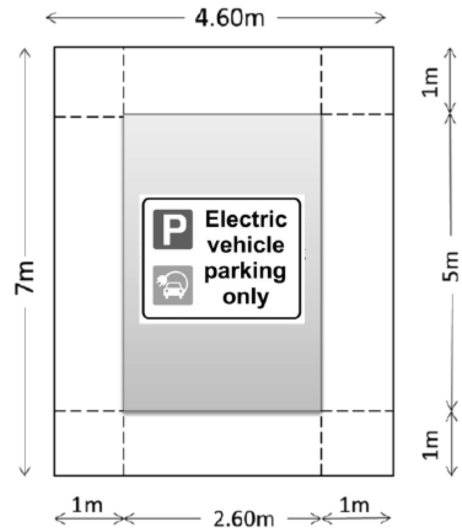

Figure 3. Outdoor Quarantine Area for staging problematic HVEVs until they are cleared for indoor repair & maintenance [7]

In this area, the problematic HVEV must remain until it is deemed safe to be moved to the Maintenance Shop interior area. Providing clearance of a quarantined HVEV means that a thermal imaging inspection must be conducted to spot any overheating problems with the power train.

That means that an infrared (IR) thermal imaging camera has to be purchased and some technicians should become certified thermographers to be able to use the camera to identify hot spots or areas at the power train prior to intervening for repair.

Additional inspections must include critical traction battery State-of-Health (SoH) assessment that includes leakages, emissions, deformation or other failures asper the manufacturer’s manual.

3.4. Hazardous chemicals exposure prevention measures

The Maintenance Shop owner must have available all hazardous chemicals Safety Data Sheets (SDS’s) and implement the prescribed safety measures.

Since, both in the HVEV Maintenance Area as well as in the Battery Storage Area hazardous chemicals are staged, transferred and used, the containers must be stored either in certified hazardous or flammable chemical cabinets or on secondary containment pallets.

Also, depending on the ATEX Study results, the installation of explosion proof equipment should be implemented.

The appropriate Chemical Spill Kits should also be installed containing appropriate to the chemicals spill materials and PPEs.

Needless to say that an effective emission extraction system must be installed at the Battery Storage Area,

which may be explosion proof should the Explosion Prevention Document requires it.
An indicative design of both Maintenance and Battery Storage Area is depicted in figure 4.

Figure 4. Schematic of HVEV Maintenance and Battery Storage Areas [9]

3.5. Emergency procedures

It has been so far clear that, in case of a fire, only the Fire Brigade can effectively intervene to suppress it; hence, an "Evacuation and Emergency Plan in case of serious and imminent danger" as well as of an "Evacuation Procedure in case of serious personnel injury" should be developed and tested at least twice a year, since in case of an incident evacuation is the only safe practice.
A "Hazardous Chemicals Spill Control Emergency Plan" should be developed, Emergency Response Teams assigned and trained and a spill drill conducted at least once a year.

3.6. The Certified HVEV Technicians

The Hellenic legislation [7] requires that two types of Technicians are appointed and certified to conduct HVEV maintenance works:
The "Level 1 HVEV Technician" is defined as the technician that, under the guidance of a Level 2 HVEV Technician, performs basic vehicle maintenance tasks, not related to the HVE system. They are familiar with the general structure of the HVE system and its associated hazards.
The "Level 2 HVEV Technician", is defined as the technician that knows and checks the power supply interruption in HVE systems, preventing accidental activation during maintenance. The Level 2 HVEV Technician knows how to remove and reinstall the battery on a HVEV, undertakes the battery repair or the recycling procedure and has the knowledge and ability to safely restart the HVE system. They are responsible for every task carried out on HVE systems and may perform tasks whether or not the HVE System is under voltage.
In each HVEV Maintenance Shop, a Level 2 HVEV Technician is appointed as the person responsible for the safe and proper execution of maintenance works on HVEVs.
Their duties include, for the HVEV Level 2 Technician:

- HVEV's reception
- IR camera battery check
- placing a "suitable or unsuitable for use" sign over the vehicle
- providing instructions to the HVEV Level 1 Technician who acts under the responsibility of Level 2 Technician

The duties of the HVEV Level 1 Technician include:

- placing a red warning sign on the vehicle windshield
- placing a yellow safety sign on top of the vehicle
- conducting the maintenance tasks under the supervision of the HVEV Level 2 Technician

The name of the HVEV Level 2 Technician must be visibly posted at the premises at all times as well as on the safety sign on the vehicle.
The abovementioned Technicians must be trained before undertaking their duties, but no specific curriculum has been mandated yet.

3.7. Other Organizational Measures

The abovementioned specifics do not supersede or cancel the general OSH requirements of the employer to conduct a Risk Assessment [10]; consequently, each HVEV Maintenance Shop Owner has to have an updated Risk Assessment Study by the Safety Practitioner in collaboration with the HVEV Level 2 Technician; then, the two professionals must develop safety procedures and guidelines regarding the HVEV maintenance and repair work.
The details of the people responsible for the implementation of the corresponding procedures must be clearly posted in every individual area of the HVEV Maintenance Shop premises.

3.8. Road Assistance Personnel

An issue that must also be tackled is the exposure of Rescue Personnel (first responders) and Road Assistance Personnel (second responders) in case not only of a fire but also in case of a traffic accident.
The deformation of the HVEV's body and frame and the fact that some of the new technology power trains comprise structural component, creates unforeseen hazards to the second responders that may be involved in towing away a HVEV, since its frame may have become under high voltage.
In this case, Road Assistance personnel must be provided or otherwise seek safe methods of tow-away a HVEV from the manufacturer itself, since, as they state at their Alliance of Original Equipment Manufacturer's (OEMs) site, "An automaker's top priority is its customers' safety, as is safeguarding the overall health of the motor vehicle fleet utilizing our nation's shared roadways every day", and "OEMs develop repair procedures to help safely restore vehicle systems to

proper conditions" [11], hence they are committed to providing these procedures to any post-collision involved party.

In any case, the Road Assistance Company Owner is also bound by the general OSH requirements of the employer to conduct a Risk Assessment [10], but they do not hold the knowhow to identify the risks especially under the conditions of an enclosed power train.

In any case, Road Assistance personnel must bear the same PPE as the ones of a HVEV Technician as described in paragraph 3.1. In case of a thermal event however, they must be aware of its indications, which are emission of smoke and popping noises when it is preferable to call the Fire Brigade and keep a safe distance of at least 20m or more according to the Fire Brigade's directions when the latter arrive.

A damaged by fire vehicle can only be towed away only under the Fire Brigade's directions; needless to say that Road Assistance personnel must also be trained on how to tow away a damaged HVEV without risking themselves.

4. Conclusions

High Voltage Electrical Vehicle (HVEV) technology may contribute to the achievement of the ambitious Global Sustainability Goals; however, despite their intense promotion and the promising business prospects, new and emerging risks are involved for the users but most severe ones for maintenance and road assistance personnel that are called to handle vehicles that may be in inoperable or problematic condition.

Main risks include electrocution, fire, explosion and exposure to storage and handling of hazardous chemicals.

Hence, all the involved parties must cooperate to reduce these risks to as low as reasonably practical.

Car manufacturers must provide information and safe methods of work to the Maintenance and Road Assistance personnel for their HVEV models prior to the new models market release.

HVEV Maintenance Shop owners must invest in their premises safety specifications upgrade and the purchase of new equipment, according to the new legal requirements as well as specialized studies on Fire Safety, Explosion Prevention, Hazardous Chemicals Spillage Handling and Emission Control; assigning duties and training their employees on the new and emerging risks of HVEV maintenance is also a requirement they must organize to comply with the new requirements.

Road Assistance owners must also invest in training their employees on the new and emerging risks of towing away a HVEV and in providing them with special PPE and other equipment.

All the above must facilitate each other in compiling effective Risk Assessment Studies that mitigate HVEV handling risks to trivial levels.

The State in cooperation with the rest of the involved parties must develop a Certification System for the HVEV Level 1 & 2 Technicians to assure easier compliance through a safety management implementation culture.

But, most of all, car manufacturers must speed up their battery trains technology research not only to achieve longer autonomous HVEV ranges, but also to assure that all stakeholders, including the users as well as first responders, stay safe and enjoy the new technology advantages while contributing to a better future of our unique planet.

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