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Chow, W. K.; Chow, C. L.

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Review On Electric Vehicle Fire Hazards Associated with Batteries, Combustibles and Smoke

W.K. Chow[1*] and C.L. Chow[2]

0000-0001-8398-3126, 0000-0001-5748-4331

[1] *Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China*
[2] *Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China*

Abstract

Electrical vehicles are planned to be the future green land traffic means in many places. However, reported vehicle fires or even explosions have raised public safety concern. Fire hazards studies of electric vehicles are commonly focused on ignition of genuine batteries. However, cheap counterfeit batteries of are widely used in electric vehicles in some countries. Counterfeit LIBs are made of unknown battery materials, electrolytes and construction with poor quality control. These counterfeit batteries are not designed for compatibility, not manufactured according to standards, and even not tested. Thus research results based on genuine batteries may not be applicable to counterfeit batteries. Batteries should be taken as a big ignition source for electric vehicles and fire hazards could occur during driving, charging or even when not in use. Further, very few works reported the effect of burning of the combustibles of car and smoke to the passengers trapped inside. Fire risk factors should be studied holistically for the entire vehicle to explore practical fire-safe engineering solutions. Key fire aspects of electric vehicles are pointed out in this paper to alert the society, particularly the authority and professionals handling fire safety.

Keywords: Counterfeit products; Electric vehicles; Fire safety; Lithium-ion batteries; Smoke toxicity.

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* Corresponding author
W.K. Chow
wan-ki.chow@polyu.edu.hk
Address: The Hong Kong Polytechnic University, Hong Kong, China
Tel:+85227665843

1. Introduction

Vehicles using internal combustion engines are being phased out for achieving carbon neutrality [1]. Electrical vehicles are designated [2] as the key land traffic means in many places several decades later. Lithium-ion batteries (LIB) [3,4] are used because they have high efficiency and long service life. The basic physics of why and how it is possible to have high energy capacity in LIB was explained [5]. Thermal hazards [6,7] due to heating might give problems. Many field incidents occurred for LIB packs [8,9] all over the world in electric vehicles and building energy supplying sources. Fire or even explosion starting from batteries are commonly reported as reviewed [10]. Fire incidents involving cars, trucks, and other highway vehicles reached about 188,000 cases [10] only in a single year in 2013. Many other fires and explosions involving electric cars were reported [11,12]. These incidents had delayed the plan of using electric vehicles in dense urban areas with many vehicular tunnels. For example, new construction projects involving enclosed car parks of electric vehicles have to go through more stringent fire hazard assessment. A long list [13,14] of fire protection systems such as sprinkler and smoke exhaust systems are required in a new car park project. Fire safety management of tunnels and underground car parks and garage spaces involving electric vehicles have to be enhanced.

Fires involving LIB must therefore be studied more realistically before widely used in electric vehicles as observed in other applications [15]. Impacts of electrical vehicle fires are not clearly understood [6,7,16,17]. Many cheap counterfeit batteries in electric vehicles, particularly those second-hand cars, give a more complicated situation. How a LIB battery will ignite by itself is not the only issue. What are the consequences upon igniting a battery should be studied. The study should not be only based on fire science such as effect due to electric ratings. Practical fire engineering experience must be included to work out viable solutions. For example, empirical correlations deduced for genuine batteries such as time to ignition with battery capacity might only be applied for new cars using genuine batteries. A genuine battery might cost up to 40% of the new electric vehicle.

2. Battery Fire and Explosion Studies

Although LIB is rapidly adopted [15] in many applications, very hazardous fire and explosion associated with them are frequently reported. Theoretical approach to the safety characteristics of using commercial LIB for cellular phones were examined [16] years ago. As reported by many groups [18], vehicles powered by LIB have highly energetic and active materials and flammable organic electrolytes. Batteries fire behaviour and impact on the fire growth, smoke toxicity, especially in confined spaces, tunnels and underground car parks should be watched with fire risk quantified by burning tests. The heat release rate and emitted toxic gases should be measured and assessed. There are many reviewing articles updated with similar focuses. Most of the studies were on genuine batteries with known electrolyte, construction materials and structure. Very little information is available for counterfeit batteries, because they are non-standard items which are much cheaper. However, not all such battery fire scenario results are applicable because the results need to be handled practically by engineers but accepted by the fire authority. Several key points to note [7] are discussed as following.

2.1 Starting Fire

LIB can undergo a self-heating thermal runaway, leading to high release of heat and toxic gases and a special burning behaviour that may bring up special safety risks. Exothermic thermal runaway reactions increase the battery temperature. Phase transition from condensed matter to gases then occur. The gas mixture generated might consist of various hydrocarbons including methane and propane. Ignition of these flammable gases can result in fire or explosion scenarios like the ones discussed previously [6].

Most of the studies were on genuine batteries. Analytical and modeling methods to estimate explosion characteristics, such as lower flammability limit, laminar flame speed, and maximum over-pressure were evaluated [17]. Effect of cell chemistry, state-of-charge and other parameters on the overall explosion hazard potential for confined cells were quantified.

Batteries, particularly the counterfeit ones, should be taken [7] as a big ignition source for electric vehicles with a higher chance of fire incident to occur during driving, charging and even parking. In fire safety assessment, the whole car must be burnt with full-scale experiments to deduce key fire parameters. Some full-scale burning tests [18] were conducted on both electric vehicles and analogous internal combustion engine vehicles.

2.2 Full-scale Burning Tests

Fire and explosion hazards delayed the development and popularity of electric vehicles [10]. Impacts of electrical vehicle fires should be explored by burning the battery and vehicle through experimental studies. In fact, some full-scale burning tests were reported either on the battery or electric vehicle [17].

Combustion performance of two LIB ($LiCoO_2$ and $LiFePO_4$) was studied [19] using a fire calorimeter. Out of many experimental studies on the combustion characteristics of primary LIB, the one reported by Chen et al. [20] is very useful. Burning tests of LIB set up were conducted in a calorimeter with adjustable radiative heat flux similar to a cone calorimeter. Heat release rates under radiative heat flux of 20 kW m^{-2} can be determined under flashover. Time to ignition, mass loss, heat release rate and plume temperature were measured. The heat release rate of burning 9 batteries can be up to 14 kW. Such data under flashover are very useful.

Effects of fire engineering system in electric vehicle battery incidents were studied [10]. Fire suppression methods and agents, personal protective equipment, and safety management operations were studied with full-scale fire testing of LIB used in electric vehicles. Review of the current emergency response tactics, and discussion on tactical changes relating to emergency response procedures for electric vehicle battery incidents were also presented.

The heat release rate (HRR) is an important parameter for fire hazard assessment of battery and electric vehicle. HRR curves for batteries and the electric vehicle are useful in fire hazard assessment. HRR of burning a battery can be applied to investigate whether a vehicle can be ignited as a whole. The fire environment in burning the whole vehicle can then be estimated. The HRR in burning the electric vehicles can be used to estimate the fire environment of tunnels or car parks.

A method to determine the heat release rate more accurately was investigated [21]. Using this approach has the advantage that a calibration with a transient HRR curve is possible, which is easier to realize in practice. Moreover, this procedure is less time consuming. Reported experimental result on measured HRR curve on vehicle battery [22] used together with that on burning vehicle [18] is shown in Fig 1. The burning duration was about 20 minutes, with HRR over 2 MW for 3 minutes. The maximum HRR is up to 6 MW, large enough to ignite electric vehicles.

2.3 Smoke Toxicity

Safety issues of LIB are related to highly volatile and flammable organic-solvent-based electrolytes as surveyed [23]. The challenges, which so far prevent the widespread replacement of organic carbonate-based electrolytes with $LiPF_6$ as the conducting salt. Separators used in liquid electrolyte LIB were reviewed [24]. According to the structure and composition of the membranes, the battery separators can be broadly divided into three groups: microporous polymer membranes, non-woven fabric mats, and inorganic composite membranes.

A more thorough comparative investigation of the toxicity threat in the case of larger-sized 0.4 kWh LIB was reported [25]. Results reveal that critical thresholds are highly dependent on the nature of the battery salt, and on the state of charge of the cell. Salt anion was responsible for the emission of a non-negligible content of irritant gas such as HF (PF_{6-}) or HF and SO_2 (FSI^-). This demonstrates that counterfeit battery hazards are unknown.

An experimental platform was constructed to investigate [26] the combustion behavior and toxicity of lithium iron phosphate battery with different states of charge and suppression efficiency of dry powder in LIB fires. The results indicate that the fully-charged battery undergoes TR when its surface temperature reaches 166.8 °C and releases combustible gases such as CO, CO_2 and HF. The LIB has a greater thermal risk and toxicity with the higher SOC value. The maximum heat release rate reaches 12.1 kW and the normalized heat release rate value is 6.2 MW m^{-2}. It is found that dry powder could extinguish LIB fires under the given appropriate conditions.

'Safe zone' [27,28] is mentioned for studying crashing vehicles safety. Such safe zones might not be well-sealed. Smoke spread to the safe zone from any leakage areas should be watched.

3. Fire and Explosion Categories

The causes behind LIB heating were explained with battery safety broadly classified into three categories [5]. The first category is cell design depending on selected materials and circuitry [29]. The second one is use of product in scenarios unexpected [30] by the supplier. The third one is accidents coming from normal recommended operating conditions, possibly due to thermal runaway [9].

The above scenarios can be assessed for batteries with known construction, materials and rating. However, the problem is more horrible for counterfeit ones. Their cost is very low and yet so widely used. The quality is poor with unknown design and materials.

As explained earlier on the basic physics [5], heating effect might be dangerous. Any thermal generating effect without proper dissipation can accumulate to heat up and even ignite the combustibles, particularly the electrolytes as reviewed above. A fire is resulted when heat dissipation is too slow. Further, electrolytes as condensed matter would be transformed to gas, heated up and generating pressure to give an explosion. The explosion scale would not be big for small rating batteries manufactured according to safety standards. However, it is very difficult to guarantee that the chemical used and the construction methods of counterfeit batteries are following safety standards. Fire and explosion can give larger scale disasters.

Fire hazard assessment with risk parameters deduced from genuine batteries are only useful for those car owners keeping genuine batteries. This might be difficult to afford in developing countries. Therefore, studying only the battery fire is not adequate. The scenario of burning the whole vehicle due to battery incident with a certain design fire is essential. A fire resulting from burning electric vehicles is different from just burning a battery. Battery is just an ignition source easier to catch fire or even explosion due to some explained reasons as in Fig. 1.

The following three points are missed, at least for electric vehicles:

- Fire hazards of battery should be taken as a starting fire only. Fire risk parameters [31-34] should be deduced from burning combustibles of the whole car.
- Both thermal and smoke toxicity must be included. Meaning of safe zones in vehicles have to be changed with appropriate fire risk parameters.
- As many counterfeit batteries are being used, it is difficult to control their fire risk parameters. Appropriate fire safety provisions have to be designed.

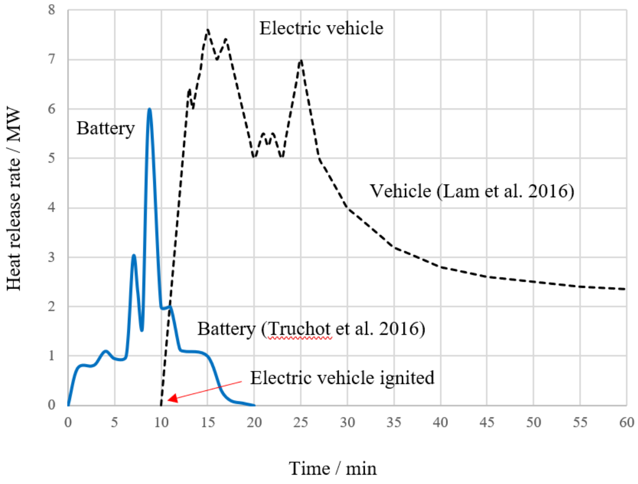

Fig. 1. Design fire curves combining battery and vehicle

Flammable gases released would pose fire and explosion hazards for the compartment housing the cells. However, there is little available information characterizing the flammability properties of the gases released after cell thermal runaway. Explosion characteristics, such as lower flammability limit, laminar flame speed, and maximum over-pressure have to be explained by physical principles as pointed out above.

4. Design Fire

A reasonable fire hazard assessment scenario for electric vehicles [5] is to take the batteries as a big ignition source. This can be determined by burning the whole car with full-scale experiments. Fire environment in the electric vehicle car can be estimated by an appropriate fire model.

Electric vehicle with big LIB fires was studied [22] with a design fire curve on burning LIB was proposed as shown in Fig. 1. The time averaged values of battery HRR over different averaging times can be estimated. The average HRR was 1.34 MW for the burning duration from 0 min to 20 min, 1.67 MW from 1.25 min to 17.5 min, 2.13 MW from 2.5 min to 5 min, and 2.97 MW from 5 min to 12.5 min.

HRR measured for burning electric vehicle was reported [18] using a 2 MW burner. It appears that a value of 2 MW used by Lam et al. [18] is a reasonable averaged value upon ignition of a battery.

An example on burning an electric vehicle [18] is also plotted with the LIB fires [22] together in Fig. 1, taking the ignition time of electric vehicle about 10 minutes after igniting the battery. Of course, the ignition time of vehicle depends on many other factors, might not be 10 minutes as used here. Anyway, upon igniting the vehicle, the burning duration is over 30 minutes, with over 5 MW for 15 minutes, and peak value almost 8 MW. This would lead to serious consequences in vehicular tunnels, car parks, garages or any other enclosed or underground spaces.

5. Fire Risk Parameters

In order to investigate the thermal failure propagation behaviors of LIB batteries, full-scale burning tests have to be conducted [11]. Theoretical physical principles have to be worked out on promoting fire safety design of large LIB energy storage equipment. Thermal fire risk parameters can then be deduced from heat release curves and transient toxic gas curves from oxygen consumption calorimetry reported before [34]. This includes ignition time, peak heat release rate, total heat release rate, total smoke release, carbon monoxide and carbon dioxide. Parameters deduced such as the propensity to flashover and total heat release rate [35] are essential in assessing fire risk [36].

There are two different approaches on assessing the risk parameters for LIB only; or for the entire vehicle.

The transient curves of the whole vehicle burning, not just the batteries, as in Fig. 1 should be used. Two thermal parameters *x* and *y* on flashover propensity and total heat released per unit surface area are proposed.

The first parameter is the flashover propensity *x* (in $kWm^{-2}s^{-1}$) given by the peak heat release rate (pkHRR) and time to ignition (TTI):

$$x = \frac{pkHRR}{TTI} \tag{1}$$

The second parameter is the total heat releases (THR) (in MJm^{-2}):

$$y = THR \tag{2}$$

Smoke toxicity effects to human beings can be assessed based on the fractional exposure dose (FED) measured in the oxygen consumption calorimeter.

The peak FED calculated from the peak concentration of CO and CO_2 denoted by [CO] and [CO_2] can get the toxic potency, ‘lethal concentration of the fire effluent emitted to produce death in 50% of test animals for a specified exposure time’ LC_{50} denoted by LC_{CO} and LC_{CO2} based on the oxygen consumption calorimeter data can be determined [31,32].

$$FED = \frac{[CO]}{LC_{CO}} + \frac{[CO_2]}{LC_{CO_2}} \tag{3}$$

Since LC_{CO2} is very large, FED can be estimated only from the peak concentration of [CO] denoted by pk[CO] and taking LC_{CO} as 5000 ppm (e.g. [33-35]:

$$FED = \frac{pk[CO]}{5000} \tag{4}$$

FED determined can be used to estimate LC_{50}, the fire effluent emitted to produce death in 50% of test animals for a specified exposure time. It is given by the specimen mass loss Δm, bench-scale volume in an oxygen consumption calorimeter ΔV, and the fractional effective dose (FED) as:

$$LC_{50} = \frac{\Delta m}{FED \cdot \Delta V} \tag{5}$$

Another parameter *z* on smoke toxicity can be taken as LC_{50} in Eq. (5) through peak carbon monoxide concentrations [36] given by Eq. (4),

$$z = LC_{50} \tag{6}$$

These three parameters x, y, and z on flashover propensity, total heat released per unit area, and LC_{50} are proposed for hazard assessment in burning the entire electric vehicle.

An example risk diagram is shown in Fig. 2 on High Risk (HR), Intermediate Risk (IR), Low Risk (LR) and Very Low Risk (VLR) divided as in fire.

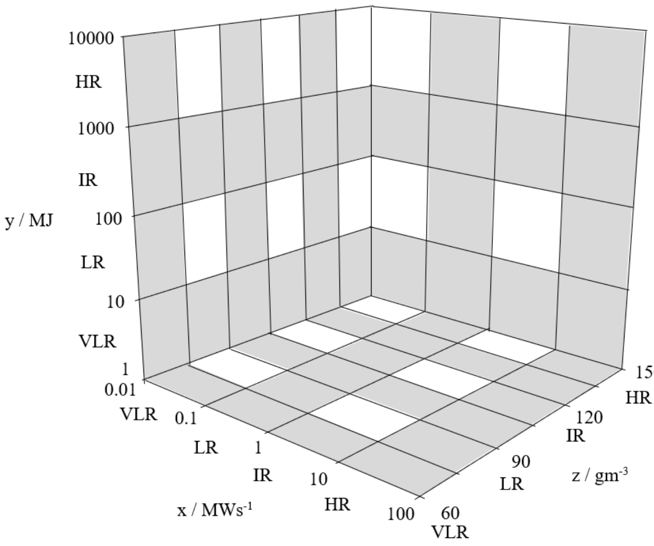

Fig. 2. Validation risk diagram on the x, y, z diagram

In view of compiled experimental curves [18,22] for electric vehicle and the battery (assumed to be a genuine one in igniting the car slowly) as shown in Fig. 1, pkHRR of electric vehicle is 8 MW, TTI is 10 minutes, giving x of 0.013 MWs^{-1} and y around 7200 MJ. As observed in the recent fast burning [12] of an electric vehicle ignited within 4 s as watched in the news, x becomes 8 MW/4s, or 2 MWs^{-1}. The risk class increased significantly by 150 times as shown in Fig. 3. Using batteries, particularly old genuine batteries or counterfeit batteries without any quality control might give such short TTI as observed in that fire burning an electric vehicle [12].

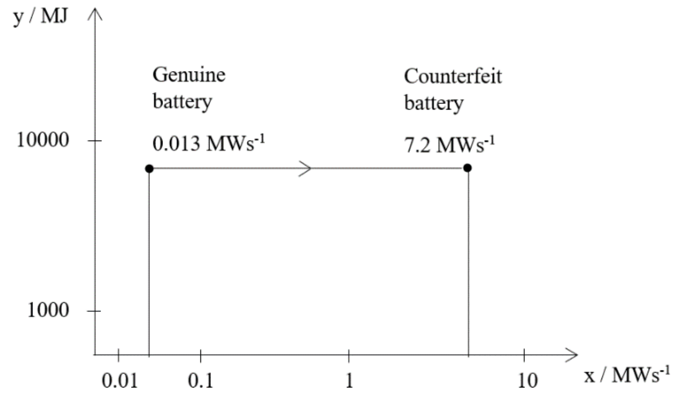

Fig. 3. Change of TTI

6. Fire Safety Provisions

With so many electric vehicle fire or even explosion incidents, fire suppression systems [10] should be considered to promote fire-safe electric vehicles, particularly in developing countries using counterfeit batteries for used cars. Emergency response procedures for electric vehicle battery incidents should include active systems.

However, traditional fire engineering systems are not appropriate to install in vehicles. New design should be considered. An apparatus was constructed [37] to investigate the extinguishment and cooling effectiveness of a single LIB dodecafluoro-2-methylpentan-3-one ($C_6F_{12}O$) suppression and rapid water mist cooling system. Tests indicated effective cooling by combining $C_6F_{12}O$ and water mist, with significant reductions in the cell's peak temperature and high-temperature duration compared to $C_6F_{12}O$ only and without suppression.

New systems might work only for some scenarios. A water mist fire suppression system is an environmental friendly design, but might not be able to extinguish a fire rapidly [38]. As reported before, using low or moderate-pressure water mist system on gasoline fires, the fire cannot be extinguished under some geometry. In studying the fire hazard of heating oil in a pan using an induction cooker under various scenarios [39], explosion might even occur.

Experimental results should be compiled in a way similar to those evaluating the performances of water mist and gas-solid composite dry powders in suppressing cooking oil fires [40]. Experiments on vehicle fires should be performed to determine heat release rate, flame temperature, burning duration and heat fluxes of battery fires. Reduction in gas temperature, changes in heat fluxes and suppression time can then be measured. Experimental data will provide necessary information for hazard assessment.

As effective suppressing system would stop the fire as many intermediate chain reactions cannot proceed. Consequently, carbon monoxide concentration might be increased. All these hazardous scenarios should be assessed rigorously before installing the active fire protection system.

A vehicle fire occurred in Tate's Cairn Tunnel during rush hours in the evening in Hong Kong recently [41]. That was a small fire but a large quantity of smoke was liberated. As the tunnel was constructed with more requirements on fire engineering systems, particularly smoke management system, two separated tunnel tubes and good fire safety management, no big disasters resulted. However, many cars were blocked inside and the tunnel was closed for several hours before resuming normal. Economic impact was huge. The situation is unknown if counterfeit LIB used in vehicles and many fires occurred. Even well-planned fire safety management cannot prevent smooth traffic operating.

7. Conclusions

LIB is the power source in electric vehicles. However, LIB suffers from limitation on its voltage, and wattage mainly due to internal heating problem that must be overcome, with basic physics explained before. Such heating effects might give fire or even explosion hazards. Scientific aspects of those thermal hazards of using LIB in electric vehicles have been pointed out in this paper for the society, particularly the authority handling fire safety, to explore in practical engineering applications. A key point is using too many counterfeit batteries. Risk parameters are not available for the counterfeit batteries. Correlations for risk parameters such as time to ignition or heat release rates with battery capacity deduced for genuine batteries are not applicable.

Studies on fire hazards were focused on electric vehicle fire following a battery fire. Consequences of burning the combustibles inside should be watched. Smoke toxicity to human must be assessed. Three parameters *x*, *y* and *z* describing fire hazards in burning electric vehicles deduced from the oxygen consumption calorimetry are proposed in this paper. Design fire curves determined from full-scale burning tests on burning electric vehicles due to battery fire is demonstrated.

As a conclusion, counterfeit LIBs are of unknown quality due to nonconformity to any standard. Thus fire hazards arising from counterfeit LIBs are more dangerous due to lack of information. Therefore, the battery fire is recommended to be taken as a starting fire for assessing the consequences of burning the whole electric vehicle. Recommending a design fire for electric battery is essential. Criteria for defining fire-safe electric vehicles according to whether they are using genuine and counterfeit batteries is necessary. It appears unnecessary to comply relationship of fire risk factors with electrical rating. The main objective of this paper is to promote realistic study on protection against many counterfeit batteries or poorly maintained old genuine batteries in second-hand vehicles in many areas to give fires and explosions. This would alert the authorities such as the Customs and Excise Department and Fire Services Department to assess fire hazards of counterfeit batteries more practically.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

W.K. Chow: Conceptualization, Investigation, Resources, Visualization, Writing-original draft, Writing-review and editing, Supervision,
C.L. Chow: Formal analysis, Validation, Writing-original draft, Writing-review and editing.

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