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Cheval, Valentin

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LUND UNIVERSITY

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

Implementation of an Electric Vehicle fire scenario in the Fire Impact Tool

Valentin CHEVAL
IMT Mines Alès

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Valentin CHEVAL
IMT Mines Alès

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Authors: Valentin CHEVAL

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Abstract

The Fire Impact Tool uses Life Cycle Assessment (LCA) and Environmental Risk Assessment (ERA) methods to assess the local and global environmental impact of the response of the Fire and Rescue Services (FRS) to enclosure fires and vehicle fires. The tool provides examples of fires and allows responder to compare the impact of different extinguishment techniques.

This report presents the methodology used to implement a new fire scenario to the tool: an Electric Vehicle (EV) fire. Same data as for the existing vehicle scenario had to be found and implemented in the new version of the tool, and some modifications or corrections were made.

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Division of Fire Safety Engineering, Faculty of Engineering, Lund University, Lund 2023

RISE Research Institutes of Sweden, Göteborg 2023

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

www.brand.lth.se

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

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List of Abbreviations

BEV	*Battery Electric Vehicle*
EEA	*European Environment Agency*
ERA	*Environmental Risk Assessment*
EV	*Electric Vehicle*
FCEV	*Fuel Cell Electric Vehicle*
FRS	*Fire and Rescue Services*
HEV	*Hybrid Electric Vehicle*
HRR	*Heat Release Rate*
ICEV	*Internal Combustion Engine Vehicle*
IEA	*International Energy Agency*
LCA	*Life Cycle Assessment*
LiB	*Lithium-ion Battery*
Li-NMC	*Lithium Nickel Manganese Cobalt oxide*
PAH	*Polycyclic Aromatic Hydrocarbon*
PHEV	*Plug-in Hybrid Electric Vehicle*
POP	*Persistant Organic Pollutants*
REEV	*Range Extended Electric Vehicle*
SOC	*State Of Charge*

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1 Introduction

1.1 Background

In the "*Civil Protection Act*" (LSO = "Lag om Skydd mot Olyckor" ≈ "Law on protection against accidents"), it is written that the firefighters must "prevent and limit damage to people, property or the environment" [1]. No distinction is made between these three objects of protection. Thus, in theory, the environment protection is as much a priority as saving lives. Yet, it seems that in reality the protection of the environment is difficult for the firefighters to assess and predict in many cases. The following case shows this very well.

In 2015, in a Swedish village outside Hudiksvall, the fire service was called to respond to a burning house. To extinguish the fire and protect the surrounding houses, the firefighters used foam additives to increase the radiation protection offered by the water spray applied to surrounding properties. Initially, they used type-A foam (non-fluorinated), but this was exhausted before the fire was fully suppressed. Therefore, they added type-B foam concentrated (fluorinated) to the water during the final stages of the firefighting. Run-off water containing this toxic (type B) foam contaminated a nearby well used to supply drinking water in the area, making its water undrinkable [2]. After complains from the people relying on the well, the chief of the rescue services who made the decision to use the foam was charged with suspicion of environmental crime. This was well summarized in a news report: "Prosecutor Stig Andersson claims that the suspected incident commander acted negligently and did not take into account the environmental impact of the use of B-foam." [3]. The firefighters used this B-foam despite information advising that they should not have in such cases, although they actually did not know that at the time [4]. The incident commander was finally acquitted in 2019 by the District Court and in 2020 by the Court of Appeal because the investigation showed that he acted with the knowledge he had at the time, which did not include the danger of the B-foam. Indeed, they thought B foam could be used in the same fires as A-foam, but that its use was restricted as it was more expensive, as this was the information provided on the safety data sheet they had [5]. In addition, they thought it was biodegradable [6]–[8].

Therefore, even if the Civil Protection Act says that firefighters must protect people, property, and environment (at the same level of priority), they are actually not able to do so in many situations due to lack of detailed knowledge of how their actions impact the environment. They do not have enough knowledge and training to properly evaluate the implications of tactical choices made during incident response. Thus, firefighters must improve their understanding of the environmental impact of fires and firefighting, to properly follow the Civil Protection Act and carry out their missions.

In support of that objective, in 2019 Swedish researchers from the Research Institute of Sweden (Francine Amon, Robert McNamee, Jonatan Gehandler); from Lund University (Margaret McNamee); and a master student from Chalmers (Azra Vilic), worked on the Fire Impact Tool. This tool consists in an **excel spreadsheet** which enables the user to compare the environmental impact of two different **extinguishment scenarios** to a reference scenario in which there is no intervention on the fire (i.e., the "let it burn scenario"). The aim of the Fire Impact Tool is to assist representatives from the firefighting community to understand the environmental implication of tactical choices. The tool is proposed to be used in training, providing an understanding of how different choices give different environmental impacts, but it does not give absolute answers to specific real-life fires to be used in actual response situations. The number of scenarios is limited to two of the most common types of fires that firefighters experience (enclosure fires and vehicle fires) but does not give a full range of all such fires that could be experience. Instead, the fires implemented into the tool represent example fires.

The user can choose the characteristics of the scenarios in an input chart included in the excel file. They can experiment different cases using the two different **fire scenarios** presently implemented while changing the extinguishment characteristics. The fire scenarios are, as stated previously, a vehicle fire and an enclosure fire. The tool includes data on Life Cycle Assessment (LCA), gases and other effluents emissions, Heat Release Rate (HRR) and Environmental Risk Assessment (ERA) and shows results on the environmental impact of the fire [9]. At the time of development of the tool, vehicles with different types of motors (electrical and internal combustion) were prevalent, but it was agreed that most detailed data could be found for internal combustion vehicles (ICEV). Therefore, only ICE vehicles were implemented into the tool. At the time, the need to include electric vehicles (EV) was recognized but the project was too small to allow the inclusion. Similarly, different types of structures were relevant to include but the focus was on a wood-framed, single stored building.

Since initial development of the Tool, the EV market has evolved significantly in the last few years, making it necessary to add an EV fire scenario to the tool. Indeed, as reported in the *Global EV outlook* from the International Energy Agency (IEA), in 2022, 14% of the car sales corresponded to electric cars, ten times the share in 2017 [10]. The EV sales in the world have been multiplied by 5 between 2019 and 2022, making the number of electric cars on the road in 2022 over 26 million (5 times the stock in 2018) [11]. With nearly 60% of the world's new electric car registration, China has a clear position in leading the electric vehicle revolution. As you can see in figure 1, more than half of the electric vehicles in the world are in China. The second most important market is in Europe, representing a quarter of all the electric vehicle sales. But Europe is divided as 77% of the European EV stock is shared between only a few countries: the Scandinavian countries, Germany, the United Kingdom, France, and the Netherlands [12]. These countries also are the ones with the highest GDP, showing the inequalities in the European market [13].

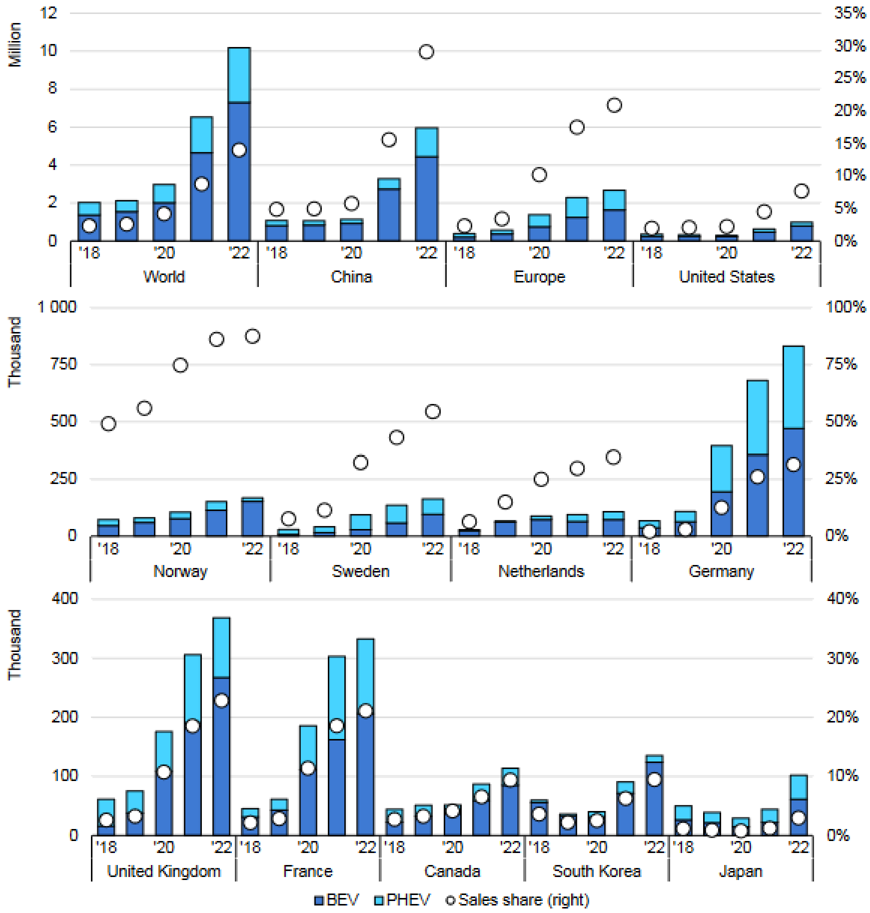

Figure 1: Electric car registration and sales share in selected countries and regions, 2018-2022 [10]

But the lead of China can be put in perspective as its population is much higher than the one of the European countries. So, for example, Norway has a small number of EV compared to the Chinese stock, but this number represents 27% of the total car stock in the country where it only represents 5% of the total number of cars in China. With this share Norway has the world record and is, with Iceland, the only country with an EV stock share higher than 10%. Still, what is also interesting is the sales share in these countries, which can be observed in the figure 1. We can see that in 2021, 16% of the car sales in China is electric, which is quite similar to the sales in Europe (18%), but still lower than in Norway or Sweden (with respectively 86% and 43%) [11].

According to the European Environmental Agency report N02/22 [14], the important growth observed after 2019 in EV sales is "*strongly influenced*" by EU policies. Indeed, after the Covid-19 pandemic, as recovery measures, the EU invested a lot in Electric Vehicles, explaining why the EV market increased while the rest of the automotive sector is declining [14].

Finally, the global trend observed in figure 1 shows that since 2019, the EV market is increasing rapidly in Europe and China. The IEA estimated that India and the USA will follow this growth, bringing the total number of electric cars in the world up to 15% of the global stock by 2030 (compared to 2.1% in 2022) [11]. The EU Reference Scenario 2020 follow these estimations as it project that by 2030 16% of the stock of cars will be electric, and this share will be of 53% in 2050 [15].

Therefore, electric vehicles are going to be more and more present on the roads in the next years. Yet, it is important to understand that even if EV seems better for the environment than Internal Combustion Engine Vehicles, they still have some risks. Indeed, electric cars use batteries to run, which can catch fire. More information about common battery types is given in Chapter 2. Fires in Li-ion batteries are typically started by a thermal runaway which can occur during a crash or while charging. This new type of fire has its own extinguishment methods which include the use of blanket or large amounts of water, but there is still a need for research to determine the best method of suppression of such vehicles not least due to their ability to re-ignite if not suppressed effectively. The need to respond to fires in EVs is still low but is expected to increase (as seen previously).

Thus, the Fire Impact Tool clearly needs the implementation of such a new scenario so that firefighters can explore the environmental impact of their response on electric vehicle fires both the similar responses to that of ICE vehicles and appropriate responses, tailored for EVs.

1.2 Goals and Research Questions

The goal of this report is to implement a new EV fire scenario into the Fire Impact tool. Ultimately, the aim is to make a new version of the Fire Impact Tool, to make it more relevant for the Fire and Rescue Services (FRS). To support this goal, the following research questions were formulated:

- Which data can be used to implement EVs into the existing vehicle model for the Fire Impact Tool? This includes some assessment of different EV technologies.
- Which limiting values for environmental pollution should be used to identify when surface and ground water are contaminated?
- How should the tool be adapted to this new fire scenario, i.e., which types of comparisons are relevant?

Answers to the research questions will be sought using a systematic literature review of electric vehicle fire data and international guidelines concerning water quality.

In addition to the literature review, the thesis will focus on implementation of data into the Excel file containing the full Fire Impact Tool.

1.3 Limitations

A large variety of electric vehicle models exist, but only a single “example” EV has been implemented. Using the same thinking as the original Fire Impact Tool development, the new scenario is useful for exemplifying the impact of different tactical choices as part of firefighter training, not for use during actual tactical response. The tool is exemplary rather than fully accurate.

Assumptions and other limitations will be further described and discussed in the rest of the report.

2 Methodology

Here is a flowchart which present the method used during the work of research leading to this report. The major points will then be detailed.

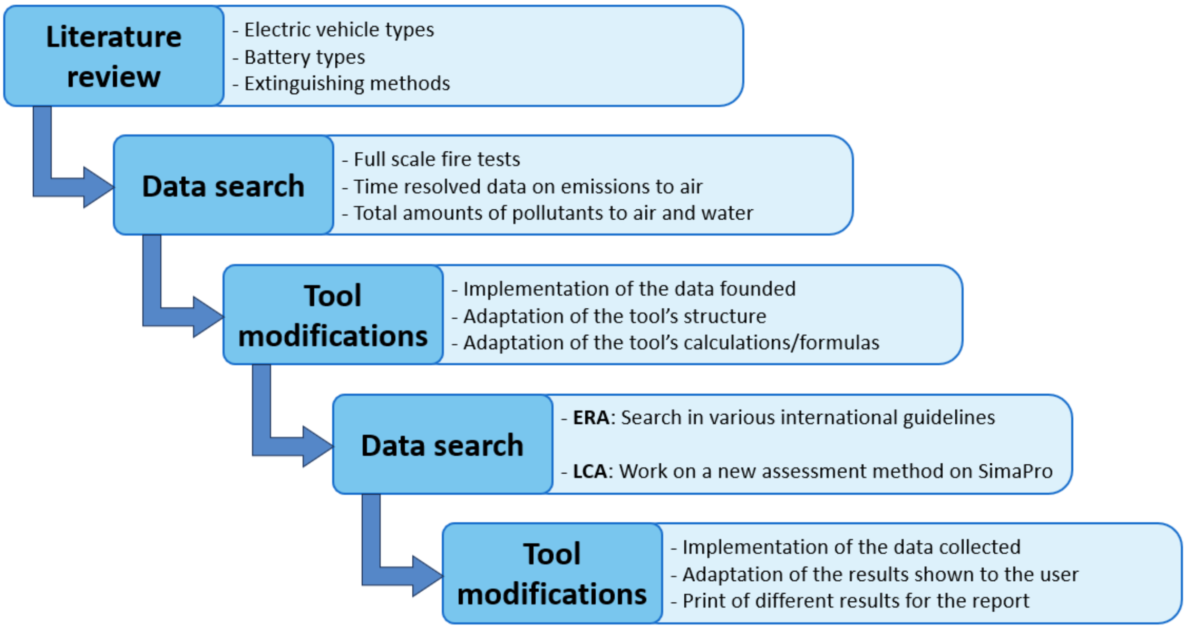

Figure 2: Flowchart describing the methodology of this report

2.1 Literature review

The literature study was conducted using sources such as the LUBSearch portal, DiVA portal, Google Scholar or ScienceDirect, and with a research by keywords. At first, simple keywords were used, and new ones were added to the search if the number of results was too important. The keywords used are presented in the following table:

Table 1: Keywords used in the Literature study

Keyword	Number of results	Selected results
electric vehicle fire	2 606	
electric vehicle fire test	405	
electric vehicle fire test measurements	47	0
electric vehicle fire consequences	45	2
electric vehicle fire environmental consequences	10	0
electric vehicle fire test water	31	3
electric vehicle fire test extinguishing water	7	2
electric vehicle fire emission	161	
electric vehicle full-scale fire test	16	3

electric cars fires	958	
electric cars fire tests	118	
electric cars fire test measurements	7	0
electric cars fire consequence	18	1
electric cars fire environmental consequences	6	0
electric cars fire test water	9	2
electric cars fire test extinguishing water	3	1
electrical cars fire emission	24	1

After reading the abstract, the interesting reports were read entirely and kept if they contained expected results. Then, a snowballing method was used: in an iterative way new reports were found using the references of the previous ones [16]. All the useful results can be found in the references at the end of this report as they were used to document this entire report.

2.2 First data search

Apart from the literature review, the first thing to do was to find data concerning electric vehicle fires. The data needed to be quite similar to the one already used in the tool so that the implementation could be easier. So, the goal was to find results of full-scale EV fire tests which included the time related HRR and gases emissions for at least CO_2, CO, HCl, HCN and SO_2; but also the analysis of extinguishing water. Only a few experiments were founded so we will see that assumptions had to be made to complete the implementation. After the interesting study were found [17], [18], a full set of data was requested of the authors. In order to verify the coherence results founded, they were compared to the one already implemented in the tool.

2.3 First modifications of the tool

The data founded on the previous data search was then implemented on the Excel tool the same way it had be done for the existing data. Adaptation and modifications of the tool were needed to restore links or correct formulas. This will be detailed in the part 4 of this report.

2.4 Second data search

With the experimental data implemented, ERA and LCA calculation then required some data update to fit the new scenario.

2.4.1 ERA data

Guideline values used in the ERA calculations had to be updated, and other had to be founded (as new components were found and implemented). To select them, a comparison was conducted between various international regulations.

2.4.2 LCA data

For this version of the tool a new method was used to conduct Life Cycle Assessment calculations. So, a new set of data was calculated with this new method using the software SimaPro [19], [20].

2.5 Second part of the tool's modifications

2.5.1 ERA data

As new possibilities for the user were added, modifications to the tool were made. New data was also implemented and linked to the rest of the calculation. Final adaptations also had to be done for this part of the tool.

2.5.2 LCA data

Previous LCA data was replaced by the new one, leading to some modifications in the calculation and evolutions in the results as some impact categories changed.

3 Theory

3.1 Overview of Electric Vehicles

3.1.1 The different types of EVs

The European Environment Agency (EEA) [21] has defined five types of electric vehicles, presented here:

- Battery Electric Vehicles (BEVs): an on-board battery is used to supply an electric motor. This battery has to be charged, using for example a plugging connected to the power grid. Electricity is the only power source of a BEV.
- Hybrid Electric Vehicles (HEVs): a small electric motor is powered by a battery which is charged using regenerative braking or while the vehicle is coasting. But the electric motor is only used to assist a conventional motor (which is the main motor) or for small distances. So, the HEVs can be describe as conventional vehicles with higher efficiency (thanks to the electric support).
- Plug-in Hybrid Electric Vehicles (PHEVs): equipped with both an electric motor and an internal combustion engine, PHEVs can be used as an ICEV or a BEV (charging the battery by plugging it to the power grid). Both motors are complementary, but the electric battery is smaller than a BEV one, so it can only be used for smaller distances than a real BEV or used to assist the internal combustion engine.
- Range-Extended Electric Vehicles (REEVs): powered only by an electric motor, powered by an on-board battery which can be charged by plugging it to the electric network or by using an auxiliary combustion engine (this engine only acts as an electricity generator).
- Fuel Cell Electric Vehicles (FCEVs): powered only by electricity, FCEVs produces the needed electricity with cell 'stack' that uses hydrogen from an on-board tank combined with oxygen from the air.

In this report, the term EV refers to all the types of electric car that we have just seen. But according to the IEA, around 70% of the EVs in the world are BEVs and 30% are PHEVs (the three other types are minor). This repartition varies slightly in Europe compared to the global averages, with only 56.4% of BEVs (the rest are PHEVs) [11]. The data founded and used in this report actually correspond to BEVs, but we will still use the term of EV for these data as **BEV** is the most common type of EV. The terms electric car or electric passenger car/vehicle will also be used to describe EVs.

The term **ICEV**, for Internal Combustion Engine Vehicle, will refer to conventional vehicles, i.e., vehicles using fossil fuels (petrol or diesel) to power the engine.

3.1.2 Batteries

The first electric battery was invented in 1799 by Alessandro Volta, and this technology kept improving over the years as its use was getting more and more common. Nowadays, electric batteries are used in a wide range of fields, but what is interesting for us is its use in electric vehicles. Various types of electric vehicle batteries exist and are used, including Lead acid (Pb-acid), Nickel-Cadmium (NiCd), Nickel-Metal-Hybrid (NiMH) and **Lithium-ion** (Li-ion) [22]. Yet, Li-ion batteries (LiB) is by far the most common type of battery used for electric vehicles as it provides the higher specific energy and cycle life [23]. Different types of LiB exist, depending on the material used for the cathode. For example, the BEV used in the experiment used in the tool used a lithium-nickel-manganese-cobalt oxide (**Li-NMC**) battery, most of the BEV use this kind of LiB. Hybrid electric vehicles generally use lithium-iron-phosphate ($LiFePO_4$). A lot of research is still conducted to determine the best type of battery, meaning the one with the smallest environmental impact and the best efficiency [24]. For the rest of this report, the term of battery will always refer to Lithium-ion batteries (otherwise it will be specified).

3.2 Electric vehicle fires

3.2.1 Cause of fire

The fire hazard in electric vehicles does not comes from the fuel as it is the case for ICEV but from the battery. Indeed, under certain circumstances, the lithium-ion battery can experience a so-called "**Thermal Runaway**", which consist in various exothermic reactions which will increase the pressure inside the battery, leading to the rupture of the cell and the production of toxic and flammable gases. If the temperature is high enough, these gases can catch fire (then spreading out to the whole vehicle). Excepted if the battery has a manufacturing disfunction, this thermal runaway cannot occur on its own but needs a cause, which can be the result of a mechanical damage, an electrical abuse, or a thermal abuse [23]. These causes are well illustrated in the following schematic from *Wang et al.* where we can also see how they are linked [25].

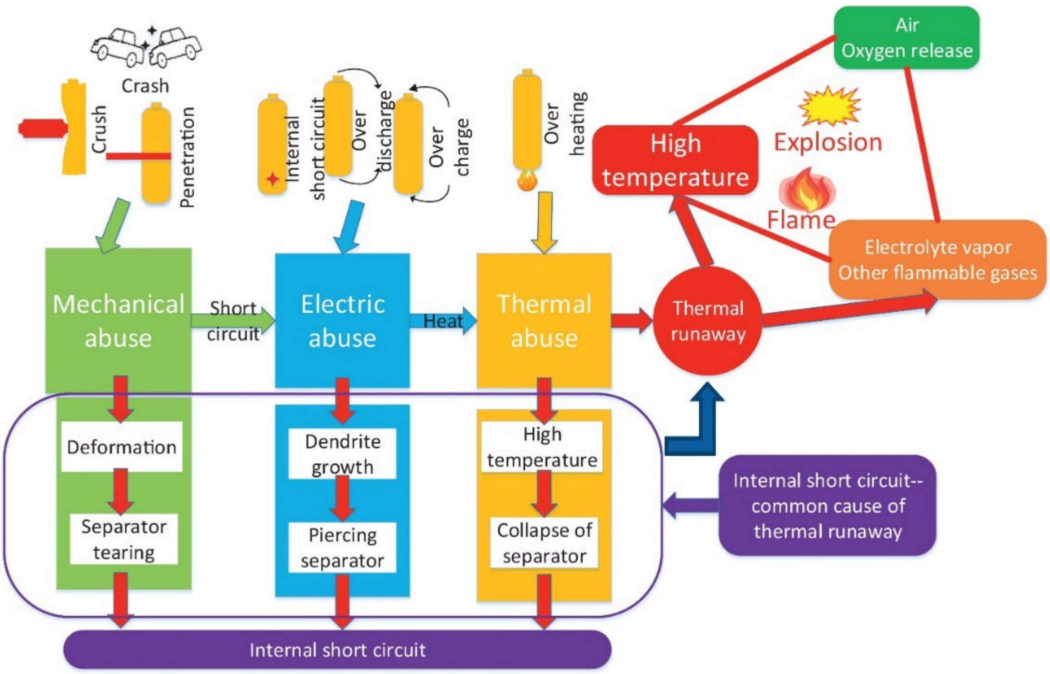

Figure 3: Schematic of the causes of LiB fire accidents [20]

Therefore, an EV can catch fire while charging, while parking or driving, because of a crash, a close fire, a contact of the battery with external substances, or by arson.

3.2.2 Extinguishment methods

Internal mitigation systems exist, which consist in aboard-technologies to prevent a fire by various means or to control it. But these technologies still need to be developed and are not commonly used in EVs, so they will not be described here. Instead, we will see the extinguishing or fire suppression methods that are used by firefighters all around the world.

In order to choose the best extinguishment method, it is necessary to qualify the EV fires. The International Standard Organization (ISO) and the National Fire Protection Agency (NFPA) define five different categories of fire, depending on the type of fuel (the electrical fire is not really a class in the ISO Standard, but the letter E is sometimes used). These categories are defined in the following table.

Table 2: The different categories of fire

Fuel type	***ISO Standard 3941***	***NFPA 10***	***Type of extinguisher to be used***
Ordinary combustibles (Solid)	Class A	Class A	Water, Foam, Dry powder (ABC), Wet chemicals
Flammable Liquid	Class B	Class B	Dry powder (ABC), Foam, CO_2
Flammable Gases	Class C	Class B	Dry powder (ABC)
Electrical Fire	(E)	Class C	CO_2, Dry powder (ABC)
Flammable Metal	Class D	Class D	Sand, Special dry powder
Cooking oils and fats	Class F	Class K	Wet chemicals

As EVs are a complex technology using various materials, it does not fit into one and only category. With the different parts of the vehicle, an EV can be considered as part of the ISO classes A, B, C, and D, so the type of extinguisher needed is hard to choose [26]. During the extinguishing process, the battery needs to be cooled down to prevent any reignition. So, **water** seems to be the best extinguishing agent to use as it allows to suppress the flames as well as cooling the vehicle (and therefore the battery), and it is indeed the mostly used method. Yet, to be truly efficient, the water needs to be applied directly into the battery, which is found to be difficult as batteries are hidden under the vehicle and well protected by various layers. Thus, firefighters need to apply **large amount of water** to cool down the LiB.

To improve the efficiency of the water, additive can be added to create a foam which will cover the vehicle, preventing the oxygen to reach and fuel the fire. Other types of additives can be added to improve the cooling or to decrease the emission of smoke or soot [23]. Finally, gaseous and aerosol systems have a reduced efficiency (especially since they do not have enough cooling effect).

The Australian government observed that currently, fire agencies mostly use one of the following methods: letting the battery and the vehicle to completely burn out; suppressing the fire and cooling the battery with water (lifting a side of the car to have better access to the battery); dropping the vehicle into a container filled with water (and possibly additives). Some other countries like Germany also use large blanket to cover the vehicle and isolate it from the ambient oxygen (and remove the inside oxygen); or other innovative technologies such as special containers with slide-in platforms to smother the fire [27].

New equipment is being developed to improve the efficiency of firefighting tactics. For example, a CTIF (International Association of Fire and Rescue Services) Associate Member called Cobra Cold Cut Systems created a new type of pressure lance which is able to penetrate the protective shell of a LiB to cool it down with fewer amount of water. This was tested in January 2023 during a real intervention in Norway [28].

All of this shows that EV fires are still new for the Fire and Rescue Services, which need to find the proper way to extinguish it. Research and tests are being made and are yet to be made, so it will take some time to find the best extinguishing method(s).

3.2.3 Differences/similarities between an ICEV and an EV fire

People are more afraid of EV fires, which are also more represented in the media, because EV is a relatively new technology on which we have fewer knowledge than ICEV. Yet, different research has shown that ICEV and EV fires are not that different.

Of course, the major difference lies in the power source, the fuel type: batteries for EVs and gasoline for ICEVs. But large-scale fire experiment conducted on four vehicles (from two French car manufacturers, with each an ICEV and an EV) [29] showed that in the same experimental conditions, the general fire behaviour was the same between ICEVs and EVs. Close values for the Maximal Heat Release Rate (MHRR) were measured for both car types for each manufacturer. Similarly, comparable cumulative masses of gases were measured (for CO_2, CO, NO, NO_2, HCL and HCN) and a similar peak in HF production was found during ICEV and EV tests. Yet, the total quantity of HF was almost twice as high in the EV fire tests, corresponding to the combustion of the LiB pack. It is good to know that in other experiments (including the ones we will use later in this report), HF levels were too low to be measured in ICEV fire tests, which might be explained by the presence of fluorinated materials in some vehicle (but not every vehicle).

It is actually quite hard to compare ICEV and EV fires as it depends on the manufacturer, the composition, size and age of the vehicle, the amount of fuel in the tank, the capacity, and State of Charge (SOC) of the battery or the type of battery (this list is not exhaustive). It also depends on the accident scenario and the time when the battery is involved in the fire [26]. So, comparing the impact of an EV or an ICEV fire is relative and depends on many variables. However, the way to face these different fires can be compared. Indeed, real interventions have shown that firemen know how to manage an ICEV fire and are able to extinguish it in five minutes, using few amounts of water, while extinguishing an EV fire requires way more time and water. Depending on the development of the fire it can take around an hour and about 10,000L of water to extinguish an EV fire [30]. Plus, there is a risk of reignition, meaning that the battery can catch fire again after extinguishment; it can even ignite a few days after a crash (see the examples).

Nevertheless, knowledge concerning EVs will continue to grow in the next years, technologies will improve and as EVs will become more and more present, the fire risk will decrease and EVs and ICEVs will be considered on the same way.

3.2.4 Statistics and Examples of EV fires

3.2.4.1 Statistics

The Swedish Civil Contingencies Agency (MSB) has noted that in 2022, almost 19 000 passenger cars in Sweden were involved in a traffic accident and that around 3400 burned [31]. Further, 18% of the cars involved in an accident caught fire and 0,067% of cars burned in 2022. MSB has also reported that in 2022, Sweden had on the road 610 716 EVs on a total of 4 980 543 passenger cars (12,3% of the Swedish cars are EVs) [32]. In the same report we can observe that 23 EVs burned in 2022 and 371 were involved in traffic accident. So, 6,2% of the accidented EVs caught fire, representing 0,004% of all the EVs in Sweden. We can see here that in Sweden, EV fires are less frequent than ICEV fires, even relative to its lower proportion of the market.

Similar observations were noted by the insurance company AutoinsuranceEZ, in the USA [33], based on data collected and analysed from the National Transportation Safety Board (NTSB), Bureau of Transportation Statistics (BTS) to calculate the number of fires per 100 000 sales. Electric vehicles (here BEV) have the lowest number of fires per 100 000 sales with only 25, while it is 1 529 for conventional vehicle. One particularly interesting thing is that they have separated BEV and HEV, and Hybrid Electric Vehicles have the higher number of fires per 100 000 sales with almost 3 500 fires.

Finally, the Australian Government [27] noted that an EV has a 0,0012% chance to catch fire while “many sources quote a 0,1% chance of your petrol or diesel car igniting”. This goes in the same way as USA and Swedish observations, which proves that the fear of EV fires is only based on false beliefs.

3.2.4.2 Examples

Here are a few examples of EV catching fire, to illustrate the previous paragraphs. In October 2022 in Sweden, after a collision with a warehouse, an EV Started to burn (the battery caught fire) [32]. In September 2021, because he was speeding, a driver lost control of his vehicle and crashed his EV into a tree, making the battery to catch fire. After the fireman’s intervention the car was taken to the tow yard, but it re-ignited a first time on the way and a second time at the tow yard five days later [30], [34]. Finally, another example shows that a crash is not the only reason for an EV to catch fire as in 2018, in West Hollywood, a car ignited itself while driving [35] and in 2019 a car ignited while it was charging in a house in England [36]. Many more such examples exist globally.

3.3 The Fire Impact Tool

3.3.1 Introduction

As said in the introduction, we can observe among firefighters and other members of the Fire and Rescue Services a lack of knowledge and training concerning the protection of the environment. To overcome this, the Fire Impact tool was created. So the aim of the tool is to allow those concerned to understand their environmental impact and to adapt their action to reduce it. It is designed to be used during trainings or as educational purposes. The users of the Fire Impact Tool are then the firefighters, those who train them and other members of the FRS. Other users such as environmental associations, insurance compagnies, government institutions or agencies might also benefit from using it.

The tool is based on a previous study for the NFPA concerning environmental and economic consequences of warehouse fires, the ENVECO tool [37]. The Fire Impact Tool now focusses on two fire models which are a vehicle fire and an enclosure fire, that will be detailed in the next parts. The tool is composed of the fire models and two assessment methods; Environmental Risk Assessment (ERA) and Life Cycle Assessment (LCA) that will be explained in the following part [9].

Basically, the tool is an Excel Spreadsheet which uses experimental data and assessment methods to compare the environmental impact of various fire responses. The user creates two scenarios, specifying the characteristics of the extinguishment method used in each scenario (number of response vehicles, amount of water used, use of additives, of fire blanket, etc…). The tool provides the comparison of the scenarios to each other and to a reference scenario where the FRS only prevent the fire from spreading but otherwise let it burn. The result is composed of charts concerning different points that will be detailed later on.

It is important to remember that the tool is built on a few scenarios using limited experimental data. The goal is not to give perfect information concerning a specific type of fire but to give examples of what can be the consequences of the firemen’s action. It is strictly indicative, and the results cannot be applicable to real fire situations. It is designed to be used in training rather than tactical response.

3.3.2 Description of the tool

The tool, as it is currently, is composed of around thirty Excel sheets, with five visible ones and the rest which is hidden to the user. These will be described in more detail below.

3.3.2.1 Visible part of the tool

Introduction sheets

The visible part includes an Introduction and an example sheet. They allow the user to understand how the tool works and what to expect of it. It also gives details on the methods used and the assumptions that were made.

Input sheets

Users then can start using it, modifying the specific cells of the input sheets, to choose the characteristics of the scenarios they want to compare. There is one input sheet for the Vehicle fire model and one for the Enclosure fire model. Only a few parts are editable, these cells are painted in green to be easily spotted. These characteristics correspond to the choices that a responder would make when responding to a vehicle or enclosure fire and includes details on the way to extinguish the fire but also, for the enclosure model, details on the building itself. The input sheets also include results, in the form of four graphs showing both local and global impacts (it will be detailed later). Finally, the two last visible sheets are the "detailed analysis" sheet (one for each model) which, as their name suggests, gives more details on the results.

3.3.2.2 Invisible sheets

The "invisible part" of the tool contains all the data and calculations used to find the results given to the user.

Data sheets

At first, there are all the sheets containing data, with time resolved data for the Heat Release Rate (HRR), for the gases emissions (CO_2, CO, HCN, HCL, SO_2). There is also the data for the composition of the run-off water (both for the vehicle fire and the enclosure fire) and the different LCA data sheets.

Calculation sheets

Finally, there are various sheets for the calculations on the structure, for the LCA and ERA parts, which will be explained in the rest of the report.

3.3.3 Fire Models

3.3.3.1 Vehicle fire models

The first model implemented in the tool was a Vehicle fire. It was chosen because it is a relatively common, simple and well-known type of fire. As it is the most common vehicle type, with more data available, Internal Combustion Engine Vehicle is the chosen type for the fire model. To actually create the models of emissions to air, soil and water from burning cars, the experiment of Lönnermark and Blomqvist [38] was used. This experiment was conducted on a medium class model from 1998, with an empty petrol tank and few parts of the vehicle (the battery, air bags, belt actuators and the hood dampers) removed for safety reasons. The car was ignited, data was collected and finally, and after the maximum HRR was reached it was extinguished, using 200L of water. 105L of run-off water was collected and analysed (the rest was vaporised or landed outside the collection system). The results consisted of data concerning emissions to air and water. The data has been applied to estimate emissions to air, water and soil [39].

Emissions to air

Time resolved data on HRR, CO_2, CO, HCN, HCl and SO_2 was collected. To be sure that the data had comparable evolution their normalisation was compared, which showed that all gases emission (excepted for CO_2) had a production peak around 20 min and then was decreasing until the fire was extinguished at 29 min. So we can assume that for the "let it burn" scenario the underestimation due to the extinguishment is minor. As all the data correspond to the same period of time, it was assumed that a truncating of the emissions curves at the extinguishing time can be used to calculate the emissions to air. A linear decline was used, for a default time of 5 min, which correspond to the average time needed for the firemen to extinguish a vehicle fire.

Gases emissions data were then used in the Life Cycle Assessment calculations (which will be described later).

Emissions to water

In their experiment, Lönnermark and Blomqvist analysed the composition of the water they used to extinguish the car. During the extinguishment, they applied water for a short period of time on the vehicle, so it can be assumed that the collected water contains pollutants from the soot washed off the surface of the car and quenched fire species. These species will be detailed later in this report.

Run-off water data are used in the Environmental Risk Assessment calculations, but as the user can choose the time of extinguishing, the amount of contaminant will change between each scenario. Indeed, if the firefighters start extinguishing the car earlier, there will be less contaminants produced. To model this, the amounts of contaminant were scaled relative to the HRR, using the HRR at the point of extinguishment in the actual experiments. The reference [39] gives an example of how this works: "*the HRR at the point of intervention (10 minutes) was 87% of that at the point of intervention in the actual experiments. Therefore, the emissions in the runoff water were scaled by 0.87 compared to the actual experimental values.*"

Emissions to soil

It was assumed that all of the run-off water which was not collected would go to the soil. So the contaminants present in the water can be found in the soil, impacting the local environment. Three types of soil are analysed in the tool: Moraine, Sand, and Clay, which represents the three most common types of soil in Sweden.

3.3.3.2 Enclosure fire model

The second fire model corresponds to an enclosure fire. It represents a school, which is a single compartment composed of four separate and independent rooms (classrooms here). School fire was chosen as a lot of documentation was available on this type of fire and because it can easily be adapted to other kind of enclosure fire. The user can choose for each of the room its size, opening, fuel load, start and end of fully developed fire, the amount of fire applied and if active suppression is used. The data implemented on the tool (data on the composition of the extinguishing water from furnished room fires) comes from experiments by Blomqvist et al. [40] and analysis from Wieczorek et al. [41]. Equations from (Karlsson and Quintiere, 2000) [42] were also used.

More information concerning this fire scenario is available on the Fire Impact Tool Report [9] but it will not be further described on this report as it is not the focus of the work conducted to expand the Fire Impact Tool this time.

3.3.4 Assessment methods

In this tool global and local impacts are separated and analysed thanks to two different assessment methods. The LCA method was chosen to assess the global impact of the fire, including the air pollution (gases emissions) while the ERA was used for the local environmental effects, like emissions to water and soil.

In both methods, the aim is to compare results from the reference scenario (where the responder only goes to the scene but do not engage any action to extinguish the fire) and the two response scenarios (which are defined by the user).

3.3.4.1 Life Cycle Assessment (LCA)

The LCA method allows to assess global environmental consequences of the entire, or just a part of the life cycle of a product or system, including its manufacturing, use and end of life. Here, the system is whether the tactical choices of the response to a vehicle fire or the tactical choices of the response to an enclosure fire and the design of the enclosure. ISO standards define its use, giving three major components: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation of results. Each of these components is detailed in reference [9].

In the "Impact Assessment" part of the current version of the tool, a method is used to calculate the system's impact. The chosen one is the Eco-Scarcity 2013 method, which enables to calculate the impact of firefighting foam. This method assesses various impact categories on which five was chosen for the tool: Global warming, Main air pollutants and PM, Water pollutants, Persistent Organic Pollutants (POP) into water, and Energy resources. All these categories have here the same unit: "UPB" or "Eco-points".

LCA is based on wide amounts of data and most of it was found in the "ecoinvent 3" database. But it also needed to use gases emissions (from Lönnermark experiment) as an input.

3.3.4.2 Environmental Risk Assessment

The ERA method is used in the tool to assess the environmental effects of the fire to its close surrounding, especially the impact of run-off water. The ERA gives quantitative analysis on the following three points: the amount of soil needed to be excavated; the quantity of water required to dilute extinguishing water to reach guideline values; and the distance between the fire and a groundwater well where it can be contaminated.

The studied components, referred to as "stressors" are mainly metals and Polycyclic Aromatic Hydrocarbons (PAHs) and comes from the fire itself or may also come from the use of additive. These stressors represent a danger to the three selected "endpoints": the soil ecosystem, aquatic life in nearby surface waters, and drinking water quality in groundwater wells. A conceptual model is also describe on the Fire Impact Tool report [9] as well as all of the details concerning calculation made for this assessment method. Some of these calculations will be detailed in the part 4 of this report.

4 Tools modification

4.1 Emissions data

4.1.1 Reference experiments

The literature review revealed that only a small number of full-scale EV fire tests were conducted yet. Here is a table of all the tests founded:

Table 3: Full-scale fire tests conducted on EVs

Reference	Date	Type of vehicle tested	Measurement	Environment
Watanabe et al. [43]	2012	ICEV BEV Battery	Mass loss, HRR, heat flux	Fire test room: 15 m × 15 m × 15 m
Lecocq et al. [29]	2014	IVEC EV	HRR, gas analysis	INERIS fire gallery: 50 m × 3.5 m × 3m
Lam et al. [44]	2015	ICEV EV PHEV	HRR, heat flux, mass loss, battery voltage	National Research Council Canada full-scale fire test facility: 6 m × 6 m
Truchot et al. [45]	2018	ICEV EV	Gaseous emissions, HRR, heat flux, mass loss	INERIS fire gallery: 50 m × 3.5 m × 3m
Willstrand et al. [17] *E-Tox 1*	2020	ICEV BEV	HRR, Temperatures, Gas analysis, Soot and Ash analysis	Large fire hall in Borås, RISE facility
Sturm et al. [46]	2022	BEV ICEV	HRR, firefighting tactics, Gases analysis, Water pollution and surface deposition analysis	Tunnel research facility Zentrum am Berg: two motorway and two
Hynynen et al. [18] *E-Tox 2*	2022	ICEV BEV	HRR, Temperatures, Gas analysis, Soot and Ash analysis, Extinguishing Water analysis	Large fire hall in Borås, RISE facility

What is really interesting in this tool is that it includes the impact on soil and water quality, assessing the run-off water. Therefore, the experiment chosen for this new version needed to include the analysis of extinguishing water for an EV fire. The only experiment founded where such an analysis is conducted is the study of Hynynen et al. [18], that we will refer to as E-Tox 2. In this experiment, sprinkler systems are used on the burning vehicles and the run-off water is then analysed, giving results on the characterisation and composition of the extinguishing water. So this is really interesting, and the results will be used in the tool.

Yet, the use of sprinklers during the fire test interfere with the gases and soot analysis as some components may get trapped in the water and therefore cannot be analysed. It was then decided to use the result of the gas analysis from the study of Willstrand et al. [17] that we will call E-Tox 1. Indeed, in this experiment gases emissions are not disrupted as the vehicles burn completely and are not extinguished. But as there is no extinguishing, no water can be analysed so these two experiments will be used complementarily. Both experiments are detailed in the following sections.

4.1.1.1 E-Tox 1

In this experiment an insurance company provided vehicles which were involved in incidents. They had minor damages, and it was supposed that it had no significant impact on the experiment. For safety reasons a few modification was made (for example, tyres, suspension, and dampers were punctured and pyrotechnics were removed). Two BEV and one ICEV were tested, with respectively 80% State of Charge (SOC) and 44l of diesel (80% of a full tank). Note that the battery was involved in the fire as early as possible. HRR, toxic gases emissions and soot content were analysed from the three free burning vehicle tests [17].

The vehicles tested in this experiment will be referred to as ICEV A, BEV A, and BEV B (A and B refers to the manufacturer) while the ICEV from Lönnermark will be referred to as ICEV 1. ICEV A was a diesel full-size van from 2011 and BEV A was a 2019 electric full-size van of 40 kWh, using an NMC battery. Finally, BEV B was a 2016 small electric family car of 24 kWh also using NMC battery.

The data implemented in the tool from this experiment is detailed in a following part.

4.1.1.2 E-Tox 2

In E-Tox 2 experiment, three vehicles were tested but only one was used for the new version of the Fire Impact Tool. This vehicle is a small electric SUV manufactured in 2021 with a Li-ion battery type NMC of 50 kWh. The SOC was around 90% and a burner was used to ignite the car, involving the battery from the beginning. A sprinkler system was used for 30 minutes during the test, delivering 11 160L of water on the vehicle, of which approximately 3 600L were analysed. Mostly metals and PAHs were found in the water, and their total amounts were implemented in the tool.

This study also included the analysis of gases emissions and HRR, but the curves were modified due to the use of water during the test, which lead to the choice of not implementing these values. Instead only the water analysis was used.

Water analysis and gases emissions are not directly linked, so it was assumed that data from the two different experiments could be used. To adjust the value from E-Tox 2 test to the ones from E-Tox 1, a scaling factor was applied to the amounts of toxicants found in the run-off water. This scaling factor uses the time related data on HRR from BEV A and B, allowing the values to fit both vehicles burning characteristics and to be adjusted to the scenarios.

4.1.2 Time resolved data

4.1.2.1 HRR

The HRR is used to scale other components so that the value is not always the same, depending on the supposed time of extinguishment. Indeed, if the firefighters start extinguishing the car early, there will be less pollutants released in the environment.

In the following figure you can see the time related HRR norm for the vehicles of the E-Tox-1 experiment and the one already implemented in the tool (ICEV 1).

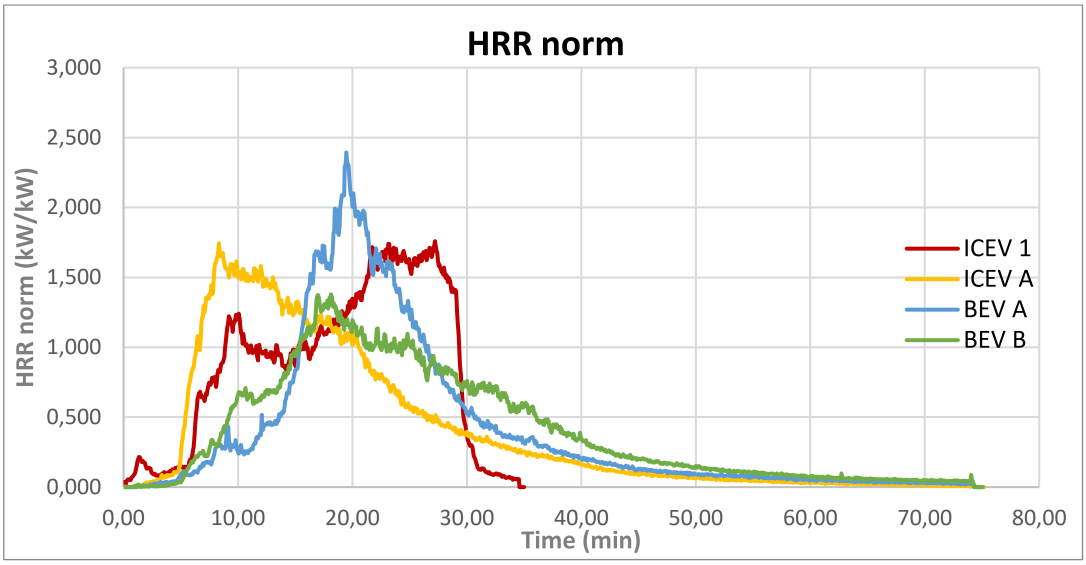

Figure 4: HRR norm for the four studied vehicles

In the current version of the tool, the scaling factor correspond to the HRR at the supposed intervention time divided by the HRR at the experiment's intervention time. But for the new version of the tool the scaling is a little bit different as the profile of the HRR curves are not similar. In the new data, the peak HRR is reached quite early and fast, so we have assumed that most of the pollutants are emitted in the growth phase and that after the peak HRR the amount of pollutant is constant. Therefore, the scaling factor equals 1 after the peak and it is equal to the HRR at the supposed intervention time divided by the peak HRR before it.

This scaling factor is used for all of the non-timed-related data implemented in the tool, including run-off water components and PAH emissions to the air.

4.1.2.2 Gases emissions

Gases emissions for CO_2, CO, HCl, HCN and SO_2 were already implemented in the tool for the ICEV 1, using results from Lönnermark and Blomqvist [38] experiment. Same species were analysed in the E-Tox 1 study, and the time resolved data was implemented in the tool the same way it had been done in the actual version.

So that the emissions could be representative to the scenario, assumptions were made, saying that at the supposed time of extinguishment, the emission of each gases start decreasing in a linear decay, fixed here at five minutes. This means that five minutes after the intervention the emissions stops: five minutes was chosen as it is an average time for extinguishing a vehicle fire.

4.1.2.3 HF

In the original experiment, the emission of HF was found too low to be measured properly (below detection limits). Yet the E-Tox 1 study showed that ICEV fires can product HF and also that BEV fires have higher HF emissions. So in the tool, HF emissions were implemented for the EVs but not for the ICEVs (as it was not significant compared to the other gases).

4.1.3 Other data

The other data implemented in the tool are not time related as they represent total amounts of different species. These pollutants were analysed from the run-off water collected during both Lönnermark and E-Tox 2 experiments and they are gathered in the following chart.

Table 4: The species analysed in the extinguishing water of experiments [33] and [43]

	ICEV 1		ICEV A		BEV	
	Result (µg/l)	Total amt (g)	Result (µg/l)	Total amt (g)	Result (µg/l)	Total amt (g)
PAHs						
Naphtalene	-	-	3,6	0,01296	-	-
Acenaphtylene	-	-	1,8	0,00648	-	-
Acenaphtene	-	-	13,5	0,0486	1,8	0,00648
Fluorene	-	-	1,3	0,00468	0,8	0,00288
Phenantrene	-	-	2,3	0,00828	-	-
Anthracene	-	-	2,5	0,009	-	-
Fluoranthene	8,1	0,00085	-	-	-	-
Benzo(b+k)fluoranthene	5,7	0,00060	-	-	-	-
Benzo(a)pyrene	5,5	0,00058	-	-	-	-
Indeno(1,2,3-cd)pyrene	3,8	0,00040	-	-	-	-
Benzo(g,h,i)perylene	4,0	0,00042	-	-	-	-
SUM PAH	27,0	0,0028	25	0,09	2,6	0,00936
Metals						
Cd	3,9	0,0004095	-	-	-	-
Pb	2300,0	0,2415	76	0,2736	-	-
As	8,6	0,000903	-	-	-	-
Sb	1500,0	0,1575	220	0,792	240	0,864
B	-	-	200	0,72	900	3,24
Cr	74	0,00777	60,4	0,21744	10	0,036
Cu	760	0,0798	140	0,504	60	0,216
Zn	8100	0,8505	7100	25,56	700	2,52
Ni	98	0,01029	40	0,144	80	0,288
Mn	-	-	90	0,324	140	0,504
Hg	0,2	0,000021	-	-	-	-
Co	60	0,0063	70	0,252	30,2	0,10872
Sn	120	0,0126	-	-	0,2	0,00072
Mo	-	-	504	1,8144	150	0,54
Al	-	-	1800	6,48	1420	5,112
Li	-	-	40	0,144	34100	122,76
Analysis						
pH	9,1		2,6-2,8		7,3-7,7	
Conductivity	760 mS/m		2,6 mS/m		750 mS/m	

In the tool, the user can choose for each scenario the time of extinguishment. So if the extinguishment starts before it was conducted in the experiment the amounts of toxicants founded in the water will be smaller. To adapt the amounts to the scenario it was decided to scale them to the HRR (the scaling factor is described in the HRR part).

Finally, the gases analysis in E-Tox 1 study also gave the total amount of PAHs and Particles which are scaled using the same factor as for the run-off water data.

4.2 Guideline values for water quality

The tool uses international guidelines values for Aquatic Life and for Drinking Water to compare it to the amounts of pollutants founded in the water and thus determine the distance to contaminate a well and the needed dilution to have harmless concentrations of toxicant in groundwaters and surface water. In the actual version of the tool the guidelines values mostly come from US and Swedish guidelines. But in this version, a comparison of various international guidelines values was conducted and the possibility to choose its origin in the users' scenarios was added.

In the following table, you can see the different guidelines chosen to be implemented in the tool. The chart showing all the values and their comparison is disponible in Appendix A.

Table 5: Origin of the guideline values implemented in the tool

Country	Organisation	Reference
Sweden	Livsmedelsverket (National Food Agency regulations) Naturvårdsverket (Swedish Environmental Protection Agency)	[47], [48]
United States	United States Environmental Protection Agency (USEPA)	[49]–[51]
Canada	Public Health Agency of Canada Canadian Council of Ministers of the Environment (CCME)	[52], [53]
Australia	Australian and New Zealand Environment and Conservation Council	[54]–[57]
Europe	European Parliament	[58]
World	World Health Organisation (WHO)	[59]

It was also decided to add another choice for the user which was named the “mix” choice. This choice is the compilation of the most restrictive guideline values founded in the selection of origins, for each species. It represents a “worst case scenario”.

4.3 ERA calculations

ERA calculations rely on the run-off water analysis results and on the guidelines values. In the new version of the tool the same method was used for the three new vehicles using the new data. Plus, the previous calculations were updated (with the new guideline values).

4.4 LCA data

The aim of this study is also to update the tool’s LCA data using a new method. Indeed, the Scarcity method was chosen as it could assess the foam, but all the results are given in UPB, which is a unit who is hard to understand and compare to other quantities.

Therefore a new method was chosen on SimaPro: the ReCiPe 2016 Midpoint (H) V1.06 / World (2010) H. It was used to calculate the new LCA data on the impact of the response (responder’s vehicles), the smoke emitted by the fire, the soil restoration, the replacement of blanket and extinguisher, and finally the replacement and treatment of water. As results, various impact categories were given, on which four were selected to replace the previous ones. They are gathered in the next figure with their corresponding unit.

Table 6: The ERA's impact categories and their unit

Previous impact category	New impact category	Unit
Global Warming	Global warming	kg CO2 eq.
Air Pollution	Fine particulate matter formation	kg PM2.5 eq.
Water Pollution	Freshwater eutrophication	kg P eq.
Energy Resources	Mineral resource scarcity	kg Cu eq.
POP into Water	-	-

Five impact categories were selected (of the 18 existing, that you can see in Appendix B) in the actual version of the tool but POP into water, which is used to assess the impact of firefighting foam, was not replaced. This is because no equivalent exists in the ReCiPe method yet. For this reason it was decided that the new version of the Fire Impact Tool will not include firefighting foam as a tactical choice for the user. So all the calculations concerning the foam (additive) and its impact were suppressed of this version of the tool.

So all of the existing data were calculated again, using the new method and new calculations were made for the emissions of the three new vehicles. Note that some processes had to be changed and updated as a new version of the Ecoinvent database was released and some of the used processes became obsolete.

4.5 LCA Calculations

The LCA data was updated in the tool and data for the three new vehicles was implemented. The calculations were adapted so that the impact of all four vehicles could be assessed. In a same way as for the ERA calculation, adaptations of the tool were made.

4.6 Input sheet

While the option to use additive (firefighting foam) in the extinguishment scenarios was suppressed, this new version also includes the possibility to choose the type of vehicle burning, between two ICEVs and two EVs, and the origin of the guideline values used in the Environmental Risk Assessment. The user can choose these new scenario characteristics using drop-down list.

To make it more understandable for the user, some comments and precisions were added to the input sheet.

Finally, the result presented to the user in this sheet were updated. This can be seen in Appendix C.

5 Discussion

The characteristics used to get all the results from the following discussion scenarios are gathered in Appendix D.

5.1 Comparison between results from the previous and new version of the tool

The first comparison to make is between the previous and the new version of the tool. Choosing the same characteristics (for the extinguishment method), the same guideline values (the one used in the previous version) and the same vehicle: the ICEV 1; the results for the ERA calculations do not change, which is to be expected as both version uses the same calculations with the same input data. But differences can be observed in the LCA results, explained by the change of method used to calculate the impacts.

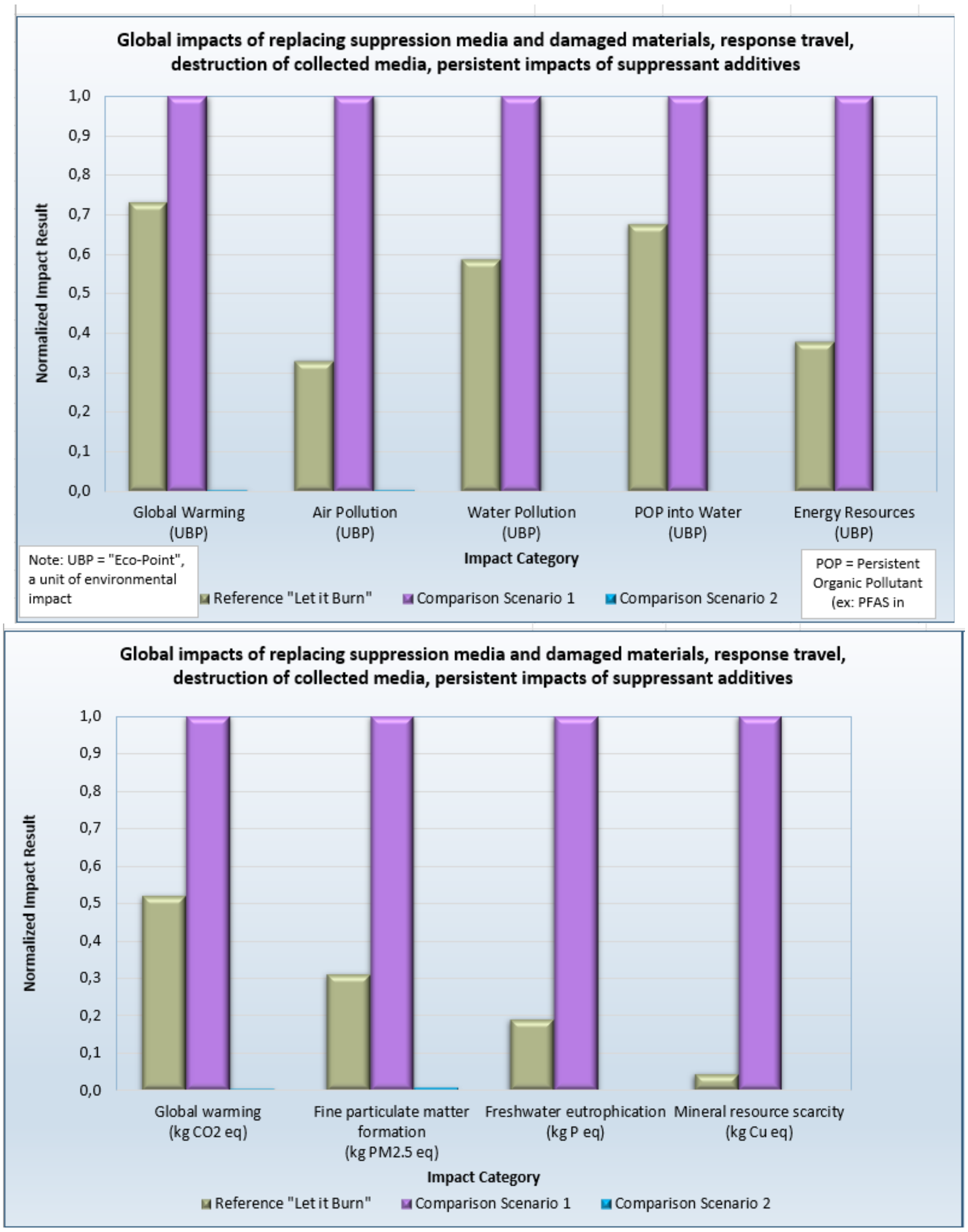

Figure 5: LCA results from both previous (above) and new (below) versions of the Tool

The main difference is obviously the impact categories, which are not the same anymore (only four in the new version while they were five in the previous version). The unit of each impact is also now different, making it harder to compare them.

We can observe that relatively to the “let it burn” scenario, the scenario from the new version seems to have a stronger impact on the environment for each impact categories. This important to note this, yet it just illustrates the difference between the versions and does not make any of the version better or worse to use. Indeed, the two versions of the tools will be used in different cases and the goal is not to compare results from both of them at the same time.

5.2 New version comparison

5.2.1 Guideline comparison for water quality

An important parameter for the comparison is the guideline values. Indeed, each country define levels to know the potential danger of a species for a given concentration. Depending on the origin of these guidelines, the critical species can vary and the importance of the estimated impact too. The choice of the guideline values origin does not have any effect on LCA results but only on ERA calculations. It has an impact on the critical species, which can vary when you change the origin of the guideline values but keep the rest of the characteristics the same. It also changes the required dilution needed to reach guideline values and the distance reached by the toxicants present in the surface water.

5.2.2 ICEV comparison

Comparing both ICEVs implemented in the tool is interesting as it allows us to have an idea of the differences in their calculated environmental impact. So here the two scenarios compared have the exact same characteristics, excepted for the type of car. ICEV 1 was used for the scenario 1 and ICEV A for the scenario 2.

We can imagine that as ICEV 1 is an older car, the pollution emitted when burning should be higher, but this is not what the results show. Indeed, we can observe that for the impact categories “global warming” and “Fine particulate matter formation”, it is ICEV 1 which has a lowest impact compared to ICEV A. Yet, for ERA criteria, ICEV A seems to have a higher impact, especially on groundwater, with a distance of contamination more than ten times higher. The amount of dilution water required to reach guideline values for surface water is about 20% higher for ICEV A.

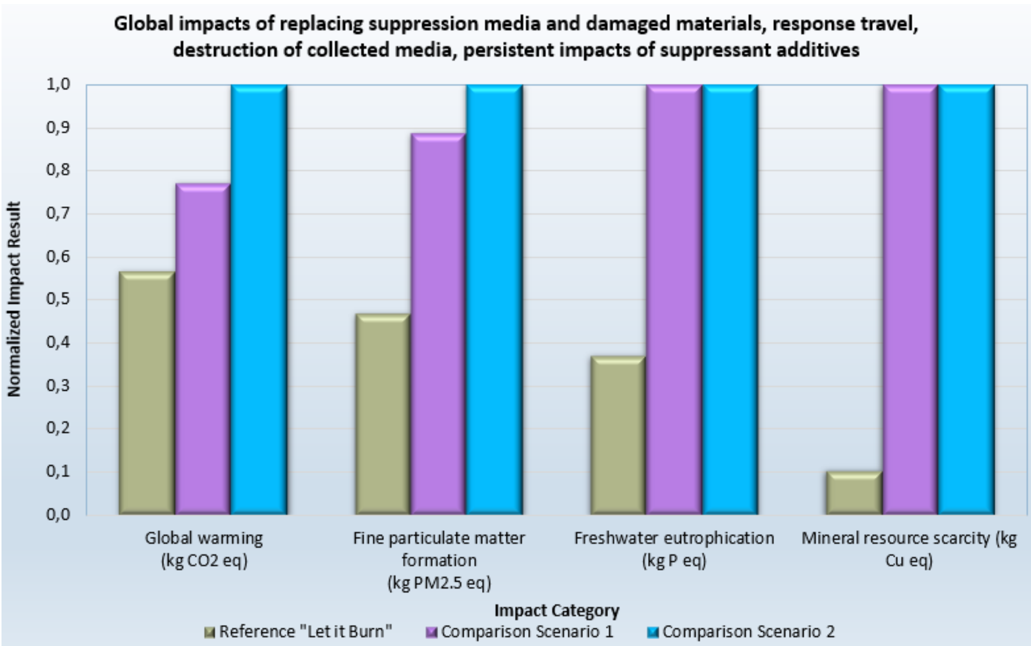

Figure 6: LCA results of the comparison between the two ICEVs (ICEV 1 on the left)

So ICEV 1 seems to have a higher local environmental impact while ICEV A has a higher global environmental impact. It is also interesting to observe that the critical species (the species which have the higher impact on the criteria) vary with the vehicle.

Table 7: Critical species for ICEV 1 and ICEV A

	Scenario 1	**Scenario 2**
Surface water *(Aquatic Life guidelines)*	Benzo(g,h,i)perylene	Zinc
Ground water *(Drinking water guideline)*	Benzo(a)pyrene	PAH

The differences observed here can be explained by the differences in the experimental conditions, setup and also by the differences between the two car models.

5.2.3 BEV comparison

One of the goals of this new version of the fire impact tool is to implement an EV fire model, and two different EVs were used to do it. The model and manufacturer for both cars is different so, as in the previous version, we can guess that the results will vary if two scenarios using the same characteristics for both EVs are compared.

Here only small differences can be found in the LCA results, with a slightly lower global warming impact for the BEV A. It also needs two times less dilution water than BEV B, but the critical species are the same. These small differences can be explained by the different models, but they are not that important because the amount of water needed to extinguish an EV fire is really important, so the impact is important, and the differences seems lower.

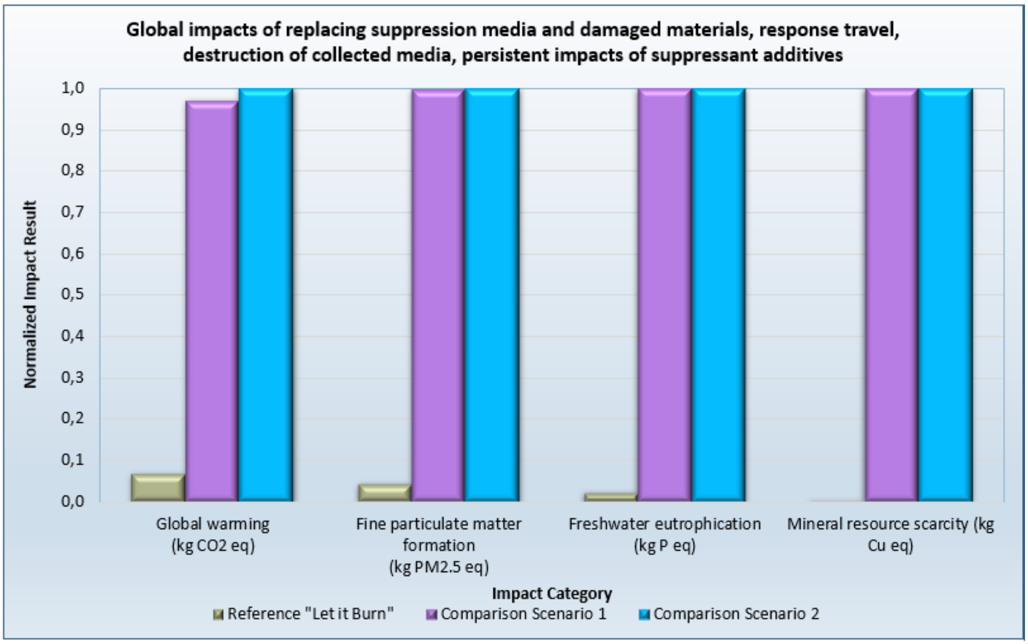

Figure 7: LCA results of the comparison between the two BEVs (BEV A on the left)

5.3 Comparison between ICEV and EV

5.3.1 Similar characteristics

Comparing the results for an EV and an ICEV is interesting, and it is possible here as ICEV A and BEV A are the same car model from the same manufacturer. Concerning the LCA results it is the EV which has a lower impact on global warming and air pollution, and both cars have a similar impact on water pollution and energy use. This is to be expected as the only difference between these cars is the type of energy used to power it. So an electric battery has a lower global impact than a conventional motor using diesel.

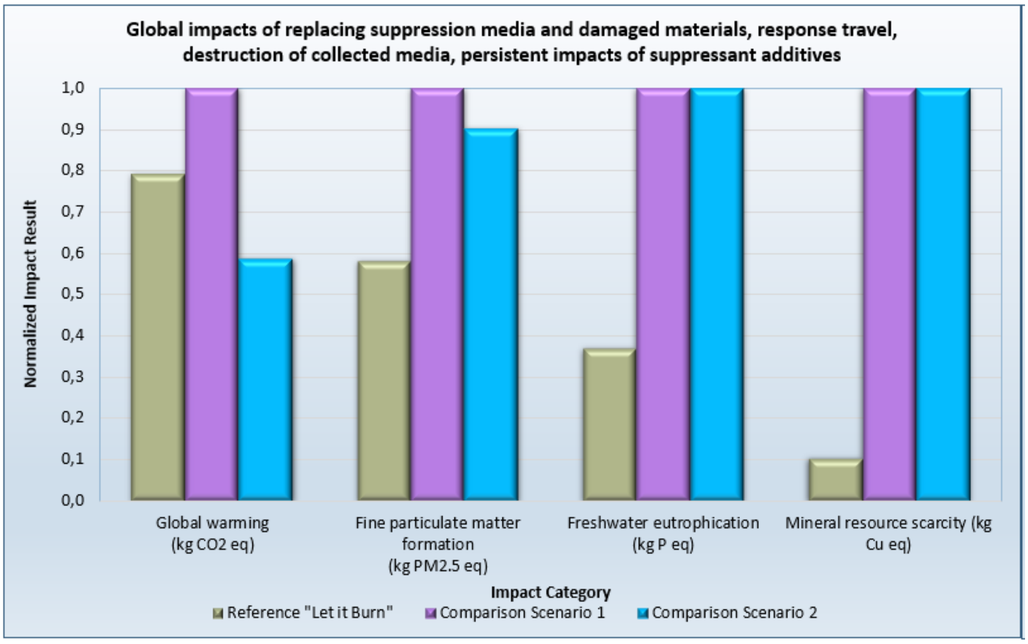

Figure 8: LCA results of the comparison between ICEV A (left) and BEV A (right)

For the ERA results we can observe that the impact on groundwater and surface water is way higher for the ICEV, meaning that components of the conventional motor are more harmful to the local environment.

Yet this comparison is not quite accurate as an EV fire require much more water to extinguish it than an ICEV fire. So the impact for the EVs should be higher and that is what we will see in the next part.

5.3.2 More realistic comparison

In the last comparison the EV had a lower global environment impact, but the comparison was not really realistic as 200L of water is not enough to extinguish an EV fire. Using more water on an ICEV fire does not make any sense so the comparison need to include this. Therefore in this new comparison between ICEV A and BEV A, all characteristics were kept similar excepted for the amount of water used, which was ten times superior for the EV. Thus, as we could have imagined, the global environmental impact of the EV was higher than the ICEV one. Due to the large amount of water used, the impact on the soil for the EV is really important compared to the ICEV. Yet the impact on local water stays more important for the ICEV as the factor used to estimate it is the amount of water used to dilute the pollutants (so here the large amount of water used allows a good dilution).

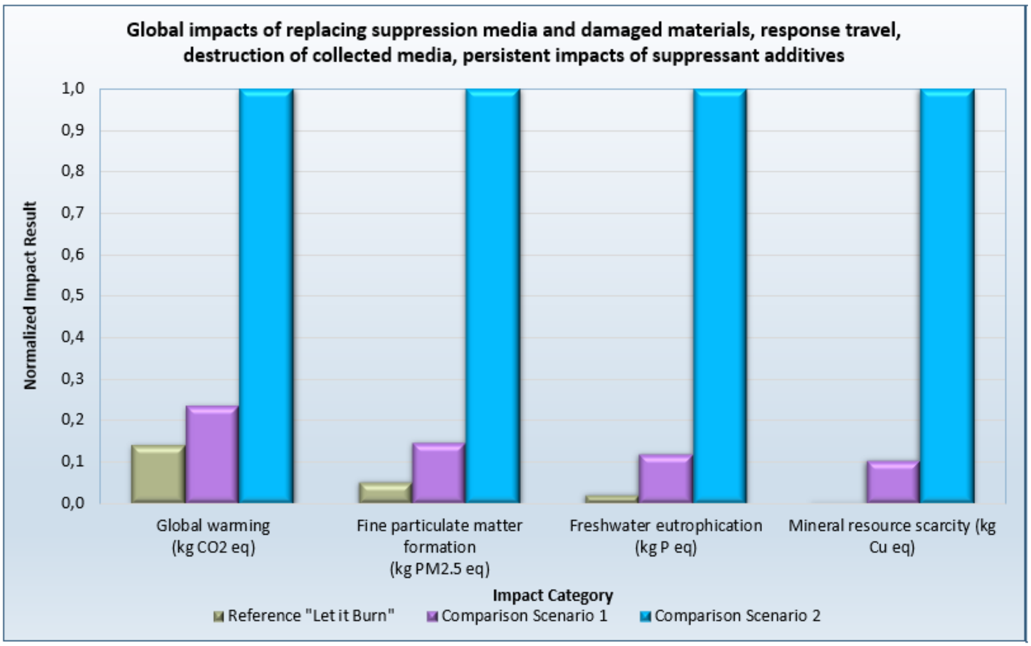

Figure 9: LCA results of the comparison between ICEV A (left) and BEV A (right)

5.4 Value of this work and future work

Adding a new fire scenario to the tool to make it more complete was planned during the creation of the first version of the tool. Yet, if it was not possible at this time, due to a lack of available data, it is now possible. Indeed, EVs are becoming more and more present on the roads all around the world so the risk of fire is increasing. Therefore, experiments are conducted to find proper extinguishment methods and to understand the impact of these fires. Meaning that new data is now available and can be used for a new version of the tool.

It is important to understand the impact of EV fires and to find the best way to respond to it. Firefighters have not yet enough knowledge to respond properly to EV fires, and this tool can be helpful during their training.

The implementation of new guideline values gave to the tool an international scope, enabling firefighters from different part of the world to benefit from it. Yet it is good to remind that every country has its own firefighting technics and technologies, which may not be included in the tool. This could be part of a future work if the tool will be aim to an international public.

Changing the LCA data allowed to access more understandable results as it uses more common units than UPB. Yet, this change restricted the possible choices for the user as foam needed to be supressed. So a future work could focus on adding foam impact assessment in the ReCiPe method (but this would represent a huge amount of work.

Finally, as the EV market is increasing rapidly these years, more research will probably be conducted, and full-scale fire experiment might be done. These experiments will be useful to gather new data and make the tool more accurate. Therefore the tool will have to be updated and upgraded in future years.

6 Conclusions

This new version of the Fire Impact Tool focuses on both ICEV and EV fire models and provides the possibility to compare them, choosing different extinguishment scenarios. To make it functional, adaptations and modifications were made.

Plus, data concerning the HRR, emissions to air and water, guideline values and LCA data on EV fires was implemented in this new version of the tool. The Battery Electric Vehicle technology is used as an example of EV in the tool, but future work might focus on other types of EVs (which were presented in this paper).

A new LCA method was used, allowing the study of global warming, air pollution, water pollution and energy resource consumption. As POP into water was not part of this method the tool was adapted, and foam was suppressed from the inputs of the tool.

With the increasing of the EV market, other experiment will be conducted, and new data will probably be available in the future, so the tool will have to be updated. New firefighting tactics might also be developed and could be interesting to implement in the tool.

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Appendix A – Guideline Comparison Sheet

	Swedish Environmental Protection Agency (Naturvårdsverket)		Swedish National Food Agency (Livsmedelsverkets författningssamling)		United State Environmental Protection Agency		Canadian Council of Minister of Environment	
	Guideline values **Aquatic Life** (mg/L)	Guideline values **Drinking Water** (mg/L)	Guideline values / (mg/L)	Guideline values **Drinking Water** (mg/L)	Guideline values **Aquatic Life** (mg/L)	Guideline values **Human Health** (mg/L)	Guideline values **Aquatic Life** (mg/L)	Guideline values **Drinking Water** (mg/L)
PAHs								
Naphtalene							0,0011	
Acenaphtylene								
Acenaphtene						0,07	0,0058	
Fluorene						0,05	0,003	
Phenantrene							0,0004	
Anthracene						0,3	0,000012	
Benzo(e)pyrene								
Dibenso(ah) anthracene						0,00000012		
Pyrene						0,02	0,000025	
Benzo [a] anthracene						0,0000012	0,000018	
Chrysene						0,00012		
Fluoranthene						0,02	0,00004	
Benzo(b+k)fluoranthene						0,0000012		
Benzo(a)pyrene				0,00001		0,00000012	0,000015	0,00004
Indeno(1,2,3-cd)pyrene						0,0000012		
Benzo(g,h,i)perylene								
PAH				0,0001				
Metals								
Cd				0,005	0,00072		0,00009	0,007
Pb				0,01	0,0025		0,0025	0,005
As				0,01	0,15	0,000018	0,005	0,01
Sb				0,01		0,0056		0,006
B				1,5			1,5	5
Cr	0,003	0,05		0,05	0,011		0,001	0,05
Cu	0,004	0,02		2		1,3	0,00041	2
Zn	0,008	3			0,12	7,4	0,007	
Ni				0,02	0,052	0,61		
Mn						0,05	0,43	
Hg				0,001	0,00077		0,000026	0,001
Co							0,001	
Ba						1		2
Sn								
Mo							0,073	
Al							0,17	2,9
Li								

	Australian National Health and Medical Research Council		European Parliament		World Health Organisation		Personalisation ("Mix") Most conservative values			
	Guideline values **Aquatic Ecosystem** (mg/L)	Guideline values **Drinking Water** (mg/L)	Guideline values **Aquatic Environment** (mg/L)	Guideline values **Drinking Water** (mg/L)	Guideline values / (mg/L)	Guideline values **Drinking Water** (mg/L)	Guideline values **Aquatic Life** (mg/L)		Guideline values **Drinking Water** (mg/L)	
PAHs										
Naphtalene	0,016		0,0024				0,0011	Canada		
Acenaphtylene										
Acenaphtene							0,0058	Canada	0,07	USA
Fluorene							0,003	Canada	0,05	USA
Phenantrene							0,0004	Canada		
Anthracene	0,0004		0,0001				0,000012	Canada	0,3	USA
Benzo(e)pyrene										
Dibenso(ah) anthracene									0,00000012	USA
Pyrene							0,000025	Canada	0,02	USA
Benzo [a] anthracene							0,000018	Canada	0,0000012	USA
Chrysene									0,00012	USA
Fluoranthene	0,0014		0,0001				0,00004	Canada	0,02	USA
Benzo(b+k)fluoranthene			0,000003				0,000003	Europe	0,0000012	USA
Benzo(a)pyrene	0,0001	0,00001	0,00005	0,00001		0,0007	0,000015	Canada	0,00000012	USA
Indeno(1,2,3-cd)pyrene			0,000002				0,000002	Europe	0,0000012	USA
Benzo(g,h,i)perylene			0,000002				0,000002	Europe		
PAH				0,0001					0,0001	Sweden
Metals										
Cd	0,0002	0,002	0,00008	0,005		0,003	0,00008	Europe	0,002	Australia
Pb	0,0034	0,01	0,0072	0,005		0,01	0,0025	***USA***	0,005	***Canada***
As	0,001	0,01		0,01		0,01	0,001	Australia	0,000018	USA
Sb		0,003		0,01		0,02			0,003	Australia
B	0,94	4		1,5		2,4	0,94	Australia	1,5	Sweden
Cr	0,001	0,05		0,025		0,05	0,001	***Canada***	0,025	Europe
Cu	0,0014	2		2		2	0,00041	Canada	1,3	USA
Zn	0,008	3					0,007	Canada	3	Australia
Ni	0,011	0,02	0,02	0,02		0,07	0,011	Australia	0,02	***Sweden***
Mn	1,9	0,5		0,05		0,08	0,43	Canada	0,05	***USA***
Hg	0,0006	0,001	0,00005	0,001		0,006	0,000026	Canada	0,001	Sweden
Co							0,001	Canada		
Ba		2				1,3			1	USA
Sn										
Mo		0,05					0,073	Canada	0,05	Australia
Al	0,055	0,2		0,2		0,1	0,055	Australia	0,1	WHO
Li										

Table of all the values collected in the various international guidelines

USA
USEPA = United States Environmental Protection Agency AWQC = Ambient Water Quality Criteria (given in µg/L) for: -***Human Health Criteria*** : https://www.epa.gov/wqc/human-health-water-quality-criteria-and-methods-toxics Human health AWQC for toxic pollutants are necessary to protect any designated uses related to ingestion of water and ingestion of aquatic organisms. These uses can include, but are not limited to, recreation in and on the water, consumption of fish or shellfish (including consumption associated with fishing or shellfish harvesting), and protection of drinking water supplies. EPA considers the following two primary pathways of human exposure to pollutants present in a particular water body when deriving human health 304(a) AWQC: (1) direct ingestion of drinking water obtained from the water body and (2) consumption of fish or shellfish obtained from the water body. (Update of Human Health Ambient Water Quality Criteria 2015) → Human Health for the consumption of **Water + Organism** (not Organism Only) (most of the values from 2015 but also others between 1980 and 2002) -***Aquatic Life Criteria*** : https://www.epa.gov/wqc/aquatic-life-water-quality-resources EPA bases aquatic life criteria on how much of a chemical can be present in surface water before it is likely to harm plant and animal life. EPA designs aquatic life criteria to protect both freshwater and saltwater organisms from short-term and long-term exposure. → **Freshwater** (not Saltwater), **CCC** = Criterion Continuous Concentration = Chronic (not CMC = " Maximum " = Acute)

Example of comment present on the Guideline Comparison Sheet, explaining how the values were selected.

Cd						
Surface water	SWEDEN	USA	CANADA	AUSTRALIA	EUROPE	WHO
SWEDEN		/	/	/	/	/
USA	/		0,125	0,277777778	0,111111111	/
CANADA	/	8		2,222222222	0,888888889	/
AUSTRALIA	/	3,6	0,45		0,4	/
EUROPE	/	9	1,125	2,5		/
WHO	/	/	/	/	/	

Cd						
Groundwater	SWEDEN	USA	CANADA	AUSTRALIA	EUROPE	WHO
SWEDEN		/	1,4	0,4	1	0,6
USA	/		/	/	/	/
CANADA	0,714285714	/		0,285714286	0,714285714	0,428571429
AUSTRALIA	2,5	/	3,5		2,5	1,5
EUROPE	1	/	1,4	0,4		0,6
WHO	1,666666667	/	2,333333333	0,666666667	1,666666667	

Pb						
Surface water	SWEDEN	USA	CANADA	AUSTRALIA	EUROPE	WHO
SWEDEN		/	/	/	/	/
USA	/		1	1,36	2,88	/
CANADA	/	1		1,36	2,88	/
AUSTRALIA	/	0,735294118	0,735294118		2,117647059	/
EUROPE	/	0,347222222	0,347222222	0,472222222		/
WHO	/	/	/	/	/	

Pb						
Groundwater	SWEDEN	USA	CANADA	AUSTRALIA	EUROPE	WHO
SWEDEN		/	0,5	1	0,5	1
USA	/		/	/	/	/
CANADA	2	/		2	1	2
AUSTRALIA	1	/	0,5		0,5	1
EUROPE	2	/	1	2		2
WHO	1	/	0,5	1	0,5	

Example of comparison made for each species between every countries/organisations to verify the coherence of all the selected values.

Appendix B – The impact categories of the ReCiPe midpoint (H) method

Impact category	Unit
Global warming*	kg CO2 eq.
Stratospheric ozone depletion	kg CFC11 eq.
Ionizing radiation	kBq Co-60 eq.
Ozone formation, Human health	kg NOx eq.
Fine particulate matter formation*	kg PM2.5 eq.
Ozone formation, Terrestrial ecosystems	kg NOx eq.
Terrestrial acidification	kg SO2 eq.
Freshwater eutrophication*	kg P eq.
Marine eutrophication	kg N eq.
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m2a crop eq.
Mineral resource scarcity*	kg Cu eq.
Fossil resource scarcity	kg oil eq.
Water consumption	m3

*The categories painted in green are the one used in the tool.

Appendix C – Modified Input Sheet

VEHICLE Fire Input	**Comparison Scenario 1**	**Comparison Scenario 2**	**Defaults**
Start of intervention (min)	15	15	15
Type of vehicle	ICEV 1	BEV A	ICEV 1
Origin of the Guideline Values	Europe	Mix	WHO
Water used (liters)	200	200	200
Additive concentrate used (liters)	0	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture	Unknown
Handheld fire extinguisher used?	No	No	Yes
Blanket used?	No	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	2	2
Number of light vehicles responding (like an ambulance)	1	1	1
Number of passenger vehicles responding (car, SUV)	1	1	1
Average 1-way distance vehicles travel (km)	15	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%	50
% of fire water run-off that goes to water treatment plant (WTP)	30%	30%	<< 25 % each
% of fire water run-off collected & destroyed	0%	0%	
% of fire water run-off that goes to soil	35%	35%	
% of fire water run-off that goes to surface water	35%	35%	

Vehicle type	Propulsion energy	SOC	Cell type	Model	Year	Reference
ICEV 1	Diesel	-	-	Medium class	1998	A. Lönnermark and P. Blomqvist, 'Emissions from an automobile fire', Chemosphere, vol. 62, no. 7, pp. 1043–1056, Feb. 2006
ICEV A	Diesel, 44l	-	-	Full-size Van	2011	O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, and J. Anderson, 'Toxic Gases from Fire in Electric Vehicles', 2020.
BEV A	40 kWh	80%	Pouch, NMC	Full-size Van	2019	
BEV B	24 kWh	80%	Prismatic, NMC	Small family car	2016	

(Table present in the comments of the Input sheet)

Appendix D – Characteristics of the Discussion Scenarios

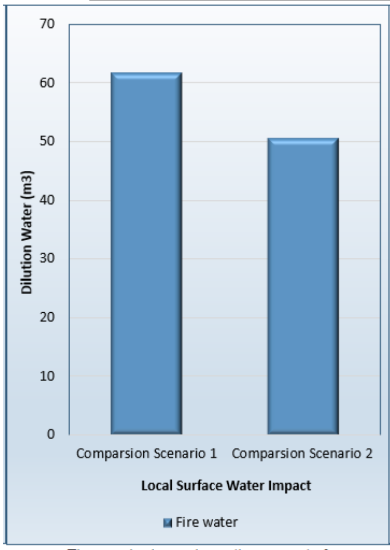
5.1

VEHICLE Fire Input	Comparison Scenario 1
Start of intervention (min)	15
Water used (liters)	500
Additive concentrate used (liters)	0
Type of additive used (select from dropdown list at right)	Unknown mixture
Handheld fire extinguisher used?	No
Blanket used?	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2
Number of light vehicles responding (like an ambulance)	1
Number of passenger vehicles responding (car, SUV)	1
Average 1-way distance vehicles travel (km)	15
% of suppressant (water + additive) that goes to the environment	50%
% of fire water run-off that goes to water treatment plant (WTP)	25%
% of fire water run-off collected & destroyed	25%
% of fire water run-off that goes to soil	25%
% of fire water run-off that goes to surface water	25%

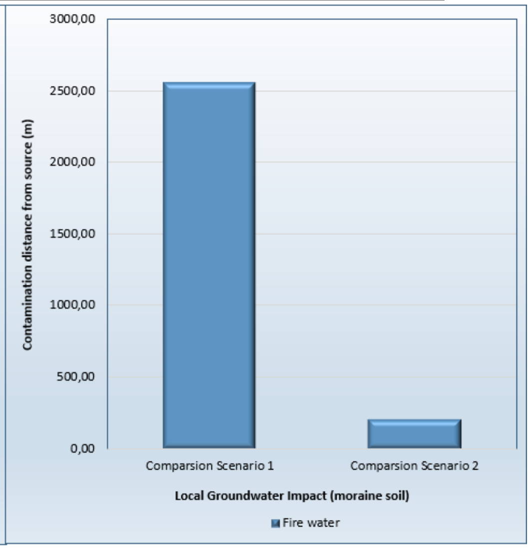
VEHICLE Fire Input	Comparison Scenario 1
Start of intervention (min)	15
Type of vehicle	ICEV 1
Origin of the Guideline Values	Sweden
Water used (liters)	500
Additive concentrate used (liters)	0
Type of additive used (select from dropdown list at right)	Unknown mixture
Handheld fire extinguisher used?	No
Blanket used?	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2
Number of light vehicles responding (like an ambulance)	1
Number of passenger vehicles responding (car, SUV)	1
Average 1-way distance vehicles travel (km)	15
% of suppressant (water + additive) that goes to the environment	50%
% of fire water run-off that goes to water treatment plant (WTP)	25%
% of fire water run-off collected & destroyed	25%
% of fire water run-off that goes to soil	25%
% of fire water run-off that goes to surface water	25%

5.2.2

VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2
Start of intervention (min)	15	15
Type of vehicle	ICEV 1	ICEV A
Origin of the Guideline Values	Mix	Mix
Water used (liters)	200	200
Additive concentrate used (liters)	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture
Handheld fire extinguisher used?	No	No
Blanket used?	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	2
Number of light vehicles responding (like an ambulance)	1	1
Number of passenger vehicles responding (car, SUV)	1	1
Average 1-way distance vehicles travel (km)	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	0%	0%
% of fire water run-off collected & destroyed	0%	0%
% of fire water run-off that goes to soil	50%	50%
% of fire water run-off that goes to surface water	50%	50%



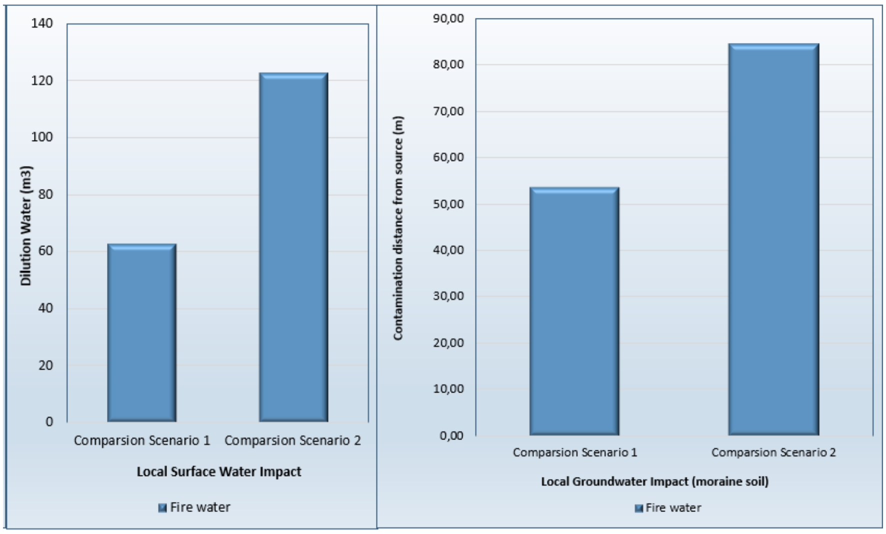
The graph above shows the amount of water required to dilute the run-off (fire water and additive) to acceptable surface water limit values.



The graph above shows the distance (m) required to reduce groundwater contamination to an acceptable level for drinking water.

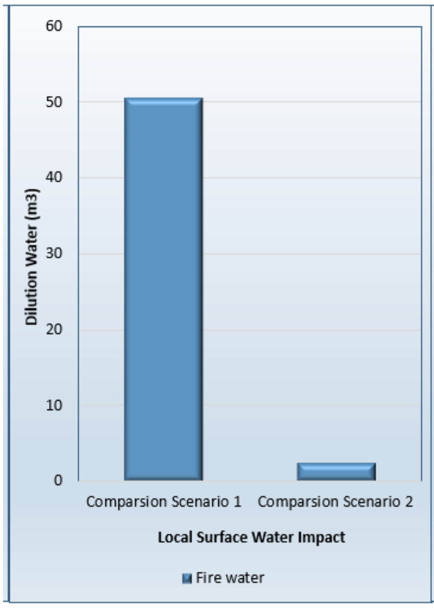
5.2.3

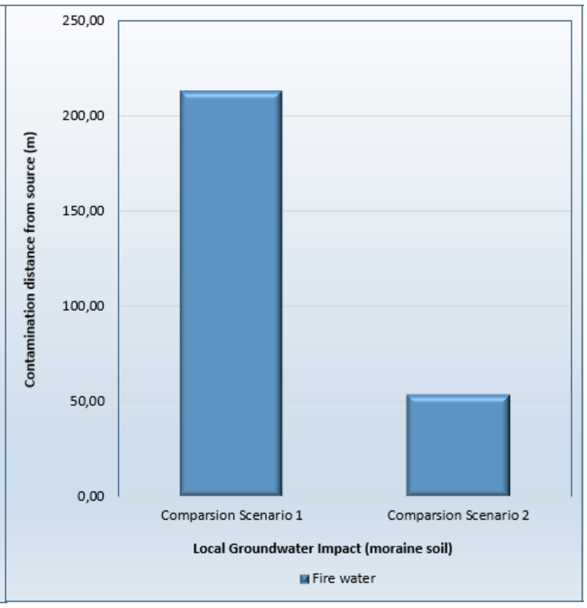
VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2
Start of intervention (min)	15	15
Type of vehicle	BEV A	BEV B
Origin of the Guideline Values	Mix	Mix
Water used (liters)	5000	5000
Additive concentrate used (liters)	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture
Handheld fire extinguisher used?	No	No
Blanket used?	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	2
Number of light vehicles responding (like an ambulance)	1	1
Number of passenger vehicles responding (car, SUV)	1	1
Average 1-way distance vehicles travel (km)	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	0%	0%
% of fire water run-off collected & destroyed	0%	0%
% of fire water run-off that goes to soil	50%	50%
% of fire water run-off that goes to surface water	50%	50%



5.3.1

VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2
Start of intervention (min)	15	15
Type of vehicle	ICEV A	BEV A
Origin of the Guideline Values	Mix	Mix
Water used (liters)	200	200
Additive concentrate used (liters)	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture
Handheld fire extinguisher used?	No	No
Blanket used?	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	2
Number of light vehicles responding (like an ambulance)	1	1
Number of passenger vehicles responding (car, SUV)	1	1
Average 1-way distance vehicles travel (km)	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	0%	0%
% of fire water run-off collected & destroyed	0%	0%
% of fire water run-off that goes to soil	50%	50%
% of fire water run-off that goes to surface water	50%	50%





5.3.2

VEHICLE Fire Input	Comparison Scenario 1	Comparison Scenario 2
Start of intervention (min)	15	15
Type of vehicle	ICEV A	BEV A
Origin of the Guideline Values	Mix	Mix
Water used (liters)	500	5000
Additive concentrate used (liters)	0	0
Type of additive used (select from dropdown list at right)	Unknown mixture	Unknown mixture
Handheld fire extinguisher used?	No	No
Blanket used?	No	No
Number of heavy vehicles responding (engine, tanker, ladder, etc...)	2	2
Number of light vehicles responding (like an ambulance)	1	1
Number of passenger vehicles responding (car, SUV)	1	1
Average 1-way distance vehicles travel (km)	15	15
% of suppressant (water + additive) that goes to the environment	50%	50%
% of fire water run-off that goes to water treatment plant (WTP)	0%	0%
% of fire water run-off collected & destroyed	0%	0%
% of fire water run-off that goes to soil	50%	50%
% of fire water run-off that goes to surface water	50%	50%