BREND 2.0: Fire simulation technical report

Alastair Temple and Johan Anderson

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Abstract

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Electric vehicles (EVs) and other vehicles with alternative energy carriers (such as hydrogen) are becoming increasingly common, and with them new fire risks. This report provides the technical details of computational fluid dynamics simulations carried out as part of the BREND 2.0 project to assess the tenability conditions within a ro-ro space from EV fires, via assessment of temperatures, radiation and spread of toxic species. The simulations primarily considered variation in compartment ventilation and fuel source. In all scenarios a selection of gaseous species, gas temperatures and radiative intensity are recorded at point locations and as 2D slices across the ro-ro space. From the gaseous species fractional effective concentrations, for irritant gases, and fraction effective doses, for asphyxiants, can be calculated to provide an assessment for tenability conditions in each scenario. This report contains the results of the simulations and some general observations but no detailed analysis of the implications of the results in terms of safety of EV fires on a ro-ro space.

Key words: toxic gases, batteries, electric vehicles, fire tests, simulations, heat release, ro-ro, ship

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Content

Abstract ......................................................................................................................... 1
Content ......................................................................................................................... 2
Preface .......................................................................................................................... 4
Summary ......................................................................................................................... 5
Sammanfattning ............................................................................................................. 6
Abbreviations .................................................................................................................. 7
1 Introduction .................................................................................................................. 8
2 Scenario 0 .................................................................................................................... 9
  2.1 Sub Scenarios .......................................................................................................... 9
  2.2 Geometry and Measurement Locations ............................................................... 9
  2.3 Fire Definition ....................................................................................................... 10
  2.4 Results and Discussion ....................................................................................... 14
3 Scenario 1 .................................................................................................................... 19
  3.1 Sub-Scenarios ...................................................................................................... 19
  3.2 Geometry .............................................................................................................. 19
  3.3 Fire Definition ....................................................................................................... 21
    3.3.1 Electric Vehicle Fires ............................................................................... 21
    3.3.2 ICEV Fires ............................................................................................... 22
  3.4 Data Sampling Locations ................................................................................... 23
  3.5 Results and Discussion ..................................................................................... 24
    3.5.1 General Observations ............................................................................ 24
    3.5.2 Maximum Recorded Values ................................................................... 30
4 Scenario 2 .................................................................................................................... 34
  4.1 Sub scenarios ....................................................................................................... 34
  4.2 Geometry ............................................................................................................. 34
  4.3 Fire Definition ....................................................................................................... 34
  4.4 Data Sampling Locations ................................................................................. 35
  4.5 Results and Discussion ..................................................................................... 36
    4.5.1 General Observations ............................................................................ 36
    4.5.2 Maximum Recorded Values ................................................................... 39
5 References .................................................................................................................. 41
Annex A – Full Results Scenario 0 ............................................................................... 43
Annex B – Full Results Scenario 1 ............................................................................... 53
  Sub Scenario a ........................................................................................................ 53
  Sub Scenario b ........................................................................................................ 57
  Sub Scenario c ........................................................................................................ 61
  Sub Scenario d ........................................................................................................ 65

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Sub Scenario e ............................................................................................................. 68
Sub Scenario f ......................................................................................................... 72

**Annex C – Full Results Scenario 2** ............................................................. 76
Sub Scenario a ........................................................................................................... 76
Sub Scenario b ......................................................................................................... 80

**Annex D – Numerical Considerations and Checks** ................................. 84
Flow Field Resolution .......................................................................................... 84
Mesh Density Sensitivity ..................................................................................... 85
Fire Momentum .................................................................................................... 95

**Annex E – FED and FEC** ............................................................................. 100
FED Calculation .................................................................................................. 100
FEC Calculation .................................................................................................. 100
Preface

The recently (in 2019) completed project BREND investigated how fires in alternative fuels (e.g., gas and batteries) for vehicles should be handled in ro-ro spaces, focusing on manual fire extinguishing. BREND identified a need for more research on how the risks of fire in alternative fuel vehicles (AFVs) should be assessed, as there were only a limited number of incidents and conducted fire tests. This project, BREND 2.0, focuses on some of the greatest uncertainties identified in BREND. These uncertainties include pressure vessel explosion of fire-exposed compressed gas containers and the risks of being exposed to toxic smoke from electric vehicle fires.

The project has actively collaborated with industry, authorities, and the public sector through established networks. A reference group with an advisory function was also established for the project. The reference group’s participants were mainly based on the participants in BREND, and its role was to provide input and advice, for example regarding which fire scenarios are to be simulated and to elaborate the resulted recommendations. Thanks to the reference group:

- Södra Älvsborgs Räddningstjänstförbund (Joel Jacobsson)
- Räddningstjänsten Storgöteborg (Jonas Ölsson, Christopher Hoff)
- Svensk Sjöfart (Carl Carlsson)
- Stena Teknik (Martin Carlsson, Lisa Gustin)
- Destination Gotland (Stellan Högström, Sofia Wikberg, Daniel Pantzarfelt)
- Wallenius Marine (Urban Lishajko, Peter Jodin, Per Westerdal)
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- Transportstyrelsen (Mattias Hörnquist, Saeed Mohebbi)
- Trafikverket (Henrik Modig, Ulf Lundström)
- Energigas Sverige (Mattias Hanson)
- Myndigheten för samhällsskydd och beredskap (Yvonne Näsman)

The project has had a steering group that included Haukur Ingason (RISE), Anders Lönnermark (RISE), Franz Evegren (RISE) and Lisa Gustin (Stena Teknik) with a role to support in decision-making, priorities and ensure that the project delivers the desired benefit in a scientific way.

Trafikverket (The Swedish Transport Administration) are acknowledged for funding of the BREND 2.0 project. The fire tests presented in this paper have also been sponsored by TUSC Tunnel Underground Safety Centre. The fire tests with biogas and hydrogen tanks will be presented in greater detail in a separate scientific paper.

In addition to this technical report, there is a final project report bringing together the work from all work packages published under the title “BREND 2.0: Fighting fires in new energy carriers on deck 2.0” (RISE Report 2022:47).

A quick guide on the formulated recommendations is also published separately under the title ”BREND 2.0: Quick guide”, and also available in an Appendix the project report.
Summary

Electric vehicles (EVs) and other vehicles with alternative energy carriers (such as hydrogen) are becoming increasingly common, with some reports suggesting that plug-in EVs (including plug-in hybrids) now make up half of new vehicle sales in Sweden. This report is part of the BREND 2.0 project which is aimed at expanding the knowledge base for the risks associated with fire alternative fuels on ro-ro space. This report provides the technical details of simulations carried out with Fire Dynamics Simulator (FDS) to assess the tenability conditions within a ro-ro space from EV fires, via assessment of temperatures, radiation and spread of toxic species.

The simulations were separated into three scenarios; Scenario 0, which assessed the likely impact of the fire variation from different EVs within a simple compartment enclosure; Scenario 1, which assessed a large multi-car (3 car) EV fire in a ro-ro space ignited by an external source; and Scenario 2, a single EV car fire growing from thermal runaway in a single battery cell to the full car. Scenarios 1 and 2 were modelled under different ventilation conditions. Three ventilations conditions were considered; an enclosed ro-ro space, a ro-ro space with a single open end (i.e. a closed ro-ro space with an open end) and an open ro-ro space. Scenario 1 was modelled in all 3 configurations and scenario 2 in the enclosed and open configurations only. In addition to these base cases Scenario 1 considers a 3 additional sensitivity cases; a fire in diesel vehicles, the presence of a suppression system and the impact of the presence of heavy goods vehicle (HGVs) on the gas flow.

In all scenarios a selection of gaseous species (carbon monoxide, carbon dioxide, hydrogen chloride, hydrogen cyanide, hydrogen fluoride and nitrogen oxide), gas temperatures and radiative intensity are recorded at point locations and as 2D slices across the ro-ro space. From the gaseous species fractional effective concentrations (FEC), for irritant gases, and fraction effective doses (FED), for asphyxiants, can be calculated and the full suite of results will allow for tenability conditions to be assessed for a range of scenarios (e.g. with and without protective firefighting equipment).

The models have been run using a mesh resolution of 0.2 m with sensitivity studies conducted both on the mesh resolution and on the fire area to check for numerically introduced errors.

This report contains the results of the simulations and some general observations but no detailed analysis of the implications of the results in terms of safety of EV fires in a ro-ro space.
Sammanfattning

Elfordon (EV) och fordon med alternativa energibärare (som vätgas) blir allt vanligare, och några nyligen publicerade rapporter tyder på att laddbara fordon (inklusive laddhybrider) nu utgör hälften av försäljningen av nya fordon i Sverige. Den här rapporten är en del av BREND 2.0-projektet som syftar till att utöka kunskapsbasen för risker förknippade med brand i alternativa bränslen. Rapporten innehåller de tekniska detaljerna för simuleringarna av elfordonsbränder som utförts med Fire Dynamics Simulator (FDS). Simuleringsarna används för riskbedömning genom uppskattningar av temperaturer, strålning och spridning av toxiska ämnen i ett rorolastutrymme.

Simuleringsarna delades upp i tre olika scenarier; Scenario 0, användes för att bedöma effekterna av variationer på brandkällan från olika elbilar i ett mindre utrymme; Scenario 1, som bedömde en stor elbilsbrand med flera bilar (3 bilar) i ett rorolastutrymme antänt av en extern källa; och Scenario 2, en brand i en enda elbil som växer från en termisk rusning i en enda battericell till att angripa hela bilen. Scenario 1 och 2 modellerades under olika ventilationsförhållanden. Totalt studerades tre ventilationsförhållanden; ett slutet rorodäck, ett rorodäck med en öppen ände (d.v.s. ett slutet rorolastutrymme med öppen ände) och ett öppet rorolastutrymme. Scenario 1 modellerades i alla tre ventilationsförhållanden och scenario 2 i det stängda och det öppna. Utöver dessa grundfall studerades varianter på scenario 1; brand i ett dieselfordon, närvaron av ett släcksystem och påverkan på gasflödet vid närvaron av lastbilar på däcket.

I alla scenarier följs ett urval av toxiska gaser (kolmonoxid, koldioxid, vätechlorid, vätecyanid, vätefluorid och kväveoxid), gastemperaturer och strålningstjänst på specifika platser och som genomskärningar i 2D av rorolastutrymmet. Från gaserna kan fraktionella effektiva koncentrationer (FEC) för irriterande gaser och fraktionella effektiva doser (FED) för kvävande gaser beräknas. Den fullständiga uppsättningen av resultat gör det möjligt att bedöma förhållandena för en rad scenarier (till exempel med och utan skyddsutrustning för brandbekämpning).

Modellerna har körts med en upplösning på beräkningsnätet på 0,2 m där känslighetsanalyser har utförts både på beräkningsnätets storlek och på brandområdet för att minimera numeriska fel.

Rapporten innehåller resultaten från simuleringarna och några allmänna observationer men ingen detaljerad analys av konsekvenserna från resultaten när det gäller säkerheten för elbilsbränder på ett rorodäck.
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>EV</td>
<td>Electric vehicle</td>
</tr>
<tr>
<td>FDS</td>
<td>Fire Dynamics Simulator</td>
</tr>
<tr>
<td>FEC</td>
<td>Fractional effective concentration of irritant gases</td>
</tr>
<tr>
<td>FED</td>
<td>Fractional effective dose of asphyxiating gases</td>
</tr>
<tr>
<td>HRR</td>
<td>Heat release rate</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal combustion engine vehicle</td>
</tr>
<tr>
<td>NFPA</td>
<td>National Fire Protection Association</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>HCl</td>
<td>Hydrogen chloride</td>
</tr>
<tr>
<td>HCN</td>
<td>Hydrogen cyanide</td>
</tr>
<tr>
<td>HF</td>
<td>Hydrogen fluoride</td>
</tr>
<tr>
<td>NO</td>
<td>Nitrogen oxide</td>
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1 Introduction

Electric vehicles (EVs) are becoming increasingly common, with some reports suggesting that plug-in EVs (including plug-in hybrids) now make up half of new vehicle sales in Sweden\(^1\). Despite this there is a relatively limited data base of both experimental and computational studies relating to fires of EVs. Recent work by RISE as part of the E-TOX project \(^1\) has looked to help expand this knowledge base via a combination of experiments, assessing the HRR of EV fires and production of toxic gases, and simulations, looking at the spread of the toxic emissions throughout an enclosed garage. The BREN\(^2\) D 2.0 project, of which this report is part, is looking to further expand this knowledge base using computational studies to investigate the impact of EV fires within ro-ro ships. This report provides the technical details of simulations carried out with Fire Dynamics Simulator (FDS) to assess the tenability conditions within a ro-ro space from EV fires, via assessment of temperatures, radiation and spread of toxic species. Other parts of the project will look at aspects such as explosion risks of gas (i.e. hydrogen) powered vehicles while further work will bring these technical studies together to provide recommendations about how ro-ro space fires in alternative fuel vehicles can be managed.

The fire modelling discussed within this report has been conducted in 3 parts. The first part, Scenario 0, looks at a variety of design fires based on the experimental data from the E-TOX project \(^1\) to assess the impact in possible variations of the fire and to select a reasonable fire for the main portion of the study, Scenario 1. Scenario 1 looks at a fire in 3 EVs within a ro-ro vehicle deck ignited by an external source (such as an oil spill). The impact of design of the deck with respect to its ventilation on the conditions during the fire is studied. The final part, Scenario 2, looks at conditions within relatively close proximity to a fire near its start (e.g. while first aid firefighting or early egress may occur). The fire for this scenario is an EV fire which starts within the battery for the vehicle itself as it builds from a single cell fire to the whole vehicle. These different parts are described separately within sections 0, 0 and 0 for scenarios 0, 1 and 2 respectively.

For all gaseous species included within he is modelling described within this document, transport only (on the basis of their density) has been modelled. No chemical interaction between the various species within the models, with the model surfaces has been taken into account. This should provide conservative estimates of the concentrations of the toxic species.

2 Scenario 0

Assessment of fire size variation.

2.1 Sub Scenarios

Scenario 0 has been split into 4 sub-scenarios to assess the impact of the variation of fire size and rate of release of toxic species, within the bounds of realistic EV fires. The sub-scenarios assessed are:

a. A fire representing a real EV based on “Test 3” of the E-TOX project.
b. A mean of the fires from all EVs tested as part of the E-TOX project.
c. A maximum envelope of all the fires tested as part of the E-TOX project.
d. A minimum envelope of all the fires tested as part of the E-TOX project.

2.2 Geometry and Measurement Locations

For this study a simple 10 m x 10 m square compartment is used with a 4 m high ceiling. The compartment has a solid ceiling and two of the sides have solid walls from the deck floor to ceiling, while the other ends are open, as sketched in Figure 1.

![Figure 1. Scenario 0 geometry in plan.](image)

To minimise the number of cells in the model, and therefore the computational cost and time taken to running it, the symmetry of the model has been utilised with only a single quarter of the model modelled and symmetry boundary conditions used in both the X and Y axis.

Point readings are taken for temperature and all toxic species included within the model (see section 2.3). 4 locations in plan are used, see Figure 2, and in each of these locations' measurements were taken at 0.5 m, 1.5 m, 2.5 m and 4.9 m above the deck.
A number of slices were taken in all 3 axes to allow a visual check of the results for concentrations or gas movement which could suggest numerical errors.

2.3 Fire Definition

The fires have been calculated based on the EV fire experiments conducted as part of the E-TOX project [1]. The gaseous species defined within the model are, carbon monoxide (CO), hydrogen fluoride (HF), hydrogen chloride (HCl), sulphur dioxide (SO₂), hydrogen cyanide (HCN) and nitrogen oxide (NO) which are the key compounds for analysing the toxicity of the smoke and were measured in significant amounts during the E-TOX experiments. Carbon dioxide is also important to consider, however this is generated by FDS via the combustion model and the results from this will be used in the analysis. The time-amplitude curves for these, including for each sub-scenario, can be found in Figure 3 to Figure 10.
Figure 3. Scenario 0 HRR time-amplitudes

Figure 4. Scenario 0 CO2 production time-amplitudes
Figure 5. Scenario 0 CO production time-amplitudes

Figure 6. Scenario 0 HF production time-amplitudes
Figure 7. Scenario 0 NO production time-amplitudes

Figure 8. Scenario 0 HCN production time-amplitudes
2.4 Results and Discussion

The results for each gaseous species from each of the Scenario 0 sub-scenarios were compared at each location, a sub-set of which can be seen in Figure 11 to Figure 14 with additional graphs in Annex A. As can be seen from these, while there are variations between which sub-scenario gives the worst conditions for any given location at any given time, there is relatively limited difference between the conditions for Test 3, the
mean and the maximum envelope fires (although the minimum envelop is further below).

On this basis it is was concluded that the E-TOX “Test 3” fire should be used for the further scenarios on the basis that it is representative of an actual EV and shows limited change in conditions from the maximum envelope fire (so is unlikely to be significantly unconservative).

Figure 11. HF results in mol/mol at 4.9m above the deck for each sub-scenario (Test 3 = T3, Avg = Mean, Min = minimum envelope, Max = maximum envelope)
Figure 12. HF results in mol/mol at 2 m above the deck for each sub-scenario (Test 3 = T3, Avg = Mean, Min = minimum envelope, Max = maximum envelope)
Figure 13. Carbon dioxide results in mol/mol at 4.9 m above the deck for each sub-scenario (Test 3 = T3, Avg = Mean, Min = minimum envelope, Max = maximum envelope)
Figure 14. HCl results in mol/mol at 4.9m above the deck for each sub-scenario (Test 3 = T3, Avg = Mean, Min = minimum envelope, Max = maximum envelope)
3 Scenario 1

Multiple Electric Vehicle Fire with Ignition from External Source

3.1 Sub-Scenarios

Scenario 1 represents a fire on a ro-ro vehicle deck which starts via an oil spill (or similar) which then rapidly spreads to 3 EVs. The scenario has 5 of sub-scenarios considering different ventilation conditions within a ro-ro deck as follows:

a) The deck is fully enclosed with leakage only. Mechanical ventilation provides main ventilation; however it is switched off upon detection of the fire (detection of 70 °C by a point detector at roof level). The mechanical ventilation is on at the start of the model.

b) The deck is enclosed on 3 sides and above but has an open stern (i.e. ramp is down). The fire is positioned at the opposite end of the deck from the opening. There is no mechanical ventilation in this case.

c) Representative of an “open” ro-ro space with an enclosed bow and ceiling but with an open stern and openings along each side amounting to ~10 % of the side area (46.8 m² of opening on each side). There is no mechanical ventilation in this case.

d) Utilised to investigate the possible impact of a drencher system on the conditions within the deck. This sub-scenario uses the ventilation conditions of sub-scenario a) (lowest levels of ventilation).

e) Scenario for comparison of the EV results with an internal combustion engine vehicle (ICEV), diesel fuelled. Scenario matches scenario a in all aspects other than fire definition.

f) Scenario to review if the presence of heavy goods vehicles (HGVs) is likely to impact on the behaviour of the smoke within the space. Scenario matches scenario b) in all aspects other than the addition of a row, on the port side, of large obstacles in the model (10.75 m long by 2.8 m high) to represent HGVs in place of two rows of cars. The ventilation of scenario b) was chosen as the low ventilation cases fill completely with smoke (and so the presence is likely to have minimal impact) while the smoke layer for scenario c) is significantly above the top of any HGV.

3.2 Geometry

The model is representative of a ro-ro vehicle deck, with a length of 91.4 m, a width of 22.3 m and a height of 5 m, as illustrated in Figure 15 below. The total plan area of the space is 2038 m² while the volume is 10,191 m³. The geometry has been designed to represent a “generic” layout with a simple rectangular shape and no additional geometry added for intrusions of stairs, access ways or similar. While ro-ro spaces may often taper towards the bow and stern of the ship the geometry has been kept rectilinear to match the limitations of FDS meshes (cuboid cells only) and avoid the creation of “sawtooth” geometry within the models.
To represent a full ro-ro space, a simplified model of the cars has been implemented within FDS, with 8 vehicle rows within the deck. Each car is 4 m long by 2 m wide while the rows are separated by 0.6 m and the cars are separated front to back by a gap of 0.1 m. A partial visualisation of the geometry (with the roof hidden) from Pyrosim can be seen in Figure 16.

The ventilation provision varies depending on the scenario and is discussed in more in section 3.1. For sub-scenario c) there are 18 openings along each side, with the first opening 3.6 m from the bow and the subsequent openings separated by 3.6 m each. Each opening is 2 m x 1.3 m (height by width).

Figure 15. Plan view of the model geometry, dimensions in meters.

Each of the 3 EVs in the scenario are defined separately within the model and have a burning area of 2 m x 1 m in plan. Discussion of the momentum due to the burning area and its impact on the results can be found in Annex D. They are positioned on the 3 vehicles closest to the bow end in the central most vehicle rows, as can be seen in Figure 16. The centreline of the fires (bow to stern) is 6 m from the bow, while the lowest fire (with respect to the plan view) has a centre point on the y-axis of -1.6 m and the topmost at 3.6 m.

Figure 16. Pyrosim visualisation of the bow end of the compartment for sub scenario c showing the fire locations (in red).
Within the models, all surfaces of the representing the ship (i.e. bulkhead, deck and ceiling) have been assumed to be steel with a specific heat capacity of 0.46 kJ/kgK, a conductivity of 45.8 W/mK and a density of 7850 kg/m³. This is the steel material built into Pyrosim and is based on experimental data by NIST [2].

A generic material has been applied to the vehicles with a specific heat capacity of 1 kJ/kgK, a conductivity of 0.8 W/mK and a density of 190 kg/m³. These properties have been calculated as average values for each, based on an assumed ratio of metal (steel), plastics and air for a car. As no fire propagation, or material assessment of the surfaces, is required within these models, the impact of the vehicle material is expected to be negligible.

No external wind or pressure conditions are applied to any of the models.

3.3 Fire Definition

3.3.1 Electric Vehicle Fires

On the basis of the results of Scenario 0, see section 0, the fire definition for the EVs in Scenario 1 is based on the “Test 3” EV from the E-TOX project [1]. Further discussion of the reasoning for this choice can be found in section 2.4. The HRR time-amplitude curve from the test can be seen in Figure 17. The gaseous species chosen for tracking match those for Scenario 0 and the species production rates can be seen in Figure 18.

![Figure 17. Heat Release Rate for EV](image-url)
Figure 18. Gaseous species emission rates for EVs

The burning surface of the fire has been specified as a 2 m² rectangle at the front of the car obstruction, 1 m above deck level, i.e. representing the level of the bonnet of a simplified car. The location of the fire can be seen in section 3.2. Note that in FDS both the HRR time-amplitude and mass release rate curves are applied as curves with a maximum of 1 and an independent multiplier for the maximum value reached per m² (e.g. 2500 kW/m² for the HRR as a 2 m² burning surface is used or for HF a maximum rate of 0.00045 kg/s/m²).

As the HRR and species release rates are prescribed for these models any suppression systems defined within FDS will not have any influence on them. Therefore for sub-scenario d) the impact of the drencher system on the HRR and gaseous species release rates must be decided prior to running the models and included in the prescribed ramps. Experimental work carried out by Long et al. for the NFPA [3] indicates that sprinkler systems can reduce the HRR of battery module fires by between 34% and 45%. No experimental data could be found on the effect of sprinklers on the production of gaseous species, and it has therefore been assumed that they are reduced proportionally with the HRR. For the purposes of this project a conservative assumption of a 35% reduction has been assumed and applied directly to the HRR and all gaseous species after activation. As this reduction is applied directly to the ramps within FDS, it cannot be activated automatically within the model (e.g. by a temperature detector), and it has been assumed that the drencher system is activated 15 minutes after the start of the fire.

3.3.2 ICEV Fires

The ICEV fire utilised for sub-scenario e is based on the “Test 1” ICEV from the E-TOX project [1]. The HRR time-amplitude curve from the test can be seen in Figure 19. The gaseous species chosen for tracking match those for the other fire definitions and the species production rates can be seen in Figure 20. As with for the EV fires, within FDS the definitions of the fire are specified as a combination of a maximum value and a ramp with amplitude between 1 and 0.
3.4 Data Sampling Locations

Two types of sampling are utilised for extracting results from the models, point samples, and 2D slices which provide a graphical representation of the measured quantity in a plane.

Point samples have been taken at 6 locations, as illustrated in Figure 21, with the following XY coordinates:

1. X = 6 m, Y = 10.6 m,
2. X = 6 m, Y = -8.1 m,
3. X = 16.5 m, Y = -0.3 m,
4. X = 16.5 m, Y = -8.1 m,
5. X = 65 m, Y = -0.3 m,
6. X = 85 m, Y = -0.3 m

The origin is the centre of the bow end of the compartment.
At each location point samples are taken at 4 different heights for gaseous species (mol/mol) and 5 heights for temperatures (°C). For gaseous species the heights are 1 m, 2 m, 3 m and 4.9 m. For temperature measurements the heights are 1 m, 2 m, 3 m, 4 m, and 4.9 m. All heights are measured from deck level. In addition to these point measurements, a temperature detector is used to turn off the mechanical ventilation in sub-scenario a. It is located at the coordinates 8 m, 0 m, 4.9 m (X, Y, Z respectively) and has an activation temperature of 70°C.

Figure 21. Point sample locations (in plan).

As discussed earlier, 2D slices can be used to provide a visual representation of the conditions along a plane at any given moment in the simulation. Within these models they are used to record volume fractions (mol/mol) of the gaseous species, gas temperatures (°C) and gas flow velocities (m/s). They are located at 6 m, 30 m, 60 m and 88 m on the X-axis; -0.3 m and 10.6 m on the Y-axis and 1 m, 2 m, 3 m, 4 m and 4.9 m on the Z-axis.

Additionally, slices recording the “integrated intensity” (i.e. radiation received at a point) have been included at -1.6 m, 1 m, and 3.6 m in the Y-axis; and 0.5 m, 1.5 m and 2 m on the Z-axis.

3.5 Results and Discussion

Full results with time amplitudes for each point measurement can be found in Annex C. An overview of the results and some general observations are provided below.

3.5.1 General Observations

No unusual smoke movement was observed in the model results. In the low ventilation sub-scenarios (a, d and e) the smoke layer quickly descends from the ceiling until it fills the whole volume of the ro-ro space, see example in Figure 22. For both of the sub scenarios with higher ventilation (b, and c) a distinct boundary between a smoke layer and clear air is formed, see Figure 23 and Figure 24. The smoke layer in these scenarios is over 2 m above deck level.
Figure 22. Smokeview capture showing the filling of the ro-ro space with smoke after 1000s in Scenario 1a.

Figure 23. Smokeview capture showing the development of a defined smoke layer in the ro-ro space in Scenario 1b. Capture taken at 1000s.

Figure 24. Smokeview capture showing the development of a defined smoke layer in the ro-ro space in Scenario 1c. Capture taken at 1000s.

Despite the space filling with smoke, the distribution of temperatures and intensity of radiation is non-uniform in Scenario 1a, see Figure 25. The impact of the low ventilation levels can still be seen in comparison with the distributions for scenarios 1b and 1c, see Figure 26 and Figure 27. In these scenarios there is a sharper drop off in radiation intensity with distance from the fire and the temperatures within the clear layer are all below 50°C except for within the immediate proximity of the fire.
Figure 25. Radiative intensity and temperature distributions for scenario 1a close to the fire’s peak.
Figure 26. Radiative intensity and temperature distributions for scenario 1b close to the fire's peak.
The distribution of temperatures within the ro-ro space for all scenarios indicate that gas/smoke temperatures do not significantly exceed 200°C in proximity to non-fire cars and as such fire spread between vehicles will be by radiation only. Radiation levels on the adjacent cars are below 20 kW/m² for the first 5 minutes but exceed 30 kW/m² by 7.5 minutes, ignition times of various plastics at this level are typically between 1 minute (plastics such as polystyrene and polypropylene) and 3 minutes (polyethylene) [4]. Ignition of adjacent vehicles is therefore unlikely until between 7.5 and 10 minutes after the fire starts at the earliest. Initial ignition of adjacent cars would be limited to areas of plastic on the external bodywork facing the initial fire and would demonstrate a slow growth rate.

Scenarios 1d (with suppression), and 1e (ICEV fire), show limited variation in behaviour from scenario 1a with regards to smoke movement, see Figure 28 and Figure 29. Likewise scenario 1f (with HGVs) shows limited change in smoke layer behaviour, as can be seen in Figure 30. The HGVs themselves do however provide a shadowing effect to the radiation from the fire as can be seen in Figure 31. Caution regarding the limitations of the modelling should be taken when considering the results for Scenario 1d (with suppression), i.e. that the “suppression” modelled is a blanket reduction in output of
HRR and gaseous species release at an assumed activation time. For example no water droplets have been modelled, and any secondary cooling of the gases from the water or in flow due to the droplet momentum will not be captured, and there will be no representation of gaseous species dissolving into the water to form acids. Likewise both the low ventilation levels, such that the space fills with smoke quickly, and lack of droplets mean conclusions about the impact of sprinklers on the distribution of smoke are likely to be limited in usefulness.

Figure 28. Smokeview capture showing the filling of the ro-ro space with smoke after 1000s in Scenario 1d.

Figure 29. Smokeview capture showing the filling of the ro-ro space with smoke after 1000s in Scenario 1e.

Figure 30. Smokeview capture showing the development of a smoke layer and a clear layer in the ro-ro at 1000s in Scenario 1f.
Figure 31. Radiative intensity distributions at 1100s for Scenario 1f showing shield effect of HGVs.

3.5.2 Maximum Recorded Values

The maximum values recorded at point locations, see section 3.4, for the concentrations of gaseous species as well as the calculated fractional effective dose (FED) for asphyxiants and fractional effective concentration (FEC) of irritant gases for each scenario can be seen in Table 1 to Table 6. Details on the calculation of FED and FEC can be found in Annex D. A value of 0.3, the point at which 11% of the general population would be incapacitated, is usually taken as the critical level for both FED and FEC.

Table 1. Maximum values at point locations for scenario 1a. Species concentrations in ppm and FEC and FED unitless.

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Table 5. Maximum values at point locations for scenario 1e (ventilation conditions of scenario 1a with ICEV cars). Species concentrations in ppm and FEC and FED unitless.

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Table 6. Maximum values at point locations for scenario 1f (ventilation conditions of scenario 1b with a row of HGVs). Species concentrations in ppm and FEC and FED unitless.
4 Scenario 2


4.1 Sub scenarios

Scenario 2 is primarily designed to consider the possible conditions people may experience during the early stages of an EV fire while undertaking first aid firefighting. Two sub-scenarios are modelled each considering different ventilation conditions within a ro-ro space. These are:

a) A closed ro-ro space with mechanical ventilation.

b) An open deck with 10% openings along each side.

4.2 Geometry

For this scenario we are interested primarily in the early stages of the fire and in conditions close to the source. However, the flow and dispersion of the gases produced by the fire will be dependent upon the whole compartment. The whole compartment geometry is therefore used matching that described for Scenario 1 in section 3.2.

![Scenario 2 geometry in plan.](image)

4.3 Fire Definition

Scenario 2 considers a fire which starts within the batteries of an EV, due to thermal runaway within a single cell which then cascades through the battery, first igniting adjacent cells building to the whole of the initial module, then adjacent modules into a pack before spreading to become a “whole car” fire. The fire location in the models is confined to the “bonnet” of the car with an area of 2m². A smaller area has been used for this scenario due to the lower peak HRR so as to prevent too low HRR/density and an
unnaturally unbuoyant fire (the early stages of a fire like this will be confined to a smaller area in reality before the fire fully spreads to the whole car).

In addition to the whole car experiments carried out during the E-TOX project, a range of experiments containing 1 cell, 2 cell, battery modules and battery packs were carried out [1]. The results from these experiments, specifically battery tests 1, 2, 4 and 8, have then been staggered along with the Test 3 car used in Scenario 1 to create a HRR profile (when taking the maximum envelope of the combined fires). This time-amplitude curve is therefore representative of a fire growing from a single cell to igniting a whole car and can be seen Figure 33. It should be noted that the first 10 minutes of the pack fire was primarily the plastic casing burning and not the cells itself and this initial portion is ignored in creating the HRR curve. In comparison to the HRR curve of Scenario 1, this curve has a slower growth and is implemented as a single car rather than 3 simultaneously burning. The fire does not reach the peak of the whole car fire due to this slower growth with a maximum over the studied period of 1 MW.

![Figure 33: Illustration of combined HRR for scenario 2](image)

Unfortunately, there was a limited amount of recording gaseous species release rates for these battery experiments, and the same methodology cannot be used for building up time-amplitude of the release gaseous species. Instead for scenario 2 it has been assumed that the gaseous species will be released proportionally to the HRR with a maximum release rate matching that of the EV curves from scenario 1 for all of carbon monoxide (peak of 0.000608 kg/m²), hydrogen fluoride (peak of 0.00009 kg/m²), hydrogen chloride (peak of 0.00019277 kg/m²), sulphur dioxide (peak of 0.00007175 kg/m²), hydrogen cyanide (peak of 0.000019 kg/m²) and nitrogen oxide (peak of 6.73334E-05 kg/m²).

### 4.4 Data Sampling Locations

As with the other scenarios two types of sampling are utilised for extracting results from the models, point samples, and 2D slices which provide a graphical representation of the measured quantity in a plane.
Point samples have been taken at 6 locations, as illustrated in Figure 21, with the following XY coordinates:

1. X = 6 m, Y = 10.6 m,
2. X = 6 m, Y = -8.1 m,
3. X = 16.5 m, Y = -0.3 m,
4. X = 16.5 m, Y = -8.1 m,
5. X = 2 m, Y = -0.3 m,
6. X = 10 m, Y = -0.3 m

At each location point samples are taken at 4 different heights for gaseous species (mol/mol) and 5 heights for temperatures (°C). For gaseous species the heights are 1 m, 2 m, 3 m and 4.9 m. For temperature measurements the heights are 1 m, 2 m, 3 m, 4 m, and 4.9 m. All heights are measured from deck level. In addition to these point measurements, a temperature detector is used to turn off the mechanical ventilation in sub-scenario a. It is located at the coordinates 8 m, 0 m, 4.9 m (X, Y, Z respectively) and has an activation temperature of 70°C.

Figure 34. Point sample locations (in plan).

As discussed earlier, 2D slices can be used to provide a visual representation of the conditions along a plane at any given moment in the simulation. Within these models they are used to record volume fractions (mol/mol) of the gaseous species, gas temperatures (°C) and gas flow velocities (m/s). They are located at 6 m on the X-axis; -0.3 m and 10.6 m on the Y-axis and 1 m, 2 m, 3 m, 4 m and 4.9 m on the Z-axis.

Additionally, slices recording the “integrated intensity” (i.e. radiation received at a point) have been included at -1.6 m, 1 m and 3.6 m in the Y-axis; and 0.5 m, 1.5 m and 2 m on the Z-axis.

4.5 Results and Discussion

Full results with time histories for each point measurement can be found in Annex C. An overview of the results and some general observations are provided below.

4.5.1 General Observations

No unusual smoke movement was observed in the model results. In the low ventilation sub scenario (a) the smoke layer quickly descends from the ceiling until it fills the whole volume of the ro-ro deck, see example in Figure 35. The smoke layer descends at a slower

---

3 The origin is the centre of the bow end of the compartment.
pace than in Scenario 1a, as expected due to the smaller fire size. For sub scenario b with higher ventilation (b) a distinct boundary between a smoke layer and clear air is formed, see Figure 36. The smoke layer is higher than in the corresponding scenario 1 case (1c).

Figure 35. Smokeview capture showing the filling of the ro-ro space with smoke after 1000s in Scenario 2a.

Figure 36. Smokeview capture showing the development of a defined smoke layer in the ro-ro space in Scenario 2b. Capture taken at 1500s.

In both scenario 2 sub scenarios regions of high temperature and radiation are very localised, with most of the ro-ro space having temperatures significantly below 50°C and radiation levels below 5 kW/m², see Figure 37 and Figure 38, at the fire’s peak. This corresponds with the smaller fire size. Scenario 2a does show a higher level of radiation across the whole space and shows a higher level of temperature uniformity as expected with filling of the space with smoke.
Figure 37. Radiative intensity and temperature distributions for scenario 2a close to the fire's peak.
4.5.2 Maximum Recorded Values

The maximum values recorded at point locations, see section 4.4, for the concentrations of gaseous species as well as the calculated fractional effective dose (FED) for asphyxiants and fractional effective concentration (FEC) of irritant gases for each scenario can be seen in Table 1 to Table 6. Details on the calculation of FED and FEC can be found in Annex D. A value of 0.3, the point at which 11% of the general population would be incapacitated, is usually taken as the critical level for both FED and FEC.

Table 7. Maximum values at point locations for scenario 2a. Species concentrations in ppm and FEC and FED unitless.

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<td>0.67</td>
<td></td>
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<tr>
<td>6</td>
<td>1040</td>
<td>10100</td>
<td>2090</td>
<td>327</td>
<td>2450</td>
<td>521</td>
<td>161000</td>
<td>1.42</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>4.9</td>
<td>1300</td>
<td>12600</td>
<td>2610</td>
<td>407</td>
<td>3050</td>
<td>649</td>
<td>200000</td>
<td>1.76</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1310</td>
<td>12700</td>
<td>2630</td>
<td>411</td>
<td>3080</td>
<td>654</td>
<td>201000</td>
<td>1.78</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1210</td>
<td>11800</td>
<td>2430</td>
<td>380</td>
<td>2850</td>
<td>606</td>
<td>188000</td>
<td>1.66</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1280</td>
<td>12400</td>
<td>2570</td>
<td>402</td>
<td>3010</td>
<td>641</td>
<td>198000</td>
<td>1.75</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1270</td>
<td>12300</td>
<td>2550</td>
<td>398</td>
<td>2980</td>
<td>634</td>
<td>197000</td>
<td>1.72</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1480</td>
<td>14300</td>
<td>2970</td>
<td>464</td>
<td>3480</td>
<td>739</td>
<td>226000</td>
<td>2.00</td>
<td>1.37</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Maximum values at point locations for scenario 2b. Species concentrations in ppm and FEC and FED unitless.
5 References


Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,200 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the futureproofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.

I internationell samverkan med akademi, näringsliv och offentlig sektor bidrar vi till ett konkurrenskraftigt näringsliv och ett hållbart samhälle. RISE 2 200 medarbetare driver och stöder alla typer av innovationsprocesser. Vi erbjuder ett 100-tal test- och demonstrationsmiljöer för framtidssäkra produkter, tekniker och tjänster. RISE Research Institutes of Sweden ägs av svenska staten.
Annex A – Full Results Scenario 0

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Annex B – Full Results Scenario 1

Sub Scenario a
Sub Scenario b
Sub Scenario c
Sub Scenario d
Sub Scenario e
Sub Scenario f
Annex C – Full Results Scenario 2

Sub Scenario a
Sub Scenario b
Annex D – Numerical Considerations and Checks

Flow Field Resolution

It is important when undertaking numerical modelling that a fine enough resolution of the domain is taken to provide sufficiently accurate results for the investigation being undertaken and to limit the numerical errors introduced. The resolution of the domain (i.e. size of the mesh cells) is particularly important in the precision of the flows in fire plumes. As the fire plume is the driving force for the movement of gases and combustion products around the space it is of particular importance to the results of this study that an appropriate resolution is used.

FDS User’s Guide [5] states that an appropriate measure of how well the flow field is resolved for a gravity-controlled fire plume (i.e. no forced convection) is given by a dimensionless expression $D^*/\delta$. $D^*$ is the characteristic diameter of the fire, as given by:

$$D^* = \left( \frac{\dot{Q}}{\rho_\infty c_p T_\infty g} \right)^{2/5}$$

Where:

$D^*$ = characteristic diameter of the fire (m)

$\dot{Q}$ = effective heat release rate (W)

$\rho_\infty$ = density of air at ambient (kg/m$^3$)

$c_p$ = specific heat capacity for air (J/kgK)

$T_\infty$ = ambient air temperature (K)

$g$ = gravitational constant (m/s$^2$)

while $\delta$ is the largest side of a mesh cell.

Nystedt [6] states that $D^*/\delta$ should be in the order of 10-20 close to any fire. As the fire size changes with time, so will the value of the $D^*/\delta$, and therefore a cell size that maximises the duration of time over which $D^*/\delta$ is in the appropriate range must be chosen. A plot of $D^*/\delta$ for different values of $\delta$ can be seen in Figure 39, and the fire for E-TOX car 3, as chosen after completion of Scenario 0. This shows that the mesh resolution with the longest period inside the 10-20 range, and within this for the peak of the fire, is where a cell size of 0.1 m (in all dimensions) is used. This mesh resolution has therefore been used as the basis for the modelling within this project. Sensitivity checks with differing mesh sizes were also conducted.
Mesh Density Sensitivity

Models of the extent of the geometry studied within this project and with 0.1 m cube cells have impractical run durations (> 9 months per model split into 11 meshes while run on a RISE computing cluster). This is an impractical length of time and so an investigation has been conducted into the sensitivity of the results to the mesh size. To conduct this study models with 0.1 m and 0.2 m mesh resolutions of Scenario 1a, b and c were run. The recorded results at each point measurement location, see section 3.4, were then compared up to the extent that the 0.1 m resolution model has run to date (19th April 2022)4.

These comparisons can be seen below in Figure 40 to Figure 66. While variation can be seen between the models there is a good match between the results for each mesh for the gaseous species (relative to their maximum values) and where the largest discrepancy is seen, in the temperature measurements, the coarser mesh definition is more conservative. On this basis it has been considered reasonable to utilise the 0.2 m mesh models for the basis of the scenario comparisons.

4 The fine mesh models for Scenario 1b and c are completed while scenario 1a was not able to be completed due to insufficient RAM available on the cluster which it was running.
Figure 40. Comparison of plate thermometer temperatures for scenario 1a between 0.1 m and 0.2 m meshes. Colours show distance from fire, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 41. Comparison of carbon dioxide concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 42. Comparison of carbon monoxide concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

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Figure 43. Comparison of hydrogen chloride concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 44. Comparison of hydrogen cyanide concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 45. Comparison of hydrogen fluoride concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 46. Comparison of nitric oxide concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 47. Comparison of sulphur dioxide concentrations for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 48. Comparison of thermocouple temperatures for scenario 1a between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 49. Comparison of plate thermometer temperatures for scenario 1b between 0.1 m and 0.2 m meshes. Colours show distance from fire, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 50. Comparison of carbon dioxide concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 51. Comparison of carbon monoxide concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 52. Comparison of hydrogen chloride concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 53. Comparison of hydrogen cyanide concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 54. Comparison of hydrogen fluoride concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

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Figure 55. Comparison of nitric oxide concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 56. Comparison of sulphur dioxide concentrations for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 57. Comparison of thermocouple temperatures for scenario 1b between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 58. Comparison of plate thermometer temperatures for scenario 1c between 0.1 m and 0.2 m meshes. Colours show distance from fire, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 59. Comparison of carbon dioxide concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 60. Comparison of carbon monoxide concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 61. Comparison of hydrogen chloride concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 62. Comparison of hydrogen cyanide concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 63. Comparison of hydrogen fluoride concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Figure 64. Comparison of nitric oxide concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 65. Comparison of sulphur dioxide concentrations for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.

Figure 66. Comparison of thermocouple temperatures for scenario 1c between 0.1 m and 0.2 m meshes. Colours show height, solid lines represent 0.1 m mesh and dashed 0.2 m mesh.
Fire Momentum

The relationship between the fire size (HRR) and fire area imports initial velocity on the fire gases in the FDS model. A large fire size over a small area will produce a jet fire, while a very large area for the same fire size will give small diffuse flames. This relationship can be assessed by comparing the dimensionless effective heat release rate [7]:

\[
\dot{Q}^* = \frac{\dot{Q}}{\rho\infty c_p T\infty \sqrt{gD^2}}
\]

Where:

\(\dot{Q}\) = Effective heat release rate (W),

\(\rho\infty\) = Density of air at ambient (kg/m³),

\(c_p\) = The specific heat capacity of air (J/kgK),

\(T\infty\) = The ambient temperature of air (K),

\(g\) = Gravitational constant (9.81 m/s²),

\(D\) = Effective fire diameter (m).

For the purpose of this check, air has been assumed to have the following properties: \(\rho = 1.2\) kg/m³, \(c_p = 1000\) J/kgK and \(T = 293\) K.

“Normal” room fires typically have a \(\dot{Q}^*\) of between 0.3 and 2.5. Calculations have been conducted to assess the \(\dot{Q}^*\) at the peak of the fire for three different scenarios, the fire constrained to the bonnet as initially modelled, the fire spread over the whole top of the car, and how large the area would need to be to restrict the \(\dot{Q}^*\) to 0.3 (the bottom of the normal range). The results of these calculations can be seen in Table 9.

Table 9. Peak \(\dot{Q}^*\) values for three different fire areas

<table>
<thead>
<tr>
<th>Fire Area</th>
<th>Peak (\dot{Q}^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m² (2 m x 1 m – car bonnet)</td>
<td>16</td>
</tr>
<tr>
<td>8 m² (2 m x 4 m – top of car obstruction)</td>
<td>3</td>
</tr>
<tr>
<td>70 m² (2 m x 35 m – calculated for comparison)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

As can be seen from the results in Table 9, the \(\dot{Q}^*\) for the base assumption of the fire area is significantly above the upper bound for normal compartment fires. To investigate the influence of the additional momentum imparted by the small area on the fire products additional cases with fire spread over the top of the whole car for each of scenarios 1a, 1b and 1c. The smoke development for these cases can be seen in Figure 67 to Figure 69 while comparisons of the point concentrations of CO and HF as well as temperature time-amplitudes can be seen in Figure 70 to Figure 78. The smoke development matches that of the observed from the 2 m² fires, with smoke filling the whole ro-ro space for scenario.
1a and distinct separation between a smoke layer and a clear layer in scenarios 1b and 1c. For scenario 1a, the concentrations of both CO and HF match very closely for both cases, while there is a slight increase in temperature at lower heights in the 8 m² fire case at some locations indicating a slight increase in the homogeneity of the conditions within the space. For scenarios 1b and 1c there is a close match at 4.9 m, 2 m, and 1 m above the deck level but an increase in both concentrations at temperatures at 3 m above the deck level when comparison is made between the 2 m² and 8 m² fires. This indicates that the smoke layer is a deeper with the larger area fire, however it remains significantly above the head height. On the basis of this sensitivity check, it can be concluded that any conclusions drawn from the cases studied in the main body of this report with a 2 m² fire are not invalidated by any extra momentum imparted upon fire products.

Figure 67. Smokeview capture showing the filling of the ro-ro space with smoke after 1000s in Scenario 1a with a fire covering the whole car.

Figure 68. Smokeview capture showing the development of a defined smoke layer in the ro-ro space in Scenario 1b with a fire covering the whole car. Capture taken at 1000s.

Figure 69. Smokeview capture showing the development of a defined smoke layer in the ro-ro space in Scenario 1c with a fire covering the whole car. Capture taken at 1500s.

Figure 70. Comparison of CO concentration point measurements for Scenario 1a with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.
Figure 71. Comparison of HF concentration point measurements for Scenario 1a with a 2m$^2$ fire area (dashed lines) and an 8m$^2$ fire area (solid lines). Colours represent height above deck level.

Figure 72. Comparison of thermocouple temperature point measurements for Scenario 1a with a 2m$^2$ fire area (dashed lines) and an 8m$^2$ fire area (solid lines). Colours represent height above deck level.

Figure 73. Comparison of CO concentration point measurements for Scenario 1b with a 2m$^2$ fire area (dashed lines) and an 8m$^2$ fire area (solid lines). Colours represent height above deck level.

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Figure 74. Comparison of HF concentration point measurements for Scenario 1b with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.

Figure 75. Comparison of thermocouple temperature point measurements for Scenario 1b with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.

Figure 76. Comparison of CO concentration point measurements for Scenario 1c with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.

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Figure 77. Comparison of HF concentration point measurements for Scenario 1c with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.

Figure 78. Comparison of thermocouple temperature point measurements for Scenario 1c with a 2m² fire area (dashed lines) and an 8m² fire area (solid lines). Colours represent height above deck level.
Annex E – FED and FEC

There are two main means by which gaseous species effect humans, via asphyxiation (i.e. preventing oxygen from reaching the lungs or circulating through the body), or irritation (e.g. highly acidic substances causing irritancy and acid burns). The fractional effective dose (FED) for asphyxiants and fractional effective concentrations (FEC) provide a means of assessing these effects as tenability conditions within a space. The methodologies used in calculating these for this report are detailed within this Annex.

FED Calculation

The FED has been calculated in accordance with ISO 13571: 2012 [8]. The FED is an accumulated measure and is calculated, between times t1 and t2, utilising the following equation:

\[ \chi_{FED} = \sum_{t_1}^{t_2} \frac{\varphi_{CO}}{35000} v_{CO_2} \Delta t + \sum_{t_1}^{t_2} \frac{\varphi_{HCN}}{1.2 \times 10^6} v_{CO_2} \Delta t \]

Where:

- \( \varphi_{CO} \) is the average concentration, expressed in parts per million (ppm) of CO over the time increment \( \Delta t \).
- \( \varphi_{HCN} \) is the average concentration, expressed ppm of HCN over the time increment \( \Delta t \).
- \( \Delta t \) is the time increment, expressed in minutes

And \( v_{CO_2} \) is a frequency factor representing the increased rate of asphyxiation due to hyperventilation in the presence of CO2. It is calculated using the following equation:

\[ v_{CO_2} = \exp\left[\frac{\varphi_{CO_2}}{5}\right] \]

Where:

- \( \varphi_{CO_2} \) is the average concentration, expressed in volume % of CO2 over the time increment \( \Delta t \).

A \( \chi_{FED} \) value equal to 1 represents the point at which 50% of the general population would be incapacitated by the level of exposure. For general design levels it is recommended that a limiting value of 0.3 [8] is used (11% of the general population would be incapacitated, i.e. those with extra underlying health concerns), although for some cases a value of 0.1 (1% of the general population incapacitated) may be appropriate.

FEC Calculation

The effects of irritants on tenability have been assessed using the fractional effective concentrations (FEC) method in accordance with ISO 13571 [8]. Unlike FED, where a cumulative effect is measured, FEC is calculated at each discrete time increment. For this
study, the only irritants present within the model are HCl, HF, NO and SO2 and so the FEC is calculated with the following equation:

$$\chi_{FEC} = \frac{\varphi_{HCl}}{F_{HCl}} + \frac{\varphi_{HF}}{F_{HF}} + \frac{\varphi_{NO}}{F_{NO}} + \frac{\varphi_{SO2}}{F_{SO2}}$$

Where:

- $\varphi$ is the average concentration, expressed in parts per million (ppm), of the irritant gas;
- $F$ is the concentration, expressed in ppm, of the irritant gas expected to seriously compromise occupants’ tenability and:

$$F_{HCl} = 1000 \text{ ppm}, F_{HF} = 500 \text{ ppm}, F_{NO} = 250 \text{ ppm}^5 \text{ and } F_{SO2} = 150 \text{ ppm}.$$

A $\chi_{FEC}$ value equal to 1 represents the point at which 50% of the general population would be incapacitated by the level of exposure. For general design levels it is recommended that a limiting value of 0.3 [8] is used (11% of the general population would be incapacitated, i.e. those with extra underlying health concerns), although for some cases a value of 0.1 (1% of the general population incapacitated) may be appropriate.

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5 ISO 13571: 2012 does not provide an F-factor specifically for NO, instead here the F-factor for NO2 of 250 ppm was used. This is a conservative estimate.