Fire safety distances for electric vehicles with damaged battery pack

Wilkens Flecknoe-Brown, Konrad; Runefors, Marcus

2024

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Wilkens Flecknoe-Brown, K., & Runefors, M. (2024). *Fire safety distances for electric vehicles with damaged battery pack*. Division of Fire Safety Engineering.

Total number of authors:
2

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Fire safety distances for electric vehicles with damaged battery pack

Konrad Wilkens Flecknoe-Brown and
Marcus Runefors
BRANDTEKNIK | LTH | LUNDS UNIVERSITET

Fire safety distances for electric vehicles with damaged battery pack

Konrad Wilkens Flecknoe-Brown and Marcus Runefors

Lund 2024

SWE: ” Säkerhetsavstånd för för elfordon med skadat batteripack”
ENG: ”Fire safety distances for electric vehicles with damaged battery pack ”

Konrad Wilkens Flecknoe-Brown and Marcus Runefors

Report 3268

Keywords: Safety distance; electric vehicles; hybrid vehicles; Car fires; Crash

Abstract

The increase in electric vehicles has led to more vehicles of this kind being involved in accidents. Since there is a risk of a delayed initiation of thermal runaway in these cases, many countries have recommendations for safety distances from crashed vehicles to buildings. This report is a part of the effort to develop similar guidance for Sweden, which was initiated by the Swedish Civil Contingencies Agency (MSB). First, guidance from a few similar countries was summarized, followed by a more detailed assessment of the scientific literature. The compilation of experimental studies and analytical models suggested a distance of 4 meters for passenger cars, 8 meters for buses, and 5 or 12 meters for trucks, depending on whether they have a load or not. A line-of-sight method for barrier sizing was also recommended, together with an EI30 fire rating. The assessment has significant uncertainty due to the scarcity of data in the literature, but this is believed to be to the best of current knowledge.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

www.brand.lth.se
Telefon: 046 - 222 73 60

Division of Fire Safety Engineering
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

www.brand.lth.se
Telephone: +46 46 222 73 60

Table of Contents

1 Background

With the increase in electric vehicles in later years, it is expected that the portion of electric vehicles among crashed vehicles will also increase. Since it has been found that crashed electric vehicles have a risk of delayed initiation of thermal runaway, this poses a challenge for repair shops since they are advised not to store the vehicles in their workshop. Even if stored outside the workshop, there is a potential risk of the fire in the vehicle spreading to the workshop, so a minimum distance is needed.

However, the distance suggestions from different parties are scattered, and the background of the recommendations is rarely documented. Therefore, the Swedish Civil Contingencies Agency (MSB) has given the task to the Division of Fire Safety Engineering at Lund University to investigate the literature and, as far as possible, develop suggestions for evidence-based distances.

The suggestions should include both passenger cars, trucks (without trailer) and buses. Since the risk is only increased for battery-induced fires, only this scenario should be evaluated, but including both combustion of the vehicle content and potential jet flames.

The objects to be protected are buildings as well as storage of combustible materials (to prevent escalation). Recommendations on barrier sizing and fire rating should also be provided.

2 General Methodology

In the initial phase of the project, a web search for any guidance or recommendation provided by other countries was undertaken. This was not an extensive search, as the main goal of the project was to review the scientific literature on the topic.

For searching the scientific literature, the Lund Library system (LUBsearch) and the Scopus database were chosen for the data sourcing. LUBsearch and Scopus cover journals and articles from most major publishers, including those in the fire science community. Google Scholar and Google search engine are used to supplement and locate the full text of journal papers and technical reports or white papers that were not published on journal platforms. A method based on the PRISMA-ScR method [1] was employed within this project to map and filter the scientific literature.

3 Review of other countries recommendations

Based on the guidance in the project description, a review of the German recommendations (by VDIK – Verband der Internationalen Kraftahrzeughersteller e.V.) – "*Technical quarantine areas for damaged vehicles with lithium-ion batteries*[1]" was used as a starting point. This review was then extended, and a basic web search was undertaken to investigate if/what other countries had in terms of recommendations on this topic. These are briefly summarised here:

3.1 Germany

The document by VDIK – Verband der Internationalen Kraftahrzeughersteller e.V. – "*Technical quarantine areas for damaged vehicles with lithium-ion batteries*" gives the following general recommendations:

- **5m from combustible materials**
- **>1.5m from non-combustible or fire-rated wall**
- Preferably an outdoor location
- Marking of electric vehicles and quarantine area (DGUV requirement)
- Possibly collecting trays for potentially leaking operating fluids
- Ban smoking and other ignition sources

3.2 USA

The document from the National Highway Traffic Safety Administration (NHTSA) – "*Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries*" gives some general guidance to various stakeholders that may be involved (general public) or come to an incident (e.g. EMS, Fire, Police) of a crashed EV.

Interestingly, at the beginning of the document, the NHTSA makes the following statement: "*NHTSA does not believe that electric vehicles present a greater risk of post-crash fire than gasoline-powered vehicles. In fact, all vehicles—both electric and gasoline-powered—have some risk of fire in the event of a serious crash. However, electric vehicles have specific attributes that should be made clear to consumers, the emergency response community, and tow truck operators and storage facilities…*"

General recommendations are summarised below (note – that only recommendations that pertain to the current project interest i.e. safety distances, are summarised here):

At the crash site:

- **Move away from the vehicle and evacuate others from the immediate area** if you detect any unusual odors or experience eye, nose, or throat irritation.

If a fire occurs:

- Establish safe perimeter

- As with any vehicle fire, the byproducts of combustion can be toxic and all individuals not properly trained, dressed, and equipped to fight the fire should be directed **a safe distance upwind and uphill from the vehicle fire** and out of the way of oncoming traffic.

---

[1] Summary here is based on a machine translate version of: Technische Quarantäneflächen
für beschädigte Fahrzeuge mit Lithium-Ionen-Batterien, published by: Verband der Internationalen Kraftahrzeughersteller e.V.

Post incident:

- Do not store a severely damaged vehicle with a lithium-ion battery inside a structure **or within 50 feet of any structure or vehicle**.

It is observed here that no concrete safety distances are provided apart from the value of 50 feet (approximately 15m). Instead, terms such as "away from the immediate area", "safe perimeter" and "safe distance" are used, which seem open to interpretation.

3.3 UK

On the GOV.UK website, the Department for Transport provides a guidance document titled "Recovery operators working with electric vehicles" (updated 4th December 2023) which states:

- Current industry guidance states that a vehicle at risk of going into a thermal runaway event should ideally **be kept 15 meters from anything else**. It should be noted that hazards such as projectiles may exist within (and in some instances, outside of) this 15-meter zone. The priority in this scenario is to defer to the fire service, evacuate all people around the vehicle and retreat to a safe place well away and upwind from the vehicle.

- When storing an EV with a suspected damaged HV system, it should ideally be in an outside quarantine area, which is a suitable distance away from any other nearby objects. According to industry guidance, **15 meters is currently considered a safe storage distance between vehicles**. This recommended distance may not be achievable in practice and, as such, risk assessments should be conducted to mitigate the risk of storing vehicles closer together.

3.4 Australia

The various states in Australia, may provide their own guidance. The Australian Capital Territory (ACT) and the state of Queensland give the following recommendations, based on the document titled: "*Electric Vehicle Safety*" by The ACT Emergency Service Agency (ESA) 2019:

- Keep clear of the vehicle (uphill and upwind) and warn passers-by to keep at a safe distance (**at least 30 meters**), even if there is no visible signs of smoke, vapors, or flames

- Damaged EVs should be kept in an open area at least **15 meters** from other vehicles, buildings, and/or other exposures.

3.5 Netherlands

Unlike the other countries above, the Nederlands Instituut Publieke Veiligheid (NIPV) has produced a document titled: "Model for calculating heat radiation from electric vehicle fires[2]".

The main objective of this project seems to be to establish a calculation model with which the heat radiation of electric vehicle fires can be calculated. The model takes measured parameters from published fire experiments (e.g. peak HRR) and uses them in the calculation procedure. Some example calculations have also been performed for 3 different vehicle types; an SUV, a bus and a truck with trailer.

They do not provide recommendations on actual safety distances, but instead provide a method to calculate the heat flux at a given distance based on the chosen fire input parameters. Figures are also

---

[2] Title and summary here is based on a machine translate version of: "Model voor het berekenen van de warmtestraling van elektrische voertuigbranden" Nederlands Instituut Publieke Veiligheid (NIPV), 2024

provided showing the calculated heat fluxes with distances using the developed model and thermal radiation contours for 3 set values of the received heat flux 4, 10 and 35kW/m^2, reproduced here in Figure 1, Figure 2 and Figure 3.

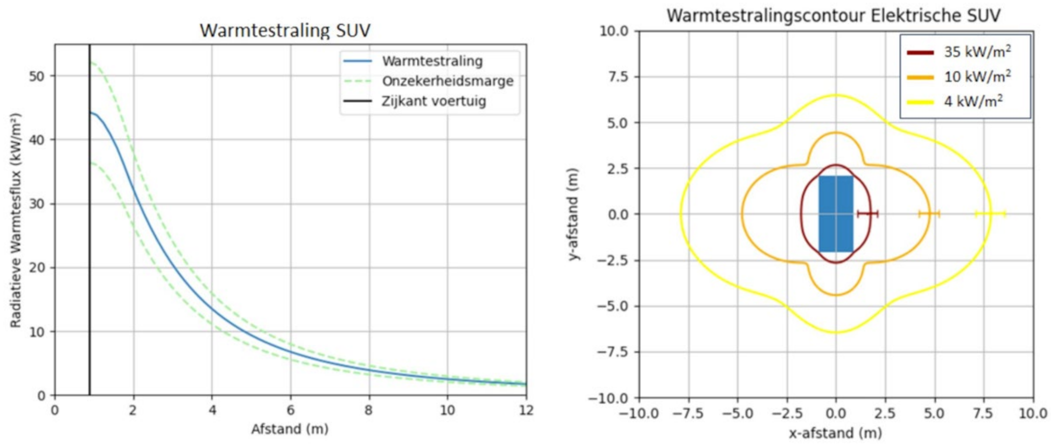


Figure 1 - heat radiation with distance for an SUV

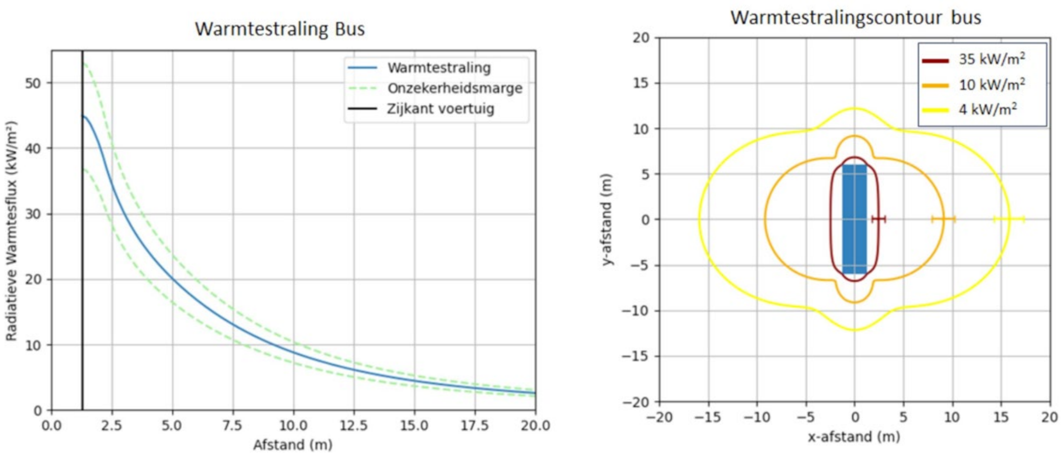


Figure 2 - heat radiation with distance for a Bus

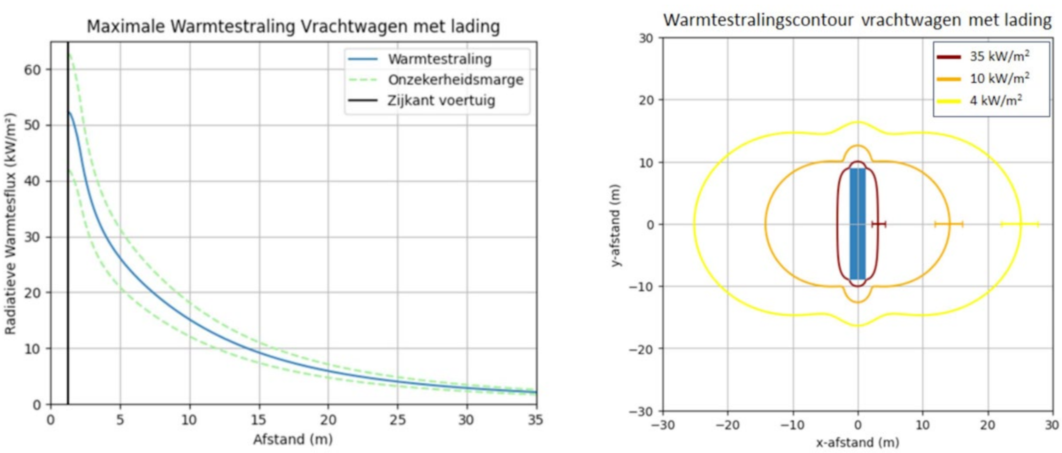


Figure 3 - heat radiation with distance for a loaded truck

While not providing recommended safety distance as such, this document provides a method by which a safety distance can be determined and performance-based, looking at the potential actual scenario rather than making a “global” value that should be used for all cases. The calculation method is based on sound principles, but has not been validated against experimental data (something addressed later in this report).

4 Fundamental theory

The main purpose of the current project was to compile and summarise the current fire research experiments with both fossil and electrical vehicles that have useful data for assessing the risk of fire spreading. When investigating what are the influencing parameters in fire spread, we consider the two dominate phenomena in fire growth. *Ignition time* and *flame spread velocity*.

The time it takes for a material to ignite (t_{ig}) given the right conditions, controls the initial risk of fire being able to spread to other materials/objects. Once ignited, the rate of fire spread, i.e. the flame spread velocity, will dominate the growth of a fire. These two phenomena are governed by the same fundamental parameters, as shown in equation 1 and 2[2].

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{(T_{ig}-T_0)^2}{\dot{Q}_R''^2}$$ - equation 1 (time to ignition)

$$V_f = \frac{\dot{q}_f''^2 \cdot L_p}{k_f \rho_f c_f (T_{ig}-T_0)^2}$$ - equation 2 (flame spread velocity)

Where; $k\rho c$, individually known as thermal conductivity (k), density (ρ) and specific heat capacity (c), together known as the *thermal inertia*, is a material property and governs the rate at which a material will heat up and reach its ignition temperature (T_{ig}). In the case of this project, these are properties of the impacted material (the material receiving the heat from the fire), and thus of less importance in this case, as they may be anything close to the EV

$\dot{Q}_R''$ or $\dot{q}_f''$, are defined as the incoming or net heat flux (kW/m^2) the material in question receives (in this case primarily radiation). This is a parameter that comes directly from the fire source itself and thus, likely the most important parameter to come from an EV fire scenario in terms of the risk of fire spreading from this initial source.

To determine a safety distance, a critical value of heat flux must be defined. A common choice is to base it on the critical heat flux for wood, which is well established and found to be 12.5 kW/m^2 ± 2 kW/m^2[3]. It can be noted that this is slightly below the value of 15 kW/m^2 suggested by the Swedish building regulations[3] and, therefore, more conservative. It is also in line with the value for fire spread between buildings (12.6 kW/m^2) suggested by Law [17]. Due to this, a value of 12.5 kW/m^2 will be used as a basis for the safety distances in this report.

Based on the above discussion, searching the scientific literature was refined to search and compile experimental data from EV fire experiments that measured actual heat flux values, or the heat release rate (HRR), as the HRR also governs how much heat can flow out to the external environment.

[3] It can be noted that the Swedish building authorities in the consequence analysis compares their value to the suggestion of 12.6 kW/m^2 by Law (1963) and write that it is lower (SIC!) and thus more conservative.

5 Compiling of Scientific literature

Using the LUBsearch and Scopus databases and search terms such as; "electric AND vehicle OR car OR truck OR bus AND heat AND release AND rate", a total of approximately 294 initial journal papers were found. These were then compiled into an excel database, and following the general PRISMA protocol[1], taken through a set of filtering steps to extract the most useful papers for more detailed analysis. Note: the use of "AND" means the word before and after must both be in the search results. Use of the word "OR" means either one word or the other word can be in the document.

Table 1 - keywords used in search and the resultant number of documents found

Keywords used	Search criteria	Number of papers
electric AND vehicle AND fire AND spread	Article title, Abstract, Keywords	51
electric AND vehicle AND fire AND heat AND flux	Article title, Abstract, Keywords	11
electric AND vehicle AND heat AND release AND rate	Article title, Abstract, Keywords	110
electric AND vehicle OR car OR truck OR bus AND heat AND release AND rate	Article title, Abstract, Keywords	122

Found document results based on the keyword searches were downloaded as reference lists and then collated in excel, this resulted in a total of approximately 299 article references. The "remove duplicates" function in excel was then used to remove all duplicate results within the collated list, reducing the total list to approximately 180 articles.

Abstract screening and Article review.

In this stage, abstracts of the remaining articles are reviewed and the most relevant are highlighted and the full article is then reviewed. After screening, the 180 articles were reduced to 62, and based on the review of the papers, a total of 25 articles were used for data extraction.

The relevance of the articles to this project can be categorized into three main subject areas:

1. Articles that provide heat flux data.
2. Articles that provide heat release data
3. Articles that provide further information that is useful for the study (e.g. jet fires).

A full list of papers from this stage is supplied in the appendix, and a sample of the most relevant information within these 3 categories from the collected articles is outlined below:

5.1 Heat flux data summary

Of the 25 papers, five ([4], [5], [6], [7], [8]) had useful heat flux data that could be extracted. This was compiled into an excel spreadsheet (refer appendix 2), along with metadata on the experimental conditions, e.g. distance from fire source, height above floor level of heat flux meters, position compared to the car etc. this led to approximately 60 heat flux data points being recorded.

Figure 4 below, shows heat flux at different distances from the fire source, it should be noted that this figure compiles all the data obtained together, un-filtered, i.e. only the distance from the fire source is recorded, other context such as position to the car (e.g. side, front or back) and height of the heat flux meter are disregarded.

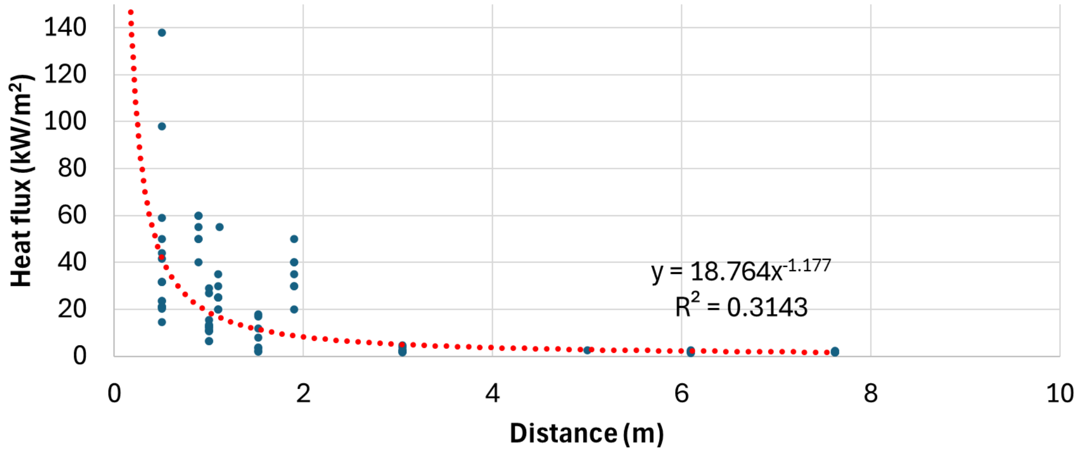


Figure 4 – heat flux data (blue points) vs distance from fire source (red points is a best-fit power law curve)

After reviewing the result presented in Figure 4, a set of data points was excluded from the set (approx. 14 data points) due to experimental conditions in[8] was different from the rest of the data and was judged not relevant since the ignition was performed using a very large burner below the vehicle simulating a pool fire which led to a simultaneous thermal runaway in large part of the battery module. This updated result is presented Figure 5 below.

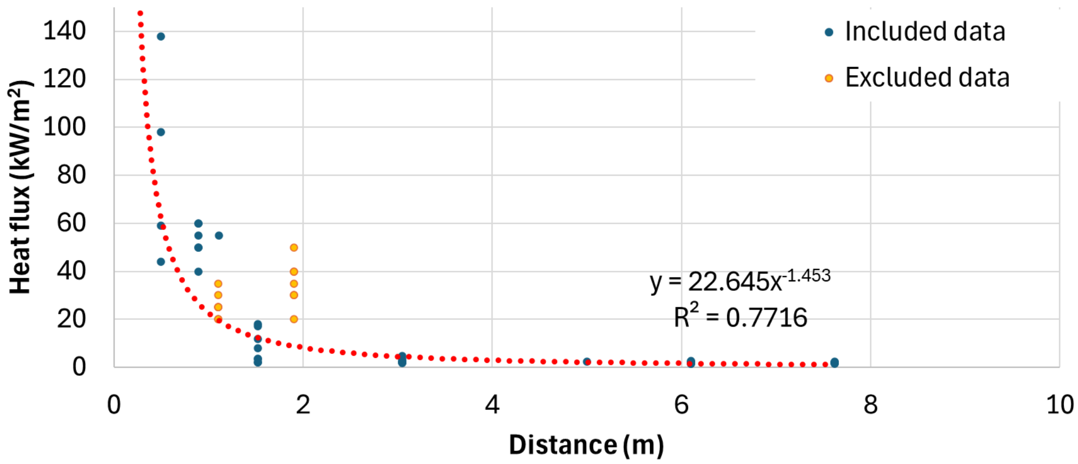


Figure 5 – included heat flux data (blue points) and excluded data vs distance from fire source (red points is a best-fit power law curve)

5.2 Heat release data summary

Investigating HRR results from EV fire tests, within the literature, there are many compilation articles, that already bring together much of the available data. When analyzing this data, and the comparisons with results from regular ICE cars, the prevailing consensus within the literature at this time seems to be that there is no significant difference in peakHRR and total heat release (THR) values as indicated in Figure 6 show that both cars fuel types (battery vs fossil fuel) fall within 1-3GJ in energy release. Given that the majority of the modern car materials are similar for both ICE and EV vehicles[7], this implies that the fire sizes should also be similar if just the drive train power of a vehicle is changed and that the largest differences between ICE and EV cars is a greater difficulty in suppressing EV battery fires, due to the inaccessibility of the battery packs[9].

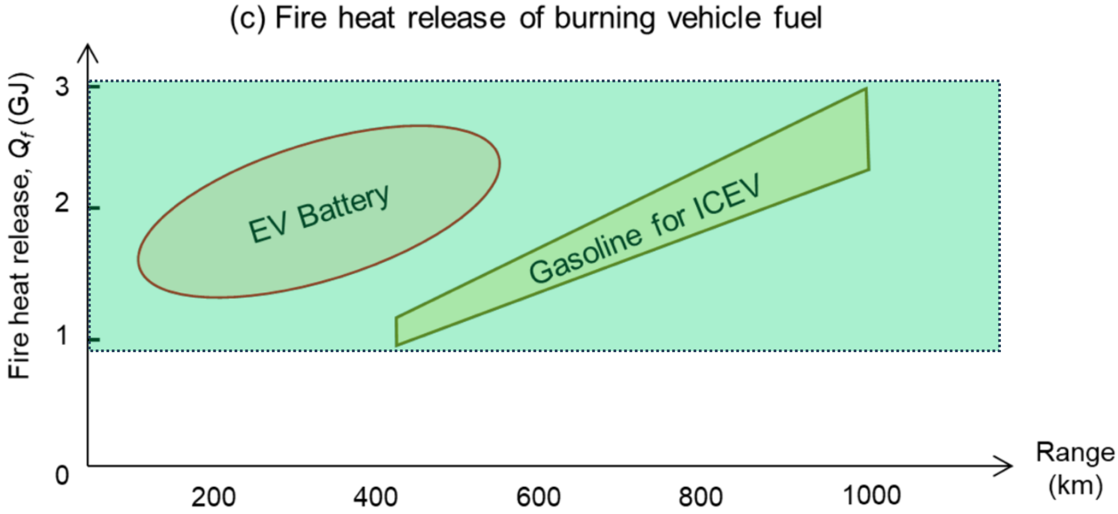


Figure 6 – total heat release comparison vs car range for ICE and EV cars (taken from [9])

Example comparisons are provided in Figure 7 below, highlighting the similarities in fire behaviour of EVs vs ICEs.

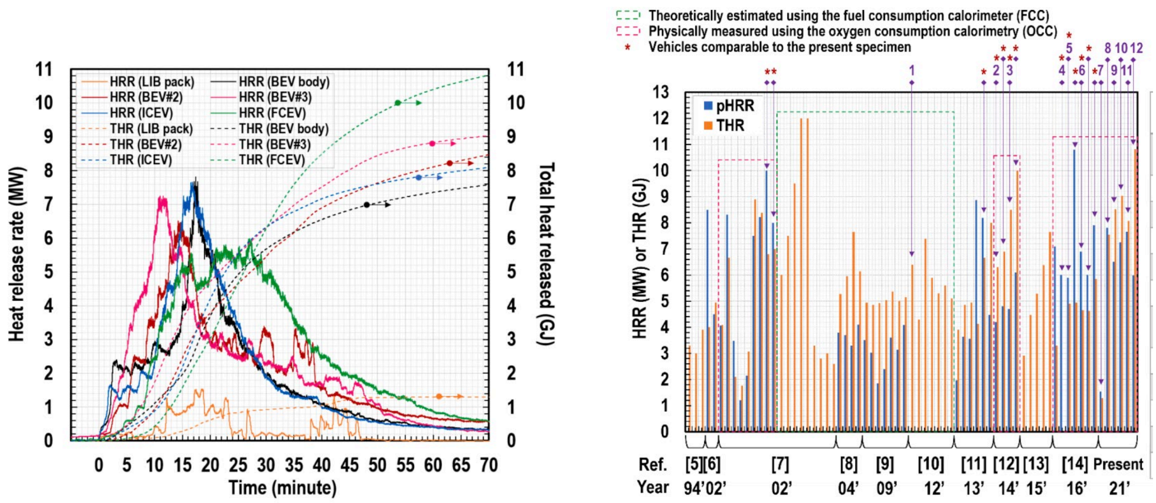


Figure 7 – compilation of various experimental results showing peakHRR and THR for EVs and ICEs (taken from[6])

In the comprehensive review paper from Sun et al. [9], they compile a large range of peakHRR vs Battery capacity, and were able to develop a relationship between the battery energy capacity (Wh) and PeakHRR (kW), and also provide evidence to strengthen the claim of similar energy release values between ICE and EV vehicles, as shown in Figure 8 below.

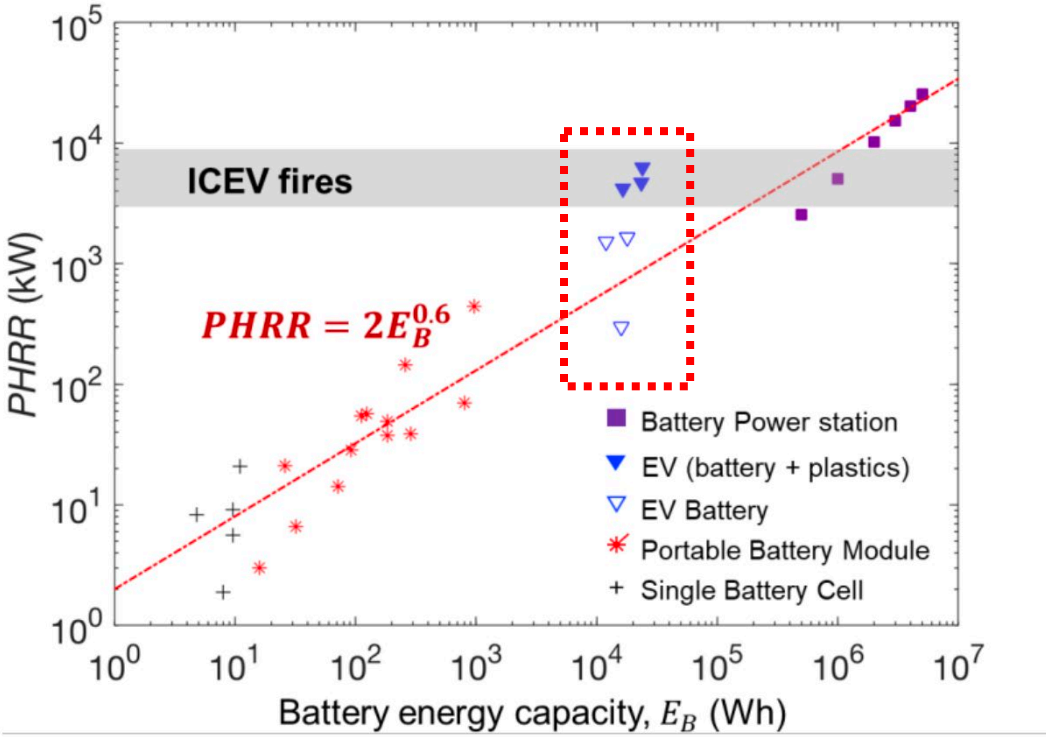


Figure 8 – relationship between battery capacity and peak HRR, also compared to ICEV fires (highlight in dashed red box).[9]

5.3 Other data summary

Additional phenomena of interest with regards to EVs fires, include observations of jet fires from the battery compartments, vapour cloud production and production of toxic species. With regards to the risks of fire spread, jet fires may be a contributing factor and are often observed[10]. However, the literature and experimental data on this phenomenon is very scarce[11].

Only two references with actual length measurements could be found in the literature[12], [13], with a total of 4 observations, summarised in Table 2.

Table 2 – jet fire observations, duration and length [12], [13]

Car type	Position	Observation	Duration (s)	length
BEV	Side	Jet fire	3	<2m
BEV	Side	Jet fire	11	<2m
BEV	Rear	Jet fire	26	2.5m
BEV	Side	Jet fire	Unknown	2.564m

Figure 9 – Longest jet flames observed in[13]

5.4 Bus and Truck data

Any sort of experimental data on buses and trucks was nearly non-existent, [14], [15]. Best estimates based on the scarce data are as follows:

- Buses: 30-35MW
- Truck with load: up to 70MW (highly dependent on cargo)

6 Models for predicting heat flux over distance

This section briefly describes the models used to predict the heat flux over distance.

The model from the NIPV document (*Model voor het berekenen van de warmtestraling van elektrische voertuigbranden" Nederlands Instituut Publieke Veiligheid (NIPV), 2024*) is included here so that its performance can also be evaluated against the other models tested and the assembled experimental data.

6.1 Point source radiation model

The point-source radiation model[16] is a simplified approach to estimating radiative heat flux from fires. It assumes the entire fire emits radiation as if it were a single point source and that the fire radiates uniformly in all directions (isotropic emission). Atmospheric attenuation and obstructions between the fire and the observation point are neglected:

$$q'' = \frac{\dot{Q} \cdot \chi_r}{4\pi R^2}$$

$\dot{Q}$ is the HRR (kW), χ_r is the radiative fraction (commonly prescribed as 30-35%) and R is the distance from the center of the fire to the edge of the target.

6.2 Solid flame radiation model

The solid flame model[16] is a more detailed approach compared to the point-source radiation model, aiming to better approximate the geometry of the flame and radiative behavior of real fires. This is particularly important relatively close to the fire (i.e. at high radiation levels such as those mostly relevant for ignition).

The fire is represented as a geometrical shape, and the flame surface is treated as a continuous radiating surface, with a specified surface emissive power.

$$q'' = E_s \cdot F$$

Where E_s is the emissive power of the surface (kW/m^2) and F is the view factor calculated from the geometrical shape chosen to represent the fire and the distance to the target. Usually, the flame is approximated as cylinder, but sometimes cones are used.

6.3 3D variation of plate-to-point radiation model

A MATLAB script based on the standard plate-to-point model radiation model was developed. The plate to point model is a method for estimating radiative heat flux from a planar surface (plate) to a specific observation point, similar to the solid flame model. The radiating surface is modeled as a flat, finite plate with a uniform emissive power or of a set temperature. The main difference for this model is that it implements plates in three dimensions to form a type of radiating "box". It then determines the radiation at a given measurement point by summing the contributions from each side of the "box" that can physically "see" the point in question, illustrated in Figure 9.

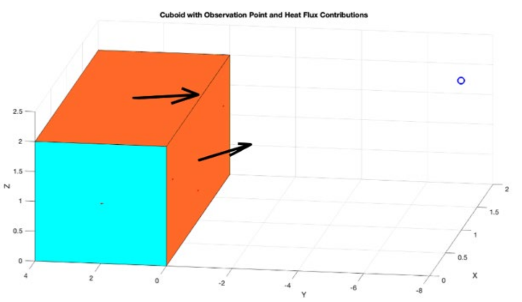


Figure 10 – MATLAB model, using 3D hot plates to model radiation from EV, black arrows indicate heat flux vectors from the radiating surfaces impacting the measurement point (blue circle located to the right of the figure).

6.4 Window radiation model

A popular variation of the solid flame model is the model based on window area developed by Law [17] where a certain level of emitted radiation per window area is assumed. This model is implemented in several building codes for distances between buildings, including the Swedish building code.

The model specifies that the radiation per window area is 167 kW/m^2 (4 cal/cm^{2}s) unless the fire load is below 25 kg/m^2 floor or window area[4] and, in that case, the outgoing radiation is 84 kW/m^2 (2 cal/cm^{2}s). The incoming radiation is then simply calculated using the plate-to-point correlation described above.

Although developed for buildings rather than vehicles, it can be seen as a first approximation in situations of lack of data.

6.5 Empirical model

All analytical models are based on assumptions that, for many situations, can be rather crude. Therefore, an alternative is to base the decay of heat radiation over distance on a curve fit of experimental results, with some added safety factors.

An empirical model based on measured radiation over distance was also developed within the IRIS project fire spread risks in informal settlements[18], [19], [20], [21]. Based on their experimental data, the correlation was proposed[18]:

$$q^{"} = 4.26 + 123.8e^{-1.3589d}$$

Where; d is the distance from heat source to the point of interest, q is the incident heat flux to the point.

[4] The area refers to window area if the enclosure is well-ventilated and otherwise the floor area.

7 Safety distances for passenger cars

To provide a method by which safety distances can be estimated, we first compare the various calculation methods with the collated experimental data to make an assessment of the predictive capabilities of the various models for passenger car-sized vehicles.

7.1 Safety distance based on radiation from car fire

Input parameters for the various models were chosen in two different ways; to compare against the model from NIPV, similar input parameters used by this model are chosen for the point-source and solid-flame models. A fire size of approximately 7.2MW is chosen for this reason, and as it is on the conservative side of the potential range in peakHRR values for passenger cars. For the MATLAB model, a plate temperature of 800 and 1000K were tested.

Distance is varied in the models to produce a plot similar to the experimental series (*Figure 10*). For models where the height from ground level is also an input (solid flame model and MATLAB model), 3m was chosen based on a calculation of heat flux over height for different distances shown in *Figure 11*. The result show that the analytical models significantly overpredicts the radiation in comparison with the experimental data.

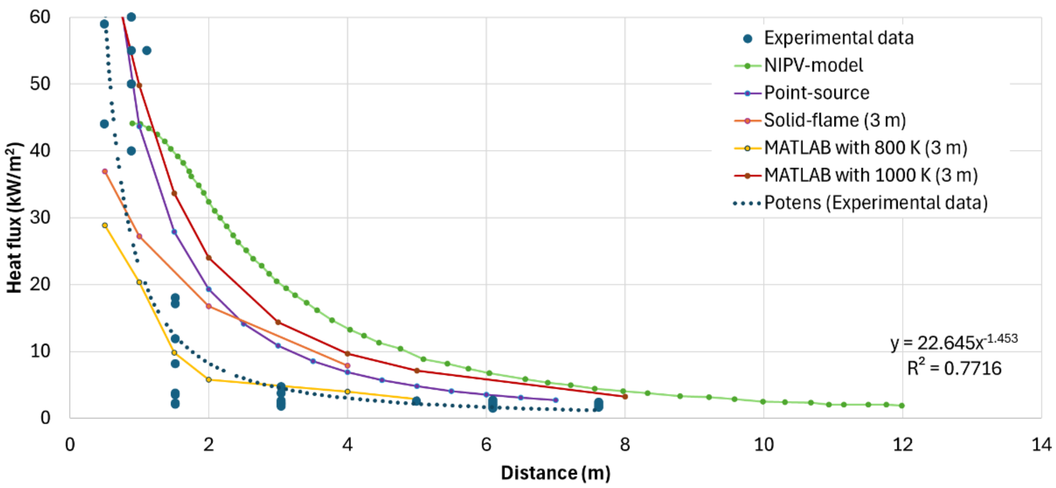


Figure 11 – experimental data compared with model prediction results (note: 3m means that calculation was done at a height of 3m above floor level).

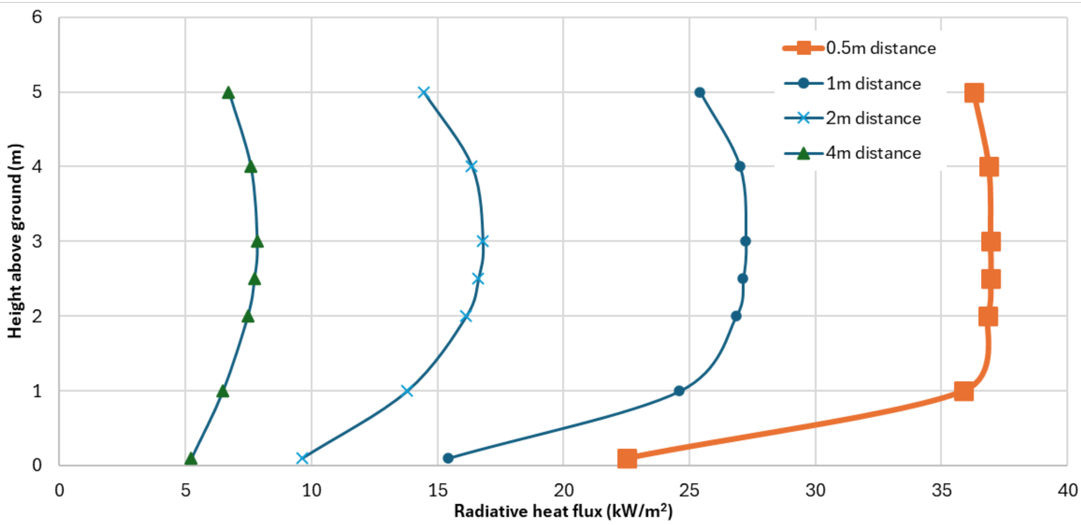


Figure 12 – heat flux variation over height (based on basic pool fire solid flame model).

Three empirical models are also tested, the first is just a basic power law curve fit of the experimental data, however this gives an average value between the experimental points, and thus may be considered slightly unconservative. To combat this, another correlation (refer to purple line in *Figure 12*) based on the initial curve fit, but with a safety factor, is also proposed. The advantage of this one is that it was made purposely more conservative to cover the majority of experimental data points gathered. The correlation from the IRIS project[18] is also added and compared in *Figure 12*.

The advantages of these models are in their simplicity, all that is required to calculate the heat flux at any distance is the actual distance measurement (in meters) itself. This allows for much more practical application of this calculation method and also reduce the need for assumptions compared to for the theoretical models.

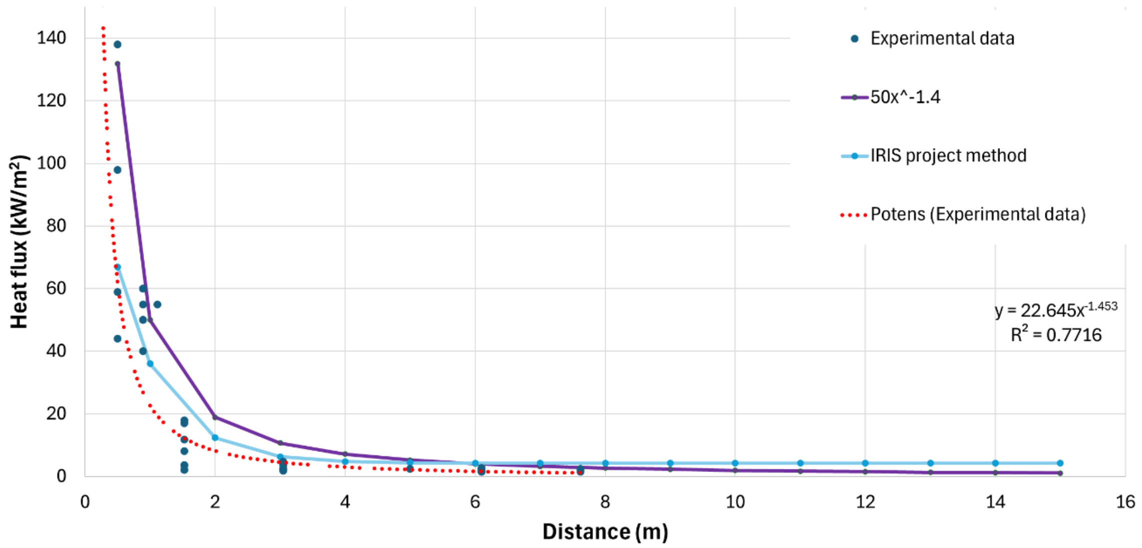


Figure 13 – heat flux vs distance for empirical models

Based on all the analysis above, it is suggested that the developed empirical correlation is employed;

$$q'' = 50x^{-1.4}$$

Where q'' is the incident heat flux a location x (in meters away from the fire source), may have the most practical application possibilities, while still giving reasonable values. Using this model, calculating the proposed safety distance using the proposed critical heat flux of 12.5kW/m^2, equates to;

$$12.5 = 50x^{-1.4} \rightarrow x \approx 2.7m \rightarrow x \approx 3m \text{ (rounded up to the nearest whole number)}$$

Based on this analysis, a safety distance of 3 m is suggested for radiation from compartment fire. This figure is backed up by the majority of the other tested models as well, however it is lower than what would be suggested by the NIPV model.

7.2 Safety distances due to jet flames

As described in section 5.3, the literature on jet flames is very scarce, and the two references found indicate that jet flames could extend up to approximately 2.5 m to the side of the vehicle. If we take a simplified battery vent gas, consisting of hydrogen, methane, and carbon dioxide, in equal proportions and select values of pressure and hole size to mimic the flame in the literature, the following radiation envelopes can be found using HyRAM developed by Sandia National Laboratories.

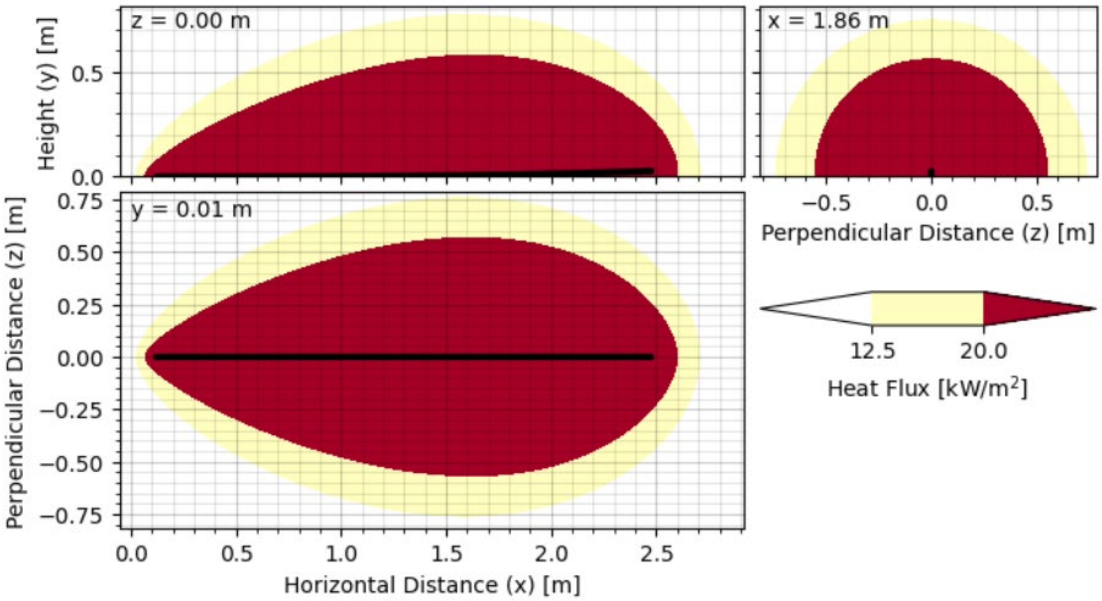


Figure 14 – Radiative heat flux around a simulated battery jet fire

It can be seen that the radiative heat flux is at potentially hazardous levels only slightly beyond (<10%) the flame length. This is due to a combination of factors, including the following;

- The temperature is highest (and thereby the radiation strongest) at around 60-70% of the flame length.
- The view factor is small since the flame resembles a small disk seen from downstream the flame
- Several of the common gases in battery vent gases have a low radiative fraction.

It should also be noted that the gas velocities are very high and the oxygen levels low downstream of the flame. The former leads to a dilution of the pyrolysis products produced by any target, and the low oxygen levels also hinder ignition. It is, therefore, likely that ignition only can occur at distances below the flame length. This assumption, however, lacks empirical verification, and this, together with the limited data available and rapid development in battery technology, requires a conservative treatment.

Therefore, a safety factor of 50% in relation to the above is recommended, which indicates a suggested <u>safety distance of 4 meters</u> (2.7 x 1.5) for passenger vehicles.

8 Safety distances for busses and trucks

8.1 Safety distances for buses

Although a few full-scale experiments with burning busses have been identified in the literature (e.g. Andersson et al., 2016[22]), none of those included heat flux measurements. The peak temperature in the compartment was however found to be slightly below 1000ºC (Andersson et al., 2016:22) and a visual examination of the pictures indicate flames extending 3-4 meters to the side (since it appears to be a windy day).

Due to the lack of experimental data, an analytical approach is suggested. For Law (1963), it is suggested that a radiation of 167 kW/m^2 over the window area is used. This corresponds to a gas temperature of 1100ºC, which is similar, but higher than the experimental value mentioned above. The window area is based on a Volvo 7900 articulated electric bus which is equal to 17.5m x 1.3 m (the non-articulated bus gives very similar distances).

Based on this, the following relation can be derived.

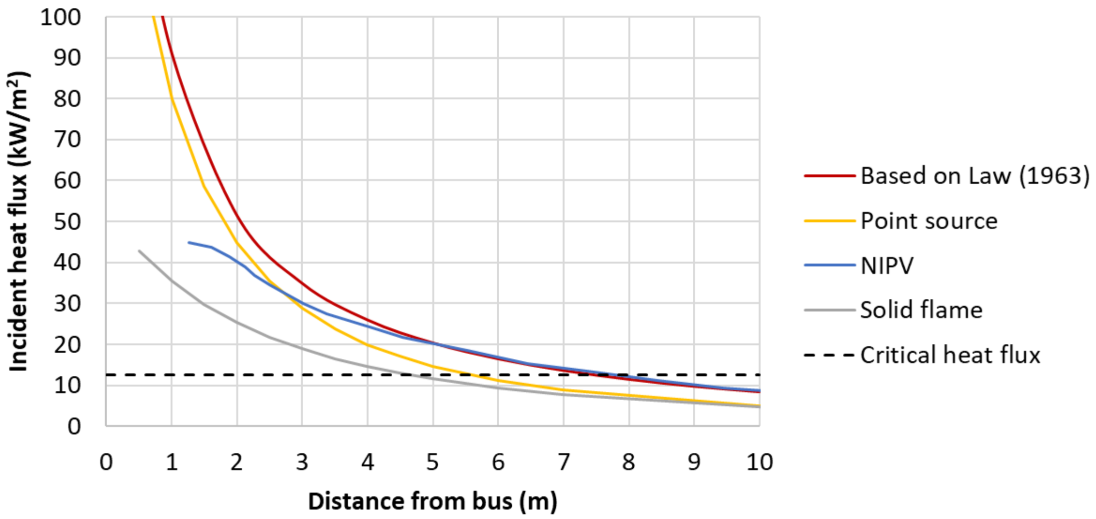


Figure 15 – Distance to critical heat flux for busses. Dashed line at 12.5 kW/m^2 added.

The method developed by Law (1963) and the NIPV-method both give safety distances of around 7.5 meters, while the point source model gives around 5.5 meters, which is similar to the solid flame model. Due to the uncertainty and lack of experimental data, a conservative value of 8 meters is suggested. This is also significantly longer than the flames seen in pictures from fires in buses.

8.2 Safety distances from trucks

Also for trucks, the literature on radiation is scarce, which requires the use of exclusively analytical models. The results can be found below.

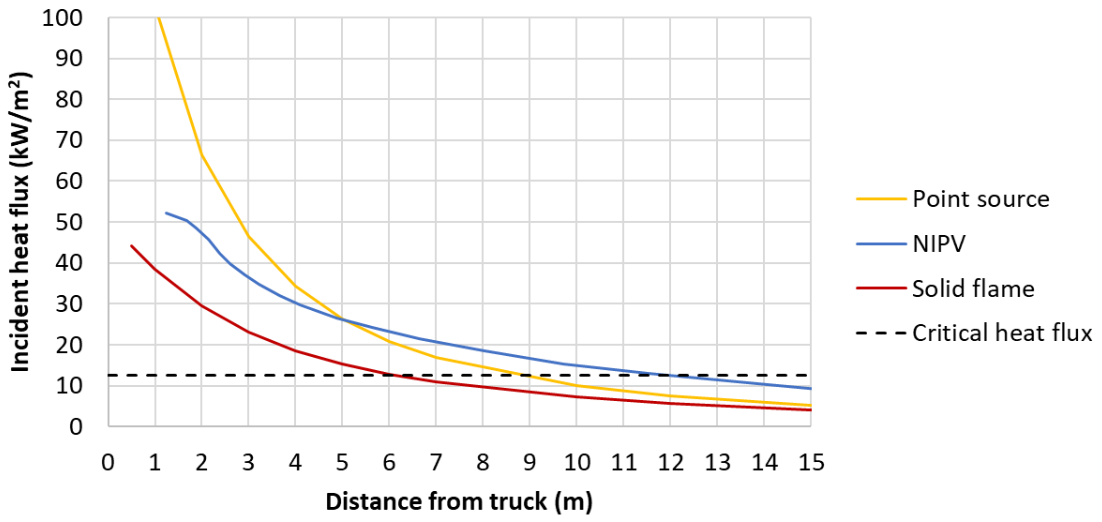


Figure 16 – Distance to critical heat flux for trucks (with load) with several different models. Dashed line at 12.5 kW/m² added.

All the models, except the NIPV-model give safety distances slightly below 10 m, while the NIPV-model gives 12 meters. Since the NIPV-model have previously been found to provide overconservative values, a safety distance of 10 m is recommended.

For an unloaded truck, the method developed by Law (1963) was used, and based on a front window area of 2.5x0.9 m from data sheet for a modern electric truck, a distance to critical radiation of 3 meters was found. However, due to the lack of experiments and relatively large batteries potentially resulting in longer jet flames, a slightly more conservative value of 5 meters is recommended.

9 Barriers

A barrier of sufficient fire rating will limit the radiation received by the building by blocking the line of sight. The exact influence of the barrier on the radiation is fairly complex since the perspective on the vehicle, and thereby the flames, will change. Although theoretically possible to account for these phenomena, the uncertainty in the safety distance determination in previous chapters together with the need for a practical method for implementation in the guidance advice against such an approach. Therefore, a simplified, line-of-sight method, is advised, where the closest line of sight between the vehicle and the building should equal to the values in previous chapters.

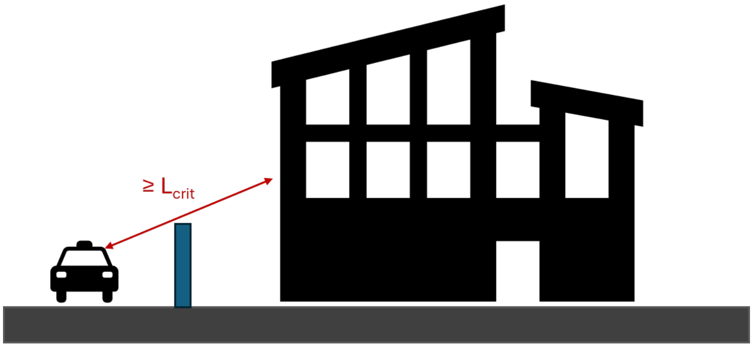


Figure 17 – Illustration of the line-of-sight method for barrier sizing.

A related question is the need for fire rating. If the barrier is close to the vehicle, flames will impinge on the barrier which induces a significant thermal load. If the barrier is further from the vehicle, the thermal load is less. However, to make the recommendation practical a single fire rating is suggested, unless the facility owner proves differently. Also in this respect, a significant uncertainty exists, but a fire rating of EI 60 has been found to have excellent performance in most fire scenarios and could therefore be seen as a conservative choice. However, due to the relatively short duration of exposure, a reduction to EI30 could be motivated without any risk of this increasing the hazard. This is expected to withstand both the impact from the burning car and from potential jet flames[5]. Barriers without insulation (e.g. a steel plate) could be used in combination with safety distance orthogonally to the barrier but should be verified through calculations.

Regardless of the rating, the barrier must be designed using materials that can withstand both the weather conditions, expected mechanical impact from daily operation and suppression water. The barrier should also have a distance to the vehicle that allows fire service intervention on all sides of the vehicle.

---

[5] Experiments on jet flames and barriers are scarce, but indicative experiments performed by Runefors[23] indicate that an EI30-construction can be expected to withstand a hydrogen jet flame for more than 10 minutes. Since jet flames from vehicles can be expected to both have a lower temperature and a shorter duration, the suggested rating is judged to withstand this impact.

10 Conclusion and Recommendations

The literature review generated 25 papers with relevant data from vehicle fires which – all of those for passenger cars. The results showed no indication of difference in peak heat flux from electric and fossil vehicles and thereby, both types were combined in the analysis. Despite a variation in experimental conditions, a useful empirical model for radiative decay over distance was found and provided a shorter distance than the purely analytical models.

For buses and trucks, no useful heat flux data was found, but since the analytical models was found to be conservative for passenger cars, the same type of models was applied also for buses and trucks. This is expected to give longer distances than experimental data, but since recommendations are needed and the number of vehicles is fewer, this was seen as acceptable, awaiting experimental data.

The data on jet flames from vehicles were even more limited, and only two papers could be identified which both indicated jet flames in the order of 2.5 m for passenger cars while no data was found for trucks or buses. For passenger cars, it was argued that, due to the uncertainty, a safety factor of 50% should be employed for potential ignition by jet flames from cars, indicating a 4 m safety distance (to be compared to 3 m for compartment fire only). For buses and truck with load, it was judged that the distance from the normal fire would enclose any potential jet flames, but for trucks without load, the distance of 3 meters was judged to be unconservative for jet flames. Since no data was available, a distance of 5 meters was chosen since the batteries are larger than passenger vehicles and thereby probably also the potential jet flames. This is, however, a crude assumption that should be developed further in the future.

The analysis resulted in the following recommended distances to prevent a potential fire in a crashed electrical vehicle from spreading to a nearby building or storage of combustible materials, based on a critical heat flux of 12.5 kW/m^2.

- Passenger car – 4 m
- Bus – 8 m
- Truck (without load) – 5 m
- Truck (with load) – 12 m

The distance is measured from the closest surface on the vehicle. If a barrier (EI30) is placed between the vehicle and the building, the distance in the closest line of sight between the vehicle and the building should reach this value, see Figure 15.

11 Future research

Due to the data scatter in the literature and lack of experiments (not least for buses and trucks) a conservative approach has been needed. It is therefore recommended that additional experiments are conducted to provide more accurate data which would most likely result in a reduction in the distances suggested above.

In addition, most of the models trialed in this report are analytical models, no complex CFD, heat transfer simulations were performed as they were out of scope of this project, however it would also be of interest to attempt more complex simulations of these scenarios to both compare with the results from this project and to provide some further insights.

Studies on jet flames are very scarce in the literature and should receive increased attention in the future. This includes both experiments with vehicles to assess the shape and heat transfer from jet flames and more general studies on ignition of materials from jet flames.

12 References

[1] A. C. Tricco *et al.*, "PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation," *Ann Intern Med*, vol. 169, no. 7, pp. 467–473, Oct. 2018, doi: 10.7326/M18-0850.

[2] D. Drysdale, *An Introduction to Fire Dynamics*, 2nd ed. Chichester: John Wiley & Sons, 1998.

[3] A. I. Bartlett, R. M. Hadden, and L. A. Bisby, "A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction," *Fire Technol*, vol. 55, no. 1, pp. 1–49, Jan. 2019, doi: 10.1007/s10694-018-0787-y.

[4] M. Arvidson and Ö. Westlund, "Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles," *Fire Technol*, vol. 59, no. 6, pp. 3391–3414, 2023, doi: 10.1007/s10694-023-01473-w.

[5] D. Zhang, G. Huang, H. Li, Q. Deng, and X. Gao, "A Study of the Factors Influencing the Thermal Radiation Received by Pedestrians from the Electric Vehicle Fire in Roadside Parking Based on PHRR," *Applied Sciences (Switzerland)*, vol. 13, no. 1, 2023, doi: 10.3390/app13010609.

[6] S. Kang, M. Kwon, J. Yoon Choi, and S. Choi, "Full-scale fire testing of battery electric vehicles," *Appl Energy*, vol. 332, 2023, doi: 10.1016/j.apenergy.2022.120497.

[7] R. Thomas Long Jr, C. F. Andrew Blum, C. J. Thomas Bress, and C. R. Benjamin Cotts, "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results Final Report," 2013. [Online]. Available: www.nfpa.org/Foundation

[8] C. Lam, D. MacNeil, Ryan Kroeker, Gary Lougheed, and Ghislain Lalime, "Full-Scale Fire Testing of Electric and Internal Combustion Engine Vehicles," in *Fourth International Conference on Fire in Vehicles*, P. Andersson and B. Sundstrom, Eds., Baltimore: RISE, Aug. 2016, pp. 95–106.

[9] P. Sun, R. Bisschop, H. Niu, and X. Huang, "A Review of Battery Fires in Electric Vehicles," *Fire Technol*, vol. 56, no. 4, pp. 1361–1410, 2020, doi: 10.1007/s10694-019-00944-3.

[10] Fredrik. Larsson, *Lithium-ion battery safety : assessment by abuse testing, fluoride gas emissions and fire propagation*. Chalmers University of Technology, 2017.

[11] Jonna Hynynen *et al.*, "Electric Vehicle Fire Safety in Enclosed Spaces," Borås, 2023.

[12] Y. Cui, J. Liu, B. Cong, X. Han, and S. Yin, "Characterization and assessment of fire evolution process of electric vehicles placed in parallel," *Process Safety and Environmental Protection*, vol. 166, pp. 524–534, 2022, doi: 10.1016/j.psep.2022.08.055.

[13] C. Zhao, W. Hu, D. Meng, W. Mi, X. Wang, and J. Wang, "Full-scale experimental study of the characteristics of electric vehicle fires process and

response measures," *Case Studies in Thermal Engineering*, vol. 53, p. 103889, Jan. 2024, doi: 10.1016/j.csite.2023.103889.

[14] H. Raza and S. Li, "The impact of battery electric bus fire on road tunnel," in *Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World- Proceedings of the ITA-AITES World Tunnel Congress, WTC 2023*, 2023, pp. 3280–3288. doi: 10.1201/9781003348030-397.

[15] P. Xu, D. Zhu, L. Li, K. Chen, B. Lin, and L. Li, "Study on the key parameters of vehicle fires for the growth stage in road tunnels," *Fire Mater*, vol. 48, no. 1, pp. 128–137, Jan. 2024, doi: 10.1002/fam.3172.

[16] M. J. Hurley *et al.*, Eds., *SFPE Handbook of Fire Protection Engineering*, 5th ed. 2016. doi: 10.1016/S0379-7112(97)00022-2.

[17] M. Law, "Heat Radiation from Fires and Building Separation," Great Britain, 1963.

[18] Y. Wang, L. Gibson, M. Beshir, and D. Rush, "Determination of Critical Separation Distance Between Dwellings in Informal Settlements Fire," *Fire Technol*, vol. 57, no. 3, pp. 987–1014, May 2021, doi: 10.1007/s10694-020-01075-w.

[19] N. de Koker *et al.*, "20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements," *Fire Technol*, vol. 56, no. 4, pp. 1599–1620, Jul. 2020, doi: 10.1007/s10694-019-00945-2.

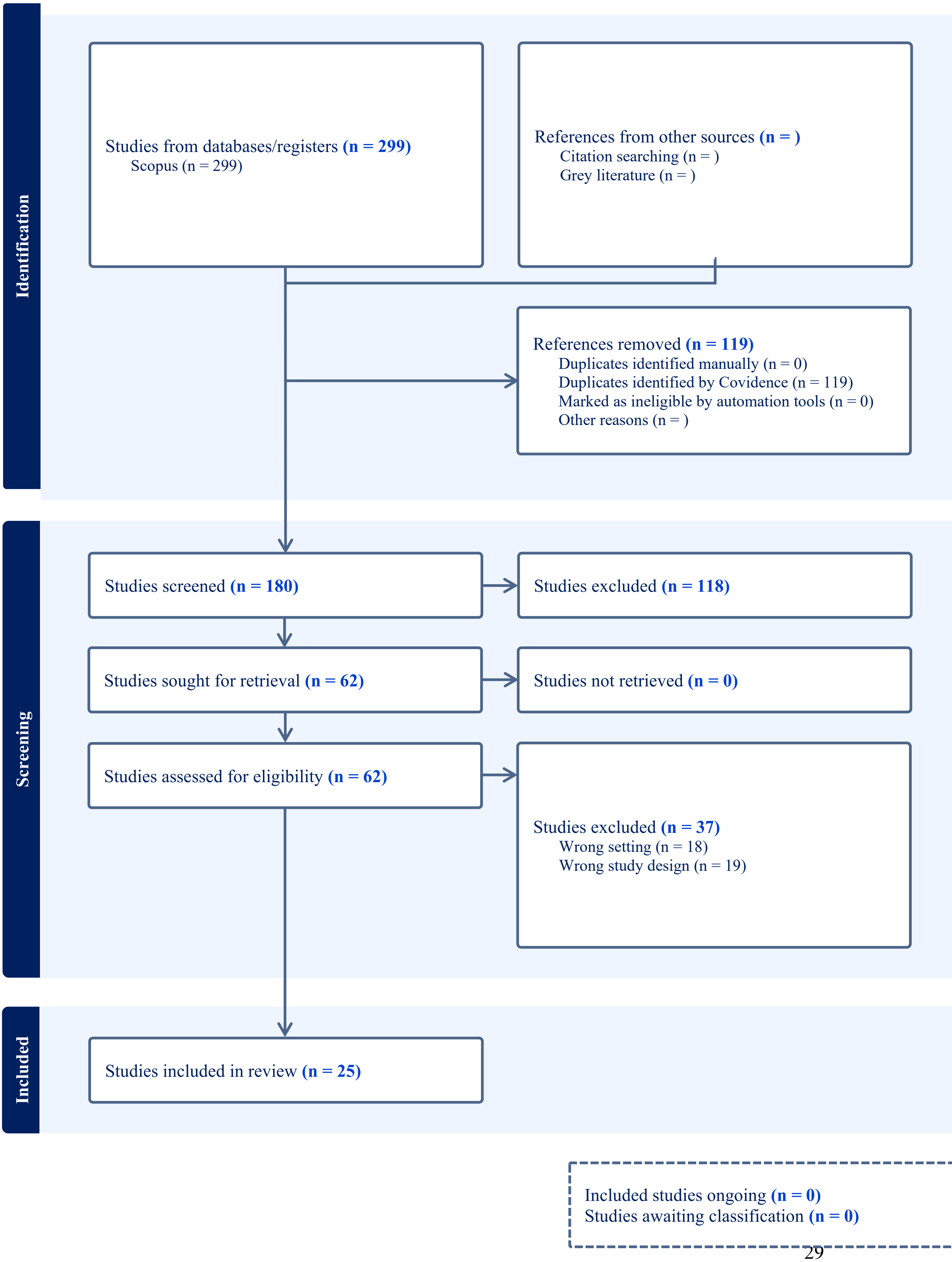
[20] A. Cicione, R. S. Walls, and C. Kahanji, "Experimental study of fire spread between multiple full scale informal settlement dwellings," *Fire Saf J*, vol. 105, pp. 19–27, Apr. 2019, doi: 10.1016/j.firesaf.2019.02.001.

[21] A. Cicione *et al.*, "The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations," *Fire Technol*, vol. 57, no. 2, pp. 873–909, Mar. 2021, doi: 10.1007/s10694-020-01023-8.

[22] P. Andersson, J. Brandt, and O. Willstrand, "Full scale fire-test of an electric hybrid bus," 2016.

[23] M. Runefors, "Säker vätgashantering i tätbebyggda områden," Lund, 2023.

Appendix A: Covidence PRISMA filtering process:



Appendix B – compiled Heat Flux data:

Paper title	object	position	measurement type	height above floor (m)	distance from object	value (max unless stated)	unit	(E)xperiment or (M)odel
Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles	ICEV1 2022	left side	heat flux meter	1.125	0.5	138	kW/m2	E
		ride side	heat flux meter	1.125	0.5	98	kW/m2	E
	ICEV2 2021	left side	heat flux meter	1.125	0.5	59	kW/m2	E
		ride side	heat flux meter	1.125	0.5	44	kW/m2	E
	BEV1 2022	left side	heat flux meter	1.125	0.5	6	kW/m2	E
		ride side	heat flux meter	1.125	0.5	7	kW/m2	E
	BEV2 2021	left side	heat flux meter	1.125	0.5	6	kW/m2	E
		ride side	heat flux meter	1.125	0.5	5	kW/m2	E
A Study of the Factors Influencing the Thermal Radiation Received by Pedestrians from the Electric Vehicle Fire in Roadside Parking Based on PHRR	simulated car	side	simulation	1.1	2.3	10	kW/m2	M
		x			1.3	4.5	kW/m2	M
		y			2.8	4.5	kW/m2	M
		vertical		1.1	4.5	10	kW/m2	M
		parallel			3	10	kW/m2	M

		vetical	radiation calcs	1.1	3.4	10	kW/m 2	M
		parallel			3	10	kW/m 2	M
		vertical	point source model	1.1	1.4	10	kW/m 2	calc
		parallel			3	10	kW/m 2	calc
DETERMINATION OF FIRE PROTECTION DISTANCES DURING A TESLA MODEL S FIRE IN A CLOSED PARKING LOT		flank	fds model of temps		10	220	°C	M
		front	fds model of temps		6	220	°C	M
Full-scale fire testing of battery electric vehicles, Kang et.al.	BEV	front	heat flux meter	1.27	1.11	110	kW/m 2	E
		front door	heat flux meter	1.27	0.89	55	kW/m 2	E
		rear door	heat flux meter	1.27	0.89	40	kW/m 2	E
		rear	heat flux meter	1.27	0.89	60	kW/m 2	E
								E
	ICE	front	heat flux meter	1.27	1.11	55	kW/m 2	E
		front door	heat flux meter	1.27	0.89	50	kW/m 2	E
		rear door	heat flux meter	1.27	0.89	60	kW/m 2	E
		rear	heat flux meter	1.27	0.89	50	kW/m 2	E
Flame spread and smoke temperature of full-scale fire test of car fire			heat flux meter	0.75	5	2.5	kW/m 2	E
Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-	EV battery only		heat flux meter		5ft	17.1	kW/m 2	E

Scale Testing Results								
			heat flux meter		10ft	4.7	kW/m2	E
			heat flux meter		5ft	18	kW/m2	E
			heat flux meter		10ft	3.7	kW/m2	E
	model version of EV		heat flux meter		5ft	3.5	kW/m2	E
			heat flux meter		10ft	2.6	kW/m2	E
			heat flux meter		20ft	2	kW/m2	E
			heat flux meter		25ft	1.6	kW/m2	E
	model version of EV test2		heat flux meter		5ft	3.7	kW/m2	E
			heat flux meter		10ft	2.2	kW/m2	E
			heat flux meter		20ft	1.6	kW/m2	E
			heat flux meter		25ft	1.8	kW/m2	E
	model version of EV test3		heat flux meter		5ft	11.9	kW/m2	E
			heat flux meter		10ft	2.4	kW/m2	E
			heat flux meter		20ft	2	kW/m2	E
			heat flux meter		25ft	2.2	kW/m2	E
	model version of EV test4		heat flux meter	1.524	5ft	2.2	kW/m2	E
			heat flux meter	3.048	10ft	2.1	kW/m2	E
			heat flux meter	6.096	20ft	1.5	kW/m2	E
			heat flux meter	7.62	25ft	1.7	kW/m2	E
	model version of EV test5		heat flux meter		5ft	2.1	kW/m2	E
			heat flux meter		10ft	1.8	kW/m2	E
			heat flux meter		20ft	2.7	kW/m2	E
			heat flux meter		25ft	2	kW/m2	E
	model version of EV test6		heat flux meter		5ft	8.1	kW/m2	E
			heat flux meter		10ft	2.1	kW/m2	E
			heat flux meter		20ft	2.4	kW/m2	E

			heat flux meter		25ft	2.4	kW/m 2	E
Full-Scale Fire Testing of Electric and Internal Combustion Engine Vehicles	ICEV	rear	heat flux meter	1.2	3.9 (from burner centre)	30	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	25	kW/m 2	E
	A-EV-100	rear	heat flux meter	1.2	3.9 (from burner centre)	40	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	20	kW/m 2	E
	A- EV-85	rear	heat flux meter	1.2	3.9 (from burner centre)	35	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	25	kW/m 2	E
	ICEV B	rear	heat flux meter	1.2	3.9 (from burner centre)	40	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	30	kW/m 2	E
	B-EV	rear	heat flux meter	1.2	3.9 (from burner centre)	20	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	20	kW/m 2	E
	C	rear	heat flux meter	1.2	3.9 (from burner centre)	30	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from burner centre)	25	kW/m 2	E
	D	rear	heat flux meter	1.2	3.9 (from burner centre)	50	kW/m 2	E
		passeng er side	heat flux meter	1.2	3.1 (from	35	kW/m 2	E

					burner centre)			
Characterization and assessment of fire evolution process of electric vehicles placed in parallel	BEV	side	jet fire	duration 3s	<2m length			
	BEV	side	jet fire		duration 11s	<2m length		
	BEV	rear	jet fire	duration 26s	2.5m length			

Appendix C Full list of included papers

Title	Authors	Year	Journal	Volume	Issue	Pages	DOI	Covidence #
Full-Scale Experimental Study on the Combustion Behavior of Lithium Ion Battery Pack Used for Electric Vehicle	Li, H.; Peng, W.; Yang, X.; Chen, H.; Sun, J.; Wang, Q.	2020	Fire Technology	56	6	2545-2564	10.1007/s10694-020-00988-w	#2
DETERMINATION OF FIRE PROTECTION DISTANCES DURING A TESLA MODEL S FIRE IN A CLOSED PARKING LOT	Gavryliuk, A.; Yakovchuk, R.; Chalyy, D.; Lemishko, M.; Tur, N.	2023	Eastern-European Journal of Enterprise Technologies	2	10-122	39-46	10.15587/1729-4061.2023.277999	#25
Thermal Modeling of the Electric Vehicle Fire Hazard Effects on Parking Building	Gavryliuk, A.; Yakovchuk, R.; Ballo, Y.; Rudyk, Y.	2023	SAE International Journal of Transportation Safety	11	3	421-434	10.4271/09-11-03-0013	#28
Numerical simulation analysis of combustion of electric sport utility vehicles	Guo, Q.; Tao, L.; Ma, Z.; Gu, Y.; Wang, Y.	2024	Energy Storage Science and Technology	13	3	1000-1008	10.19799/j.cnki.2095-4239.2023.0762	#30
Full-scale experimental study of the characteristics of electric vehicle fires process and response measures	Zhao, C.; Hu, W.; Meng, D.; Mi, W.; Wang, X.; Wang, J.	2024	Case Studies in Thermal Engineering	53			10.1016/j.csite.2023.103889	#32
Full-scale experimental study on suppressing lithium-ion battery pack fires from electric vehicles	Cui, Y.; Liu, J.; Han, X.; Sun, S.; Cong, B.	2022	Fire Safety Journal	129			10.1016/j.firesaf.2022.103562	#37
Fire risk of electric vehicles and fuel-driven vehicles in open car parks. Part 1: Fire scenarios and fire effects	Sander, L.; Zehfu√ü, J.; Meyer, P.; Schaumann, P.	2021	Stahlbau	90	7	486-497	10.1002/stab.202100039	#39
Explosion hazards due to failures of lithium-ion batteries	Marr, K.C.; Somandepalli, V.; Horn, Q.	2013	AIChE Annual Meeting, Conference Proceedings					#48
Fire extinguishment tests of electric vehicles in an open sided enclosure	Funk, E.; Flecknoe-Brown, K.W.; Wijesekere, T.; Husted, B.P.; Andres, B.	2023	Fire Safety Journal	141			10.1016/j.firesaf.2023.103920	#50
Characterization and assessment of fire evolution process of electric vehicles placed in parallel	Cui, Y.; Liu, J.; Cong, B.; Han, X.; Yin, S.	2022	Process Safety and	166		524-534	10.1016/j.psep.2022.08.055	#51

			Environmental Protection					
Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles	Hodges, J.L.; Salvi, U.; Kapahi, A.	2024	Fire Safety Journal	146			10.1016/j.firesaf.2024.104145	#70
Fire Tests on E-vehicle Battery Cells and Packs	Sturk, D.; Hoffmann, L.; Ahlberg Tidblad, A.	2015	Traffic Injury Prevention	16		S159-S164	10.1080/15389588.2015.1015117	#85
Analysis of combustion gases from large-scale electric vehicle fire tests	Hynynen, J.; Willstrand, O.; Blomqvist, P.; Andersson, P.	2023	Fire Safety Journal	139			10.1016/j.firesaf.2023.103829	#87
Dataset of fire tests with lithium-ion battery electric vehicles in road tunnels	Sturm, P.; F√∂√üleitner, P.; Fruhwirt, D.; Heindl, S.F.; Heger, O.; Galler, R.; Wenighofer, R.; Krausbar, S.	2023	Data in Brief	46			10.1016/j.dib.2022.108839	#88
Water Spray Fire Suppression Tests Comparing Gasoline-Fuelled and Battery Electric Vehicles	Arvidson, M.; Westlund, √ñ.	2023	Fire Technology	59	6	3391-3414	10.1007/s10694-023-01473-w	#94
A Review of Battery Fires in Electric Vehicles	Sun, P.; Bisschop, R.; Niu, H.; Huang, X.	2020	Fire Technology	56	4	1361-1410	10.1007/s10694-019-00944-3	#95
Experimental study on the thermal runaway and fire behavior of LiNi0.8Co0.1Mn0.1O2 battery in open and confined spaces	Liu, P.; Sun, H.; Qiao, Y.; Sun, S.; Wang, C.; Jin, K.; Mao, B.; Wang, Q.	2022	Process Safety and Environmental Protection	158		711-726	10.1016/j.psep.2021.12.056	#106
Analysis of fire hazards associated with the operation of electric vehicles in enclosed structures	Dorsz, A.; Lewandowski, M.	2022	Energies	15	1		10.3390/en15010011	#107
Influence of the state of charge on the heat release rate of Li-ion batteries	Biteau, H.; Somandepalli, V.	2015	Fire and Materials 2015 - 14th International Conference and Exhibition, Proceedings			87-102		#126
CFD-analysis of the Sensible Enthalpy Rise Approach to determine the heat release rate of electric-vehicle-scale lithium-ion battery fires	Voigt, S.; Str√§ubig, F.; Palis, S.; Kwade, A.; Knaust, C.	2020	Fire Safety Journal	114			10.1016/j.firesaf.2020.102989	#136
Fire tests with lithium-ion battery electric vehicles in road tunnels	Sturm, P.; F√∂√üleitner, P.; Fruhwirt, D.; Galler, R.; Wenighofer, R.; Heindl, S.F.; Krausbar, S.; Heger, O.	2022	Fire Safety Journal	134			10.1016/j.firesaf.2022.103695	#139

Calculating Heat Release Rates from Lithium-Ion Battery Fires: A Methodology Using Digital Imaging	Wise, M.S.; Christensen, P.A.; Dickman, N.; McDonald, J.; Mrozik, W.; Lambert, S.M.; Restuccia, F.	2023	Fire Technology	59	6	3565-3587	10.1007/s10694-023-01484-7	#143
A Study of the Factors Influencing the Thermal Radiation Received by Pedestrians from the Electric Vehicle Fire in Roadside Parking Based on PHRR	Zhang, D.; Huang, G.; Li, H.; Deng, Q.; Gao, X.	2023	Applied Sciences (Switzerland)	13	1		10.3390/app13010609	#151
Full-scale fire testing of battery electric vehicles	Kang, S.; Kwon, M.; Yoon Choi, J.; Choi, S.	2023	Applied Energy	332			10.1016/j.apenergy.2022.120497	#153
The impact of battery electric bus fire on road tunnel	Raza, H.; Li, S.	2023	Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World- Proceedings of the ITA-AITES World Tunnel Congress, WTC 2023			3280-3288	10.1201/9781003348030-397	#211