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Comparative risk assessment of diesel and BEV construction machinery

Case study for the Rogfast tunnel construction project

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Comparative risk assessment of diesel and BEV construction machinery

Case study for the Rogfast tunnel construction project

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Abbreviations

Abbreviation	Definition
BEV	Battery Electric Vehicle
BMS	Battery Management System
CAN	Controller Area Network
HCN	Hydrogen cyanide
HRR	Heat release rate
HSE	Health Safety and Environment
ICE	Internal Combustion Engine
IDLH	Immediate Dangerous to Life or Health limit
ISC	Internal Short Circuit
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate Oxide
NCA	Nickel Cobalt Aluminium Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
OEM	Original Equipment Manufacturer
PHRR	Peak Heat Release Rate
PMSM	Permanent Magnet Synchronous Motor
SoC	State of Charge
SVV	The Norwegian Public Roads Administration (Statens Vegvesen)

1. Introduction

Statens Vegvesen has asked Rambøll to carry out an analysis of the relative safety risk of performing tunnel construction work activities using Battery Electric Vehicles (BEV). The risk should be compared to the risk using ordinary Internal Combustion Engines (ICEs) as e.g., diesel driven equipment. It has been agreed with Statens Vegvesen to use the Rogfast tunnel construction project as an example, but that the identified risks should be described in a way such that they also could be evaluated for other future tunnel construction projects. In the present report, a number of activities are described to obtain the risk analysis results. This includes the following:

- Description of background information
- Risk identification
- Risk modelling
- Risk results
- Conclusion and recommendations

The scope and structure of the study is addressed further in the following.

1.1 Scope of the study

The overall purpose of the study is to address a concern related to allowing and/or requiring use of BEVs in tunnel construction works. With a goal of progressing construction works in a more sustainable direction, the use of BEVs seems to be a natural choice. Such vehicles are considered cleaner and may even be powered by green electricity, whereas diesel vehicles use fossile fuels and produce significant amounts of CO_2 emissions. Moreover, diesel vehicles and combustion engines have a much higher level of noise and vibrations compared to electric engines.

On the other hand, use of BEVs may represent a safety risk, and stories of fires in batteries, emission of toxic gasses, explosions, etc. flourish in the media. Introducing such potential hazards into confined tunnel construction works may therefore result in a significant safety risk.

The scope of the study is therefore to address this concern. Hence, identify relevant scenarios, and assess the magnitude of this perceived safety risk compared to the more well-known and currently accepted risks involved with the use of diesel-powered construction equipment.

The study therefore involves a thorough analysis of available battery technologies as well as an investigation of fire frequencies and potential consequences.

1.2 Reading guide

The study is structured with an initial part describing the specific Rogfast tunnel project as well as tunnel construction activities in general. Another essential part of the background for the risk assessment is a thorough description of current battery technologies as well as typical ventilation and emergency responses.

This background information was used as the primary foundation to conduct a workshop where scenarios involving incidents with BEVs and diesel vehicles were discussed and evaluated. Initial evaluation of scenarios on the workshop was in turn used to structure a more detailed evaluation of the tunnel fire scenarios.

Finally, the risk modelling of the fire scenarios is combined with the background information and assessments done through the risk workshop into final conclusions and recommendations.

Figure 1-1 below shows details of these activities and where in the report they are described.

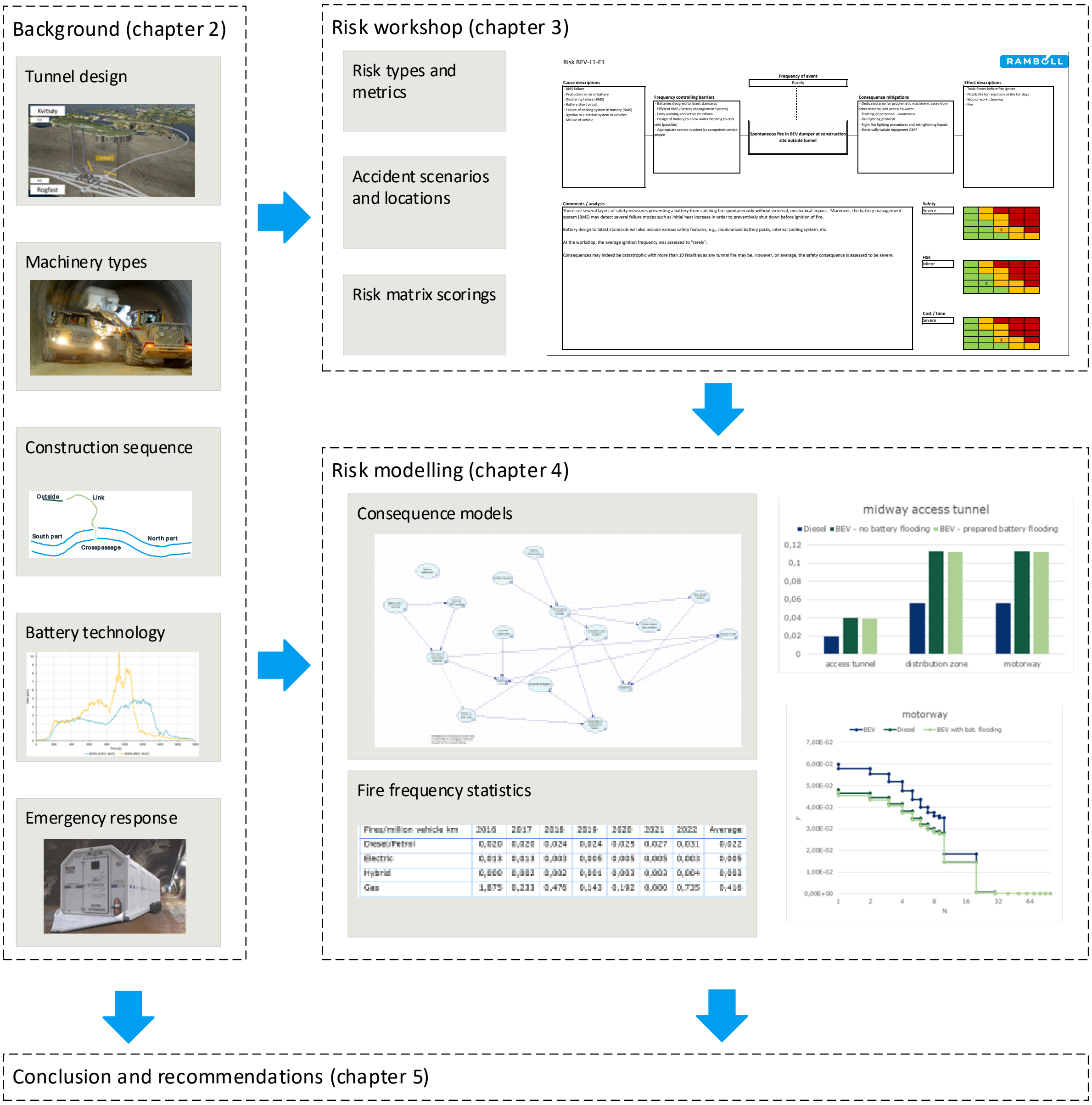

Figure 1-1 Overview of risk analysis activities.

2. Background information

2.1 The Rogfast tunnel

The construction of the Rogfast tunnel is chosen as an example case as basis for the risk analysis for BEVs versus ordinary diesel vehicles. For this reason, in the following a short description of the Rogfast tunnel project is given below.

The project is located in the southwestern part of Norway near Stavanger. The main project covers contracts E02, E03 and E04 as shown in Figure 2-1. These sections cover 21km, 16km, and 19km of motorway tunnels, respectively. The Rogfast tunnel will go from Harestad in the south and Bokn in the north. The smaller contracts E11, E13, and E15 cover access tunnels, while the contracts E02, E03 and E04 cover the motorway stretches. Some of the contracts also include ventilation systems.

Figure 2-1. Outline of the Rogfast tunnel project with main contracts E02, E03, E04, E11, E13, and E15, ref. /1/.

The present analysis focuses on the central tunnel contract E02, which will be constructed using the E15 tunnel as entry and exit point.

The E15 tunnel is planned as a bi-directional single tube tunnel leading traffic up from/down to a distribution area from which the E02 motorway tunnel is constructed simultaneously towards north and south. The E02 motorway stretch is planned as two parallel tunnel tubes with each two lanes. An illustration of the access tunnel, the distribution zone, ventilation shafts, and the motorway tunnels is seen in Figure 2-2.

In practice, the access tunnel E15 is finished prior to constructing the motorway tunnels covered by E02. However, for the comparative risk analysis of risk involved with using BEV versus diesel powered vehicles for transport of material from the excavations, both the construction of the access tunnel E15, as well as the motorway tunnels E02 are considered. Moreover, the ventilation towers seen in Figure 2-2 are first constructed as part of E02 and are therefore not available during the main part of the excavations for both tunnel systems. All material from the excavations of E02 and E15 shall be transported by dumpers through the access tunnel to Kvitsøy.

The construction of the motorway tunnel as part of E02 will include construction of cross passages for each 250 m allowing for access from one motorway tunnel tube to the other. The cross passages will be made progressively along with the construction of the tunnel tubes and ensures that the maximum distance for getting access to the adjacent tunnel will be 250 m.

Figure 2-2. Illustration of access tunnel on Kvitsøy, distribution zone, ventilation towers, and motorway tunnels, ref. /1/.

2.2 Typical construction phase activities

When undertaking rock tunnelling using the drill and blast technique, several construction phases are repeated cyclically. Each phase requires specialised equipment, typically in the form of adapted vehicles. This section provides an overview of the construction phases as well as the applied equipment used in each phase of the construction cycle.

The construction cycle phases are shown in Figure 2-3 and each stage is briefly described in section 2.2.1 to 2.2.8. As a rough estimation, the cycle might be repeated once or twice a day, depending on tunnel sizes, and rock composition.

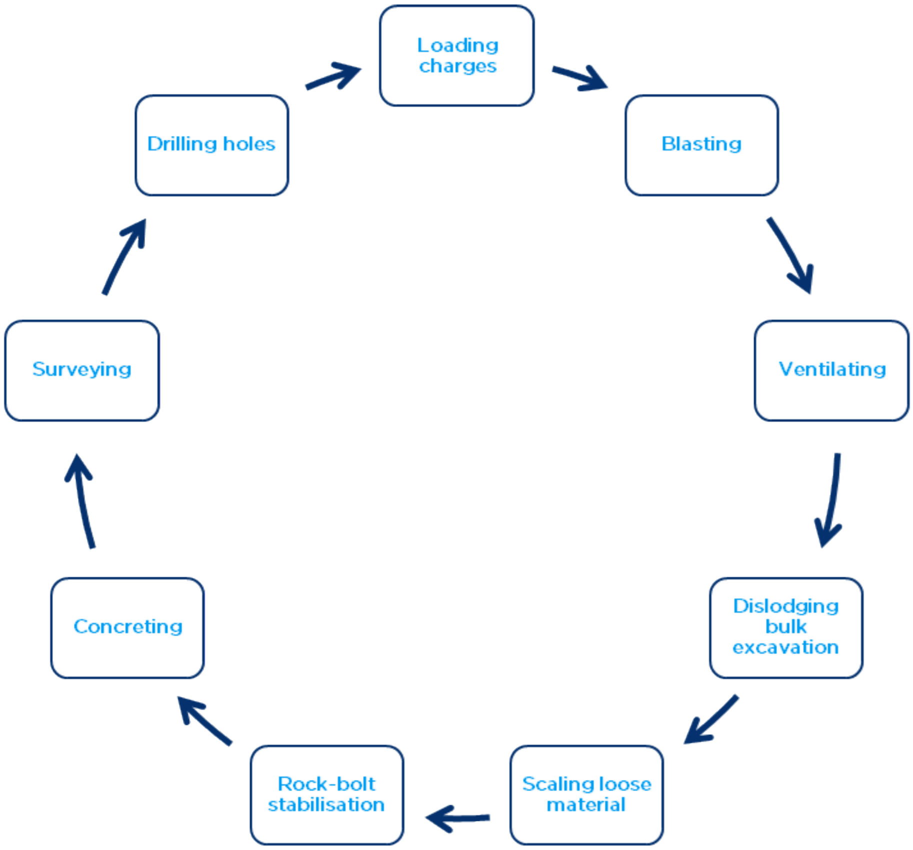

Figure 2-3 Drill and blast tunnelling construction phases, from ref. /2/.

2.2.1 Drilling

The jumbo drilling rig bores holes in the tunnel face. The holes are designed in a specific pattern determined in advance for the rock section specifically taking the local conditions into consideration.

A jumbo is used to drill holes into the rock face. The jumbo is usually equipped with three drilling arms and an operator tower. Typically, the machinery is electrically driven, and powered by an electric cable from the surface. The jumbo operates with the assistance of a hose that supplies water to the drills and the drills themselves can be pneumatic or hydraulic. As the drilling takes place, water is used to flush out the broken rock fragments from the holes.

2.2.2 Loading explosives

The holes are filled with explosives. Explosives are connected to one another and to a detonator.

The cherry picker is a hydraulic crane with a platform used to reach high spaces. It enables personnel to fill drilled holes with explosives and conduct face investigations.

2.2.3 Blasting

Once the zone is secured, the blast master triggers the blasting machine which is programmed to blast the explosives in a specific sequence and in specific intervals.

2.2.4 Ventilating

Blasting of rock causes dispersing clouds of dust and blast fumes which must be removed before personal can re-enter the tunnel face. This is done by using air ducts constructed and suspended from the tunnel ceiling.

2.2.5 Dislodging and spoil transport

The cracked rock from the blasting is removed from the area around the rock face. Once the loose pieces of rock are removed, the rubble material is loaded on dumpers and transported to the landfill. The time needed for this step is dependent on the following:

- Amount of blasted rock
- Dumper capacity
- Dumper quantity
- Tunnel length and distance to the landfill.

Material, or rubble, is loaded onto the dumper trucks using wheel loaders. The dumper trucks transport the rubble from the tunnel excavation face to the surface and an external landfill or disposal site. Both machineries are available with battery driven drivetrain.

2.2.6 Scale

To ensure that the working area is safe for further activities, loose rock, that has not been fully released during blasting, is removed. This work is performed using a scaling rig. The excavated material from this phase is also transported out of the tunnel as described in section 2.2.5.

The tunnel scaling rig is utilized to remove loose rock fragments that remain after the blasting process. This step allows the clearance of any remaining loose rock and ensures the safety of the operatives before the next phase commences.

2.2.7 Bolting

The tunnel face is inspected and mapped from a distance. The quality of the rock (tunnel walls and ceiling) informs the requirements for the bolting rig in terms of:

- Number of rock bolts
- Bolt spacing
- Bolt length to be installed in the tunnel lining to secure it.

After adding the bolts, a shotcrete spraying machine is used to apply a sufficient amount of shotcrete to the tunnel lining. Following this the tunnel is considered secure and personal can enter the previous "danger" zone.

Bolting rigs, or mining bolters, are specialized mining machines designed for drilling holes and installation of safety bolts in the roof and walls of underground mining excavations. These can be supplied with electric cable or with battery electrically driven drivetrain.

Shotcrete equipment enables the high-pressure projection of a rapidly setting concrete mixture that provides additional support to the tunnel structure. It consists of a variety of components including a concrete mixer, additive pump, compressor, sprayer arm, and control system. The equipment is typically mounted on a motorized chassis and is available with battery-electric drive train.

2.2.8 Surveying

The tunnel is surveyed to capture the final contour and ensure the alignment is correct. After surveying the work moves forward, and the cycle repeats with drilling of the next part as describe in 2.2.1.

2.2.9 Summary of construction phases and equipment

The equipment used in the tunnel is typically all available as either diesel powered, or electrically powered, and more recently with battery-electric power supply, rather than cable-supply from the surface. Most of the vehicles only shunt to and from the working face as needed, and when not in use, they are located nearby within the tunnel complex.

The activities of the dumpers are a little different as they move material out of the tunnel. Therefore, they shuttle from the surface to the tunnel face and back, removing excavated material. This risk assessment only focus on the dumper usage in the tunnel, and the risk associated with either diesel powered to BEV powered dumpers.

2.3 Specific dumper activities

Dumpers are used in the dislodging and spoil transport phase (section 2.2.5). Todays practise is to use diesel powered machinery for all dumper activities. As this risk assessment aims to investigate the difference in the risk level when changing the BEV driven dumpers, the following sections describe the two different dumper types.

2.3.1 BEV Dumpers

This section presents the example of an EV-converted Komatsu HD605-7 (the "eDumper") and its specifications. The eDumper is a heavy-duty electric vehicle designed for efficient and sustainable operations in mining. The eDumpers dimensions are 5.4m width, 4.8m height, and 10.2m length. Given these dimensions the eDumper can only pass each other at local widenings (passing locations) in the E15 tunnel. The vehicle has a loading capacity of 40m^3, and the vehicle weighs 55 tonnes (120 tonnes fully loaded).

The eDumper is equipped with a substantial 600 kWh battery capacity. It has a climbing ability of 14%, even fully loaded, and can reach a top speed of 40 km/h. A notable feature is its regenerative braking system, which allows for the recapture and utilization of excess energy. This feature enables the eDumper to recharge while travelling downhill or when braking. The service intervals for the dump truck are approximately every 4,000 hours for the hydraulic oil.

An example of a smaller BEV dumper is the Propel EV 45 CED. The vehicles dimensions are width 2.8m, a height of 3.65m and 8.3m length, allowing two Propel dumpers to pass each other in the E15 tunnel at Kvitsøy. The vehicle has a volumetric loading capacity of 18m^3, and it own self-weight is 45 tonnes.

The Propel dumper is equipped with a Permanent Magnet Synchronous Motor (PMSM) type motor with a maximum power of 350 kW and a maximum torque of 2800 Nm. Its power is supplied by a lithium-ion battery pack with a capacity of 163 kWh. The vehicle is equipped with a regenerative braking system, which allows for the recapture and utilization of excess energy when braking or travelling downhill. The service intervals for the dump truck are approximately every 4,000 hours for the hydraulic oil.

2.3.2 Charging of BEV dumpers

BEV dumpers can be charged in different ways depending on the location and the specific dumper constraints. Charging options can be mainly divided into slow and fast charging. Slow charging is where the vehicle can be connected to the AC-grid using existing industrial plugs. Fast charging happens with a charging station that can be installed at the site. The vehicle in this case is connected to the station using DC plugs, and the charging station does the conversion from the DC to the AC. Additionally, to avoid situations where the dumper is discharged on the way, moveable chargers are also available.

An alternative option to battery charging is battery swapping. Battery swapping is an electric vehicle technology that allows BEVs to quickly exchange a discharged battery pack with a fully charged battery pack, as an alternative to recharging the vehicle via a charging station. An example of this is VIK TH550B Battery electric truck. For this truck it is stated that the battery pack can be swapped in about three minutes, and the operator can remain in the cabin during the process. In the development of the SANDVIK TH550B electrical truck special attention was given to arc flash risk reduction during the design. This was done to protect technicians from the hazards of high voltage, ref. /3/.

2.3.3 Diesel Dumpers

This section presents an example of the Komatsu HD605-7 diesel dumper truck. The Komatsu dumper trucks dimensions are 5.4m width, 4.8m height, and 10.2m length. Given these dimensions the Komatsu dumper truck can only pass each other at local widenings (passing locations) in the E15 tunnel. The truck has a capacity of 40 m3 for spoil transport.

The Komatsu dumper truck has an engine power of 575 kW (771 HP) and is equipped with a 780-litre fuel tank. The average fuel consumption of the HD605-7 ranges from 30-35 litres per 100 kilometres, depending on various factors such as load weight, terrain, and operating conditions. The service intervals for the truck are approximately 500 hours for engine oil and 4,000 hours for hydraulic oil.

This section presents an example of the Volvo FMX 440 diesel dumper. The Volvo dumper trucks dimensions are 2.6 m width, 3.5 m height and 10 m length allowing two of the Volvo dumpers to passage each other in the E15 tunnel at Kvitsøy. The vehicle has a loading capacity of 13.5 tonnes. The vehicle weights 31 tonnes empty and 44 tonnes when loaded.

The Volvo FMX 440 has a 8x2 axle configuration and is a diesel dump truck with an engine power of 328kW (440HP). The truck is equipped with a 315-liter fuel tank with an average consumption of 55 litres per 100 km. The service intervals for the truck are approximately 500 hours for engine oil and 4,000 hours for hydraulic oil.

2.3.4 Rockfast tunnel dumper distance/time calculations

The following calculates present an estimation of the time spent in the tunnel as well as the total distance covered by dumpers throughout the construction process. The calculations were performed under the assumption of subdividing the tunnel into five sections as indicated in Figure 2-4.

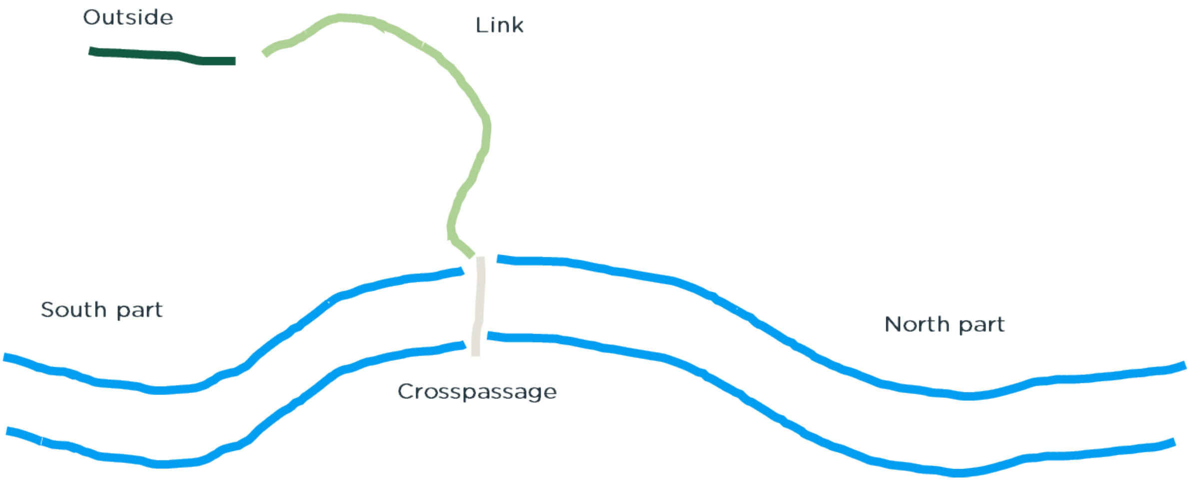

Figure 2-4 Tunnel sections division.

In the calculations it is conditioned that the link section will be excavated first and afterwards the northern and southern tunnel tubes will be excavated simultaneously, with two tubes in each direction. Assumptions made for the tunnel dimensions are given in Table 2-1, while assumed parameters for blasting and progress are listed in Table 2-2.

Table 2-1 Tunnel parameters.

Tunnel parameter		Unit	Comment
Tunnel Diameter	10.5	m	Assumption
Length of link section (E15)	3,750	m	
Grade of link section (E15)	7	%	
Length of motorway towards south (E02)	4,700	m	
Grade of motoreway towards sourth	1	%	
Length ig motorway towards north (E02)	3,700	m	
Grade og motorway towards north	4.5	%	
Length of cross passage	200	m	
Distance from tunnel exit to unloading place	2,000	m	Assumption

Table 2-2 Blasting and advance parameters.

Blasting and advance		Unit	
Advance advance per week	25	m	
Unloading time	10	min	Assumption
Loading time	10	min	Assumption

Calculations were performed to compare large and small dumpers based on their capacity and speed parameters listed in Table 2-3. The capacities and speed limits apply universally to both diesel and BEV dumpers.

Table 2-3 Dumper parameters applied, valid for both BEV and diesel dumpers.

	Capacity m3	Average speed linking route km/h	Average speed south km/h	Average speed north km/h	Average speed to unloading site km/h
Large dumper BEV/Diesel	40	10	10	10	40
Small dumper BEV/Diesel	18	10	10	10	40

The dumpers are assumed to make a round trip from a depot 2000 m away from the tunnel entrance to the face of the tunnel excavation. At the tunnel face the dumpers are filled up with the excavated material and they then return to the depot where they dump off the material.

As the excavation progresses the distance of the round trip increases throughout the duration of the project. Based on this the overall number of km required to be driven to remove the excavated material for the full project has been calculated. One scenario considers using the large capacity dumper, the other considers using the small capacity dumper. The calculation also considers which part of the tunnel (Figure 2-4) the dumper drives, such that the probabilistic risk modelling can take the location of the truck into account. The results are presented in Table 2-4.

Table 2-4 Total distance driven by dumpers given per section.

	Large dumper (BEV/Diesel) km	Small dumper (BEV/Diesel) km
Outside	71,500	160,800
Link section (E15)	315,600	710,200
Cross passage	1,100	2,400
Motorway stretch south (E02)	99,500	223,900
Motorway stretch north (E02)	61,700	138,900
Total	**549,400**	**1,236,200**

The calculations show that the majority of the distance is driven in the link tunnel (E15) from Kvitsøy to the cross passage.

The total driven time in each section is based on the total distance driven, as shown above, the project and are calculated based on the travelling speed assumptions given in Table 2-3. The number of hours does not include the estimated time spent standing still when loading and unloading the vehicle.

Table 2-5 Total driven time per section

	Large dumper (BEV/Diesel) hours	Small dumper (BEV/Diesel) hours
Outside	1,800	4,000
Link section (E15)	31,600	71,000
Cross passage	100	200
Motorway stretch south (E02)	9,900	22,400
Motorway stretch north (E02)	6,200	13,900
Total	**49,600**	**111,600**

The calculated time spent overall for the vehicle in each section at a standstill while off-loading or loading material is given in Table 2-6.

Table 2-6 Total time spent loading/unloading in project in each section.

	Large dumper (BEV/Diesel) hours	**Small dumper (BEV/Diesel)** hours
Outside (unloading)	7,700	17,300
Link section (E15) (loading)	1,400	3,100
Motorway stretch south (E02) (loading)	3,500	7,900
Motorway stretch north (E02) (loading)	2,800	6,200
Total	**15,400**	**34,500**

The overall number of passes required in the cross passage during transportation throughout the duration of the project is shown in Table 2-7. Only trucks carrying material from the north and south tunnel tubes (E02) furthest away from the link access tunnel are considered here. The vehicles in the north and south tunnel tubes closest to the link access tunnel are considered to drive straight from the tunnel tube and into the link tube without driving through the cross-passage. A trip from the depot outside, through the cross passage to the rock face and back again is counted as two passes.

Table 2-7 Total number of passages of the cross section.

	Large dumper (BEV/Diesel)	**Small dumper (BEV/Diesel)**
South	3,000	6,800
North	2,400	5,400
Total	**5,400**	**12,200**

The following table summarizes he proportion of time spent for a dumper truck in each section of the tunnel during the duration of the project. This includes the times spent loading the vehicle at the rock face and off-loading the vehicle outside. This only considers the time that the vehicle is operational, i.e., either driving or being loaded or off-loaded with material, it does not include considerations of any storage or parking of the vehicle over night for example. As the speed for the large and small truck vehicle is considered to be the same, the proportion of time spent in each section is the same for smaller and larger trucks.

Table 2-8 Amount of the total dumper time distributed to the different areas

Location	**%**
Outside	14,58%
Link section (E15)	50,75%
Crosspassage	0,17%
Motorway stretch south (E02)	20,73%
Motorway stretch north (E02)	13,77%

2.4 Battery technology

A battery converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation reduction (redox) reaction. A battery consists of one or more electrochemical cells, which are composed of two electrodes—a cathode and an anode—separated by an electrolyte. Batteries come in many shapes and sizes, Figure 2-5 shows two examples of how battery cells are connected to form a module and the entire battery pack. The first example considers prismatic cells and the second cylindrical cells.

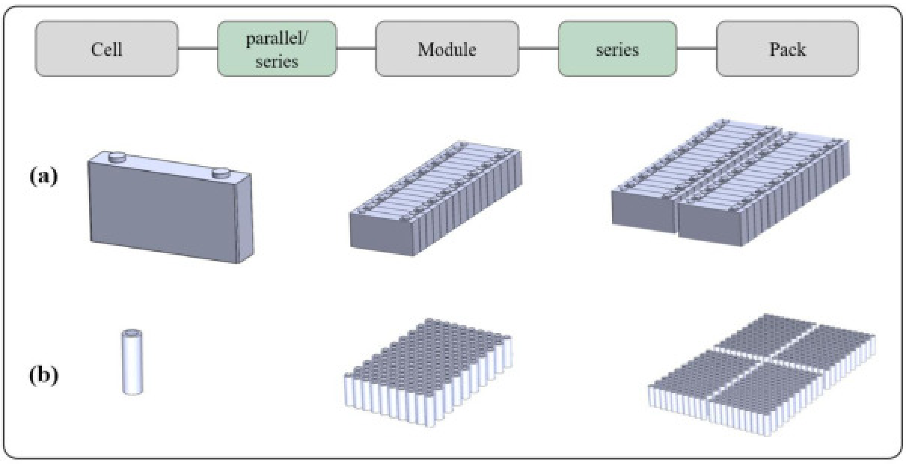

Figure 2-5. Examples of battery packs indicating two constructions with (a) prismatic and (b) cylindrical cells, ref. /6/.

There are two main kinds of batteries. The single-use batteries (e.g., an alkaline battery) are the ones that can be used only once and then they are discarded as the electrode materials are irreversibly changed during discharge. Rechargeable batteries are those batteries that can be discharged and recharged multiple times using an applied electric current. These batteries can e.g. be lead-acid and lithium-ion batteries. The rechargeable batteries are the most interesting for transport application and thus are those which are considered in this study.

2.4.1 Battery chemistry characteristics

The most prevalent battery chemistry in 2022 was lithium Nickel Manganese Cobalt Oxide (NMC), which held a majority market share of 60%. The second most used technology was Lithium Iron Phosphate (LFP), with a market share of slightly less than 30%, while Nickel Cobalt Aluminium Oxide (NCA) accounted for about 8% of the market share, ref. /7/.

Companies developing Li-ion batteries account for 60% of early-stage venture capital investments in the battery segment in the period 2018-2022, but new chemistry technologies are on the rise, both lithium- and non-lithium-based. Li-ion batteries are expected to have the largest market share for automotive and transport, ref. /7/.

Li-ion batteries can be summarized into the following chemistry categories:

- NMC (Lithium Nickel Manganese Cobalt Oxide)
- NCA (Lithium Nickel Cobalt Aluminum Oxide)
- LCO (Lithium Cobalt Oxide)
- LFP (Lithium Iron Phosphate)
- LTO (Lithium Titanate Oxide).

Each chemistry has advantages and disadvantages and is more appropriate for one or another application. For example, NMC batteries are widely used in electric vehicles (EVs) and energy storage systems due to their high energy density, long cycle life, and relatively low cost. NMC batteries have higher specific energy (energy per unit mass) and specific power (power per unit mass) compared to other batteries. On the other hand, LFP batteries are known for their long cycle life, high thermal stability, and safety. They are commonly used in applications that require high power output and safety. LFP batteries have a lower energy density than NMC and NCA batteries, ref. /8/. In terms of safety, LFP and LTO chemistries are considered safer than the NMC, NCA and LCO, ref. /8/. One reason for this is that NMC/NCA/LCO batteries can store more energy in a smaller volume and weight than LFP and LTO, why there is more possibility for energy release at these higher energy density chemistries. The advantage and disadvantages of the different battery chemistries are summarized in Figure 2-6.

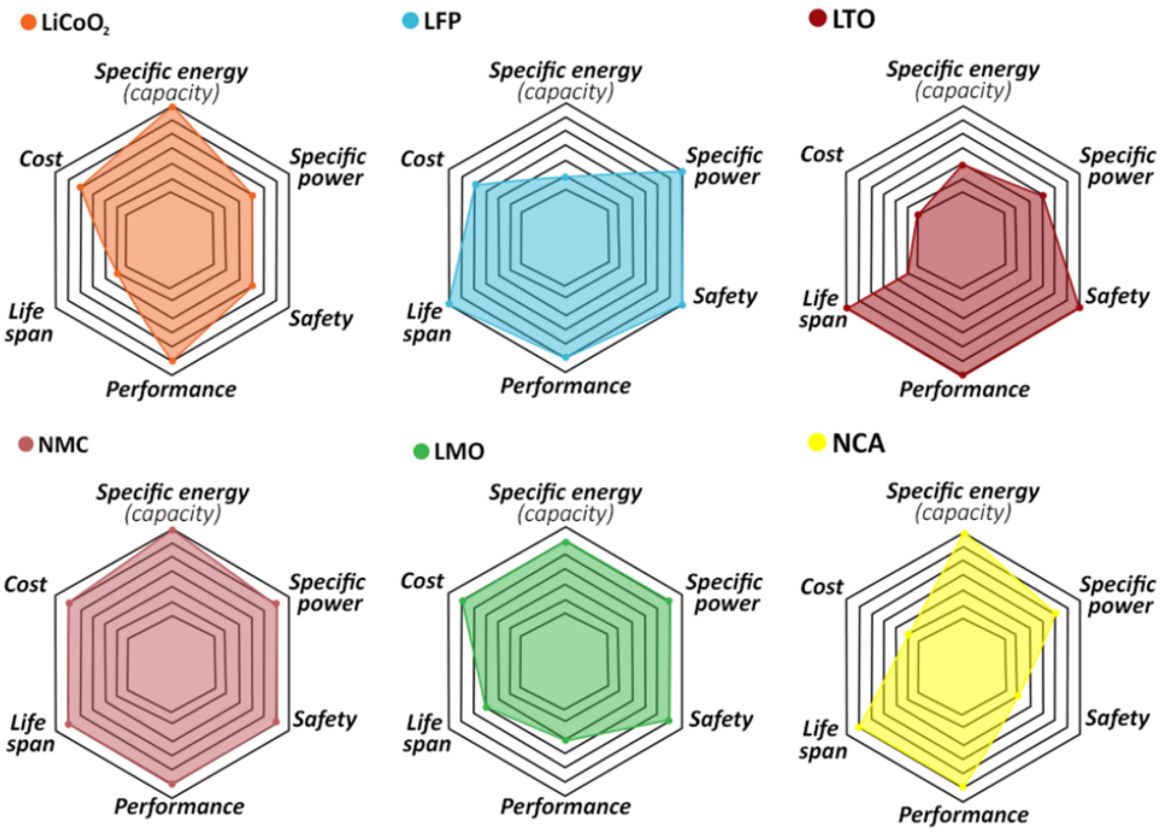

Figure 2-6 Comparison of different lithium-ion batteries, ref. /9/.

2.4.2 Battery management system

A battery management system (BMS) is an electronic control unit designed to monitor and manage the operation of rechargeable batteries. It is commonly used in various applications such as electric vehicles (EVs), hybrid electric vehicles (HEVs), renewable energy systems, portable electronic devices, etc. The primary function of a BMS is to ensure a safe and efficient operation of the battery pack.

The BMS performs several key tasks, as e.g.:

- Monitoring the energy level of the battery
- Safeguarding the battery pack from operating outside safe voltage limits
- Monitoring the battery temperature

Overall, a BMS plays a critical role in maximizing the battery performance, safety, and lifespan of rechargeable. Overall, the BMS ensures optimal utilization of battery capacity, protects against potential risks, and provides valuable insights into battery health and operation. As sketch of the BMS is shown in Figure 2-7.

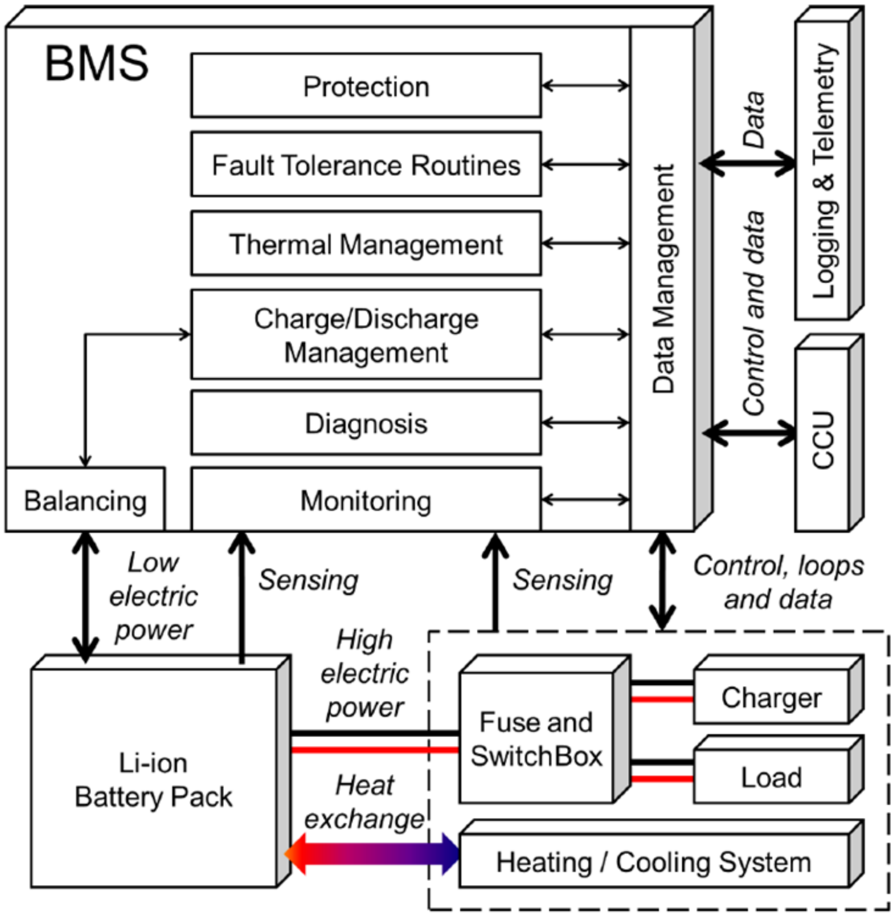

Figure 2-7 Overview of typical BMS functions and interfaces, ref. /10/.

2.4.3 Thermal Runaway

The phenomenon of thermal runaway is a significant risk factor for Li-ion cells, primarily caused by the materials used in their chemistry. This occurs when the battery heats up during use due to conditions as e.g., overload or adverse climate. The outcome of thermal runaway varies depending on the battery cell's level of charge and it can potentially result in inflammation or even an explosion of the Li-ion cell. Because cells are densely packed, thermal runaway of one cell is likely to propagate to neighbouring cells and eventually set the whole battery on fire, ref. /11/.

A representation of the process of the thermal runaway is provided in Figure 2-8.

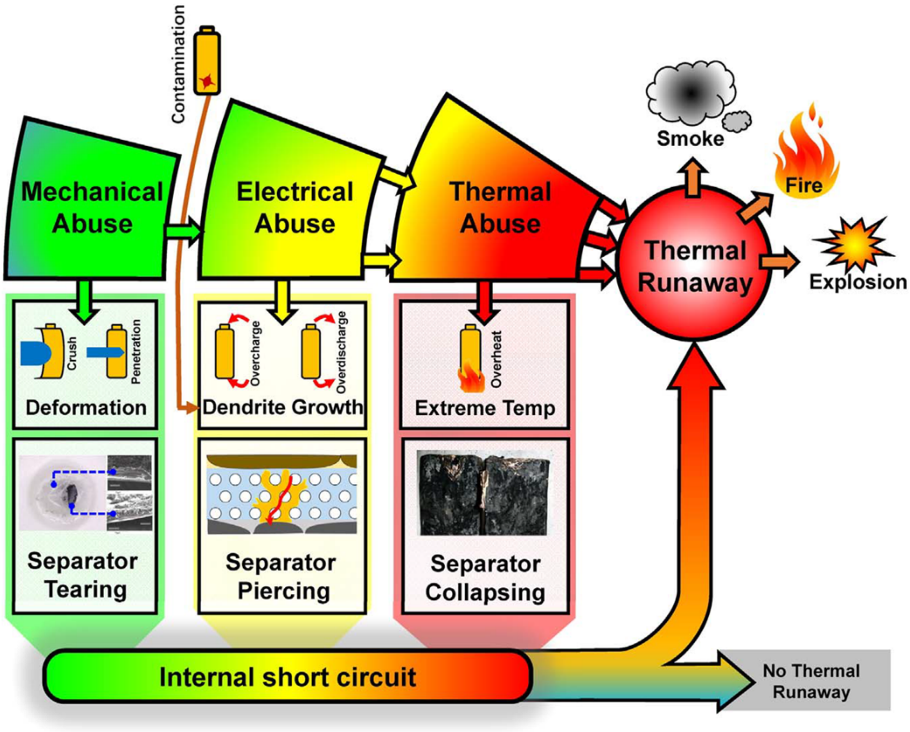

Figure 2-8 Internal Short Circuit (ISC), the most common feature of thermal runaway, ref. /11/.

In ref. /10/ it is described that the abuses leading to the thermal runaway can be divided into four categories:

1. Mechanical abuse is typically characterized by two common features, namely destructive deformation and displacement caused by applied forces. In the case of EVs, a typical scenario for mechanical abuse is a vehicle collision resulting in the crushing or penetration of the battery pack.
2. The electrical abuse can be caused by three different behaviours, namely external short circuit of the battery pack; overcharging; and over-discharge.
    - External short circuit can be caused by deformation during a car collision, water immersion, contamination with conductors, electric shock during maintenance, etc.
    - The failure of the BMS to stop the charging process before the upper voltage limit is an ordinary cause of overcharge abuse. Heat and gas generation are the two common characteristics during overcharge.
    - If the BMS fails to monitor the voltage of any individual cell, the cell with the lowest voltage will experience over discharge. It is generally inevitable to have voltage inconsistencies among the cells within a battery pack.
3. Thermal abuse: The thermal abuse is the direct cause of the battery thermal runaway.
4. Internal Short Circuit (ISC) occurs when the cathode and anode get into contact with each other due to the failure of the battery separator. Once the ISC is triggered, the electrochemical energy stored in the materials releases spontaneously with heat generation.

Comparing with the crush conditions, fierce ISC can be instantaneously triggered when penetration starts, thus the abuse condition of penetration is more severe than that of simple mechanical or electric abuse. In addition, the overcharge-induced thermal runaway can be harsher than other abuse conditions because excessive energy is filled into the battery during overcharge. Finally, the mechanism and potential hazards associated with over discharge abuse differ from other conditions, and their severity may be underestimated. In the event of over discharge, the cell with the lowest voltage in the battery pack can be forcefully discharged by the other cells connected in series. This causes abnormal heat generation within the over discharged cell.

2.4.4 Summary

Most used battery chemistries in the automotive sector are the NMC, LFP, and NCA. These have different characteristics, however, the LFP is the least subject to thermal runaways. Thermal runaways can be caused by different abuses: mechanical, electrical, and thermal. To avoid thermal runaway the BMS plays a crucial role in the battery operation, ensuring optimal utilization of battery capacity and protecting it from potential risks.

2.5 Environment and physical conditions from operating vehicles

2.5.1 Emissions during normal operation

Both diesel and BEVs dissipate heat, but the amount of heat dissipated depends on different factors such as the size of the engine, the efficiency of the cooling system, and the type of driving conditions. Diesel engines generally produce more heat than electric motors. This means that more energy from the fuel is converted into heat, which must be dissipated through the cooling system. EVs also generate heat through their motors and battery systems, but the amount of heat generated is generally lower than that of diesel engines.

Diesel engines have a thermal efficiency of around 30-50%, meaning that around 60% of the energy from the fuel is lost as heat, exhaust gas, water coolant and oil. In contrast, electric motors have an efficiency of around 80-90%, which means that only 10-20% of the energy input is lost as heat. In a BEV, the BMS regulates the temperature of the battery and the electric motor to prevent overheating, which can reduce the amount of heat emitted by the car. However, EVs can generate heat also during fast charging, which can cause the battery and charging cables to heat up. To mitigate this issue, many EVs have cooling systems built into their battery packs and charging systems. Diesel engines, on the other hand, typically have a more limited cooling system, which can lead to more heat being emitted by the engine and the exhaust system.

Apart from heat, diesel combustion engines produce several gases as by-products of their combustion process which are toxic to humans and can cause respiratory problems. These gasses include carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), sulphur dioxide (SO2), hydrocarbons (HC), and water. Modern diesel engines are designed to minimize the emissions of these gases using exhaust after-treatment systems such as diesel particle filters, selective catalytic reduction, and exhaust gas recirculation.

Emissions can also be produced by other vehicle components than internal combustion engines. Of special concern are non-exhaust particle emissions that consist of airborne particulate matter generated by the wearing down of brakes, clutches, tires, and road surfaces, as well as by the suspension of road dust, ref. /12/. However, non-exhaust particle emissions are also produced by EVs. Here, brake wear can be reduced compared to combustion engine vehicles using regenerative braking. Tire wear emissions, on the other hand, can be higher in EVs due to their heavier weight and higher wheel torque gradient.

2.5.2 Emissions during a fire

For an EV, once the onboard battery is involved in fire, there is a greater difficulty in suppressing EV fires than for diesel vehicles. This is because the burning battery pack inside the vehicle is inaccessible to externally applied suppressant and can re-ignite without sufficient cooling. As a result, an excessive amount of suppression agent is needed to cool the battery, extinguish the fire, and prevent reignition.

An important variable during a fire is the Peak Heat Release Rate (PHRR). The PHRR of a diesel car or EV can vary depending on several factors, such as the size of the fire, the type of fuel or battery, and the environmental conditions. Therefore, it is difficult to provide a definitive range of peak heat release rates. Studies have shown that the PHRR of a burning electric vehicle battery (passenger cars) reported values in the range of 4 to 7 MW, whereas PHRR of a burning diesel car range from about 2 to 11 MW, ref. /13/. In ref. /14/ two BEVs are compared with two diesel vehicles from the same manufacturer. The vehicles were exposed to the same external heat stress, and showed similar PHRR, for the BEVs the PHRR was 4.2-4.7 MW whereas for the diesel cars it was 4.8-6.1 MW. These values are all examples for passenger cars. Since the PHRR depends on the tank and battery sizes, a dumper tank or battery is larger and as such the PHRR are likely to be higher.

Figure 2-9 shows the Heat Release Rate (HRR) for two identically built SUVs: one propelled by a diesel-fuelled ICE; and the other fuelled by an 80 kWh NMC battery at 100% state of charge (SOC), ref. /15/. In both cases, the fire ignition took place in the rear seats. The battery was not involved in the fire for the first 800 s. While fire suppression was ongoing a thermal runaway was triggered in the battery by injecting a saline solution into the battery casing. This resulted in a very quick thermal reaction of the whole battery and in an extremely quick increase of the HRR within a short time.

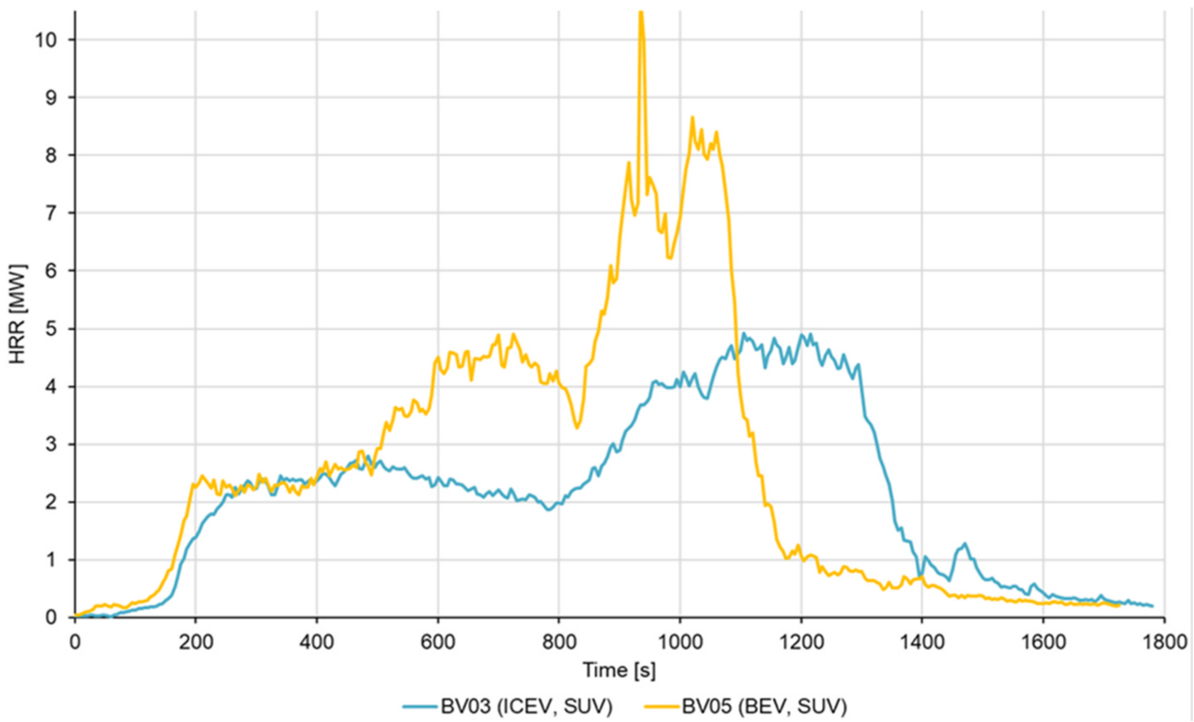

Figure 2-9 HHR for two almost identical SUVs, ICE and BEV with 80kWh NMC battery, from ref. /15/.

Figure 2-10 show the normalized heating rate for various battery chemistries as a function of the temperature. From this the impact of cell chemistry on the thermal runaway is evident. Chemistries like LCO and NCA have a higher normalized heating rate, which means that they are also more dangerous, whereas LFP technology is less subject to thermal runaways.

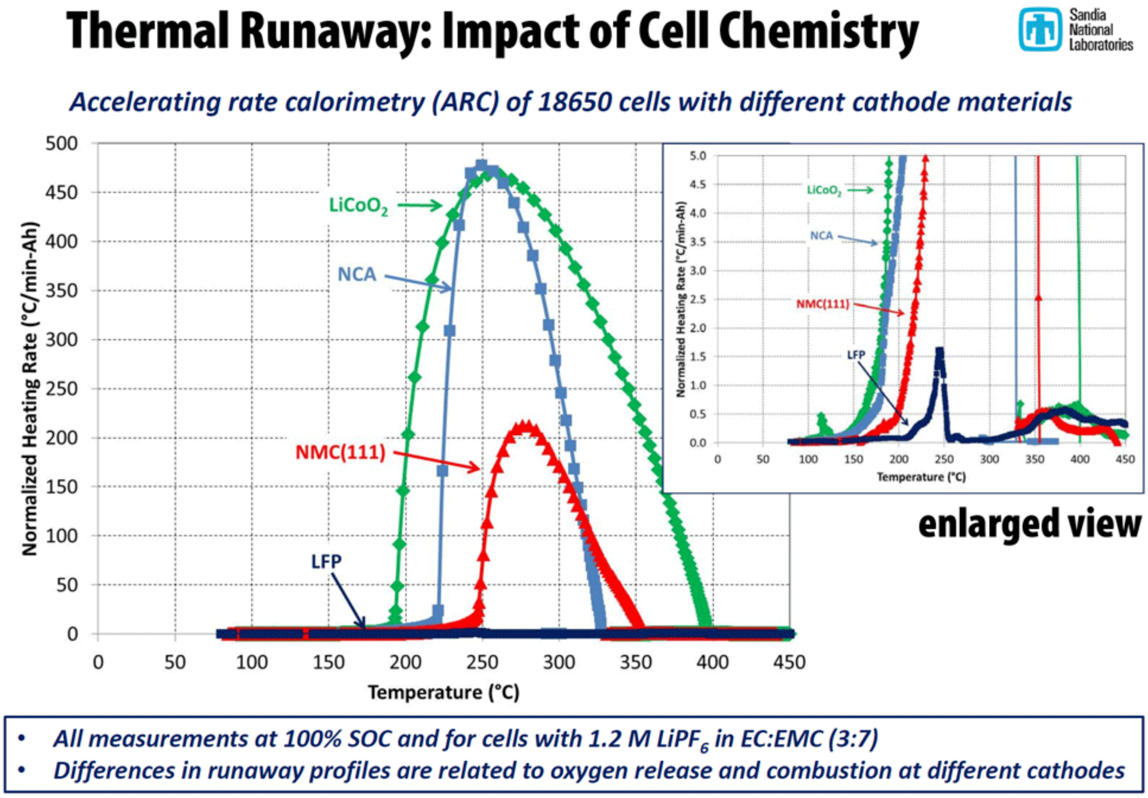

Figure 2-10 Thermal Runaway Li-ion - Impact of cell chemistry, ref. /10/.

The order of thermal stability among different battery chemistries is LFP > NMC111 > NCA > LCO. LFP is found to be the most stable cathode material during thermal runaway process, ref. /10/.

In ref. /16/, the thermal behaviour of different battery chemistries is tested by heating up batteries in a canister. In terms of heat to failure of the batteries, the LFP battery required the most external heat before failure indicating the best thermal stability. The time to thermal runaway was found to 134-170 min, whereas the LTO battery type showed 114 min and finally the NMC chemistry 98-107 min, ref. /16/.

In ref. /14/ where two BEVs are compared with two diesel vehicles from the same manufacturer, the analysis of the combustion gases from car fires highlighted that the cumulative masses of CO2, CO, HC, NO, NO2, HCl (hydrochloric acid) and HCN (hydrogen cyanide) were similar for both types of vehicles. A significant quantity of Hydrofluoric acid (HF) was measured during both BEV and diesel vehicle fire tests. However, it was higher in cumulative mass terms for the EVs, due to the combustion of the Li-ion battery pack. In addition to HF, a significant quantity of toxic gases including CO and HCl was produced during the fire tests on both types of vehicles.

In contrast to the impact of HRR, the State of Charge (SoC) seems to have an inverse effect, lower SoC levels result in higher amounts of released HF. It should be noted, however, that due to the evaporation/combustion of the air conditioning coolant, HF also occurs in conventional vehicle fires, albeit at high concentrations of very short duration. However, in EVs concentration levels exceeding critical threshold values for human health were found only in the smoke layer at relatively large heights in the tunnel, ref. /15/.

Hydrogen fluoride solutions with concentrations above 20% can cause immediate pain upon contact with the skin, while solutions below 20% may not cause immediate pain but can still cause delayed serious injuries. It is important to note that the effects of HF absorption through the skin or inhalation-induced lung injury can be delayed for 2-3 days, ref. /17/.

In ref. /18/, LFP batteries in the range of a few kWh were investigated. The study shows that significant amounts of HF, ranging between 20 and 200 mg/Wh of nominal battery energy capacity, were detected from the burning of the battery. If extrapolated for large battery packs the amounts would be 2–20 kg for a 100 kWh battery system, as used for e.g., an electric vehicle. The Immediate Dangerous to Life or Health limit (IDLH) for HF is 0.025 g/m3. The release of HF from a Li-ion battery fire can therefore be a severe risk and an even greater risk in confined or semi-confined spaces, as in a tunnel system.

While similar amounts of combustion gases CO_2, CO, total hydrocarbons, NO, NO_2, HCl and HCN were generated by BEV and diesel vehicle fires, BEV fires produced about twice the amount of HF. Furthermore, some critical concentrations of the two heavy metals cobalt and manganese as well as lithium in the form of aerosols after combustion of NMC battery modules are also observed during combustion, ref. /19/.

Particles smaller than 10 µm can be inhaled and can reach deep into the lungs. In ref. /18/ a study on vehicle fires found that such fires generate approximately 64 grams of particles per kilogram of burned material, with most particles having a diameter below 1 µm. The small size of the particles allows them to deposit in the bronchial tree. Moreover, when examining the concentration of particles per unit volume, it was observed that most particles had a diameter of approximately 0.1 µm, enabling them to deposit on lung surfaces and small airways. This information highlights the potential long-term health effects associated with inhaling these particles, particularly due to their high concentrations of zinc, lead, and chlorine.

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Comparing the emissions during a fire of a diesel and electric vehicle is not straightforward, due to limited studies, but also due to the many parameters influencing the results, e.g., vehicle and battery size, chemistry, fire causes, etc. However, in terms of toxic substances, the hydrofluoric acid gas is a major concern during combustion of battery fires.

2.5.3 Dumper size impact on pavement

The size, particularly the weight, of dumpers can have a substantial impact on pavement destruction. Larger dumpers exert more weight on the pavement, potentially causing more damage. However, it is important to note that smaller dumpers expose the pavement to more frequent usage as more trips are needed to carry out the load.

2.5.4 CO_2 emissions from diesel dumpers

Diesel dumpers emit CO_2, and an estimate is given when using the large diesel dumpers according to the distance/time estimates given in section 2.3.4. The calculation considers the return transportation time from the assumed unloading point, located 2km away from the tunnel entry to the tunnel face.

According to ref. /20/ fuel consumption for dumper can be estimated considering the factors indicated in Figure 2-11 and the vehicle engine performance parameters in Figure 2-12.

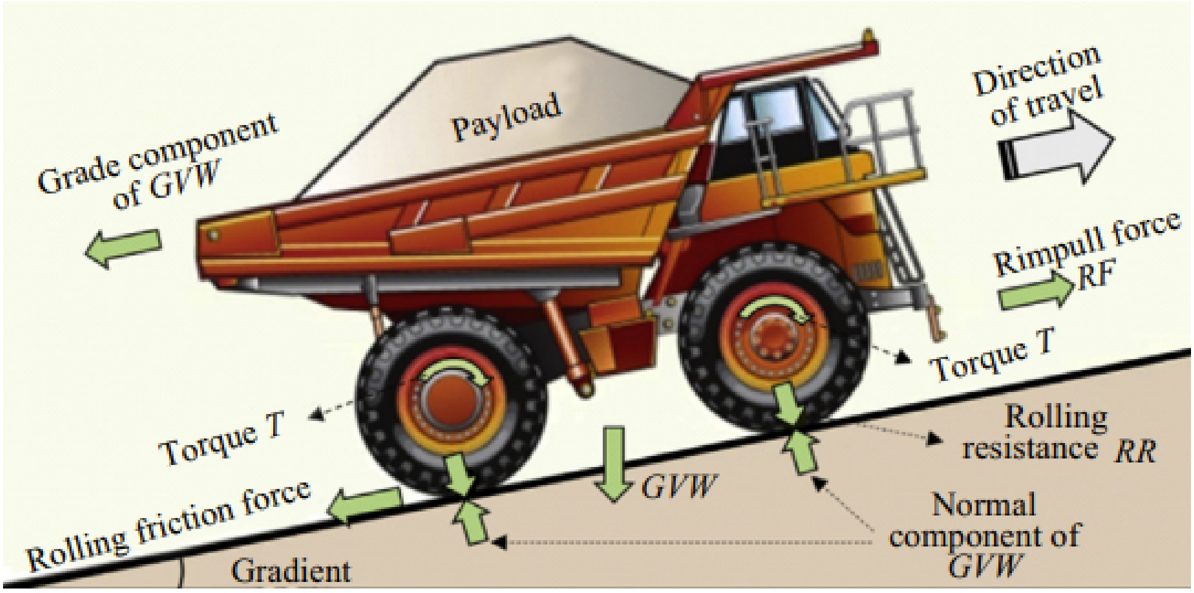

Figure 2-11 A schematic diagram of a typical haul truck and effective key factors on truck, ref. /20/.

The tunnel has a weighted average grade (GR) of 5%. However, since the vehicle operates against the tilt only half of the time, a rough assumption is a grade of 2.5%. Additionally, it is assumed that the vehicles operate on bitumen, resulting in a rolling resistance (RR) of 1.5% according to Table 2-9.

$$TR = RR + GR = 1{,}5\% + 2{,}5\% = 4\%$$

Table 2-9 Typical values for rolling resistance (RR) (%), ref. /20/.

Road condition	Rolling resistance
Bitumen, concrete	1.5
Dirt: smooth, hard, dry and well maintained	2.0
Gravel: well compacted, dry and free of loos material	2.0
Dirt: dry but not firmly packed	3.0
Gravel: dry not firmly compacted	3.0
Mud: with firm base	4.0
Gravel or sand: loose	10.0
Mud: with soft spongy base	16.0

Given that the vehicle operates half the time fully loaded and the other half empty, the Gross Vehicle Weight (GVW) is assumed to be the average weight of those, resulting in a GVW of 83.5 tons. The Rimpull (R) is obtained from the manufacturer diagram for the Komatsu, shown in Figure 2-12.

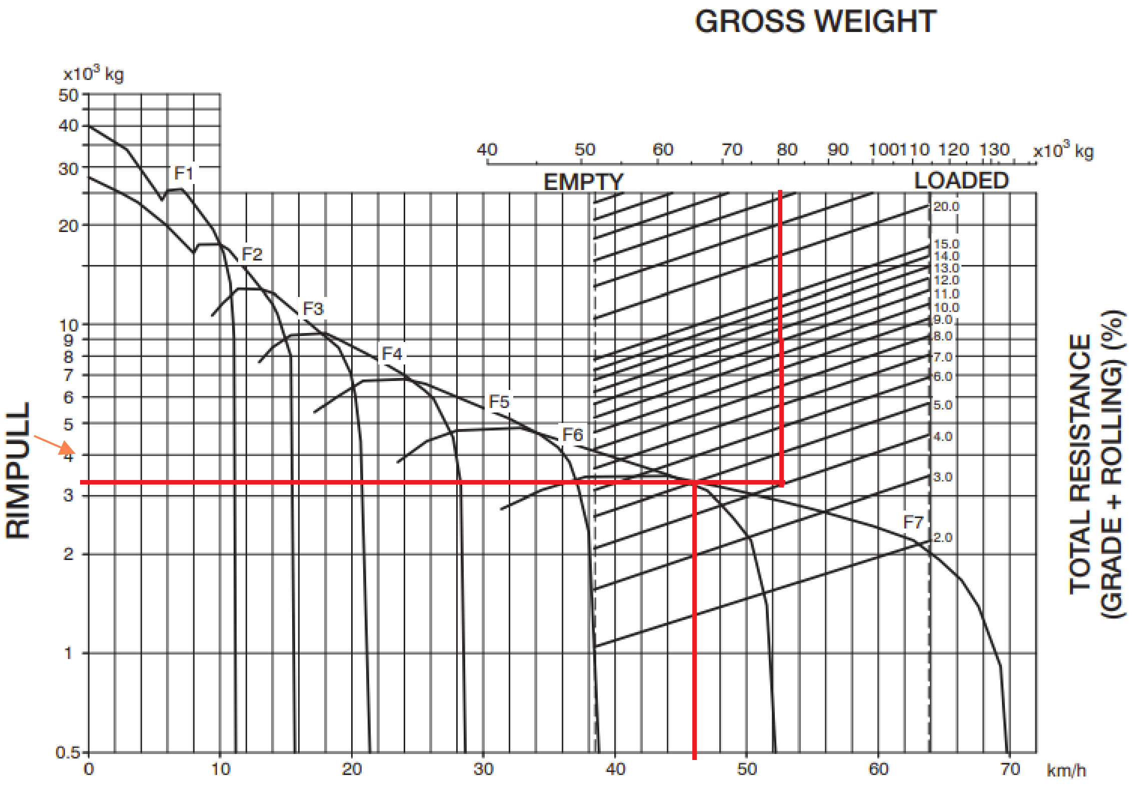

Figure 2-12 Vehicle performance parameters from manufacture diagram showing the rimpull-speed-grade ability curve for Komatsu HD605-7, ref. /4/.

The rimpull force is therefore found to be:

$$RF = R \cdot g = 34N$$

For the best performance of the truck operation, the truck power P (kW) is determined as:

$$P = \frac{1}{3.6}(RF \cdot V_{max}) = 509kW$$

Where the vehicle maximum velocity:

$$V_{max} = 53{,}867 - 54.906 \cdot e^{-37{,}979 \cdot R^{-1{,}309}} = 54\ km/h$$

Finally, the fuel consumption (FC) is calculated using the equation:

$$FC = 0.3(LF \cdot P) = 38\ l/h$$

Where engine load factor (LF) is assumed to be at 25% according to Table 2-10.

Table 2-10 Typical values of load factors (LF), ref. /20/.

Operating conditions	LF (%)	Conditions
Low	20-30	Continuous operatio at an average GVW less than recommended, No overloading
Medium	30-40	Continuous operation at an average GVW recommended, minimal overloading
High	40-50	Continuous operation at or above the maximum recommended GVW

With the fuel consumption rate given in litres per hour and the operation time given in Table 2-5 as well as considering that one litre of diesel emits approximately 2.68 grams of CO_2 are calculated as given in Table 2-11.

Table 2-11 Summary of total fuel consumption and CO2 emissions.

Parameter	Value	Unit	Comment
Fuel Consuption	38	L/hour	
Total Operation Time	49,581	Hours	
Total Diesel Consumption	1,884,081	L	
CO_2	5068	tonnes	2.68kg of CO_2 is emitted per liter of diesel

2.5.5 Summary

Comparing the emissions during a fire of a diesel and electric vehicle is not straightforward due to limited studies, but also due to the many parameters influencing the results, e.g., vehicle and battery size, chemistry, fire causes, etc. However, in terms of toxic substances, the hydrofluoric acid gas is a major concern during combustion of battery fires.

There are also emissions during ordinary operations, and one of the reasons for investigating use of BEVs over diesel vehicles is the reduction in CO_2 emissions locally at the worksite and specifically within the tunnels. This has an impact on the overall sustainability targets of the project as well as the occupational health and safety in the tunnels as diesel vehicles produce considerable amounts of CO_2 emissions locally at the construction site whereas BEVs have no local emissions. The power for the BEVs may even come (partially) from green energy sources.

Utilizing a smaller dumper in construction activities often leads to a noticeably longer construction time and longer total travelled distances with more vehicles passes when compared to employing a larger dumper. In the case of the Rogfast tunnel, the client has informed that a paved surface will be installed in the tunnel during the construction. While the paved surface will limit dust in the tunnel, it may be necessary to protect the paved surface against damage. Resulting in the need for using the lighter dumper trucks. However, if the pavement is considered sacrificial instead, any potential damage to the temporary pavement should not be a significant concern. Given this consideration and information mentioned in section 2.5.3, opting for a larger dumper is generally regarded as a better choice in terms of efficiency and overall project timeline.

2.6 Fire statistics

Very few statistics are available regarding electric vehicles (BEVs) fires – especially for large BEV dumpers. This makes the comparison with conventional internal combustion vehicles (diesel/petrol) difficult. To be able to make a rational comparison between fires in BEV/diesel dumpers, a more detailed review of fire statistics for ordinary vehicles has been carried out.

Afterwardsit is then assumed that the fire statistics for these vehicles can be taken as a basis for also comparing fires in BEV and diesel dumpers.

Many countries do not differentiate between types of vehicle propulsion when registering fire incidents. Further, some statistics simply count fires pr. 100.000 vehicles and do not consider the number of car kilometers. In the following, a review of overall statistics has been made and some general conclusions has been drawn.

Based on ref. /17/, the probability of a fire occurrence in a battery electric passenger car in Norway is roughly five times lower than that in a conventional car. Likewise, in Sweden, the likelihood of an EV fire is approximately twenty times lower compared to a fire incident in a conventional vehicle. It should be noted that while the statistical data may not be exhaustive, it can still be inferred that fires involving or originating from the traction battery are infrequent and extraordinary occurrences. It should also be noted that in general the BEV.

The fire statistics studies made in Denmark, ref. /21/, in Sweden, ref. /22/ and in US, ref. /23/ all compare number of fires and number of vehicles and finds differences between fires in BEVs and diesel/petrol vehicles. In ref. /21/ it is found that fires in BEVs appear less frequent than fires in diesel/petrol vehicles. They find a factor of approximately 1,5 in difference. In ref. /22/ and ref. /23/ the factors are found to be even higher – up to a factor of 20 in difference between BEVs and Diesel/petrol vehicles.

In relation to the operational risk assessment for the Bjørnafjord Floating Bridge (part of the Norwegian Public Roads Administration (SVV) E39 project), ref. /24/, detailed studies of vehicle fires in BEVs and diesel/petrol vehicles were carried out. These studies considered both number of fires per vehicle (data from ref. /25/) and the number of driven kilometers per vehicle type (data from ref. /26/). Detailed results are shown in Table 2-12.

Table 2-12 Vehicle fire statistics for different fuel types - number of fires per million vehicle km

Fires per million vehicle km	2016	2017	2018	2019	2020	2021	2022	Average
Diesel/Petrol	0,020	0,020	0,024	0,024	0,025	0,027	0,031	0,022
Electric	0,013	0,013	0,003	0,005	0,005	0,005	0,003	0,005
Hybrid	0,000	0,002	0,002	0,001	0,003	0,003	0,004	0,003
Gas	1,875	0,233	0,476	0,143	0,192	0,000	0,735	0,416

It is seen from Table 2-12, that fires in BEVs appear less frequent than fires in diesel/petrol vehicles – here with a factor of 4.6 in difference.

It is in all the above-mentioned studies noted that the fire statistics are counted per vehicle and hence does not consider the actual number of kilometers driven by the vehicles. Further, it is noted that the BEV vehicle fleet is not as old as the diesel/petrol vehicle fleet, and an increase in fire frequencies for BEVs may be seen as the BEV fleet age increases. However, the battery technology is quite new and still improving, and a lot of focus and effort is put into technology. Hence, batteries might become safer in the future, which then may lead to a decrease in the fire frequency.

2.6.1 Summary

Solid statistics related exclusively to BEV/diesel dumpers are not found available, and therefore it is chosen to do a review of fire statistics for ordinary BEV and diesel/petrol vehicles and use findings from this review to represent quantified differences in fires between BEV dumpers and diesel dumpers.

The review reveals large uncertainties in numbers and differences in ways the statistics are presented (per vehicle or per vehicle kilometer). The studies all show that fires in BEVs occur less frequent (reduction factors in interval from 2.5 to 20) than for a diesel/petrol vehicle. A representative frequency reduction factor of 4.6 is chosen.

It is noted that these numbers are subjected to large uncertainties, and that the age of the vehicle fleet also can affect the found fire probabilities. The resulting risk analysis must deal with this uncertainty by solid sensitivity studies.

2.7 Emergency response – internal and external

Fires in a BEV for construction works can be divided into two categories:

1. Vehicle fire where the battery is not ignited.
2. Vehicle fire which spreads to the battery – or where the fire starts directly in the battery.

Today's BEV's for construction work are basically converted diesel driven vehicles. Hence a fire where the battery is not ignited will be largely similar to a fire in a diesel driven vehicle. However, the potential fire load in a BEV may be smaller since the total amount of oil (fuel and hydraulics) is smaller. For both vehicle types, the driver cabin fit out and the tires will contribute to the fire load.

A noticeable difference between a BEV and a diesel vehicle fire is that the diesel content of the fuel tank may spill out and run for quite a distance down-hill. This can lead to the fire spreading over a large area, whereas a BEV battery fire will be concentrated to the small area where the vehicle is located.

In a closed tunnel construction site environment, the fire brigade will most probably make no attempt to extinguish the fire which might last for less than an hour, no matter of the fuel type of the vehicle.

For a fire which spread to the battery, the fire brigade during an open-air incident would try to extinguish the fire in the vehicle and then take action towards the battery. One way of tackling a battery fire is to punch a spear (see photo) into the affected section of the battery and then flood the battery with water through the spear. Some batteries might even have a build-in lid, such that the battery can be opened, and fire suppression can happen directly into the battery, without the need for piercing the battery first.

Figure 2-13 Demonstration of use of spears to flood the battery (private photo).

In a closed environment fire suppression and actions towards the battery will be hampered by the smoke development which creates low visibility and high temperatures at the incident location, as well as in the access road used by the fire brigade.

Consequently, in case of a fire in a vehicle battery, the fire brigade will in many cases have no other option than letting the fire burn out. The fire incident duration could be in the same order of magnitude as for a diesel driven vehicle – but with the important difference that the battery may spontaneously re-ignite. This makes the fire brigade intervention more risky and time consuming. In the Rogfast tunnel construction project this is critical for incident locations in the access tunnel or in the distribution zone at the bottom of the access tunnel since a vehicle fire at these locations will block the only available access route for people working at the tunnel faces.

The safety of these people must be provided by refuge chambers where a safe environment can be provided for up to e.g., 24 hours or more.
If the fire location is within one of the main tunnel tubes, personnel in the affected tube may escape to the adjacent non-affected tube via a cross passage and from there further to the distribution zone, access tunnel and out in free air.

2.8 Ventilation

For both categories of fire (vehicle fire or battery fire) a major challenge for the fire brigade would be clearing the tunnel system for smoke. The temporary ventilation system will utilize textile hoses mounted in the tunnel ceiling ducts.

Such textile ventilation hoses cannot withstand the smoke temperature during a fire. Hence, in case of a fire in the access tunnel or distribution area the ventilation hose would quickly collapse – leaving the tunnel system without any supply of fresh air. The challenges of clearing the tunnel system for smoke are further enhanced by the gradual cooling of the smoke which reduces the thermal buoyancy. Ideally, the ventilation should be re-established as soon as the location of the damaged section is accessible.

A breakdown of the ventilation system will affect the smoke clearing operation causing it to lasting significantly longer than the actual fire incident duration. Of this reason the specific duration of the fire is less important, and the decisive factor for the personal safety is the time it takes to provide accessibility for the rescue personnel and safe conditions for bringing the workers out.

Finally, the fire brigade may be more reluctant to approach an incident BEV because of the risk of re-ignition and the increased content of toxic gases in the smoke.

3. Risk identification

As part of the work of assessing the risks related to tunnel construction activities using battery driven or diesel driven construction machinery, a risk workshop was carried out. The purpose of the risk workshop was to gather experts with relevant information and discuss critical scenarios, critical locations, critical activities etc., and to have a first overview of all the risks. Focus on the workshop was given to construction activities for dumpers moving material from the tunnel face to the surface and various incidents (fires, collisions) in this relation, considering both diesel dumpers and BEV dumpers.

3.1 Workshop basis

As a preparation for the workshop, the critical locations where incidents could take place, were identified:

L1: At the construction site outside access tunnel
L2: At the work front/tunnel face during construction in the access tunnel
L3: Midway in the access tunnel during construction of motorway tunnel
L4: Midway in the motorway tunnel

The different locations are shown in Figure 3-1.

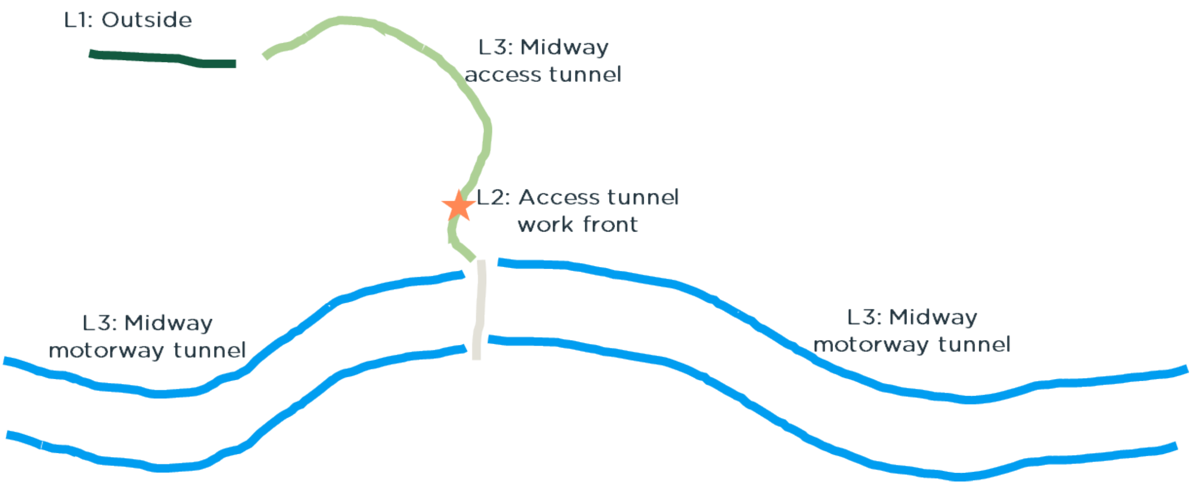

Figure 3-1 Locations used in the risk identification.

For each of the identified locations, a set of scenarios were identified:

E1: Spontaneous fire
E2: Mechanical impact starting a fire
E3: Mechanical impact not leading to fire
E4: Charging/refuelling leading to fire
E5: Loss of power/propulsion
E6: Noise and vibration during operation
E7: Pollution during operation
E8: Vehicle run-away
E9: Explosion

It is noted that the latter two were identified and included during the workshop. By combining scenarios and locations, a systematic approach to identify causes and effects of various scenarios were established. Effects – impact types - were initially related to:

- Injuries and fatalities

- Environment, health, and safety
- Project cost and time

On basis of the identified locations and scenarios, a methodology used at the workshop to ensure a systematic approach to describing risks was established. This methodology is sketched in Figure 3-2.

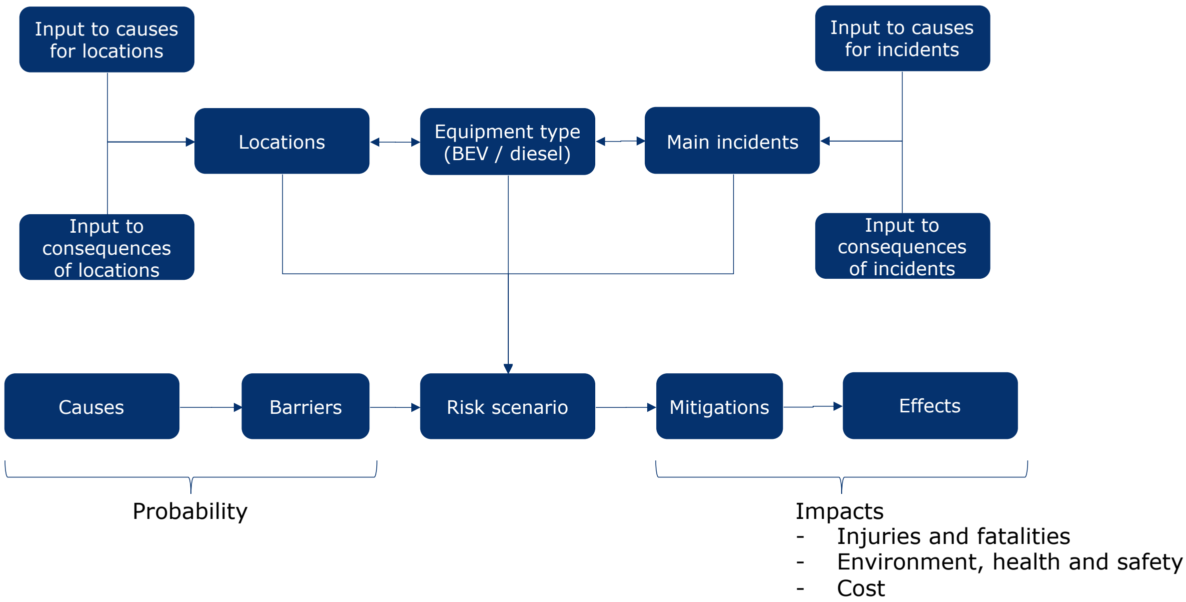

Figure 3-2 Basis for identifying risks at the workshop.

To evaluate score risks – semi quantitatively – a risk matrix set-up was been established. It is based on a 5x5 matrix with one probability axis and a consequence axis depending on the impact type. The risk matrix set-up is shown in Figure 3-3.

			Consequences				
			Insignificant	**Minor**	**Severe**	**Critical**	**Catastrophic**
		Safety	Minor injuries	One serious injury	1-10 serious injuries / one fatality	1-10 fatalities	> 10 fatalities
		Health, safety and environment (HSE) (e.g., excessive noise or emission of (toxic) gasses incl. CO2)	Insignificant impact on (work) environment	Minor impact on (work) environment	Severe impact on (work) environment	Critical impact on (work) environment	Catastrophic impact on (work) environment, e.g. causing early fatality
		Cost and time	Insignificant cost or delay (<1% of total budget and/or project duration)	Minor cost or delay (1 - 3% of total budget and/or project duration)	Severe cost or delay (3-10% of total budget and/or project duration)	Critical cost or delay (10-25% of total budget and/or project duration)	Catastrophic cost or delay (> 25 % of total budget and/or project duration)
Occurrence	**Often / always**	almost always for all projects					
	Likely	about once for every projects					
	Possible	about once for every 10 projects					
	Rarely	about once for every 100 projects					
	Unlikely	about once for every 1000 projects or less					

Figure 3-3 Risk matrix for semi quantitatively risk scoring.

3.2 Risk workshop activities

The workshop was arranged in Rambøll Head Office, Copenhagen and was conducted on June 12, 2023. Participants at the workshop are given in Table 3-1.

Table 3-1 workshop participants

Name	Company	Title/Role	Expertise area
Oddvar Kaarmo	Statens Vegvesen	Project Manager, Rogfast	Tunnel Construction
Tore Askeland	Statens Vegvesen	Project Manager, E39, Ph. D.	Risk analysis
Ross Dimmock	Normet	Vice president, tunnelling	Electrical Machinery
Mark Ryan	Normet	Vice president, Equipment	Electrical Machinery
Timo Oikarinen	Normet	Technology implementation manager	Electrical Machinery
Toke Koldborg Jensen	Rambøll	Senior Chief Project Manager, Ph. D., Workshop facilitator	Risk analysis
Søren Wegener Gamst	Rambøll	Head of Department	Tunnel design and construction
Louise Bjerrum Paillet	Rambøll	Senior Engineer, Ph. D., Workshop scribe	Risk analysis
Jørn Treldal	Rambøll	Senior Specialist	Fire and ventilation
Lisa Calearo	Rambøll	Senior Engineer, Ph. D	Battery technology
Markus Vestermark Jensen	Rambøll	Senior Engineer	Tunnel construction
Søren Randrup-Thomsen	Rambøll	Head of Department, Ph. D	Risk analysis

The workshop was initiated by short subject matter expert contributions regarding:

- Construction of the Rogfast tunnel
- Battery technology – chemistry, thermal runaway, and emissions
- Fire accident statistics

This was followed by various sessions to work on the pre-identified risks in a systematic way. The first session was concerned with incident locations, and the characteristics of the locations L1 to L4 were discussed, i.e., addressing the number of people present. During the second session, discussions concerned the identified incidents E1 to E9, while in the last session the risks were structured and combined from locations and incidents.

During the final part of the workshop the participants were given risk matrix schemes, for individually scoring the identified risks scenarios based on perception, knowledge and the prevailing discussions. All risks were evaluated for both a BEV and a diesel dumper.

3.3 Risk workshop results

As an outcome from the risk workshop, a risk register was established containing all the combinations of locations (L1-L4) and scenarios (E1-E9). For each combination (e.g., L1-E1), a sheet with the following information was established:

- Short description of the scenario.
- Frequency of the scenario at the given location.
- Causes for the scenario.
- Barriers to prevent the scenario/causes from occurring.

- Descriptions of the effect if the scenario occurs.
- Barriers to minimise the effect, if the scenario occurs.
- Risk matrices for Safety, Health Safety and Environment (HSE) and Cost/Time - average workshop participant scoring.

All risks were during the workshop scribed into an Excel risk database. Afterwards the risks were reviewed and updated. Identical events and locations were addressed for BEVs and diesel equipment in two separate Excel sheets. Transcripts of the detailed risk registers are shown in Appendix 1. Summary of risk matrix scorings are shown in Appendix 2 (number of risks at different locations in the risk matrices) and in Appendix 3 (average risk levels for each combination of scenario and location).

A summary of the risk evaluations for the three types of consequences based on workshop participant scoring and each of the scenarios are shown in Figure 3-4 and Figure 3-5. The colours show how many of the four locations that are evaluated to risk level red, yellow, and green, respectively. No risks are evaluated in the red area.

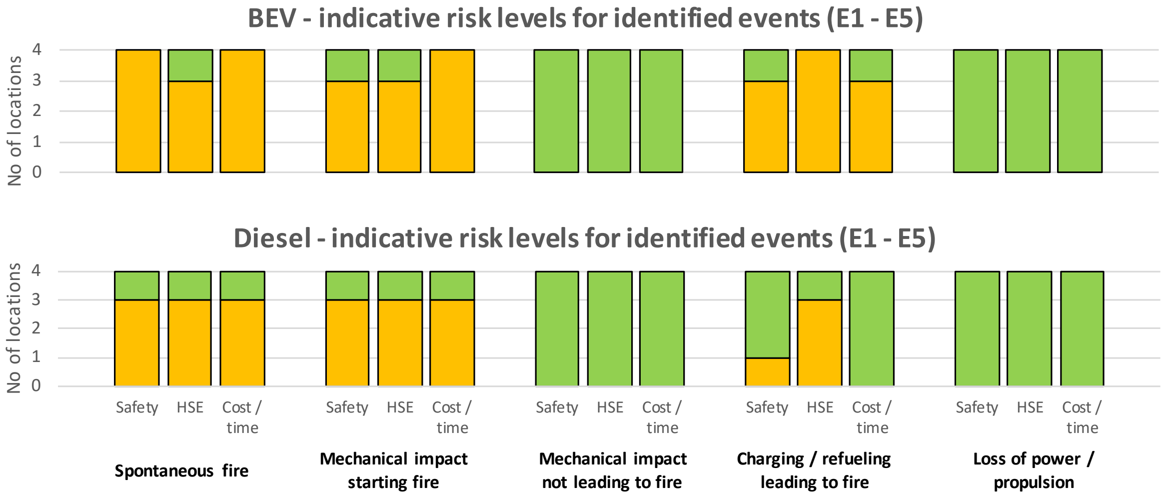

Figure 3-4 Risk overview based on number of locations evaluated to red, yellow, and green risk level for incidents E1 to E5.

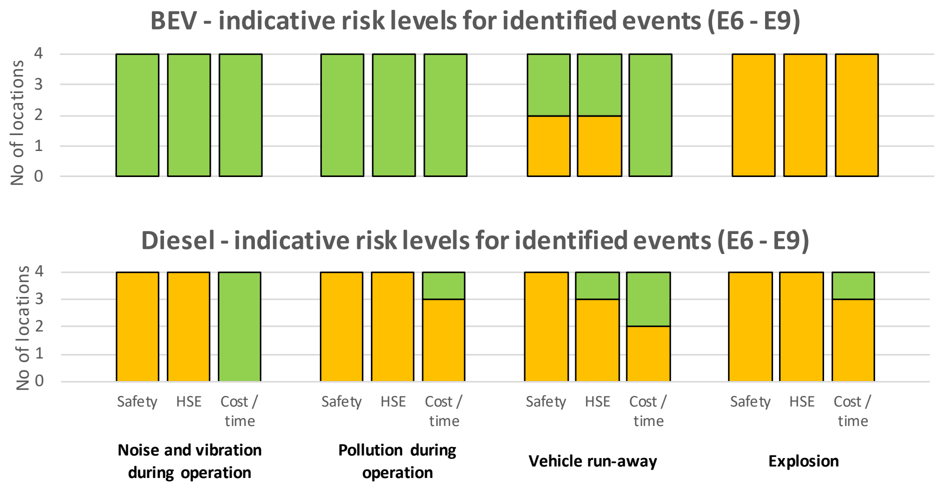

Figure 3-5 Risk overview based on number of locations evaluated to red, yellow, and green risk level for incidents E6 to E9.

From the results it is evident that there are risks for both BEVs and diesel vehicles. It is also clear that the scenarios related to fire and explosion in general are assessed to be slightly more critical for BEVs than for diesel vehicles. On the other hand, consequences related to noise, vibration and pollution are only significant for diesel vehicles. A special risk related to vehicle run-away is also assessed to be higher for diesel vehicles compared to BEVs, mainly due to differences in the brake systems where BEVs will do most braking by means of the electrical engine and not mechanical brakes.

The events are not equally worrying, and while the reduced noise and pollution may qualitatively favour the BEVs, it was concluded from the risk workshop, that the fire scenarios at various locations were those with largest concern. For this reason, a more detailed risk analysis, described in the next sections, addresses solely fire events at various locations.

4. Risk analysis

Results from the workshop show that critical scenarios are related to fire incidents occurring at different locations in the tunnel during construction of the tunnel. The focus in the risk modelling is therefore on the fire scenarios, which are studied in detail in this chapter.

4.1 Basis for the risk modelling

Based on the descriptions of the identified risks from the workshop, a risk model has been established to capture details of the identified fire incidents in the tunnel. The risk modelling of the identified risks (accident scenarios) consists of three parts:

1. Modelling of the frequency *f* of occurrence of the risk.
2. Modelling of the consequence *c* if the risk occurs.
3. Calculation of the risk level *R*=*f* x *c.*

4.1.1 Frequency modelling

For the modelling of fire frequencies, it is chosen to use the fire frequency statistics given in section 2.6 for BEVs and for diesel vehicles. It is acknowledged that these statistics are based on fires in ordinary vehicles and not specifically on dumpers used in construction works, as such statistics are not available. Uncertainties to these numbers are considered when evaluating the final risk results (see section5.4).

4.1.2 Consequence modelling

For the modelling of consequences of the fire some contributing elements are the same regardless if the dumper is a BEVs or diesel type. The elements are, e.g., the number of people present in the tunnel; the work phases; and possible incident locations. However, some main parameters are governing when looking at differences in BEV and diesel dumper fires, namely:

- The intensity of the fire.
- The duration of the fire.
- The smoke development during the fire.
- The accessibility of emergency response.

During the risk workshop (chapter 3), the number of people present at various locations and construction phases were discussed, and the resulting estimates used in the risk modelling are shown in Table 4-1.

Table 4-1 Estimated number of people in tunnel sections during different construction phases.

Location	Work phase		
	Access tunnel	**Distribution zone**	**Motorway**
Outside	1	1	1
Midway access tunnel	7	20	20
Work front access tunnel	4	*Not relevant*	*Not relevant*
Distribution zone	*Not relevant*	20	20
One motorway tube	*Not relevant*	*Not relevant*	5

The numbers in Table 4-1 are based on an evaluation of the required workload at different locations and during different work phases, hence, they represent an average number of people. Uncertainty variation of these number are included in the risk model. The uncertainty modelling is shown in Appendix 5.

During the risk identification phase at the risk workshop, the conditions during a fire were discussed for both BEV fires and fires in diesel dumpers. Critical issues as reignition of fires in batteries and longer fire durations for batteries were discussed. The fire intensity related to battery and diesel fires, smoke development over time, and the corresponding time before the rescue services can enter the tunnel, were also discussed. The following conclusions (also described in the risk register) were drawn and are taken as input to the risk modelling:

- Fire intensities for diesel and battery fires do not differ significantly.
- Diesel fires tends to degrade and die out within a few hours.
- Battery fires can reignite and may hence have longer durations, sometimes more than 24 hours.
- The smoke clearing operation might last significantly longer than the actual fire incident, hence the specific duration of the fire is less important.
- The fire brigade may be more reluctant to approach a BEV incident because of the risk of reignition and the increased content of toxic gases in the smoke.

The consequence part of the risk model must capture the above conditions, as well as causes and effects of the established accident scenarios, and interdependencies between various kinds between causes, failure modes etc. For this reason, it has been chosen to establish the risk model by use of Bayesian Network (BN) modelling techniques (see Appendix 4 for descriptions of basic principles of BN models).

BN-models have been established for two operational modes for transporting material out of the tunnel: One for the use of BEV dumpers; and one for the use of diesel dumpers. In the following, the models are described in terms of:

- Description of the BN model and different model parts for diesel dumpers.
- Description of the BN model and different model parts for BEV dumpers.
- Output from the models.

On basis of the output from the BN-models, the calculated probabilities of fatalities are illustrated as F-N diagrams for both operational modes. These are then compared to determine if risk of one operational mode is significantly different from the other operational mode.

4.2 The elements of the Bayesian networks

The Bayesian networks used to model fire and battery related risks contain four basic elements, three types of nodes, and edges to connect the nodes. The nodes represent different states of the model's elements. The node categories are:

- Chance node.
- Decision node.
- Utility node.

In a chance node the probabilities are assigned to the different states of the node. E.g., suppressing a fire on a diesel truck with a handheld extinguisher has a chance of 30% to succeed and 70% to fail. These probabilities will influence the nodes, the chance node is connected to. A decision is like a switch. If a state is selected this is the only possible state of the node. In this way it is possible to model different scenarios and to consider, e.g., different construction phases and the corresponding number of persons working in the tunnel. Finally, the utility node is the resulting node expressing the expected number of fatalities.

For illustration purposes of how a BN works, an example of a simple BN is given in Appendix 4.

4.3 Description of the BN models for diesel dumpers

The BN-model for diesel dumpers includes the following model parts:

1. Failures in diesel engine leading to a fire.
2. Consequences of the fire, means to supress the fire, and duration of the fire.
3. Location of the fire and expected number of people at or below the fire location.
4. Possibilities to escape the fire or be protected from the fire.
5. Final modelling of fatalities as result of the fire.

An illustration of the BN is shown in Figure 4-1.

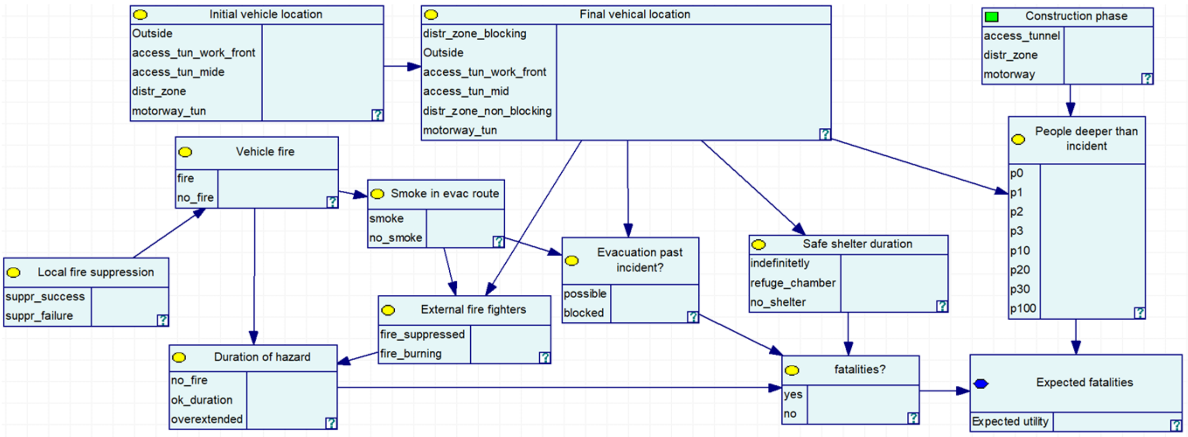

Figure 4-1 Bayesian Network model for fire in diesel dumpers.

Descriptions of the different parts of the model are given in the following.

4.3.1 Failures in diesel engine leading to fire

A diesel truck fire can have various causes e.g., overheated brakes, oil spilt on hot engine surfaces, electric sparks, and others. All the cause are collected in the chance node 'Vehicle fire'. It models the probability of a fire starting. The possible states of the node are:

- Fire
- No fire.

Once a fire is detected, the driver or bystanders will attempt to suppress it with handheld fire extinguishers. The suppression probability is modelled in the chance node 'Local fire suppression'. The possible states of the node are:

- Successfully suppressed.
- Not suppressed.

This part of the Bayesian network (BN) is shown in Figure 4-2.

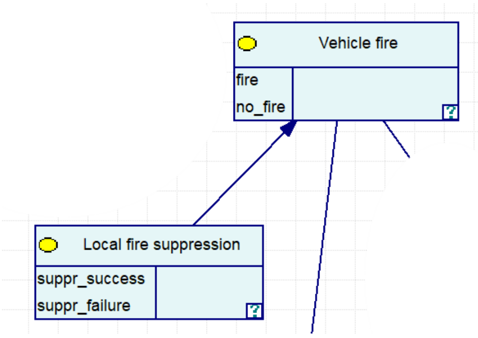

Figure 4-2 Model part concerning the vehicle fire and the local fire suppression in the BN for diesel dumpers.

4.3.2 Consequences of fires and duration of fire

If a fire breaks out it will cause smoke in the tunnel, hindering evacuation, and will burn for some time. The duration with which the hazard affects people under ground is important, this part of the BN is presented in Figure 4-3.

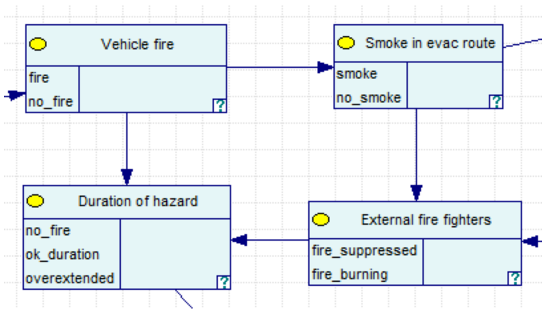

Figure 4-3 Model part concerning the effect of the fire, the fire incident duration and fire suppression in the BN for diesel dumpers.

The chance node 'Smoke in evac route' controls weather or not it is possible to evacuate due to smoke in the tunnel. The possible states of the node are:

- Smoke
- No smoke.

The duration of an event can cause fatalities to people who manage to escape to a refuge chamber, if they are not able to escape from the chamber within the safe occupational time of the chamber. This is represented by the chance node 'Duration of hazard'. The possible states of this node are:

- No fire
- Ok duration (meaning the refuge chambers can provide protection long enough)
- Overextended (meaning the incident lasts longer than the refuge chamber can provide protection).

The incident duration is also indirectly influenced by smoke. Dense smoke may prevent the fire fighters to reach the incident location. The chance node 'External fire fighter' models if the probability that the fire brigade can successfully enter the tunnel and suppress the fire. The possible states of this node are:

- Fire suppressed.
- Fire burning.

4.3.3 Location of fire and expected number of persons trapped by the fire

Depending on the location of the fire and the progress of the excavation, the number of people that are trapped by the fire will vary. This part of the model is shown in Figure 4-4.

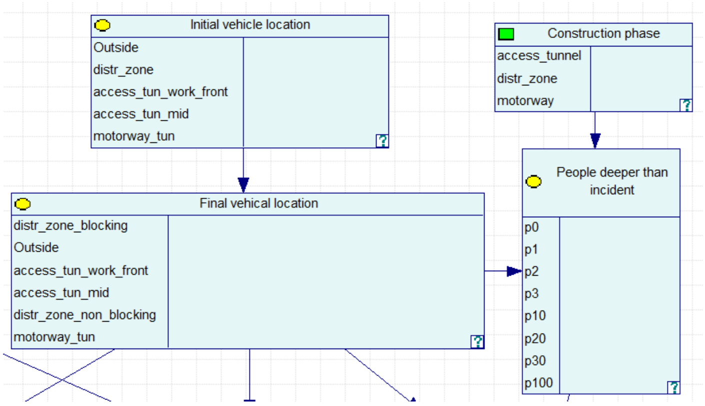

Figure 4-4 Model part concerning the location of the fire and the number of people trapped below the fire in the BN for diesel dumpers.

The state of the excavation is determined by the decision node 'Construction phase'. This node models the progress of the tunnel construction, and the possible states of this node are:

- Access tunnel
- Distribution zone
- Motorway.

The location of the diesel dumper when the incident is detected is represented by the chance node 'Initial vehicle location' models where the burning vehicle is located initially in the tunnel when the incident is detected. The possible states of this node are:

- Outside
- Somewhere in the distribution zone.
- Access tunnel at the work front.
- Somewhere along the access tunnel.
- Motorway tunnel.

The location of the diesel dumper where the fire will continue is represented by the chance node 'Final vehicle location'. The vehicle can in some incidents block the evacuation routes, leading to an increased number of trapped people. The possible states of the node are:

- Outside
- In the distribution zone and blocking the evacuation route.
- In the distribution zone but not blocking the evacuation route.
- Access tunnel at the work front.
- Somewhere along the access tunnel.
- Motorway tunnel.

The reason for using both 'initial' and 'final' location is that it in some cases it will be possible to move the vehicle to a safer place before the fire is developing out of control.

The decision node 'Construction phase' and the chance node 'Final vehicle location' determine the conditional probabilities in the node 'People deeper than incident'. Hence, this node models how many people are affected because they are located deeper than the fire, and therefore trapped.

4.3.4 Possibilities to escape the fire or protect from fire

Figure 4-5 shows the network part modelling evacuation and protection from fire. The outcome of evacuation or appropriate protection is determining if fatalities occur.

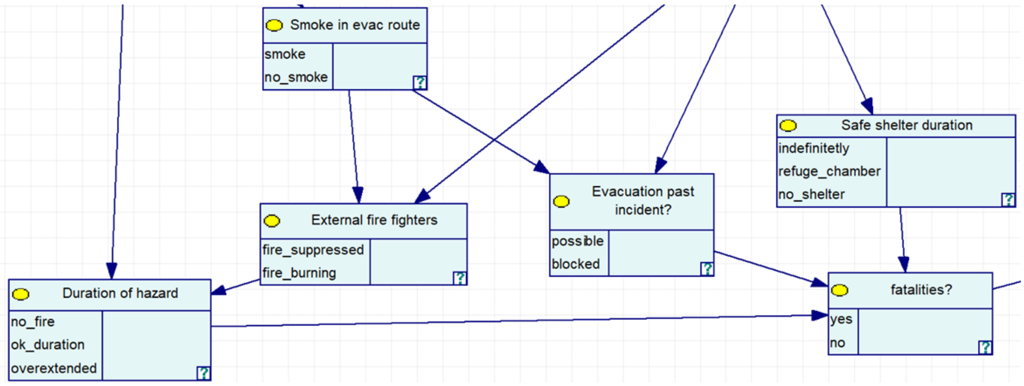

Figure 4-5 Model part concerning the fire protection and escape possibilities in the BN for diesel dumpers.

The chance node describing if an evacuation is possible is modelled by the node 'Evacuation past incident?'. It is impossible to evacuate if the tunnel is filled with smoke, or if the burning vehicle blocks the escape route. The possible states of this node are:

- Possible
- Blocked.

The chance node 'Safe shelter duration' models how people can find protection from the incident. Depending on the location of the incident, people may be able to reach either a refuge chamber or exit the tunnel. The possible states for this node are:

- Indefinitely (people reach free air).
- Refuge chamber.
- No shelter.

Indefinitely is set such that all people can leave the tunnel, meaning that the time limit of the shelter duration then becomes irrelevant. The refuge chamber is a safe space for people trapped inside the tunnel. The refuge chamber will provide safety for a limited time. No shelter is used if no shelter can be reached because of e.g., injuries preventing self-rescue.

Weather there will be fatalities or not during an event is controlled by the chance node 'fatalities?'. This node is conditional on the nodes 'Duration of hazard', 'Evacuation past incident?', and 'Safe shelter duration'. If the fire duration exceeds the protection time of a refuge chamber the shelter cannot protect long enough and fatalities occur. Likewise, if evacuation is not possible fatalities will also occur. The possible states of the chance node 'fatalities?' are:

- Yes
- No.

4.3.5 Final modelling of fatalities as result of the fire

With the indication of the 'fatalities?' node and the distribution of people in the tunnel deeper than the incident the expected number of fatalities is calculated by the 'Expected fatalities' node. The relation of these nodes is shown in Figure 4-6.

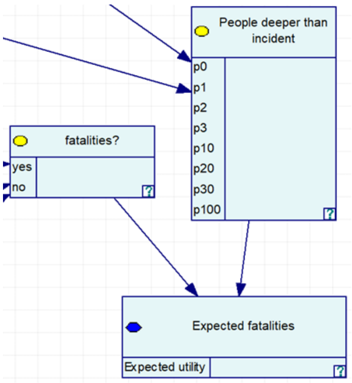

Figure 4-6 Model part concerning fatalities in case of a fire in the BN for diesel dumpers.

The node 'People deeper than incident' holds probabilities for the number of people present conditional on incident location and construction phase. The presence of 0 up to 100 persons is modelled.

4.4 Node input parameters for the diesel BN model

A quickly discovered fire in an easily accessible location may be suppressed by workers using quick response firefighting equipment e.g., handheld extinguishers. Once a fire becomes too large, local suppression is no longer possible. Because local suppression reduces only the likelihood of non-battery related fires, the mitigation measure has a larger reduction effect in terms of fatalities for a diesel dumper than for a BEV dumper. Therefore, the value is a conservative assumption. The probability table for local firefighting is identical in the BEV model. Probabilities are shown in Table 4-2.

Table 4-2 Conditional probabilities applied for local fire suppression.

Local fire suppression by workers	Distribution (%)
Success	30
Failure	70

The duration of the hazard (fire or smoke filled, unbreathable air) has three states. No fire, meaning that everything is in order, and the hazard is avoided. Ok duration means that the refuge chambers have enough capacity to protect people until they can be safely evacuated. Overextended represents the case of event that the tunnel atmosphere was not restored in time in order to facilitate a safe evacuation. Due to lack of experience with dumper fire in tunnels under construction a rather high overextension probability was chosen to be conservative. A dumper fire will burnout within a couple of hours. This is significantly shorter than the protection time a refuge chamber can offer. Probabilities are shown in Table 4-3.

Table 4-3 Conditional probabilities applied in the node for the duration of the hazard.

External fire fighters	Distribution (%)		
	Fire		No fire
	Suppressed	Burning	
No fire	100	0	100
Ok duration	0	90	0
Overextended	0	10	0

With the progression of work, different parts of the tunnel become accessible. Some parts like the access tunnel must always be driven to reach or leave deeper pats of the tunnel system. The distribution below is based on the distances driven in each section as presented in Table 2-8 and assuming an average speed of 10 km/h in the tunnel and 40 km/h outside. Probabilities applied are shown in Table 4-4.

Table 4-4 Conditional probabilities applied for the initial vehicle location.

Final vehicle location	Distribution (%)
Outside	14.58
Distribution zone	0.17
Access tunnel work front	0.75
Access tunnel midway	50.00
Motorway tunnel	34.50

The 'initial vehicle location' models the location where the incident is first noticed. In case of a diesel dumper this is also the final location. The only modification is applied to vehicles in the distribution zone. The distribution zone has many connections to other tunnels; therefore, the vehicle can end up in a place where it hinders evacuation (blocking) or allows for evacuation (non-blocking). This random outcome of blocking or non-blocking is governed by Table 4-5. The state 'Distribution zone' from Table 4-4 is split evenly into a blocking and non-blocking state. The equal chance of ending up in a blocking or non-blocking position shall model the recognition of a fire in a random spot in the distribution zone.

Table 4-5 Conditional probabilities for the final vehicle location.

Final vehicle location	Distribution (%)	
	Distribution zone	Other
Distribution zone (blocking evacuation)	50	0
Distribution zone (not blocking evacuation)	50	0
Other	0	100

The safe shelter duration has three states, indefinite shelter is only set for outside the tunnel. Due to injury or other circumstances, it is also possible that a person will not reach safe shelter. The refuge chambers inside the tunnel can protect trapped people for some time. Probabilities applied are shown in Table 4-6. 0.5% probability for failed self-rescue / no shelter seems conservative because injury in case of a fire most likely occurs close to the fire from which people will move away. Furthermore, safety drills will help to maintain a high level of preparedness.

Table 4-6 Conditional probabilities for the duration of the safe shelter.

	Distribution (%)	
	Outside	**Inside**
Indefinitely	99.5	0
Refuge chamber	0	99.5
No shelter	0.5	0.5

The shelter time can vary depending on the equipment e.g., O_2 tank capacity, CO_2 filters, and the occupancy in case of an emergency. These variables are not modelled, it is here assumed that the chambers protect for an unspecified time that is either sufficient or overextended. The overextension is modelled in the 'Duration of hazard' node with its conditional probabilities listed in Table 4-3.

Depending on where the incident occurs, fire fighters from outside may be able to reach the fire and suppress it. The deeper inside the tunnel a fire occurs, the less likely it is that it can be reached by external fire fighters due to smoke making the tunnel inaccessible. The accessibility will change overtime with the tunnel construction progress therefore the probabilities are based on engineering judgements, they are of low importance because, the same probabilities are applied to the BEV model. Probabilities applied are shown in Table 4-7.

Table 4-7 Conditional probability table for probability of fire suppression by external fire fighters.

	Distribution (%)					
	Smoke					
Final vehicle location	**Outside**	**Access tunnel work front**	**Access tunnel midway**	**Distribution zone**	**Motorway**	**No smoke**
Fire suppressed	100	10	20	1	1	100
Fire burning	0	90	80	99	99	0

4.5 Description of the BN models and different model parts for BEV dumpers

The BN—model for BEVs include the following model parts:

1. Hazardous incidents of the BEV (battery or non-battery related) leading to a fire.
2. Implementation of BMS.
3. Possibility of performing a battery flooding.
4. Possibility of moving vehicle away in case of BMS warning.
5. Consequences of the fire, means to suppress the fire and duration of the fire.
6. Location of the fire and expected number of people at or below the fire location.
7. Possibilities to escape the fire or be protected from the fire.
8. Final modelling of fatalities as a result of the fire.

An illustration of the BN for BEVs is shown in Figure 4-7.

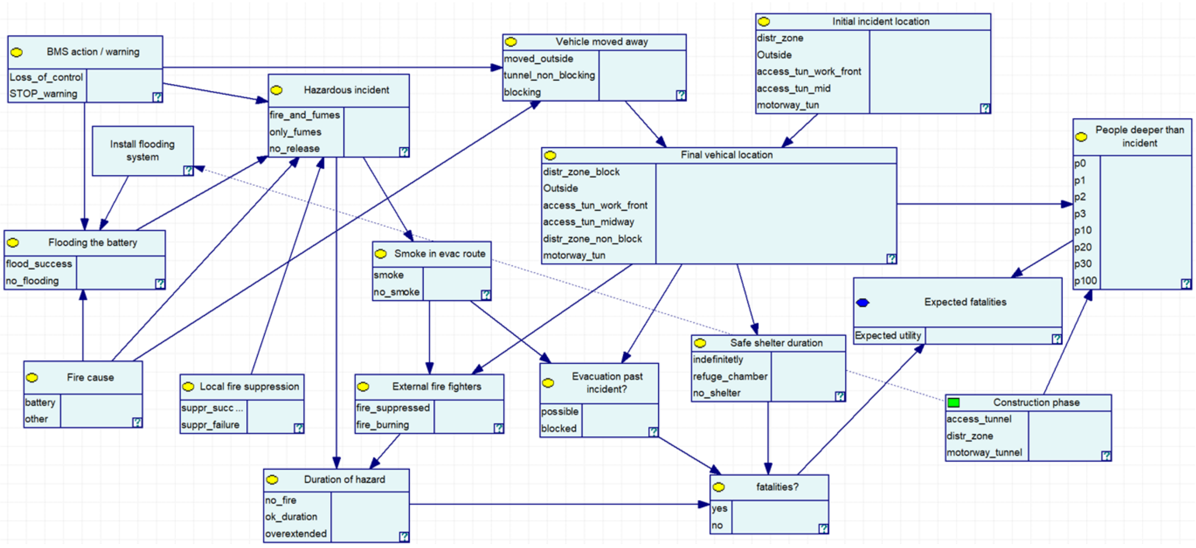

Figure 4-7 Bayesian Network model for hazardous events in BEV dumpers.

Comparing Figure 4-1 and As seen from Figure 4-7, the principles in setting up the BEV model and the diesel model are the same. There are however distinguishing factors between the two models. This includes some nodes added to the BEV model to account for:

- Fires having both battery causes and other (also diesel applicable) causes.
- Implementation of BMS-system.
- Possibility of having battery flooding.
- Possibility of moving vehicle away in case of BMS-warning.

In general, it is seen that the model includes the following model parts:

1. Fire due to battery failure or other causes.
2. Consequences of fires, means to suppress fire and duration of fire.
3. Location of fire and expected number of persons at or below fire location.
4. Possibilities to escape the fire or protect them from fire.
5. Final modelling of fatalities as result of the fire.

Descriptions of the different parts of the model are given in the following.

4.5.1 Fire due to battery failure or other causes

Batteries can, due to various causes, sustain damage, see section 2.4.3, that can lead to malfunction and ultimately to a thermal runaway with a release of fumes and even a fire.

The network part modelling fire, fire causes, and mitigation measures are depicted in Figure 4-8.

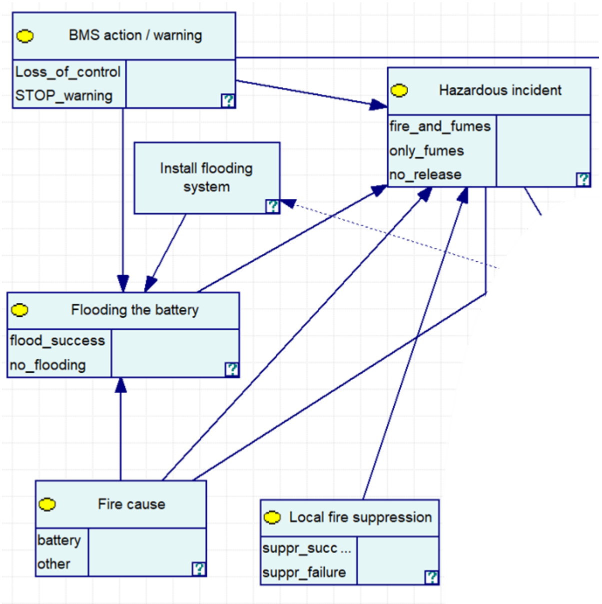

Figure 4-8 Model part concerning the BMS, battery failure and battery flooding in the BN for BEVs.

The causes for fires in a BEV are collected in the chance node 'Fire cause'. This node models the probability of the cause of the fire. The possible states of the node are:

- Battery
- Other.

Given a BMS some incidents can be caught early. This is captured in the chance node 'BMS action/warning'. This node models the probability of the BMS system successfully warn the driver of the BEV. The possible states are:

- Loss of control
- Stop-warning.

The node 'Install flooding system' is a decision node to model if the batteries are equipped with a pre-install flooding system, such that the fire mitigation is easier. This node can either be tuned on or off, depending on the model setup.

Modelling if the mitigation of flooding the battery, which is the most reliable way to suppress a battery fire, is successful or not is captured in the chance node 'Flooding the battery'. The possible states of this node are:

- Successfully flooded.
- Flooding failure.

Once a fire is detected, the driver or bystanders will attempt to suppress it with handheld fire extinguishers. The suppression probability is modelled in the chance node 'Local fire suppression'. The possible states of the node are:

- Successfully suppressed.
- Not suppressed.

Finally, the chance node 'Hazardous incident' express what type of effect the incident will have, and weather the fire is handles or not. The possible states of this node are:

- Fire and fumes.
- Only fumes.
- No release.

The outcome of the node 'Hazardous incident', depend on the success of:

- Actions by the BMS.
- The success of battery flooding with water if suggested by the BMS.
- Whether a general fire broke out that was not suppressed locally.

Above actions influence the probability of fumes releases and fires.

4.5.2 Consequences of fires, means to supress fire and duration of fire

If a fire breaks out it will cause smoke in the tunnel, hindering evacuation, and will burn for some time. The duration with which the hazard affects people underground is important, this part of the BN is presented in Figure 4-9.

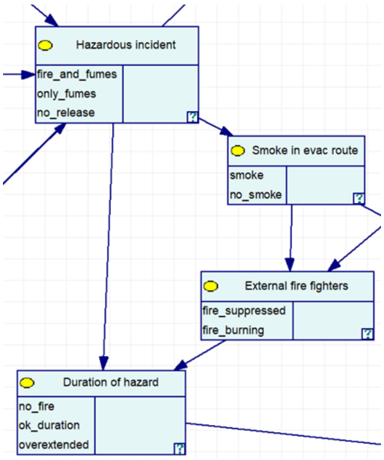

Figure 4-9 Model part concerning the effect of the fire, the fire incident duration and fire suppression in the BN for BEVs.

The chance node 'Smoke in evac route' models the probability of intensive smoke release, it is noted that smoke release from at BEV is also possible during a battery malfunction, and hence possible without a fire. The possible states of the node are:

- Smoke
- No smoke.

The duration of an event can cause fatalities to people who actually managed to reach an refuge chamber, if the hazard continues longer than the refuge chamber can keep workers in the tunnel safe. This is represented by the chance node 'Duration of hazard'. The possible states of this node are:

- No fire'
- Ok duration (meaning the refuge chamber can protect long enough).
- Overextended (meaning the refuge chamber cannot protect long enough).

The fire incident duration is also indirectly influenced by smoke. Dense smoke may prevent the fire fighters to reach the incident location. The chance node 'External fire fighters' models the probability that the fire brigade can successfully enter the tunnel and suppress the fire. The possible states of this node are:

  - Fire suppressed.
  - Fire burning.

4.5.3 Location of fire and expected number of persons at or below fire location

Depending on the location of the fire or fumes release, and the progress of excavation, the number of people trapped in the tunnel will vary. This part of the model is shown in Figure 4-10.

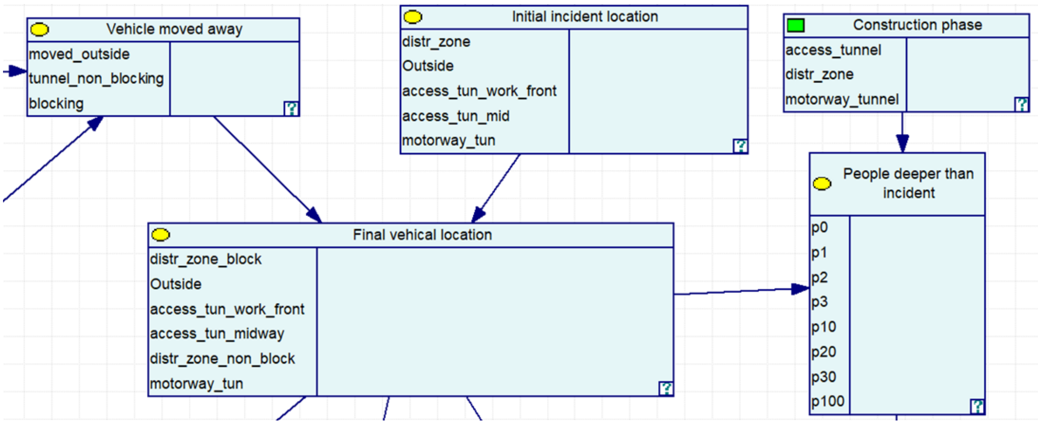

Figure 4-10 Model part concerning the location of the fire and the number of people trapped below the fire in the BN for diesel dumpers.

The excavation progress is determined by the decision node 'Construction phase'. This node models the progress of the tunnel construction, and the possible states or decisions of this node are:

- 'Access tunnel'.
- Distribution zone'.
- Motorway tunnel'.

The location of the BEV when the incident is detected is represented by the chance node 'Initial incident location'. The incident 'battery malfunction' can occur anywhere and thereby indirectly influence mitigation action. The possible states of the node 'Initial vehicle location' are:

- Distribution zone'
- Outside.
- Access tunnel work front.
- Access tunnel midway.
- Motorway tunnel.

In case the BMS present a warning, the driver may be able to drive the vehicle to a safer location. The vehicle could end up in a location where it blocks the evacuation route or at a location where is does not block or even be outside where evacuation is not hindered, and the firefighters have easy access. Theis is collected in the chance node 'Vehicle moved away'. This node has the following possible states:

- Moved outside.
- In the tunnel in a non-blocking location.
- In the tunnel in an evacuation blocking location.

The location of the BEV where it will burn or emit fumes is represented by the chance node 'Final vehicle location'. The vehicle can in some situations block evacuation routes, leading to an increased number of trapped people. The possible states of the node 'Final vehicle location' are:

- Distribution zone blocking'.
- Distribution zone non-blocking.
- Outside.
- Access tunnel work front.
- Access tunnel midway.
- Motorway tunnel.

The decision node of 'Construction phase' together with probabilities of 'Final vehicle location' determine the conditional probabilities in the node 'People deeper than incident' is giving how many people that are affected because they are located deeper than the 'Final vehicle location' fire and therefore are trapped.

4.5.4 Possibilities to escape the fire or protect from fire

Figure 4-11 shows the network part modelling evacuation and protection from fire. The outcome of evacuation or appropriate protection is determining if fatalities occur.

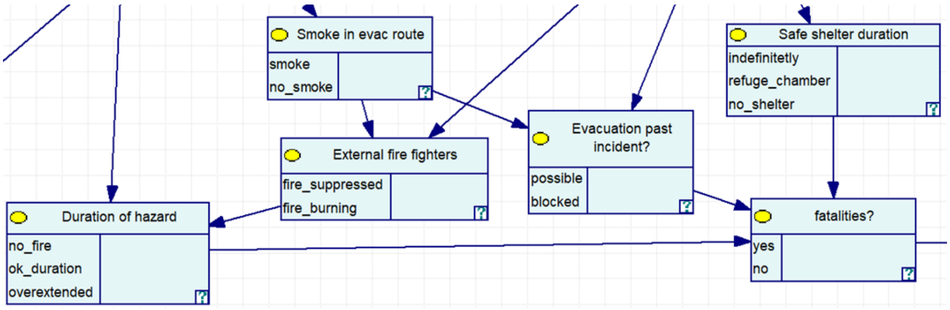

Figure 4-11 Model part concerning the fire protection and escape possibilities in the BN for BEVs.

The node describing if an evacuation is possible is modelled by the node 'Evacuation past incident?'. It is impossible to evacuate if the tunnel is filled with smoke, or if the burning vehicle blocks the escape route. The possible states of this node are:

- Possible
- Not possible.

The node 'Safe shelter duration' models how people can find protection from the incident. Depending on the location of the incident, people may be able to reach either a refuge chamber or exit the tunnel. The possible states for this node are:

- Indefinitely (people reach free air).
- Refuge chamber.
- No shelter.

Indefinitely is set such that all people can leave the tunnel, meaning that the time limit of the shelter duration then becomes irrelevant. The refuge chamber is a safe space for people trapped inside the tunnel. The refuge chamber will provide safety for a limited time. No shelter is used if no shelter can be reached because of e.g., injuries preventing self-rescue.

Weather there will be fatalities or not during an event is controlled by the chance node 'fatalities?'. This node is conditional on the nodes 'Duration of hazard', 'Evacuation past incident?', and 'Safe shelter duration'. If the fire duration exceeds the protection time of a refuge chamber the shelter cannot protect long enough and fatalities occur. Likewise, if evacuation is not possible fatalities will also occur. The possible states of the chance node 'fatalities?' are:

- Yes
- No.

4.5.5 Final modelling of fatalities as result of the fire

With the indication of the 'fatalities?' node and the distribution of people in the tunnel deeper than the incident the expected number of fatalities is calculated by the 'Expected fatalities' node. The node 'People deeper than incident' holds probabilities for the number of people present conditional on incident location and construction phase. The presence of 0 up to 100 persons is modelled.

4.6 Node input parameters for the BEV BN model

In the Danish statistics for vehicle fire causes, ref. /21/, the initial cause for a fire is given. A number of causes are given as:

- Battery related.
- Arson.
- Spread of fire from a burning object nearby.

Battery causes may relate to charging or (re-)ignition after battery damage. Probabilities are given in Table 4-8 and based on ref. /21/.

Table 4-8 Conditional probabilities applied for the fire incident cause.

	Distribution (%)
Battery	53.1
Other	46.9

Fire hazards due to different causes are modelled separately. A general fire is a non-battery caused fire, and it is assumed that there is a possibility of local fire suppression. This is valid for both the BEV and the diesel vehicle case. A general fire can of course over time also ignite the battery in a BEV. Local fire suppression probabilities are given in Table 4-9 and are identical to those applied in the diesel model. Because local suppression reduces only the likelihood of non-battery related fires, the mitigation measure has a larger reduction effect in terms of fatalities for a diesel dumper than for a BEV dumper. Therefore, this is a conservative assumption.

Table 4-9 Conditional probabilities applied for the success of suppressing a general fire.

Local fire suppression by workers	Distribution (%)
Success	30
Failure	70

In case the root cause of the fire lies within the battery, the BMS can lose control in two different ways. The first scenario is a rapid loss of control leaving hardly any time for the vehicle operator to react, while in the second scenario, the loss of control is slower and the BMS issues a warning before the battery is out of control. Upon this warning mitigation actions may be possible. Estimated, conservative probabilities are given in Table 4-10. From news reports it is known that battery malfunctions in BEV usually result in warning to the users allowing them to vacate the car before the thermal runaway reaches critical temperatures.

Table 4-10 Conditional probabilities applied for the BMS functionality.

BMS action	Distribution (%)
Loss of control	50 %
'Stop' warning	50 %

If the BMS issues a warning, a mitigation action may be to flood the battery with water. This will almost certainly prevent or stop a thermal runaway. In order to actually carry out flooding of battery, the battery pack must be equipped with a simple flooding mechanism that can be used by the vehicle operator if the BMS recommends doing so. Estimated probabilities, based on engineering judgement, for flooding the battery are given in Table 4-11.

Table 4-11 Conditional probabilities applied for the potential battery flooding function.

	Distribution (%)					
BMS action	**Loss of control**			**'Stop' warning**		
Instant flooding system	**Yes**		**No**	**Yes**		**No**
Fire cause	**Battery**	**Other**		**Battery**	**Other**	
Flooding successful	10	0	0	90	0	0
No flooding	90	100	100	10	100	100

How the fire develops, depends on the available extinguishing alternatives. In case of a general fire, fire and fumes will always occur. In case of a battery caused incident, the outcome can either be:

- Fire and fumes.
- A release of fumes without ignition.
- No release at all.

Engineering judgement based probabilities of these development alternatives are given in Table 4-12.

Table 4-12 Conditional probabilities applied for the fire development. B stands for battery, and O for other cause.

	Distribution (%)													
BMS action	**Loss of control**							**'Stop' warning**						
Flooding the battery	**Success**				**No flooding**			**Success**				**No flooding**		
Local fire suppression	Yes		No		Yes		No	Yes		No		Yes		No
Fire cause	**B**	**O**	**B**	**O**	**B**	**O**		**B**	**O**	**B**	**O**	**B**	**O**	
Fire and fumes	0	0	0	100	100	0	100	0	0	0	100	100	0	100
Only fumes	95	100	95	0	0	100	0	5	100	5	0	0	100	0
No release	5	0	5	0	0	0	0	95	0	95	0	0	0	0

Table 4-13 show the applied incident location probabilities, which are identical to those applied for the diesel vehicle model (Table 4-4). Here, the distribution zone is presented as one state because weather the dumper will be blocking evacuation routes or not is modelled in another node.

Table 4-13 Conditional probabilities applied for the initial location of an incident.

Initial vehicle location	Distribution (%)
Outside	14.58
Distribution zone	0.17
Access tunnel work front	0.75
Access tunnel midway	50.00
Motorway tunnel	34.50

The location of the burning BEV is modelled a bit different than the location of the burning diesel vehicle. This is due to the fact that warnings from the BMS allow for the possibility to move the BEV before the fire ignites. In case of a BMS warning there may be time to move the dumper to a less critical location e.g., out of the tunnel or to a non-blocking location in the distribution zone, or even into one of the tunnel tubes. Table 4-14 summarizes the probabilities of moving the BEV. In case of a general fire or an accident-causing damage to the battery without a BMS warning, the probabilities of the final location will be the same as the initial location. For this reason, the probabilities in Table 4-14 modify location of an incident in case a warning was issued. For the diesel dumper the corresponding tables contains the same probabilities as in column 'Loss of control', meaning that the diesel dumper will not be attempted to move after ignition. The values are based on engineering judgement as there currently are no experience with BEV dumper fires in tunnel construction sites.

Table 4-14 Conditional probabilities applied for moving the vehicle in case of an incident.

	Distribution (%)		
BMS action	**Loss of control**	**'Stop' warning**	
Fire cause		**Battery**	**Other**
Moved outside	0	30	0
Non-blocking	50	70	50
Blocking	50	0	50

Reaching the outside, a refuge chamber, or failing to self-rescue is independent of the fuel type and therefore, the safe shelter node with its conditional probabilities in Table 4-15 is identical to the one in the diesel model (Table 4-6).

Table 4-15 Conditional probability table for the duration of safe shelter.

Safe shelter duration	Distribution (%)	
	Outside	Inside
Indefinitely	99.5	0
Refuge chamber	0	99.5
No shelter	0.5	0.5

Smoke is considered to prevent evacuation and fire fighter access, i.e. fuel type independent and therefore, the conditional probability table, Table 4-16, concerning evacuation is identical to the one applied in the diesel model (Table 4-7).

Table 4-16 Conditional probability table for probability of evacuating past the incident.

Smoke in evacuation route	Distribution (%)					
	Smoke					No smoke
Final vehicle location	Outside	Access tunnel work front	Access tunnel midway	Distribution zone	Motorway	
Fire suppressed	100	10	20	1	1	100
Fire burning	0	90	80	99	99	0

4.7 Output from the models

For both the BEV and the diesel model, the output is given in terms of an estimated number of fatalities. This is the average number of fatalities weighed by the probability distributions for the number of people in the tunnel. The BN models allow for making the results conditional on various states e.g., location of the fire, duration of the fire, external fire fighter's access, possibility to evacuate past incident etc. Hence, results can be presented for a number of initial conditions.

Results are presented in chapter 5 both in terms of fatalities given a fire as outcomes of the described models in this section and also as risk numbers combining fatalities given a fire and the probabilities that fires will occur.

5. Results

Risk results are in the following given for fire scenarios at various locations in the tunnel for both BEV and diesel dumpers. The results are shown for final incident locations that are logically possible for the considered construction phase. For instance, it is not possible to have an incident in the motorway tunnel when the work front is still in the access tunnel. Final incident location means where the vehicle will stand while burning. This can be the same as the 'initial incident location' which is where a hazard was noticed, if the dumper was stopped right-away. Otherwise, it is different from the 'initial incident location', if it is possible to move the dumper to a less critical location. The possible combinations of 'incident location' (1 to 5) and work phase (1 to 3) are listed in Table 5-1.

Table 5-1 Valid incident location and work phase combinations.

	Work phase		
	Access tunnel	Distribution zone	Motorway
Outside	Case 1.1	Case 2.1	Case 3.1
Midway access tunnel	Case 1.2	Case 2.2	Case 3.2
Work front access tunnel	Case 1.3	—	—
Distribution zone	—	Case 2.4	Case 3.4
Motorway	—	—	Case 3.5

In the following, consequences in terms of expected number of fatalities given a fire in a dumper are estimated both with and without early mitigation measures (local fire suppression or battery flooding). The risk is afterwards estimated considering the frequency of fires.

The following three subsections are structured as illustrated in Figure 5-1.

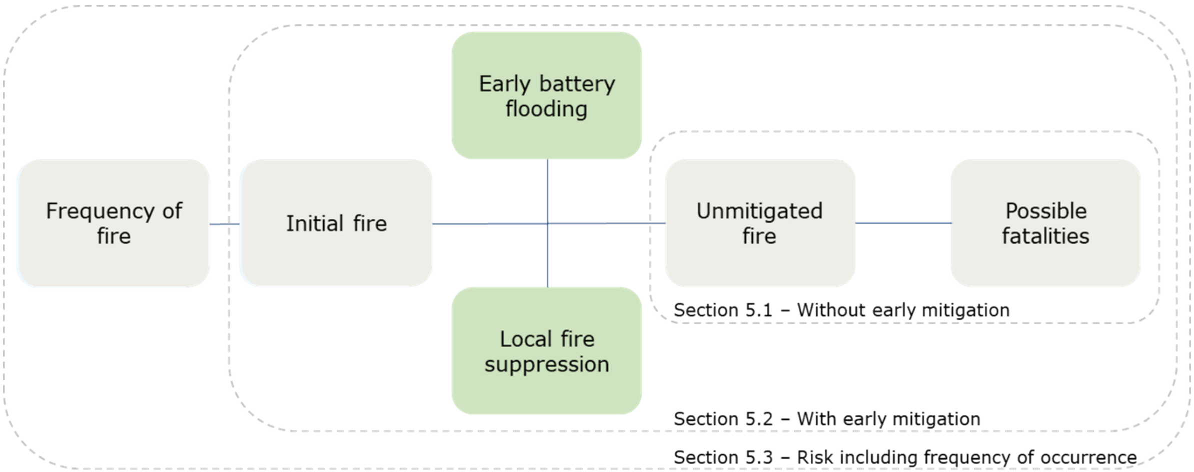

Figure 5-1 Estimation of consequences with and without early mitigation measures.

In sections 5.1 and 5.2 the results shown are expected number of fatalities given a dumper fire at various locations. To compare the results from BEV and diesel dumpers further, F-N-diagrams have been prepared. These are used to illustrate not only the average number of fatalities but also how number of fatalities are foreseen to be distributed in the tunnel, see Appendix 6. The F-N diagrams give corresponding values of the probability (F) of N or more fatalities. It is therefore possible to study differences from BEV and diesel dumper results regarding both the actual level and the change in shape of the F-N curves.

In section 5.3 the risk is calculated considering the fatalities as found in sections 5.1 and 5.2 but also taking into account the likelihood that a fire will actually occur. Fire statistics indicate that there is a difference in likelihood between BEV fires and diesel/petrol vehicles. Fires in diesel vehicles are found to be a factor of 4.6 more likely than BEV fires, see section 2.6. These fire statistics are based on passenger cars, and it is assumed that early mitigation by fire suppression from the driver are not in general applied. Therefore, the effect of early mitigations is considered insignificant in relation to the general difference in fire frequencies between BEV and diesel/petrol fires.

5.1 Estimated number of fatalities – without early mitigation measures

The estimated number of fatalities are presented below as bar charts (Figure 5- and Figure 5-3) for the five different 'final incident locations' in a situation, where a fire breaks out and no local fire suppression and battery flooding are considered.

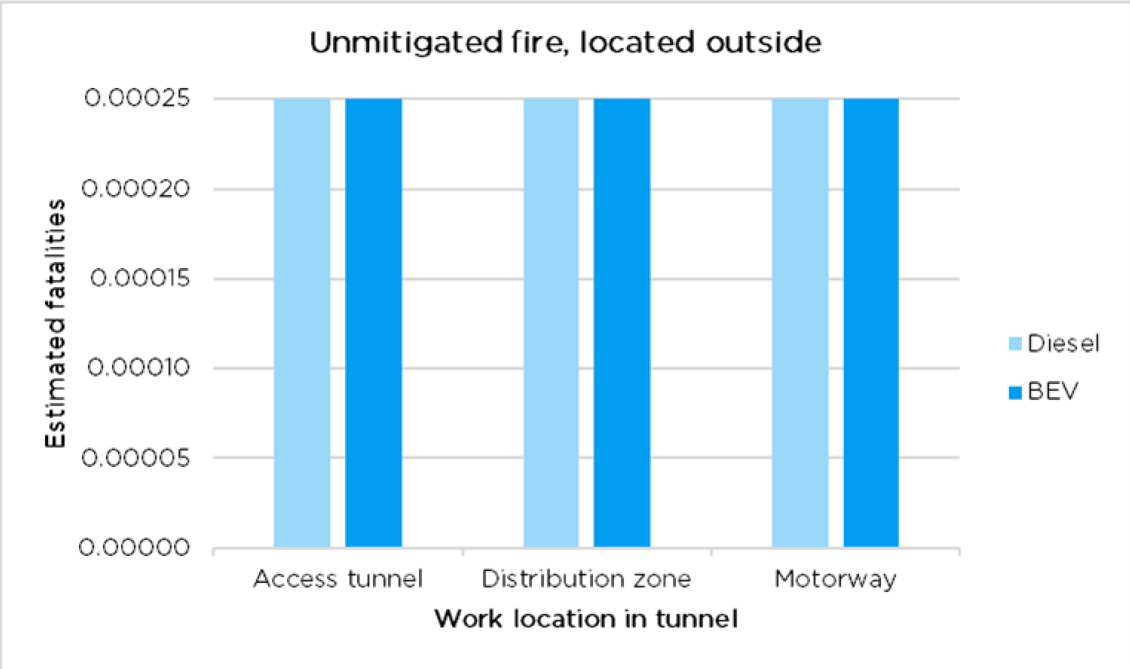

Figure 5-2 Estimated fatalities for an incident occurring outside the tunnel, where the fires is not mitigated, while working in either the access tunnel, distribution zone or motorway tunnels.

As seen in Figure 5-2, incidents occurring outside the tunnel have the same estimated number of fatalities for all construction phases and both types of fuel. This is due to the fire being located outside, where the only requirement for being safe, is to reach a safe area, hence the presence of refuge chambers are irrelevant. This probability of personnel reaching a safe area does not differ for diesel and BEV dumpers when fire breaks out outside the tunnel.

Figure 5-3 show the estimated number of fatalities for unmitigated fires with different incident locations inside the tunnel.

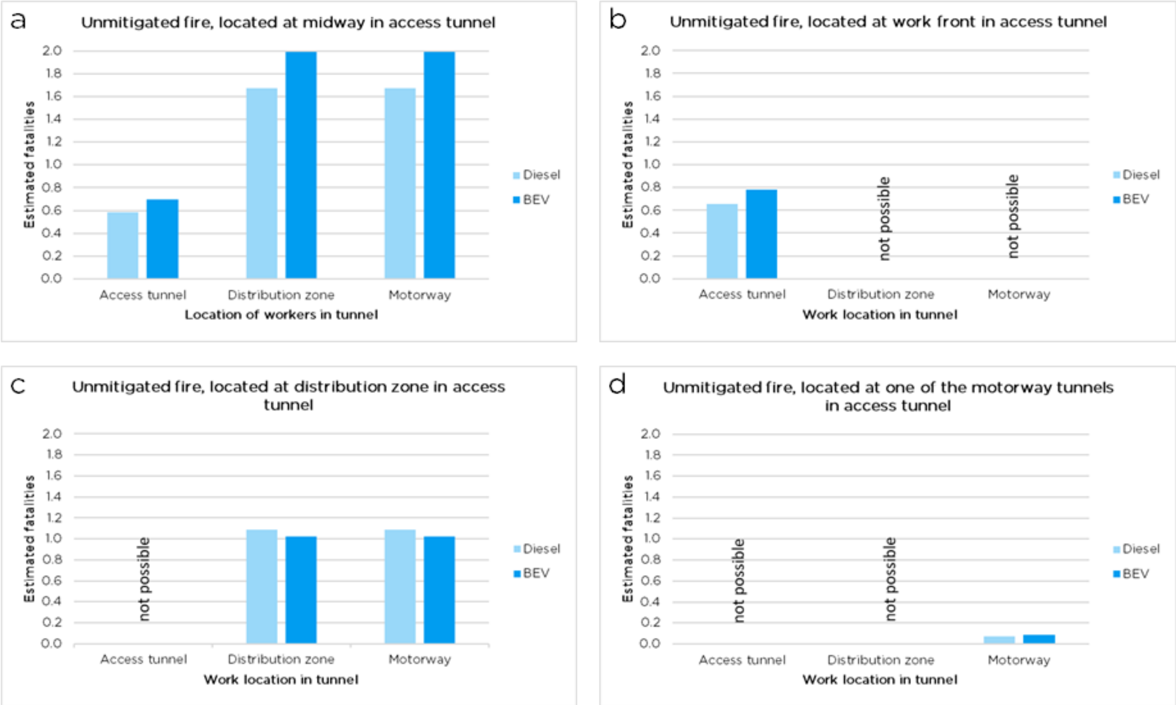

Figure 5-3 Estimated fatalities for incidents occurring at various locations inside the tunnel, where the fire is not mitigated, while working at different locations. a) Midway in the access tunnel while working in the access tunnel, distribution zone, or motorway tunnel; b) Work front of the access tunnel while working in the access tunnel; c) Distribution zone while working in the distribution zone or the motorway tunnels; and d) Motorway tubes while working in the motorway tunnels.

In all incident cases occurring inside the tunnel (Figure 5-3), a fire in a diesel-powered dumper result in lower consequences than a fire in a BEV dumper. The reason for this is, that fires for BEV are assumed to have longer durations than fires in diesel dumpers. Therefore, the probability of not being able to get people out in due time is larger for BEVs than for diesel dumpers. It is, however, also seen that the differences in the estimated number of fatalities are not very large. This is primarily due to the fact, that in the Rogfast tunnel the smoke will be present in the access tunnel for quite a while (even if the fire is extinguished quite fast) making it hard for the emergency response personnel to enter the tunnel.

5.2 Estimated number of fatalities – with early mitigation measures

This section presents the estimated number of fatalities assuming early mitigation measures are in place. It is assumed that fire extinguishers to suppress a small fire, e.g., a fire starting from the ignition of a hydraulic oil leak, will be available and fully functioning. Furthermore, it is assumed that the BEVs are prepared for battery flooding. It is noted that even if early mitigation is possible, it will not succeed in all cases. This depends on the nature of the fire, early detection etc. In this study the following probabilities of successful fire extinguishing (see sections 4.4 and 4.6) are assumed:

- Local suppression of fires = 30%
- Flooding of battery with BMS warning = 90%
- Flooding of battery without BMS warning = 10%

Results for the estimated fatalities for the different incident locations, when mitigation measures are attempted, are given in Figure 5-4 and Figure 5-5.

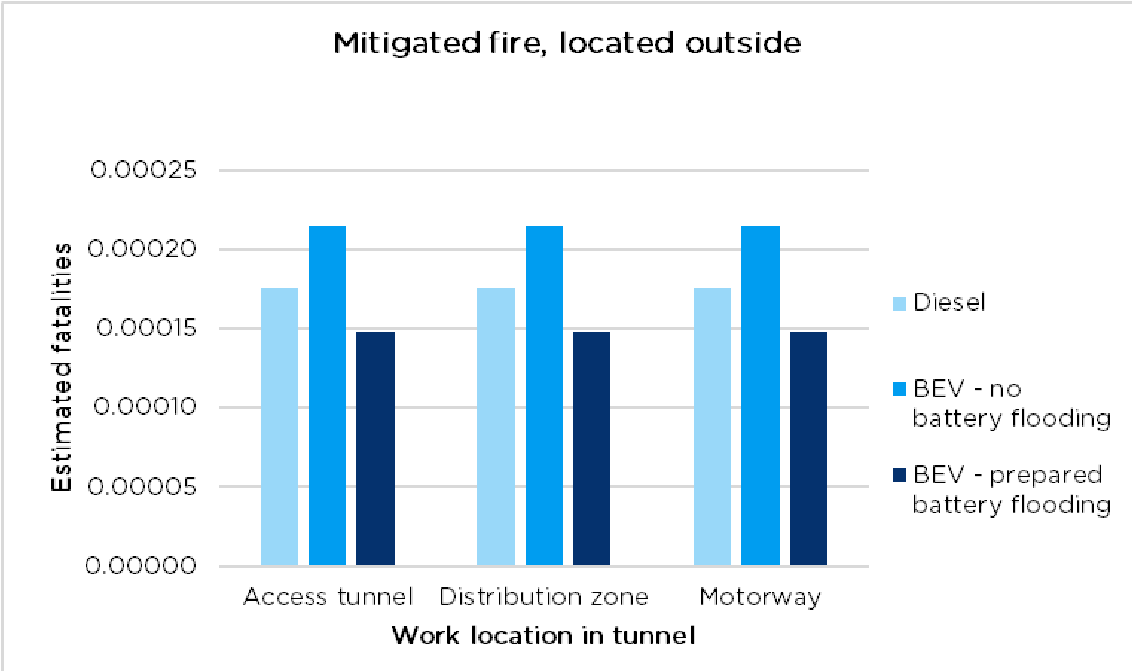

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Figure 5-4 Estimated fatalities for an incident occurring outside the tunnel, where the fire is attempted to be mitigated, while working in the access tunnel, distribution zone or the motorway tunnels.

Figure 5-4 shows identical results for all three construction phases, this is because the number of people close to the fire outside will be same regardless. In all cases the consequences are rather small. The BEV with a battery flooding system is performing marginally better than the others.

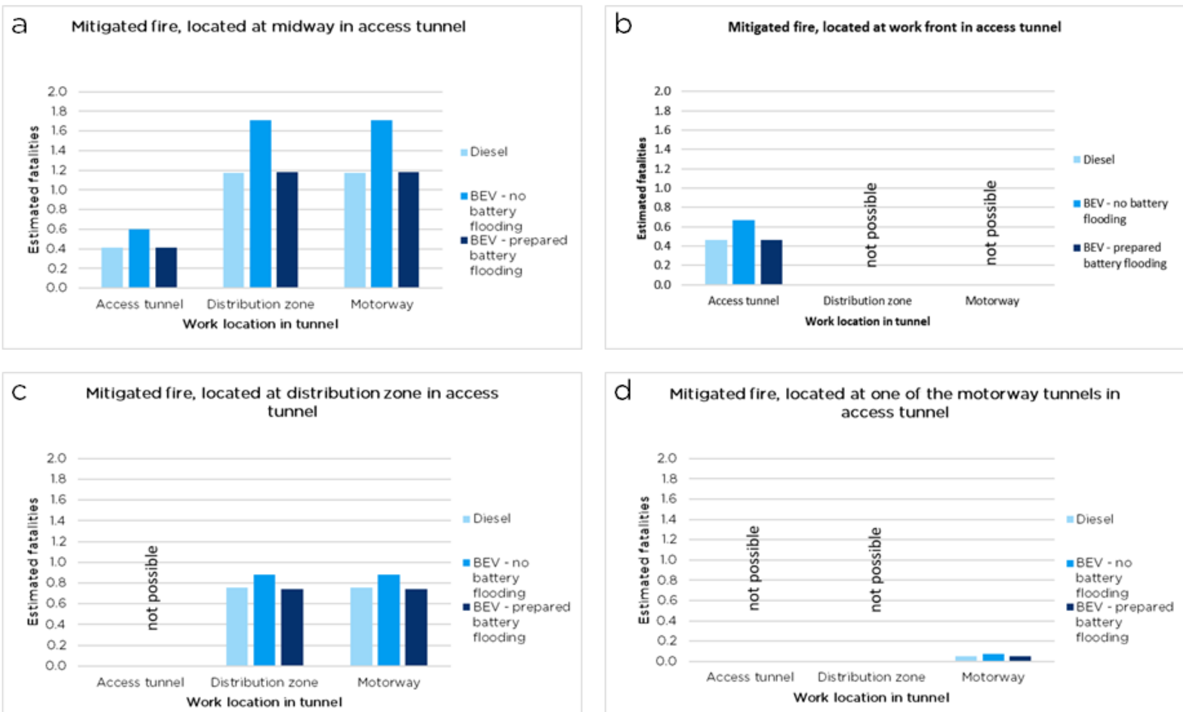

Figure 5-5 Estimated fatalities for incidents occurring at various locations inside the tunnel, where the fire is attempted to be mitigated, while working at different locations. a) Midway in the access tunnel while working in the access tunnel, distribution zone, or motorway tunnel; b) Work front of the access tunnel while working in the access tunnel; c) Distribution zone while working in the distribution zone or the motorway tunnels; and d) Motorway tubes while working in the motorway tunnels.

From Figure 5-5 it is seen that the BEV is estimated to result in the highest number fatalities in all work phases and incident locations. Diesel dumpers and BEVs with a battery flooding system perform nearly identical and show the best estimates. The bar charts show that the consequences in case of fires with early mitigation measures like local fire suppression and battery flooding are reduced compared to the cases with no early mitigation. Further, it is seen that the effect of the battery flooding brings down the number of fatalities for the BEV dumpers to a level very close to the diesel dumpers.

5.3 Risk of fatalities

The bar charts in sections 5.1 and 5.2 showed consequences in terms of estimated number of fatalities given a fire in BEV and diesel dumpers for situations with or without early mitigation measures in place. However, in order to make a more precise comparison of the two dumper types, it is necessary to also consider the probability of a fire in the two different dupers. In this way, the risks are compared directly rather than only focussing on the consequences. Since fire frequency statistics are given per driven kilometre (determined in section 2.6), it is important to also consider:

- The driving distances for different construction phases.
- The time it takes to complete a work phase.
- The entire construction period.

From this, the risk R can be expressed as the expected number of fatalities per year.

In Figure 5-6 and Figure 5-7 the risk in terms of expected fatalities per year are given for the different considered incident locations.

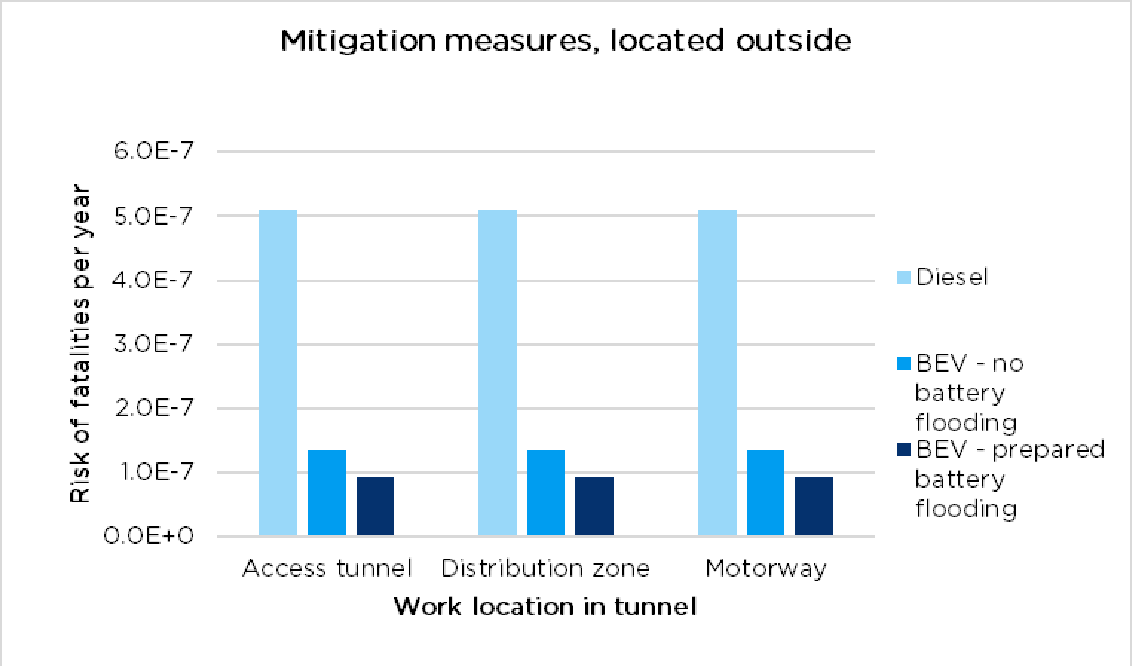

Figure 5-6 Calculated risk of fire incidents outside the tunnel, where the fire is attempted to be mitigated, while working in the access tunnel, the distribution zone, or motorway tunnels.

Figure 5-6 shows the risk of fatalities per year outside the tunnel due to a dumper truck fire. The BEV variants perform significantly better than the diesel dumper. A battery flooding system improves the estimated risk even further.

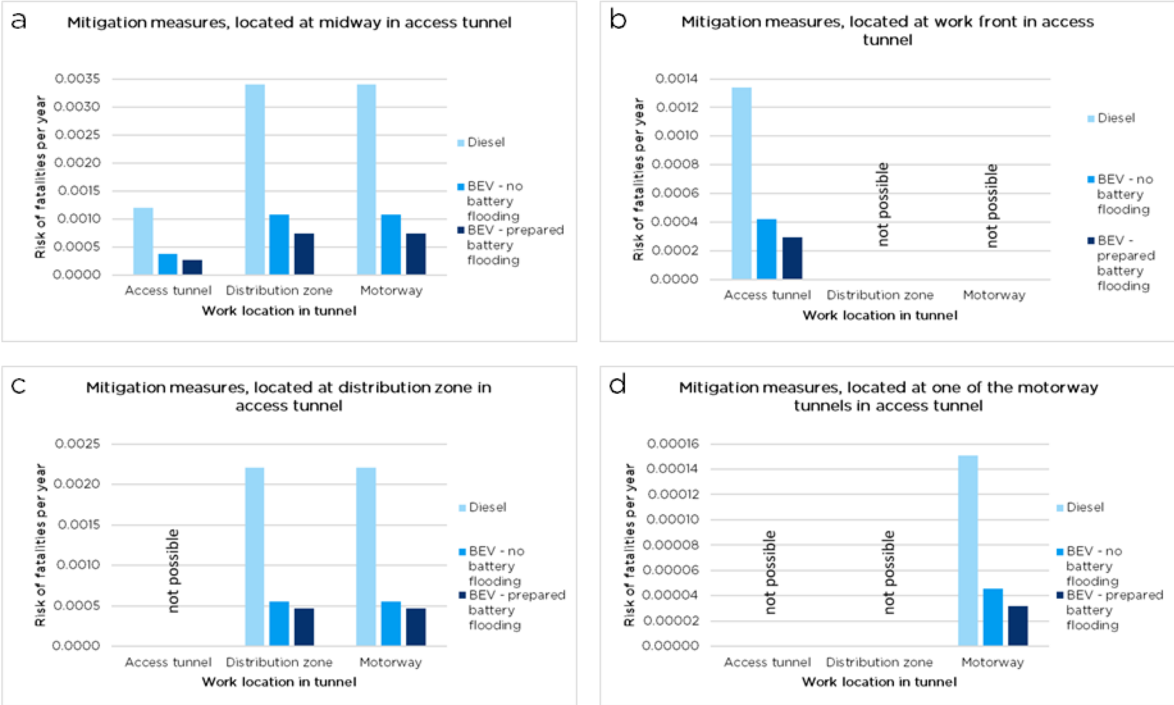

Figure 5-7 Calculated risk of fire incidents inside the tunnel, where the fire is attempted to be mitigated, while working at different locations. a) Midway in the access tunnel while working in the access tunnel, distribution zone, or motorway tunnel; b) Work front of the access tunnel while working in the access tunnel; c) Distribution zone while working in the distribution zone or the motorway tunnels; and d) Motorway tubes while working in the motorway tunnels.

It is seen in Figure 5-7 that in a risk perspective accounting for both incident consequences and incident frequencies, the BEVs perform better in terms of the estimated number of fatalities per year. The ratio between the estimated risk of fatalities for diesel fires and BEV fires without the possibility for battery flooding range from about 3.2 to 3.8 depending on incident location and location of workers. In case of successful installation of battery flooding systems, the ratio between diesel fires and possibly mitigated BEV fires may be even higher, up to about 4.6 to 5.5.

The results given in this section shows in general, that consequences in case of a fire tends to be a little more serious for BEVs than for diesel (all depending on successful installation of early mitigation measures). However, the large difference in a risk perspective lies in the fire frequencies where statistics shows that fires in BEVs tends to occur less frequent than for diesel dumpers. In order to verify the overall risk numbers given in this section, it is recommended to follow up on these frequency statistics, or at least to try to verify that statistics for ordinary vehicles can be taken as a basis also for special construction vehicles.

5.4 Sensitivity analysis

The BN-model tool used to determine fatalities given a fire incident as described in chapter 4 has installed features to carry out studies of the importance of the single nodes and the relations between the nodes. Hence, it is possible to determine which input parameters will be having significant impact on the resulting consequences, and it is also possible to look into critical pathways through the network. The resulting influence of single nodes and node connections are represented by arrow thicknesses in Figure 5-8 and Figure 5-9.

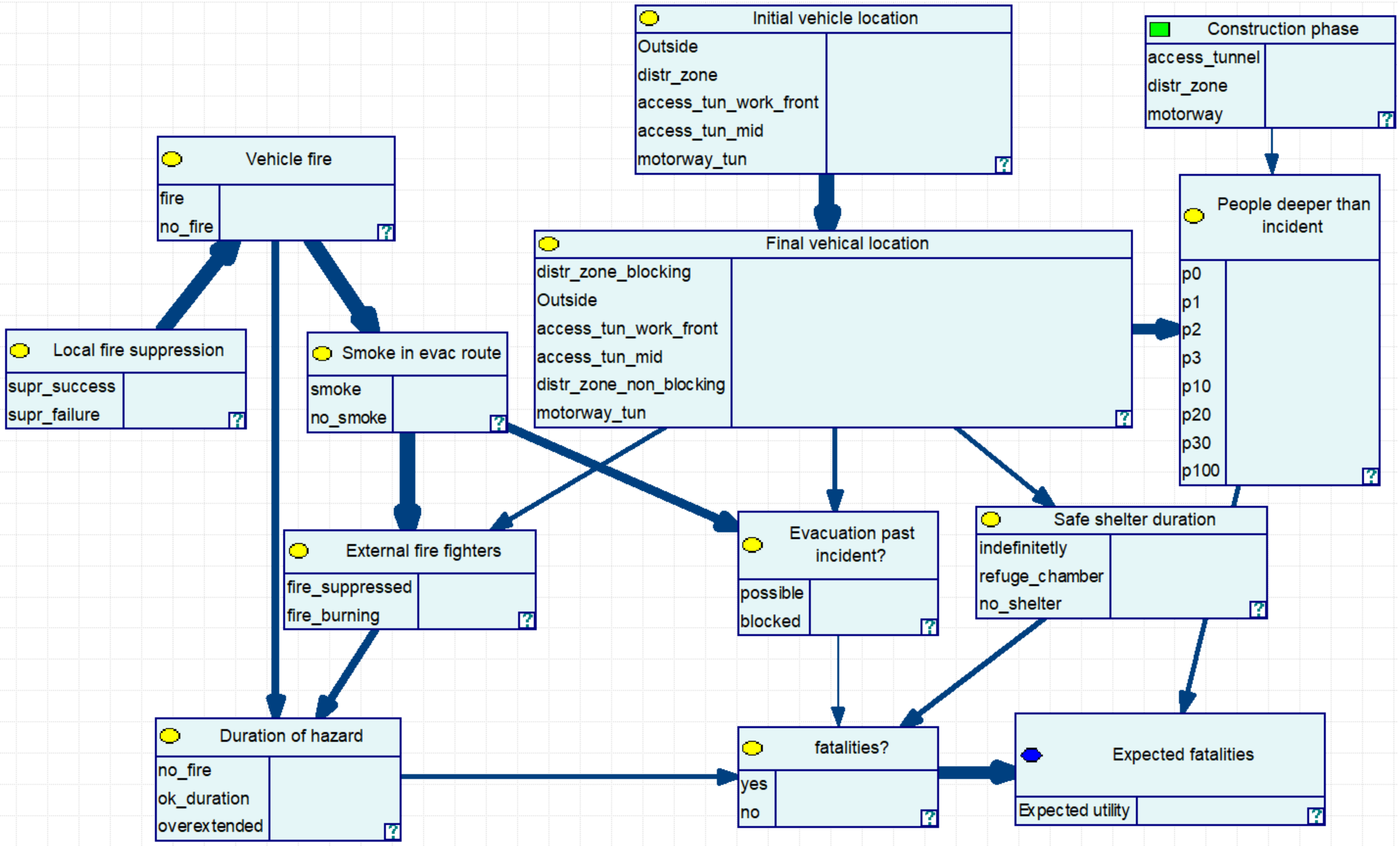

Figure 5-8 Sensitivity study of the BN diesel vehicle model.

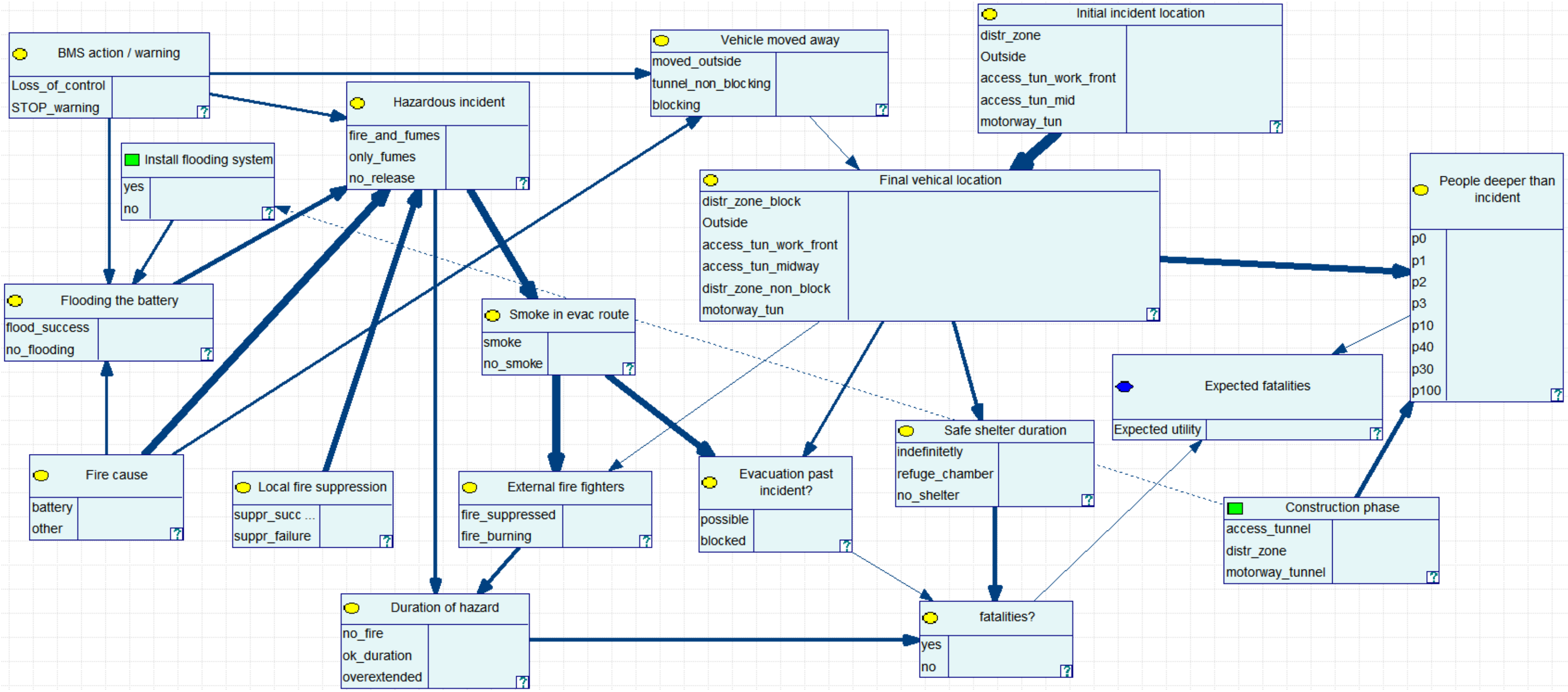

Figure 5-9 Sensitivity study of the BN BEV model.

It is noted that the arrow thickness do not alone decide if the node or node connection points is relevant to study further. It also relates to the type of input given in in the individual node. For this reason, the arrow thicknesses and node parameters shown in Figure 5-8 and Figure 5-9 are reviewed and discussed in the following as a basis for determining parameters for the sensitivity study.

For both the diesel model and the BEV model, the node 'Local fire suppression' has a significant effect on the results. For this reason, the probability of successful local fire suppression is undertaken in the sensitivity study.

For the BEV-model it is seen that also the fire cause (battery related or other) is influencing the results. For this reason, the probability of the cause of fire is battery related is investigated in the sensitivity study.

Further, for both the BN BEV-model and the BN diesel model the three nodes leading up to the 'fatalities?' node are highly relevant due to their direct influence on occurrence of fatalities. Hence, parameters influencing these nodes are investigated further. By studying input to these nodes, it turns out that in general two parameters have significant influence:

- The probability of not being able to evacuate past the incident in case of a fire.
- The duration of the fire, and hence the ability to stay safe in rescue chambers.

For the above-mentioned parameters, sensitivity studies are carried out to study the effect from changes of these parameters to the resulting number of fatalities.

Besides parameters influencing the consequence model, a sensitivity study of the fire frequencies, or the ratio between fire frequencies in BEV and diesel vehicles is carried out. Results of all the sensitivity calculations are given in the following.

5.4.1 Local fire suppression

The graphs in Figure 5-10 visualize the sensitivity of the BN-models to various success probabilities of local fire suppression. In the calculations the initial incident location 'midway in the access tunnel' is applied because this location is the most critical, and the location is relevant in all three construction phases. The local fire suppression sensitivity tests is based on consequences and not risks. Hence frequencies are not included.

For each construction phase two graphs are presented. The figures in the left column of Figure 5-10 (a, c, e) show the fatality ratio. This is the ratio of the fatality for the displayed probability of local fire suppression and the diesel base case fatalities. The diesel base case is the fatalities of a diesel dumper fire with a 30% chance of suppressing the fire locally. The inclination of these graphs indicates how sensitive a model is to a change in the success of the local fire suppression probability. The steeper the graph, the more sensitive the parameter is found to the modelled results. The figures in the right column of Figure 5-10(b, d, f) show the estimated number of fatalities. These figure types reveals if the probability of the success of the local fire suppression changes the ranking between the models in terms of the estimated number of fatalities.

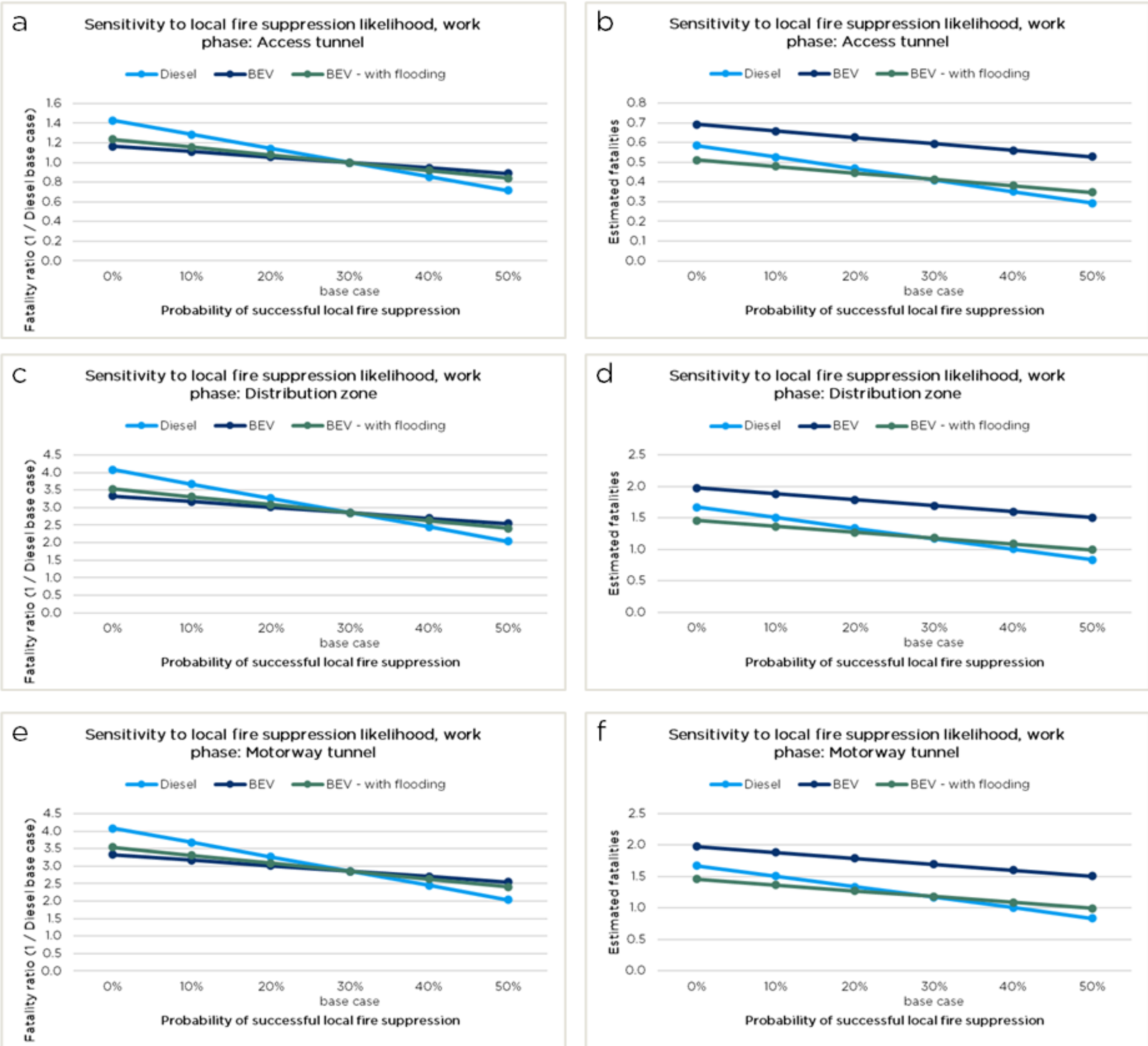

Figure 5-10 Sensitivity test results for the test where the success likelihood of local fire suppression is investigated. The left colum (a, c, e) visualizes the sensity through the steepness of the graphs. The right column (b, d, f) shows the effect of fire suppression on estimated number of fatalities.

From Figure 5-10 a, c, and e it becomes clear, that the diesel model is most sensitive to a change in the success rate of the local fire suppression parameter. This is the case because local fire suppression acts on all possible fires. For the BEV, fire suppression is possible to other means than just local fire suppression which makes the BEV BN model less sensitive to the local fire suppression than the diesel BN model.

From Figure 5-10 b, d, and f it is seen that consequences calculated from the BEV model remain higher than the consequences of the diesel and the BEV with battery flooding models for all parameter values. The consequences of the diesel and the BEV with battery flooding models show similar consequence levels.

5.4.2 BEV fire cause

The fire causes of the BEV are divided into two causes: battery related and other. The graphs in Figure 5-11 visualize the sensitivity of the model to various ratios of these causes. In the calculations the initial incident location 'midway in the access tunnel' is applied because this location is the most critical, and the location is relevant in all three construction phases.

For each construction phase two graphs are shown. The figures in the left column of Figure 5-11 (a, c, e) show the fatality ratio. This is the ratio of the fatality for the displayed fire cause and the diesel base case fatality. The diesel base case the fatalities of a diesel dumper fire. The diesel case is only used to normalize the values, it is not shown because all diesel fires are unrelated to the battery. the inclination of the graphs indicates how sensitive a model is to a change in the fire cause probability distribution. The steeper the graph, the more sensitive the parameter is found to the modelled results. The figures in the right column of Figure 5-11 (b, d, f) show the estimated number of fatalities. These figure types reveals if the probability of fire cause changes the ranking between the models in terms of estimated fatalities. The base case has a ratio battery related to unrelated fires of 53% : 47% and is based data from, ref. /21/.

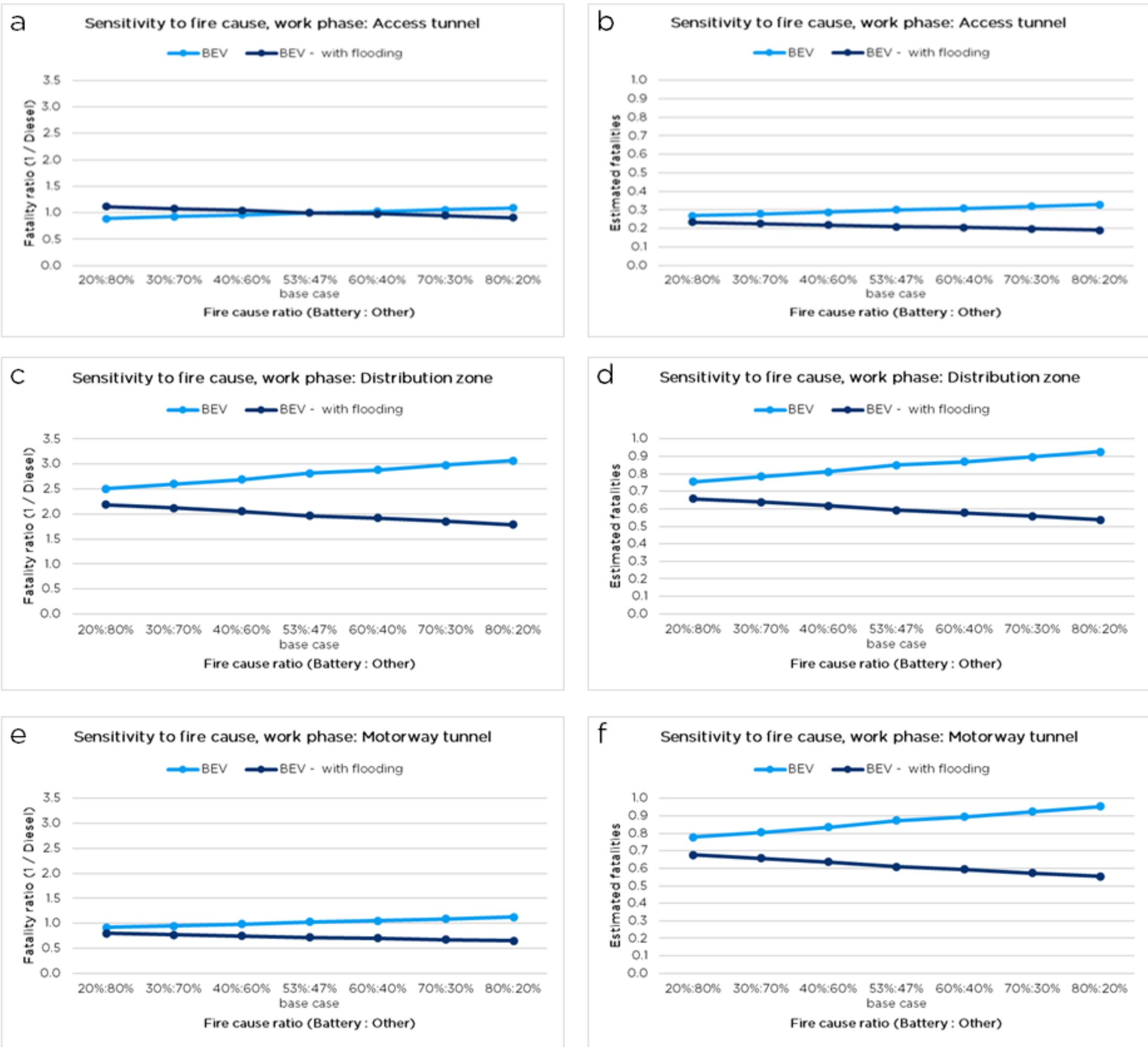

Figure 5-11 Sensitivity test results for the test where the fire cause is investigated. The left column (a, c, e) visualizes the sensitivity through the steepness of the graphs. The right column (b, d, f) shows the effect of fire suppression on estimated number of fatalities.

From Figure 5-11 a, c, and e it becomes clear, that the BEV models regardless of the presence of battery flooding system are nearly equally sensitive to the parameter changes. Notice, that the graphs are diverging, which means that the BEV without a battery flooding system will perform worse with a higher likelihood of the fire being battery related. On the hand, the model for the BEV with battery flooding performs worse if more fires are started as other causes. This is due to that in the BEV model without battery flooding system, only local fire suppression can act, which is limited to fire causes which are non-battery related. For the BEV model with flooding of the battery being a possibility the desired effect of battery flooding is reduced if less fires are battery related.

From Figure 5-11 b, d, and f it is observed, that consequences obtained from the BEV model remain higher than the BEV model with battery flooding for all parameter values.

5.4.3 Evacuation probability

The graphs in Figure 5-12 visualize the sensitivity of the BN-models to various probabilities of the evacuation route(s) being blocked by smoke. In the calculations the initial incident location 'midway in the access tunnel' is applied because this location is the most critical, the location is relevant in all three construction phases. The sensitivity tests of evacuation likelihood in case of a fire incident the access tunnel is based on consequences and not risks. Hence frequencies are not included.

It is assumed that evacuation is impossible if there is smoke is in the tunnel. Exceptions are possible evacuation through the distribution zone with its roundabouts and possible detours via motorway tunnels. For this reason, blocking and non-blocking scenarios are modelled. The second exception are incidents in a motorway tunnel. In such a case the motorway tunnel will fill up with smoke. The model assumes a 90% chance of people being able to evacuate because of the presence of cross passage which may allow entering into a safe tunnel. For the sensitivity study, a range of different evacuation probabilities are considered. Table 5-2 summarize the conditional probabilities applied in the two sensitivity tests. Differences from the base scenario are highlighted in yellow.

Table 5-2 Conditional evacuation table used in the assessment model for 'final vehicle location'.

Smoke	Distribution zone blocking		Distribution zone non-blocking		Access tunnel midway		Motorway	
	Yes	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
Possible	0.9 to 0	1	1	1	0.9 to 0	1	0.9	1
Blocked	1 to 0.1	0	0	0	1 to 0.1	0	0.1	0

For each construction phase two graphs are presented. The figures in the left column of Figure 5-12 (a, c, e) show the fatality ratio. This is the ratio of the fatality for the displayed probability of blocked evacuation routes and the diesel base case fatality. The diesel base case is the fatalities of a diesel dumper fire preventing evacuation due to a smoke-filled tunnel with a probability of 100%. The inclination of the graphs indicates how sensitive a model is to a change in the probability of evacuation route blockage. The steeper the graph, the more sensitive the parameter is found to the modelled results. The figures in the right column of Figure 5-12 (b, d, f) show the estimated number of fatalities. These figure types reveals if the probability of an evacuation route being blocked changes the ranking between the model in terms of estimated fatalities.

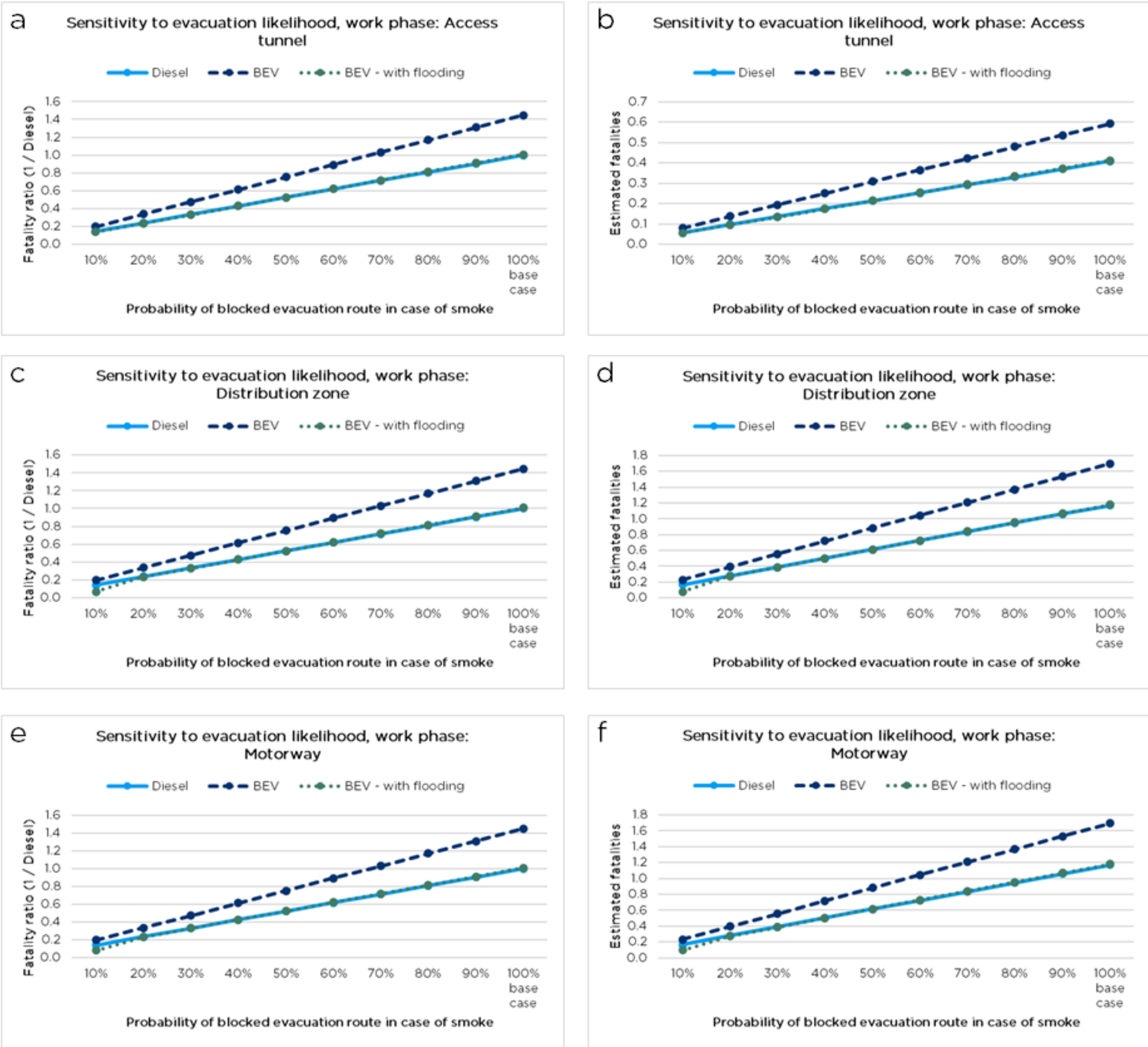

Figure 5-12 Sensitivity test results for the test where the probability for blockage of evacuation routes is investigated. The left colum (a, c, e) visualizes the sensity through the steepness of the graphs. The right column (b, d, f) shows the effect of fire suppression on estimated number of fatalities.

From Figure 5-12 a, c, and e it becomes clear, that the BEV with a battery flooding system model and diesel model are nearly equally sensitive to parameter changes of the blockage of evacuation routes. The larger steepness of the BEV model indicates that the more unlikely it is to evacuate, the more important local fire suppression mitigations become.

From Figure 5-12 b, d, and f it is seen that consequences calculated from the BEV model remain higher than the consequences of the diesel and the BEV with battery flooding models for all parameter values. The consequences of the BEV with battery flooding and the diesel models show similar consequence levels.

5.4.4 Duration of the fire

In the sensitivity tests regarding the fire duration the relevant parameter to be tested in this regard is the probability of overextending the protection time of a refuge chamber. Figure 5-13 concerns unmitigated fires, while Figure 5-14 concerns fires which are possibly mitigated. The figures visualize the sensitivity of the BN models to various probabilities of a BEV fire leading to an overextension of the protection time of a refuge chamber. The probability of an overextension of the protection time of a refuge chamber in case of a diesel fire is kept constant at 10% in the sensitivity tests. The sensitivity study of exceeding the protection time is based on consequences and not risks. Hence, frequencies are not included.

For each construction phase two graphs are presented. The figures in the left column of Figure 5-13 and Figure 5-14 (a, c, e) show the fatality ratio. This is the ratio of the fatality for the displayed probability of safe shelter duration and the diesel base case fatalities. The diesel base case is the fatalities of a diesel dumper fire exceeding the protection time with a probability of 10%. The inclination of these graphs indicates how sensitive a model is to a change in the probability of the safe shelter duration being overextended. The steeper the graph, the more sensitive the parameters is found to the modelled results. The figures in the right column of Figure 5-13 and Figure 5-14 (b, d, f) show the estimated number of fatalities. These figure types reveals if the probability of the overextending the time of the refuge chambers changes the ranking between the models in terms of the estimated number of fatalities.

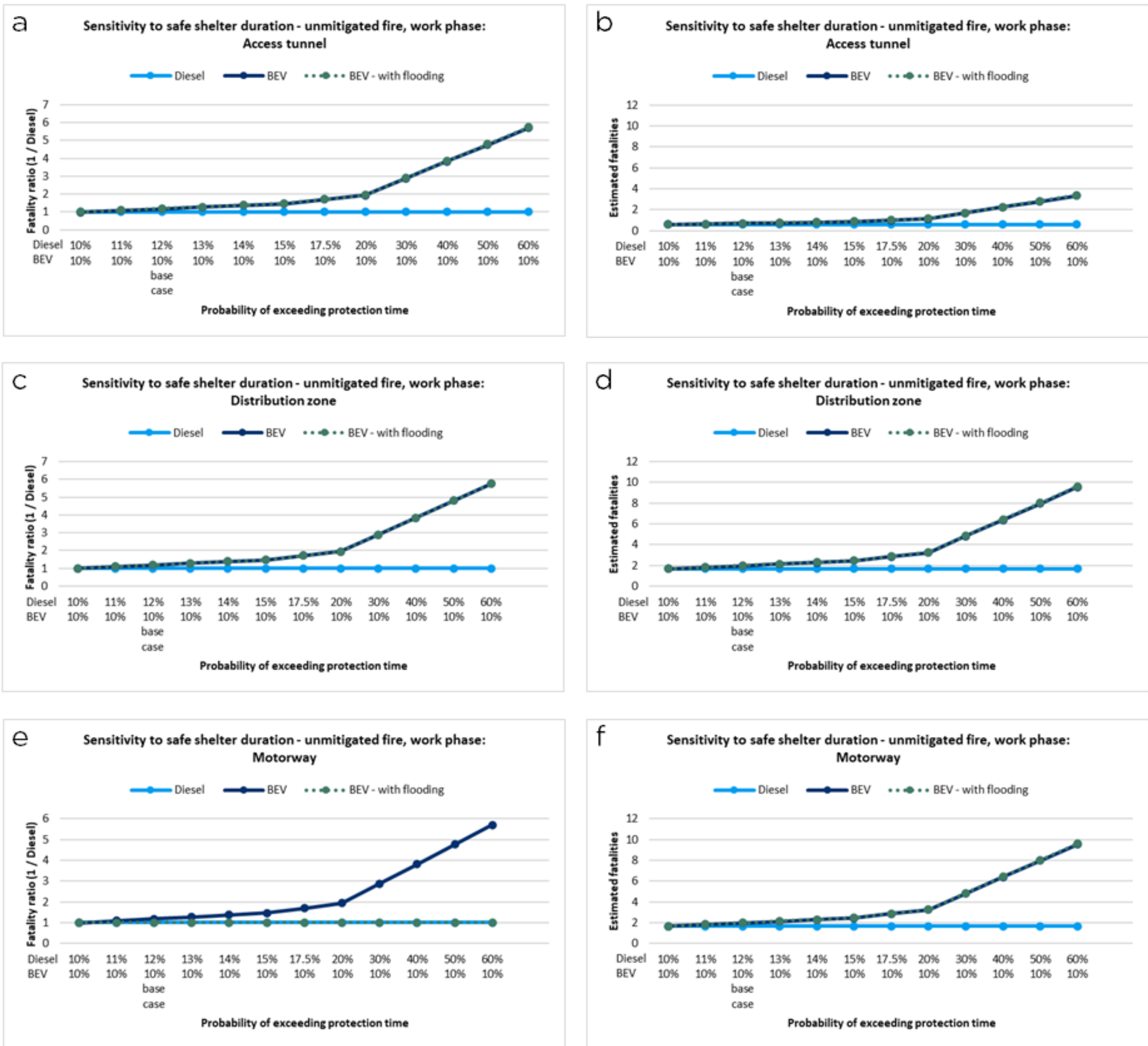

Figure 5-13 Sensitivity test results for the test where the safe shelter duration in case of an unmitigated fire is investigated. The left colum (a, c, e) visualizes the sensity through the steepness of the graphs. The right column (b, d, f) shows the effect of fire suppression on estimated number of fatalities.

Figure 5-13 and Figure 5-14 both show that the time the tunnel atmosphere is not breathable in combination with the protection time of a refuge chamber is the most important factor influencing the number of fatalities given a fire. No difference in consequences is expected if the probability of overextending the protection time for a diesel or BEV fire are equal, meaning both have a 10% probability of overextending the safe shelter duration. Important factors to ensure the safety of people in the refuge chambers is the restoration time of the ventilation hoses after a fire such that smoke and toxic gasses can be cleared out. As the probability for overextending the safe shelter duration skew the results, a higher overextension probability was assigned to BEV fires since they can reignite in case of remaining charge in the battery pack.

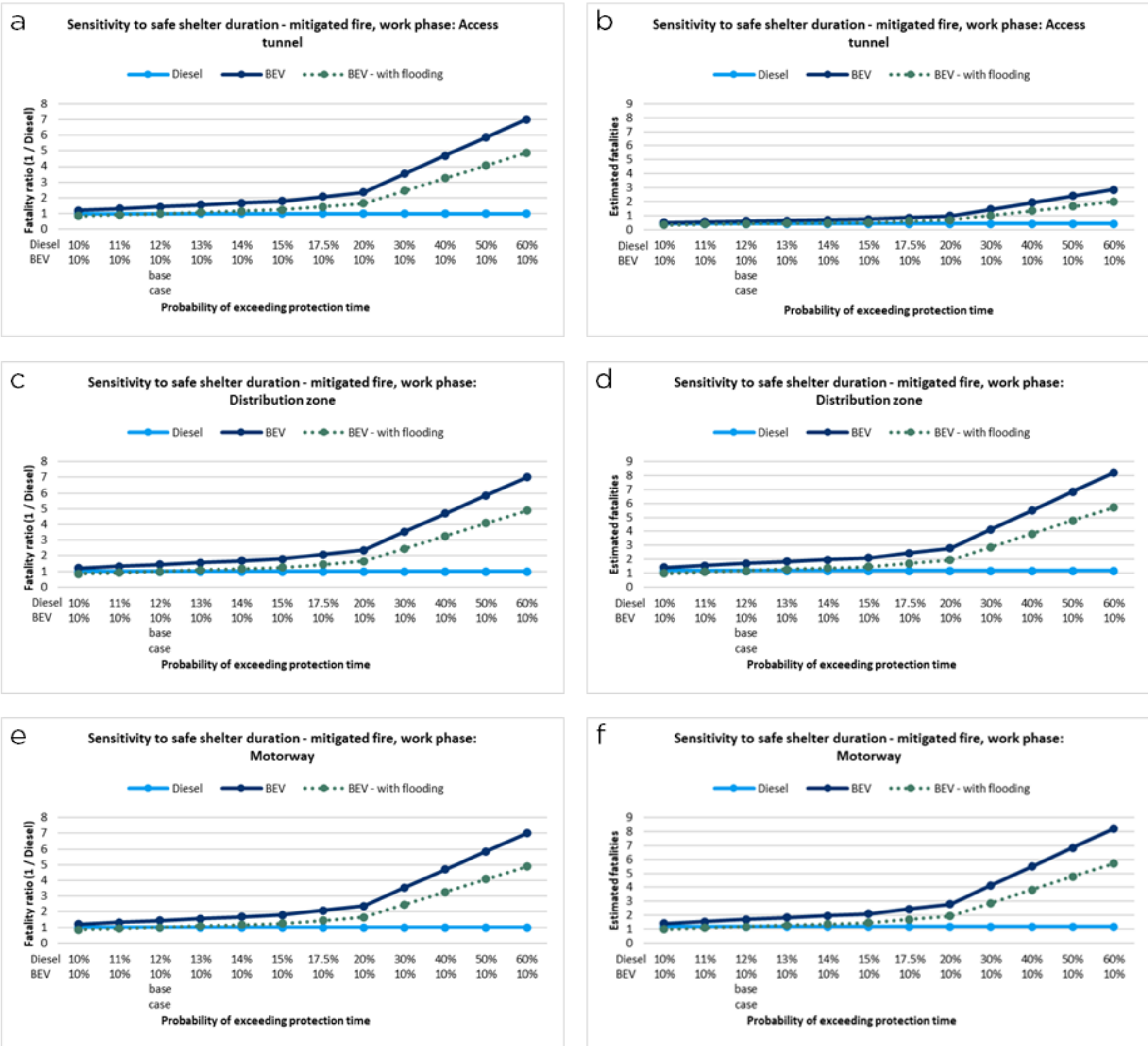

Figure 5-14 Sensitivity test results for the test where the safe shelter duration in case of a possibly mitigated fire is investigated. The left colum (a, c, e) visualizes the sensity through the steepness of the graphs. The right column (b, d, f) shows the effect of fire suppression on estimated number of fatalities.

Considering the possibility for early mitigation measures, the local extinguishing of general fires, and the effect of a battery flooding system can be evaluated. Figure 5-14 shows that an early warning by the BMS in combination with a battery flooding system can reduce the expected consequences and sensitivity of the protection time of refuge chambers.

In case of a 40% chance of overextending the duration of the refuge chambers in case of a possibly mitigated BEV fire, the estimated number of fatalities involved with BEV fires is only about a factor 1.7 higher than what is found for diesel fires. With the possibility for early battery flooding, the factor becomes even lower. Considering the different initial fire frequencies as seen in section 5.3, it is assessed that the overall risk is still not higher for BEVs than for diesel vehicles.

5.4.5 Fire frequencies

The base case of the fire frequency ratio is 1:4.6 for diesel to BEV fires according to ref. /24/. For the sensitivity study this ratio is varied from 1:20 (small) up to 1:1 (large). The graphs in Figure 5-15 visualize the sensitivity of the BN models to various fire frequencies. In the calculations the initial incident location 'midway in the access tunnel' is applied because this location is the most critical, and the location is relevant in all three construction phases. The tests are based on frequencies and are displaying the calculated risk. Hence, the y-axis shows how much more relative risk is estimated in the BEV model compared to the diesel model.

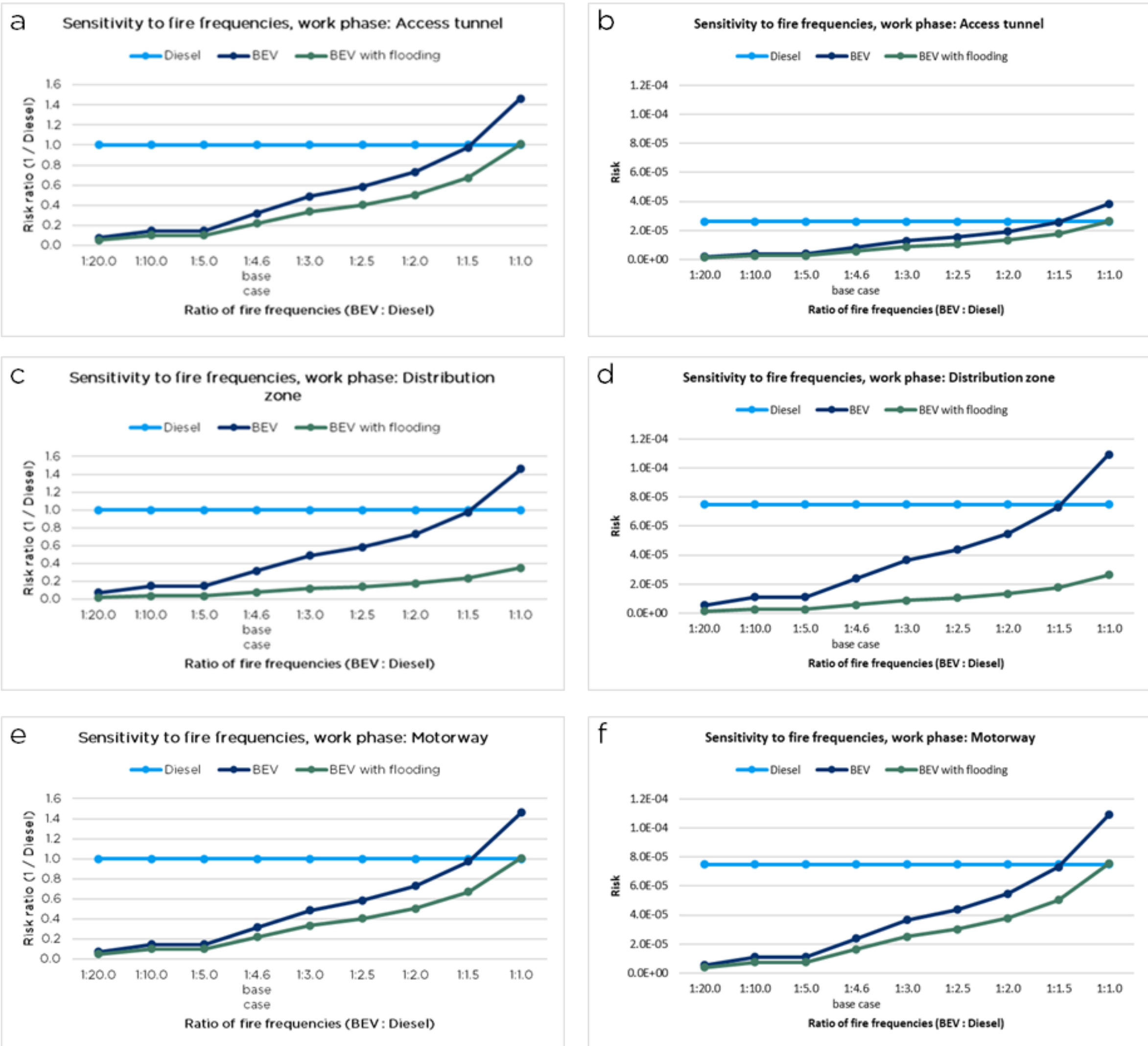

Figure 5-15 Sensitivity test results for the test of the fire frequency shown as the ratio of battery related to unrealted fire causes. The left colum (a, c, e) visualizes the ratio of risk ratio to the diesel case. The right column (b, d, f) shows the calculated risk for each model.

For each construction phase two graphs are presented. The figures in the left column of Figure 5-15 (a, c, e) show the risk ratio. This is the ratio of the fatality for the displayed probability of local fire suppression and the diesel base fatalities. The diesel base case risk is the risk of a diesel dumper fire. The inclination of these graphs indicates how sensitive a model is to a change in the fire frequency. The steeper the graph, the more sensitive the parameter is found to the modelled results. The figures in the right column of Figure 5-15 (b, d, f) show the risk. These figure types reveals if the fire frequency changes the ranking between the model in terms of risk.

Figure 5-15 show that there is generally lower risk associated to BEVs, for a fire frequency ratio between diesel and BEV dumpers of 1:1.5 or smaller. The BEV with a battery flooding system performance equally well or better than a diesel dumper even with a fire frequency ratio 1:1.

5.5 Incidents other than fires

Hazards discussed at the workshop included other scenarios than fire, see chapter 3. However, besides fire, the only incident modelled is the release of fumes from a battery pack. These fumes are toxic and may require people to use breathing apparatus and to find shelter in a refuge chamber or go deeper in the tunnel. As long as the fumes do not ignite, the ventilation system will not be destroyed. For this reason, fumes will be pushed out of the tunnel within an acceptable time frame. Fatalities are not expected, but disruption of work would occur.

The remaining scenarios are assessed qualitatively in the following.

5.5.1 Charging / refuelling

At the workshop, the risk related to charging was initially assessed to be higher for BEVs than for a similar refuelling of diesel dumpers, and indeed overcharging is a cause of fire in BEVs. This contribution to the fire frequency is not explicitly covered in the model. However, fire scenarios as such are described and modelled, and it is found that early mitigation including flooding of the battery is assessed to have a large, positive effect on the risk. Considering a charging situation, the location of the charging is known. Charging outside will only marginally affect the overall risk as the consequences of any fire event outside the tunnel are assessed to be small. In case charging is needed in the tunnel, the location is assumed to be chosen adequately such that a potential fire will not block the escape routes and may be easier managed by early flooding of the battery. Hence, charging may contribute to the risk, but considering the risk in section 5.3, it is assessed that a contribution from possible charging-related fires only add insignificantly to the overall risk for fires related to BEVs.

5.5.2 Mechanical collisions, loss of propulsion, and vehicle run-away

Other incidents like mechanical collisions without fires are not modelled because the fuel type has little to no influence on them. A mechanical collision involving a BEV may damage the battery leading to fire which is covered under the fire events included in the model.

Loss of propulsion and vehicle run-away are also events that are generally comparable between BEVs and diesel dumpers. In case of loss of propulsion, the dumpers will have to be removed in any case, and while some details in providing a spare battery, an extra fuel tank, or towing the vehicles may differ, the difference in risk is assessed to be insignificant. In case of vehicle run-away, the brake systems of the vehicles differ. In general, for BEVs the electrical motor acts as a brake. Also, the BEVs are assumed to have fail-safe brakes such that any loss of power will engage the brakes. This may not be the case for diesel dumpers where the more mechanical brakes may fail, leading to a dumper rolling downwards in the tunnel. The risk is assessed qualitatively to be similar between the two types of dumpers, and at least not worse for the BEVs compared to the diesel dumpers.

5.5.3 Noise, vibrations, and pollution

The risks involved with noise, vibrations and pollution were semi-quantitatively assessed at the workshop, and indeed the limited pollution and noise onsite is one of the main arguments for selecting BEVs over diesel dumpers. The risk is not in the same way as fires directly linked to fatalities, and a detailed, quantitative weighting of the consequences against the fire risk is not performed. However, it is concluded that diesel-powered dumpers may fatigue drivers faster because of the high noise and vibrations. Furthermore, the pollution during ordinary operation impacts health and safety more severely than when using BEVs.

5.5.4 Consequences apart from fatalities and HSE

Besides the risk of fatalities, the fire scenarios as well as scenarios with stranded dumpers will also cause additional costs and delays which may influence the total project costs and the timeline for the project. However, clean-up after fire scenarios will occur after both BEV and diesel dumper fires. Even if clean-up costs after BEV fires should turn out higher than for diesel dumper fires, the lower fire frequency indicate that the total cost may still be in favour of the BEVs.

There may also be logistic differences between using BEVs and diesel dumpers, e.g., the need for additional charging stations or additional vehicles depending on battery capacity and operational conditions compared to standard diesel dumpers. The logistic setup using BEVs may therefore be more costly compared to using standard diesel dumpers. With the risk related to fires assessed to be on par or better for the BEVs, this is a cost that should be compared to the potential sustainability related benefits as well as the health and safety benefits for the personnel related to a reduction in noise, vibrations, and pollution on work site.

6. Conclusion

The analysis shows that the estimated consequences in case of a fire are higher if a BEV is burning compared to a diesel dumper. However, considering that the frequency of BEV fires is assessed to be lower than similar fires in diesel dumpers, the resulting risk is estimated to be lower for BEVs than for diesel dumpers. There are also possible mitigation measures involving early identification of battery problems by mean of the BMS such that the battery can be flooded before a full fire emerges.

Several uncertainties are identified in the study as the statistical background material is limited. It is therefore suggested that any relevant mitigation measures should be investigated to further lower the risk. Such measures include:

- Using the latest battery developments, technologies, and safety features in BMS systems.
- Possibility for early extinguishing of non-battery related fires.
- Possibility for flooding a battery as an early mitigation.
- Placing any underground charging stations in adequate locations not to interfere with escape routes.

Apart from the direct safety risk related to fires, there are other differences between using BEVs and diesel dumpers. Some count in favour of BEVs and some count in favour of diesel dumpers. In terms of logistics, diesel vehicles are the well-known choice, and using BEVs introduces a need for charging stations and potentially additional dumpers depending on the logistics planning. On the other hand, noise, vibrations, and pollution on site is reduced when using BEVs.

6.1 Overall conclusions

The overall conclusions are the following:

- In terms of *risk* (*frequency* x *consequence*) it is assessed not to be more dangerous to perform tunnel operations with BEV dumpers compared to diesel dumpers.
- *The fire frequency* for electrical vehicles is lower than for diesel vehicles (statistics for ordinary vehicles shows a factor 4.6 in favour of BEVs).
- Models show that in case of a fire, the *estimated number of fatalities* is higher for a BEV fire than for a diesel dumper fire.
- Other factors such as logistics may favour use of BEVs or diesel dumpers.
- Disregarding the vehicle type (battery versus diesel), the restricted access for firefighters through the access tunnel tends to make fires critical.

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Appendix 1
Risk register

Appendix 1.1 – Detailed risk register for BEV
Appendix 1.2 – Detailed risk register for diesel

Appendix 2
Risk matrix scoring overview

Appendix 2.1 – Risk matrix scoring overview for BEV
Appendix 2.2 – Risk matrix scoring overview for diesel

Appendix 3
Risk summary overview

Appendix 3.1 – Risk summary overview for BEV
Appendix 3.2 – Risk summary overview for diesel

Appendix 4
Bayesian Network Models

A Bayesian network (BN) is a probabilistic graphical model that allows for reasoning in complex and uncertain problem setting.

BNs define a joint probability distribution (giving the probability for any combination of parameters present in the problem) and represent the joint probability distribution as conditional probabilities a graph structure.

Each node in the graph corresponds to a random variable and the edges connecting nodes represent the dependence relations. In below example node A depends on nodes B and E. Each node represents a conditional probability distribution.

Imagine that Holmes gets a call from Watson W about his alarm A going off. Holmes rushes to his car believing that a burglar B has triggered the alarm. On his way home, the radio news report R an earthquake E in the area. This additional piece of information makes him change his belief in the burglary scenario, as the reported earthquake "explains away" the triggered alarm.

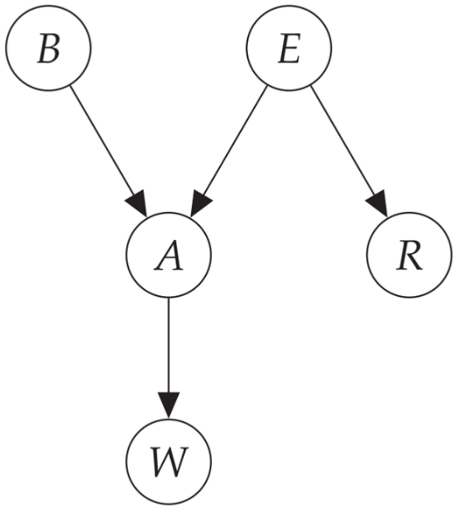


Figure A4. 1 Example Bayesian network propagating information about either a break-in or an earthquake.

B has a prior probability, that is the probability of a burglar entering Holmes' home. The prior probability of break-ins will be low because Holmes has very strong door locks. If the alarm A goes of Holmes will update his belief on the probability of a burglar in his home, his believe will increase the probability. The radio news R could report shaking ground E in the area, which would reinforce Holmes' belief, or report about an earthquake that could trigger the alarm too. So, the radio information can influence the strength of Holmes' belief, i.e., adjust the probability conditional on the alarm and conditional on occurrence or absence of the seismic event.

Appendix 5
Bayesian Network Model Parameters

People affected by vehicle incident

The tunnel is divided into sections as shown in Figure A5.1. The sections are outside, access tunnel work front, access tunnel midway, distribution zone, and motorway tunnel. For an incident in a motorway tunnel only people in that tunnel are potentially prevented from evacuating.

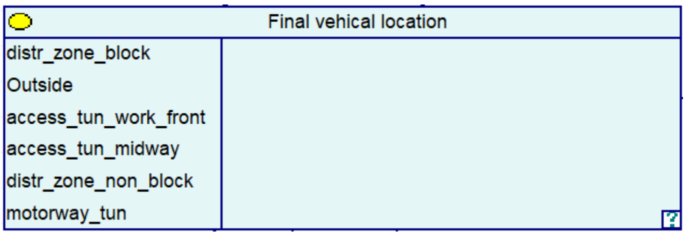


Figure A5.1 Tunnel division in sections.

The number of people present in a certain section of the tunnel is modelled using the Poisson distribution. The probability mass function

$$Pois_{pmf} = \frac{\lambda^k e^\wedge - \lambda}{k!}$$

will show how many people k are present with the probability $Pois_{pmf}$. λ is the rate or mean of people present.

A table of number of people present (mean values) at the incident location in different work phases is shown in Figure A5.1. The final incident location is where the vehicle comes to a still stand to consider the possibility that it could have been moved to a less critical location.

Table A5.1 Mean number of people at the incident location in different work phases.

Incident location	Work phase		
	Access tunnel	**Distribution zone**	**Motorway**
Outside	1	1	1
Midway access tunnel	7	20	20
Work front access tunnel	4	0	0
Distribution zone	0	20	20
One motorway tube	0	0	5

The distributions resulting from above mean values are plotted in the following graphs (Figure A5.2 to Figure A5.7). Note, there is no rate for cross passage non-blocking, this has the same rate as cross passage but is in the model to capture differences in the possibility to evacuate.

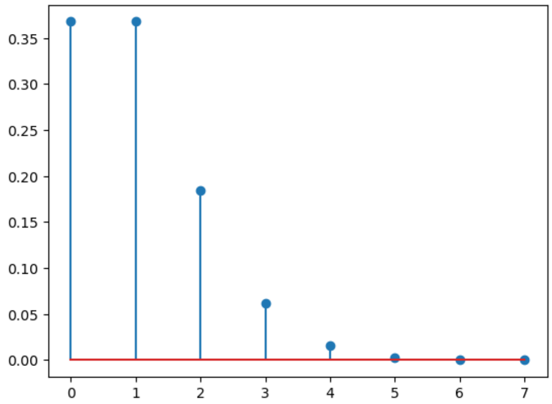


Figure A5.2 All work phases, incident outside. The mean of people present is 1.

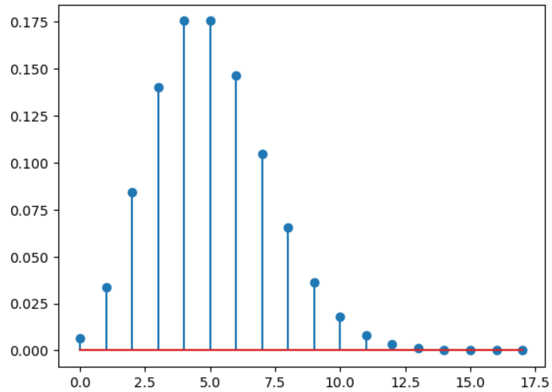


Figure A5.3 Work phase motorway and incident in a motorway tube. The mean of people present is 5.

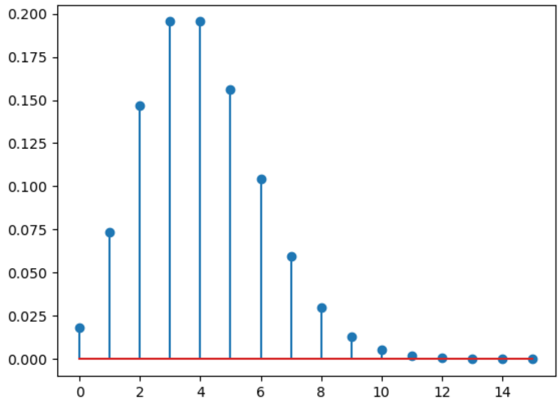


Figure A5.4 Work phase "access tunnel", incident at the work front. The mean of people present is 4.

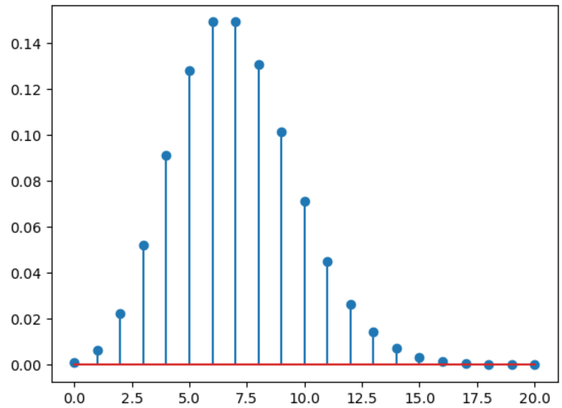


Figure A5.5 Work phase "access tunnel", incident at midway in the tunnel. The mean of people present is 7.

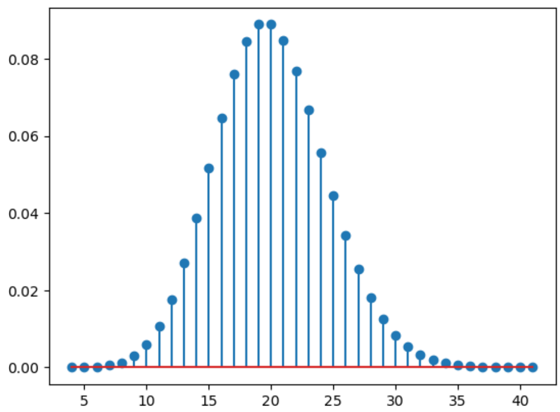


Figure A5.6 Work phase "distribution zone" and "motorway", incident midway single tunnel and in the cross section. The mean of people present is 20.

Nodes common between BEV and diesel Bayesian networks

Safe shelter duration

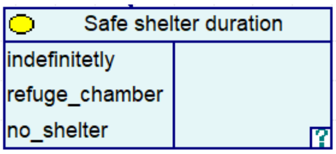


Figure A5.7 States of the 'Safe shelter duration' chance node

This chance node, Figure A5.7, models if a safe shelter is reached by people in the tunnel and what type of shelter. The type influences how long persons are protected by it e.g., refuge chamber or outside of tunnel. In case the incident occurs, and people are deeper in the tunnel than the final incident location 0.5% are assumed to not reach safe shelter. It is seen as a conservative estimate for cases where injury prevents self-rescue.

What type of shelter is reached by people depends on the final incident location. People outside can reach indefinite shelter or do not reach shelter e.g., due to injury. In all other location it is either a refuge chamber or no shelter as detailed in Figure A5.8.

Final vehical location	distr_zone	Outside	access_tun_work_front	access_tun_midway	distr_zone_non_block	motorway_tun
indefinitetly	0	0.995	0	0	0	0
refuge_chamber	0.995	0	0.995	0.995	0.995	0.995
no_shelter	0.005	0.005	0.005	0.005	0.005	0.005

Figure A5.8 'Safe shelter duration' node probabilities

Fatalities?

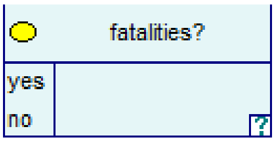


Figure A5.9 States of the 'Fatalities?' chance node

This chance node models whether fatalities occur, see Figure A5.9. Its inputs come for the 'Safe shelter duration', 'Evacuation past incident', and 'Duration of hazard' nodes. If evacuation succeeds no fatalities occur. If no shelter is found or the protective time of the refuge chamber is overextended fatalities occur. The inference is governed by the values shown in Figure A5.10.

Evacuation past incident?	possible						
Duration of hazard	no_fire		ok_duration			overextended	
Safe shelter duration	refuge_chamber	no_shelter	indefinitetly	refuge_chamber	no_shelter	indefinitetly	refuge_chamber
yes	0	0	0	0	1	0	0
no	1	1	1	1	0	1	1

Evacuation past incident?	blocked							
Duration of hazard	no_fire			ok_duration			overextended	
Safe shelter duration	indefinitetly	refuge_chamber	no_shelter	indefinitetly	refuge_chamber	no_shelter	indefinitetly	refuge_chambe
yes	0	0	0	0	0	1	0	
no	1	1	1	1	1	0	1	

Evacuation past incident?	possible							
Duration of hazard	no_fire		ok_duration			overextended		
Safe shelter duration	refuge_chamber	no_shelter	indefinitetly	refuge_chamber	no_shelter	indefinitetly	refuge_chamber	no_shelter
yes	0	0	0	0	1	0	0	1
no	1	1	1	1	0	1	1	0

Figure A5.10 Probabilities of the 'Fatalities?' node

Evacuation past incident?

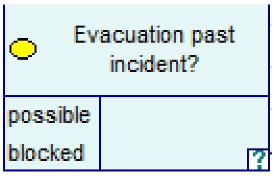


Figure A5.11 States of the 'Evacuation past incident?' chance node

This chance node, Figure A5.11, models whether it is possible to move past the incident to the outside. The node is conditional on smoke in the evacuation route and final vehicle location. If the tunnel, that must be passed to evacuate, is smoke filled it is considered blocked. If there are evacuation routes e.g., in the motorway tubes, it is assumed that in 90% of cases it is possible to change to an unaffected tunnel and escape to the surface. If escape is not possible refuge chambers are the next step in the model. The inference is governed by the values shown in Figure A5.10.

Final vehical location	distr_zone		Outside		access_tun_work_front	
Smoke in evac route	smoke	no_smoke	smoke	no_smoke	smoke	no_smoke
possible	0	0	1	1	0	1
blocked	1	1	0	0	1	0

Final vehical location	access_tun_midway		distr_zone_non_block		motorway_tun	
Smoke in evac route	smoke	no_smoke	smoke	no_smoke	smoke	no_smoke
possible	0	1	1	1	0.9	1
blocked	1	0	0	0	0.1	0

Figure A5.12 'Evacuation past incident?' node probabilities

External fire fighters

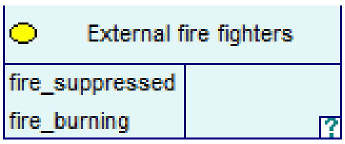


Figure A5.13 States of the 'External fire fighters' chance node

This chance node, Figure A5.13, models whether fire fighters can reach the incident site from outside the tunnel. The deeper the incident is the less likely fire fighters will be able to reach it if smoke is released from the battery or a fire. The inference is governed by the values shown in Figure A5.14.

Smoke in evac route	smoke					
Final vehical location	distr_zone	Outside	access_tun_work_front	access_tun_midway	distr_zone_non_block	motorway_tun
fire_suppressed	0.01	0.95	0.1	0.2	0.01	0
fire_burning	0.99	0.05	0.9	0.8	0.99	1

Smoke in evac route	no_smoke					
Final vehical location	distr_zone	Outside	access_tun_work_front	access_tun_midway	distr_zone_non_block	motorway_tun
fire_suppressed	1	1	1	1	1	1
fire_burning	0	0	0	0	0	0

Figure A5.14 Probabilities of the 'External fire fighters' node

Duration of hazard

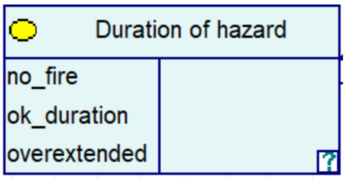


Figure A5.15 States of the 'Duration of hazard' chance node

This chance node, Figure A5.15, models the duration of the hazard, that is the time the tunnel inaccessible due to a non-breathable atmosphere or fire. This duration is crucial to determine if the safe shelter duration of refuge chambers is overextended.

The parameters differ between BEV and diesel truck, see Figure A5.16. Regardless of the vehicle types responsible for an incident that produces a non-breathable atmosphere, the challenge is the same. The toxic air must be removed from the tunnel before people can emerge to the surface. It is assumed that due to the potentially longer burning time of a BEV it is 20% more likely that a BEV incident will overextend the save shelter time of refuge chambers.

Diesel

Vehicle fire	fire		no_fire	
External fire fighters	fire_suppressed	fire_burning	fire_suppressed	fire_burning
no_fire	1	0	1	1
ok_duration	0	0.9	0	0
overextended	0	0.1	0	0

BEV

Hazardous incident	fire_and_fumes		only_fumes		no_release	
External fire fighters	fire_suppressed	fire_burning	fire_suppressed	fire_burning	fire_suppressed	fire_burning
no_fire	1	0	1	1	1	1
ok_duration	0	0.88	0	0	0	0
overextended	0	0.12	0	0	0	0

Figure A5.16 Probabilities of the 'Duration of hazard' node for diesel vehicles and BEVs

Smoke in evacuation route

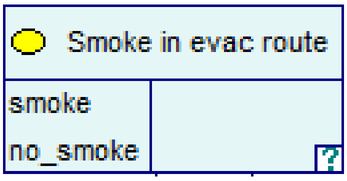


Figure A5.17 States of the 'Smoke in evacuation route' chance node

This chance node,. Figure A5.17, models whether smoke fills the evacuation route. The node is different for the BEV and the diesel model because the hazardous event in case of a BEV can release fumes without fire as presented in Figure A5.18.

Diesel

Vehicle fire	fire	no_fire
smoke	1	0
no_smoke	0	1

BEV

Hazardous incident	fire_and_fumes	only_fumes	no_release
smoke	1	1	0
no_smoke	0	0	1

Figure A5.18 Probabilities of the 'Smoke in evacuation route' node for diesel vehicles and BEVs

Local fire suppression

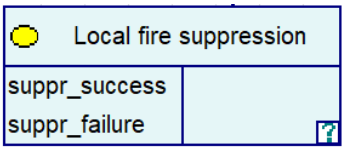


Figure A5.19 States of the 'Local fire suppression' chance node

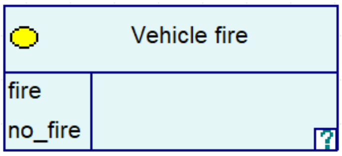
This chance node, Figure A5.19, models whether workers in the tunnel are able to suppress the fire. This may be possible for traction battery unrelated fires that can be suppressed with handheld extinguishers with probabilities given in Figure A5.20.

suppr_success	0.3
suppr_failure	0.7

Figure A5.20 'Local fire suppression' node probabilities

Hazardous incidents

Diesel



BEV

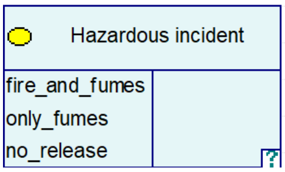


Figure A5.21 States of the 'Hazardous incidents' chance node

This chance node, Figure A5.21, models the occurrence of incidents. A BEV fire can have to a large extent the same causes as diesel dumper, here those causes are called 'other'. Mitigation measure modify the outbreak of a full fire. The governing conditional probabilities are given in Figure A5.22.

Diesel

Local fire suppression	suppr_success	suppr_failure
fire	0	1
no_fire	1	0

BEV

BMS action / warning	Loss_of_control							
Flooding the battery	flood_success				no_flooding			
Local fire suppression	suppr_success		suppr_failure		suppr_success		suppr_failure	
Fire cause	battery	other	battery	other	battery	other	battery	other
fire_and_fumes	0	0	0	1	1	0	1	1
only_fumes	0.95	1	0.95	0	0	1	0	0
no_release	0.05	0	0.05	0	0	0	0	0

BMS action / warning	STOP_warning							
Flooding the battery	flood_success				no_flooding			
Local fire suppression	suppr_success		suppr_failure		suppr_success		suppr_failure	
Fire cause	battery	other	battery	other	battery	other	battery	other
fire_and_fumes	0	0	0	1	1	0	1	1
only_fumes	0.05	1	0.05	0	0	1	0	0
no_release	0.95	0	0.95	0	0	0	0	0

Figure A5.22 Probabilities of the 'Hazardous incidents' node for diesel vehicles and BEVs

People deeper than incident

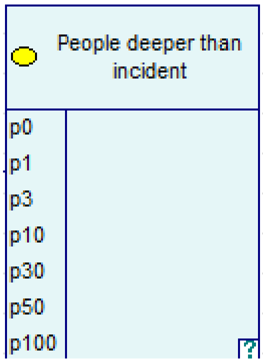


Figure A5.23 States of the 'People deeper than incident' chance node

This chance node, Figure A5.23, models the distribution of people that are deeper than the incident location.
For the actual distribution see above description about People affected by vehicle incident with Figure A5.2 to Figure A5.6 and Table A5.1.

Construction phase

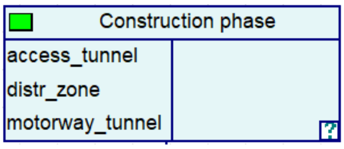


Figure A5.24 States of the 'Construction phase' decision node

This decision node, Figure A5.24, models the progress of the excavation. It is a decision node to represent the sequential i.e., non-random work. At first the access tunnel must be completed, then the distribution zone, and finally the motorway tunnels.

Expected fatalities

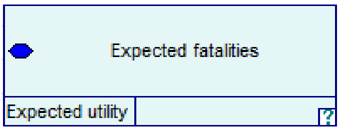


Figure A5.25 States of the 'Expected fatalities' utility node

This utility node, Figure A5.25, evaluates the probabilities from "People deeper than incident" and "fatalities?" to compute the number of expected fatalities.

Nodes present only in the BEV Bayesian network

Fire cause

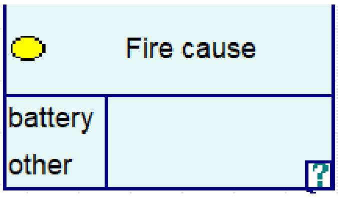


Figure A5.26 States of the 'Expected fatalities' utility node

This chance node, Figure A5.26, models the probability of a fire starting and whether this fire begins as traction battery related or if it has other causes. The probabilities are based on (Beredskabsstyrelsen, 2021) with data from Denmark and Sweden that separate different fire causes. This report categorizes fire causes as fire spreading from other fire, re-ignition, traffic accident, suspected arson, and other. The three categories re-ignition, traffic accident, and other are classified as battery related fire causes by us. That leads to about 53% of fire begin caused by the battery in this model, the remaining 47% are general causes like they are also found on a diesel dumper. The detailed probabilities are listed in Figure A5.27.

battery	0.53125
other	0.46875

Figure A5.27 Probabilities of the 'Expected fatalities' utility node

BMS action / warning

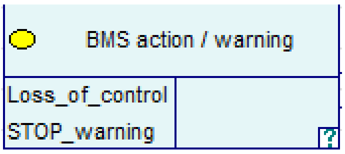


Figure A5.28 States of the 'BMS action/warning' chance node

This chance node, Figure A5.28, models two states.

1. The BMS losses completely and rapidly control. This is likely in case of mechanical damage that severely deforms or raptures the battery and thereby cause instantaneous short circuits.
2. The BMS is losing control but issues a timely warning to the driver to stop the vehicle. This would be the case for e.g., battery degradation.
   This would allow for a placement of the vehicle in a less critical location before abandoning it or even prepare a risk mitigation measure like battery flooding.

The chosen values are guesses based on news reports that passengers were often warned to leave a BEV before a thermal runaway reached harmful levels and shown in Figure A5.29.

Loss_of_control	0.5
STOP_warning	0.5

Figure A5.29 probabilities of the 'BMS action/warning' chance node

Flooding the battery

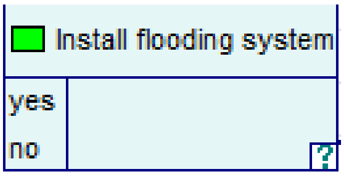


Figure A5.30 States of the 'Install flooding system' decision node

This decision node, Figure A5.30, models the availability of a battery flooding system.

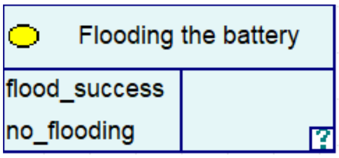


Figure A5.31 States of the 'Flooding the battery' chance node

This chance node, Figure A5.31, models the success of a battery flooding attempt. As a risk mitigation it can successfully suppress fire development in a battery with high probability. The 10% failure probability in case of STOP warning is assumed to model human failure in preparing the water line connection properly. In case the BMS lost control rapidly it may not be possible to approach the vehicle to prepare the water connection and it is assumed a 90% failure probability. All conditional probabilities are given in Figure A5.32.

BMS action / warning	Loss_of_control				STOP_warning			
Install flooding system	yes		no		yes		no	
Fire cause	battery	other	battery	other	battery	other	battery	other
flood_success	0.1	0	0	0	0.9	0	0	0
no_flooding	0.9	1	1	1	0.1	1	1	1

Figure A5.32 Probabilities of the 'Flooding the battery' node

Vehicle moved away

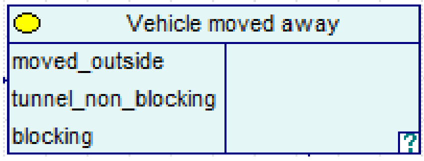


Figure A5.33 States of the 'Vehicle moved away' chance node

This chance node, Figure A5.33, models if the vehicle was successfully moved to a less critical location after a warning was issued by the BMS. Assuming LFP battery chemistry the pre-warning time can be several minutes long. If a general fire breaks out the assumed action is to stop the dumper and attempt location fire suppression. If no general fire has broken out the dumper could be moved to a less critical location to facilitate evacuation of people below the incident. The conditional probabilities are given in Figure A5.34.

BMS action / warning	Loss_of_control		STOP_warning	
Fire cause	battery	other	battery	other
moved_outside	0	0	0.3	0
tunnel_non_blocking	0.5	0.5	0.7	0.5
blocking	0.5	0.5	0	0.5

Figure A5.34 Probabilities of the 'Vehicle moved away' node

Initial incident location

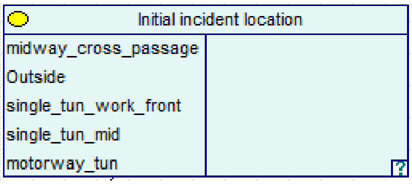


Figure A5.35 States of the 'Initial location' chance node

This chance node, Figure A5.35, models where the incident begins. This is different from the final incident location for a BEV because a warning from the BMS may allow for relocation to a less critical location.

distr_zone	0.00180018
Outside	0.0523052...
access_tun_work_front	0.0030003
access_tun_mid	0.56005601
motorway_tun	0.38283828

Figure A5.36 Probabilities of the 'Initial incident location' node

The distribution, see Figure A5.36, was derived from estimates of the required distances travelled by trucks to clear the tunnels of debris and their assumed speed in the tunnels and above ground. See section 2.3.4 for driven distances.

Appendix 6
F-N curves

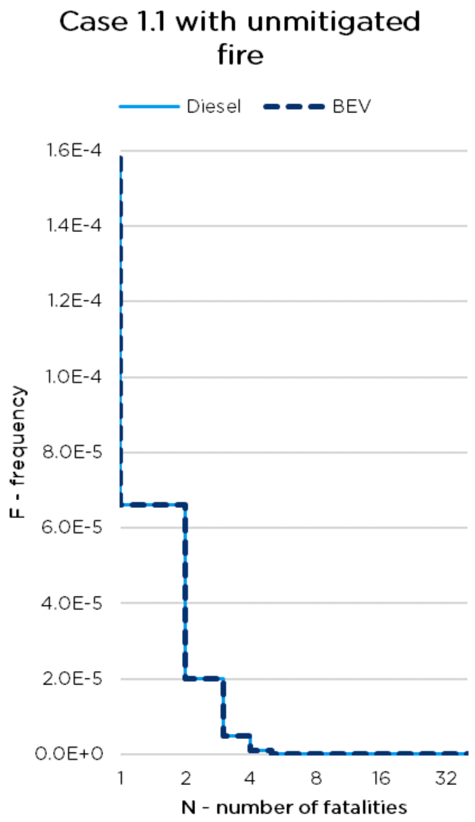
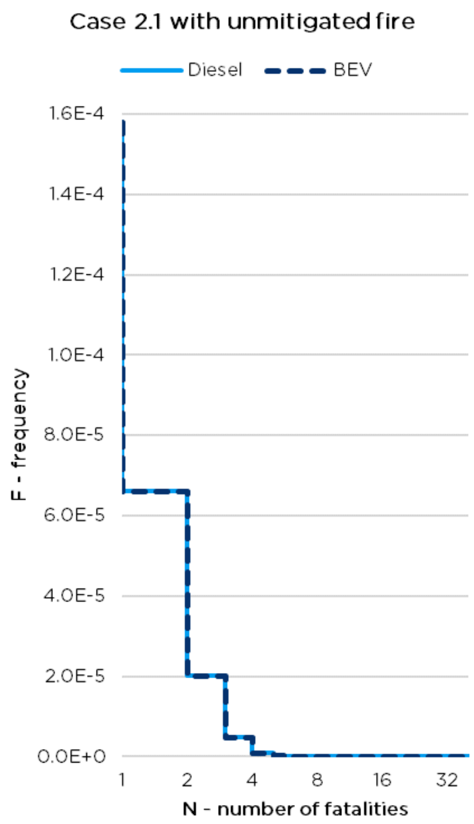
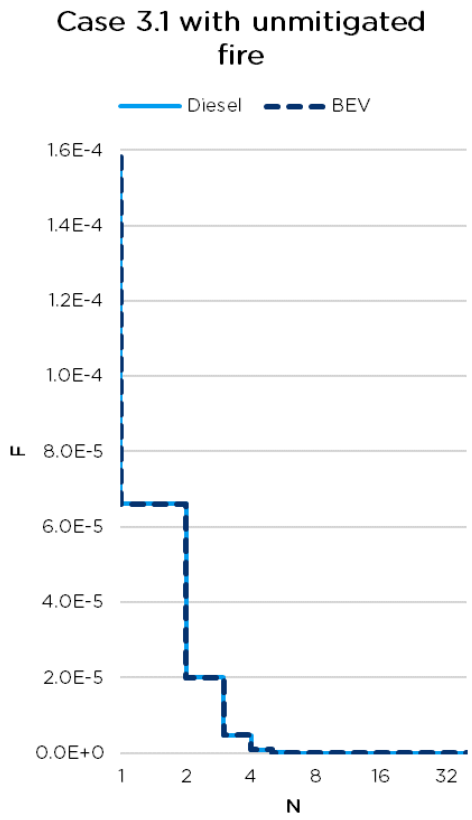
The vertical scale, F, shows the frequency of the hazardous events represented, and the horizontal scale represents the consequences i.e., the number of fatalities, N. A point (F, N) on the curve represents the cumulative frequency of experiencing N or more fatalities due to the fires of dumpers. They are presented for each considered incident location.

F-N curves in case of a fire

The fire considered here is so large that people will be trapped inside the tunnel if they are deeper than the fire cannot evacuate past it. Smaller fires are inconsequential in terms of fatalities. All figures but the graphs about incidents outside of the tunnel use the same y-axis scale. The outside graphs (1.1, 2.1, and 3.1) are need a lower maximum scale to visualize differences in the graphs.

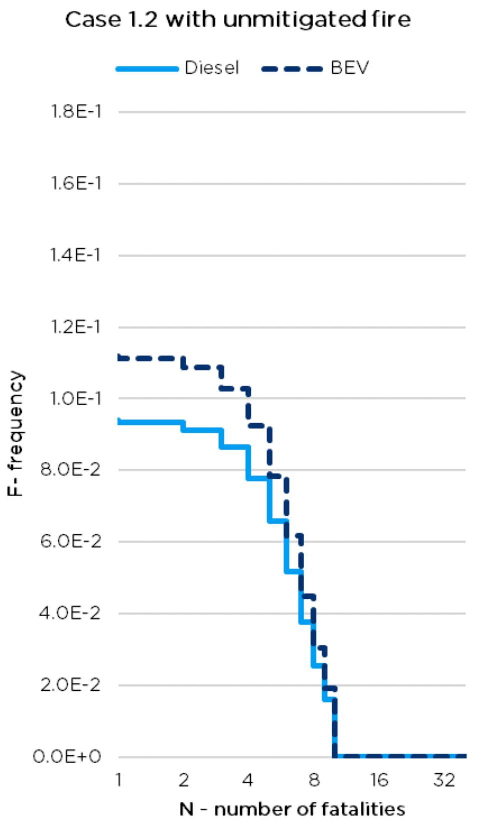
Incidents outside of the tunnel

Regardless of work phase the consequences are the same for a fire occurring outside of the tunnel. Also diesel-powered or BEV dumpers perform the same.

Access tunnel construction	Distribution zone construction	Motorway construction
		

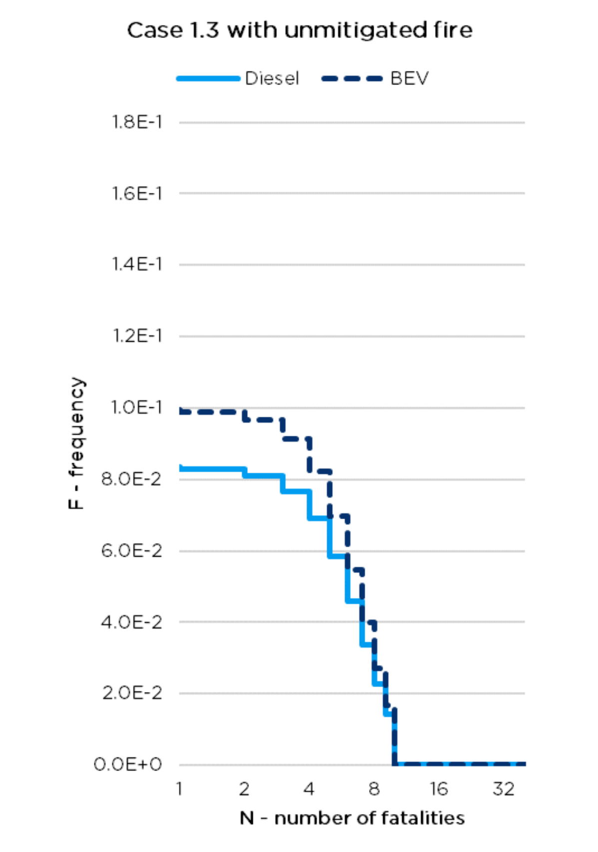
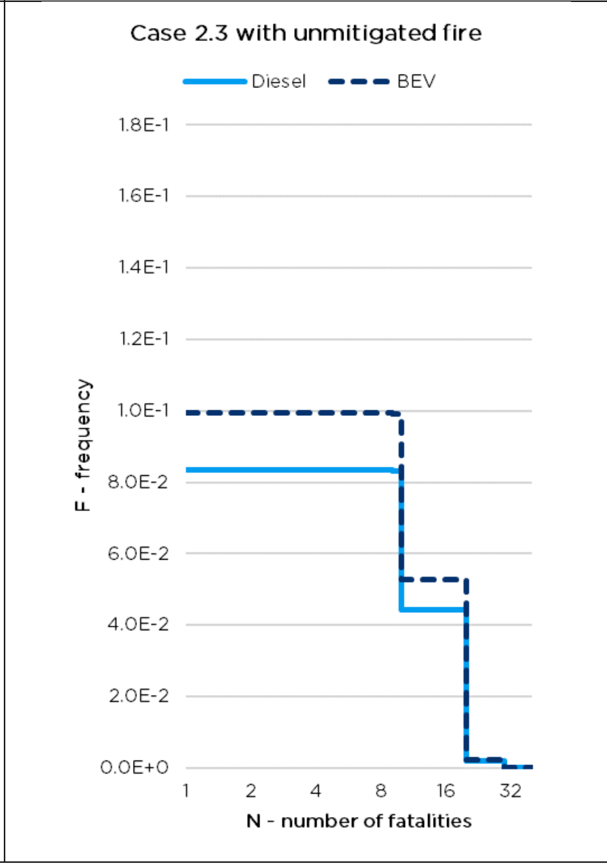
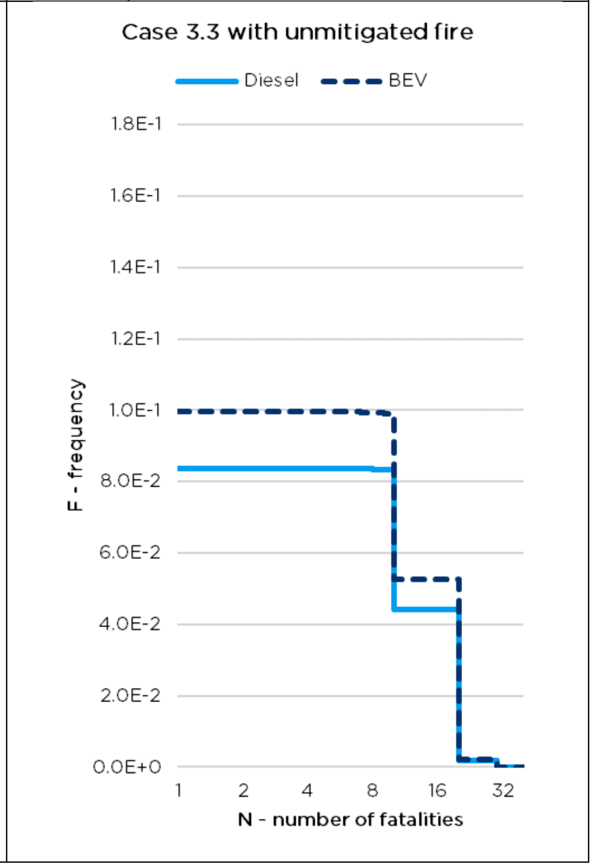
Incidents in the access tunnel at the work front

For a fire at the access tunnel work front the frequencies of fatalities are slightly lower for a diesel-powered dumper. Consider the uncertainties in the models and their parameters they can considered to perform equal.

Access tunnel construction	Distribution zone construction	Motorway construction
	*Not possible*	*Not possible*

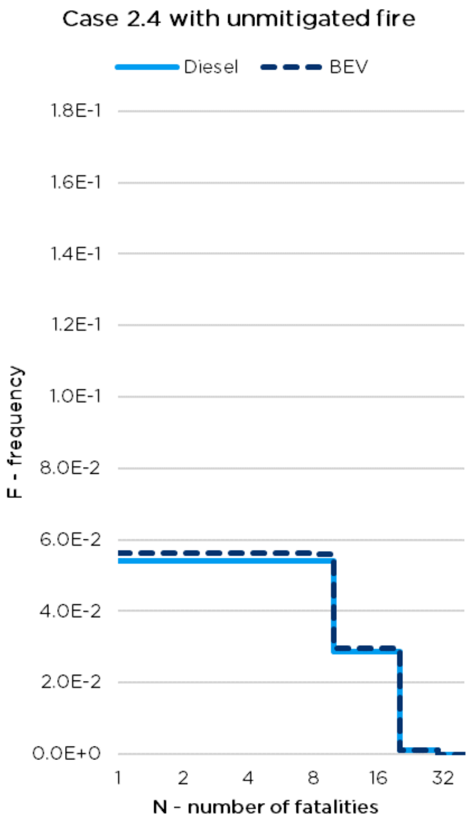
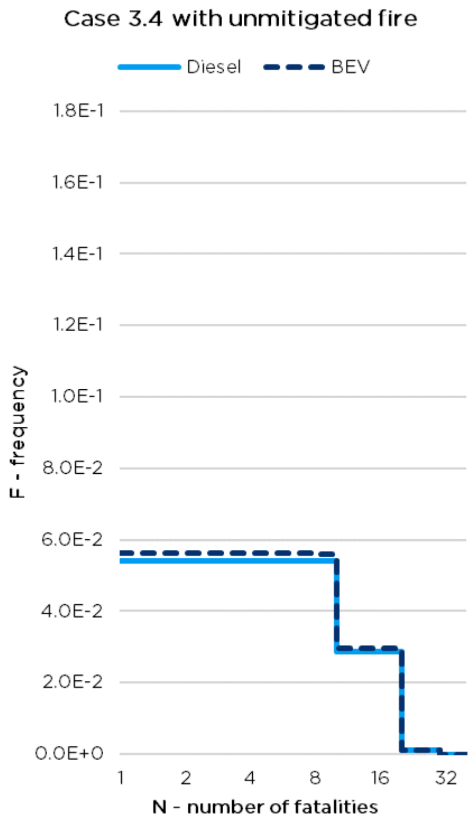
Incidents in access tunnel midway

For a fire midway in the access tunnel, the frequencies of fatalities are slightly lower for a diesel-powered dumper. Consider the uncertainties in the models and their parameters they can considered to perform equal.

Access tunnel construction	Distribution zone construction	Motorway construction
		

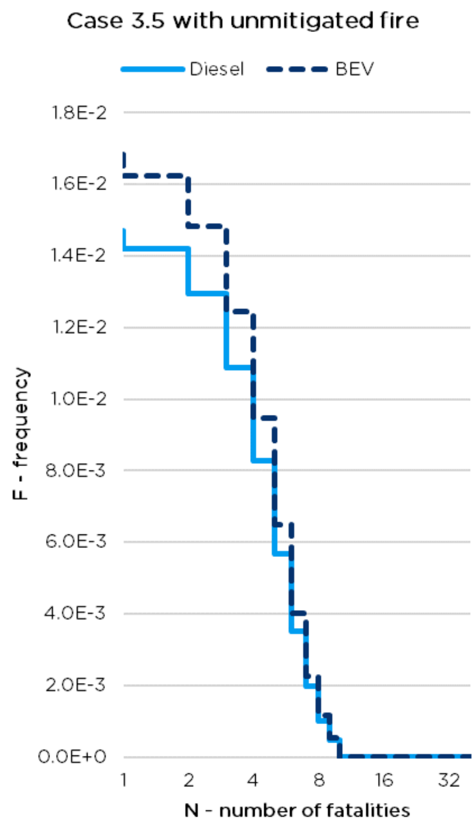
Incidents in the distribution zone

For a fire in the distribution zone, the frequencies of fatalities are nearly equal. Consider the uncertainties in the models and their parameters they can considered to perform equal. The frequencies are so close because the BMS may be able to issue an early warning of an imminent thermal runaway.

Access tunnel construction	Distribution zone construction	Motorway construction
Not possible		

Incidents in the motorway tunnel

For a fire in a motorway tunnel, the frequencies of fatalities are slightly lower for a diesel-powered dumper. Consider the uncertainties in the models and their parameters they can considered to perform equal.

Access tunnel construction	Distribution zone construction	Motorway construction
Not possible	*Not possible*	

F-N curves for incidents when early mitigation measures are available

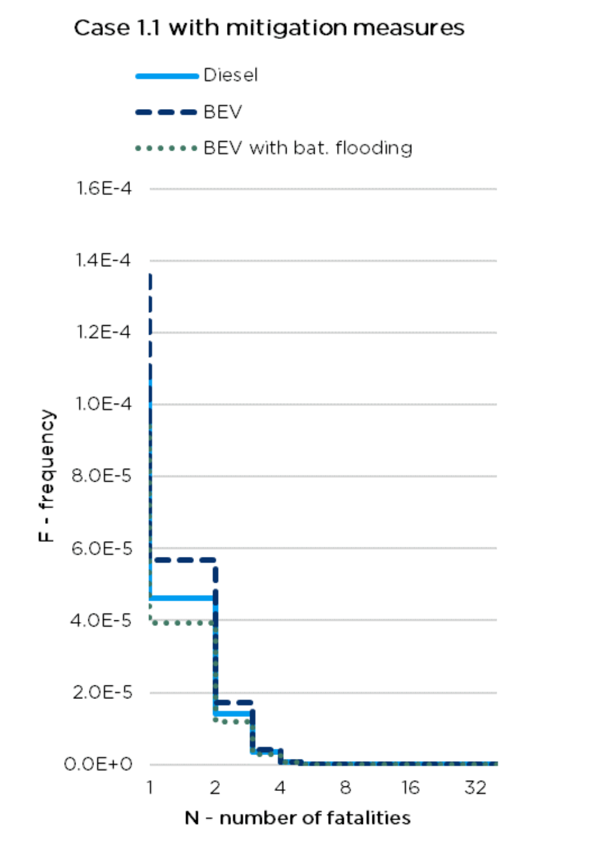
Unlike the F-N curves presented above, the following graphs are the result of the same Bayesian networks but with the possibility to use fire mitigation measures. Local fire suppression using a handheld fire extinguisher may stop a small fire from growing to a fire large enough cause fatalities by trapping people inside the tunnel.

All figures, but the graphs about incidents outside of the tunnel, use the same y-axis scale. The outside graphs (1.1, 2.1, and 3.1) need a lower maximum scale to visualize differences in the graphs.

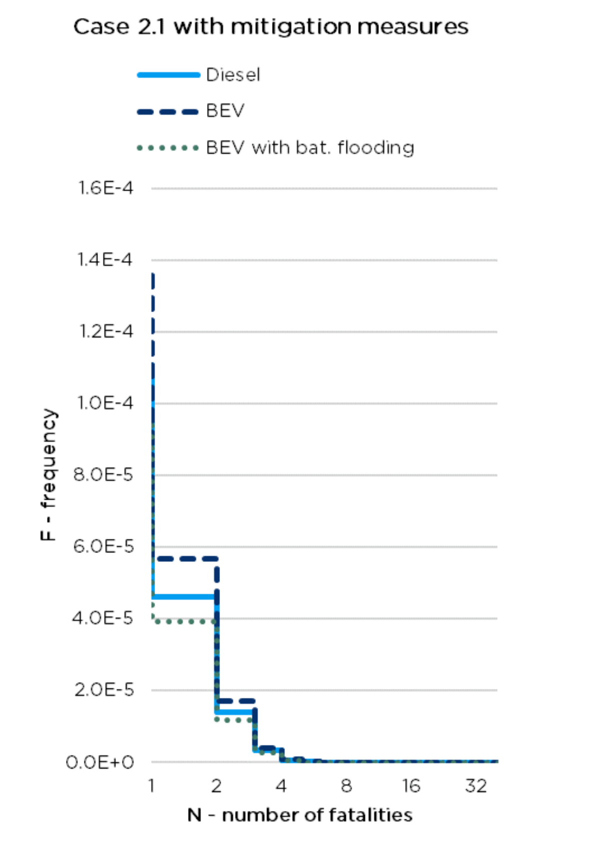
Incidents outside of the tunnel

Regardless of work phase the consequences are the same for a fire occurring outside of the tunnel. With mitigation measures are available, the BEV with battery flooding performs best, but all options are within a factor of 1.5 and therefore not really different considering uncertainties.

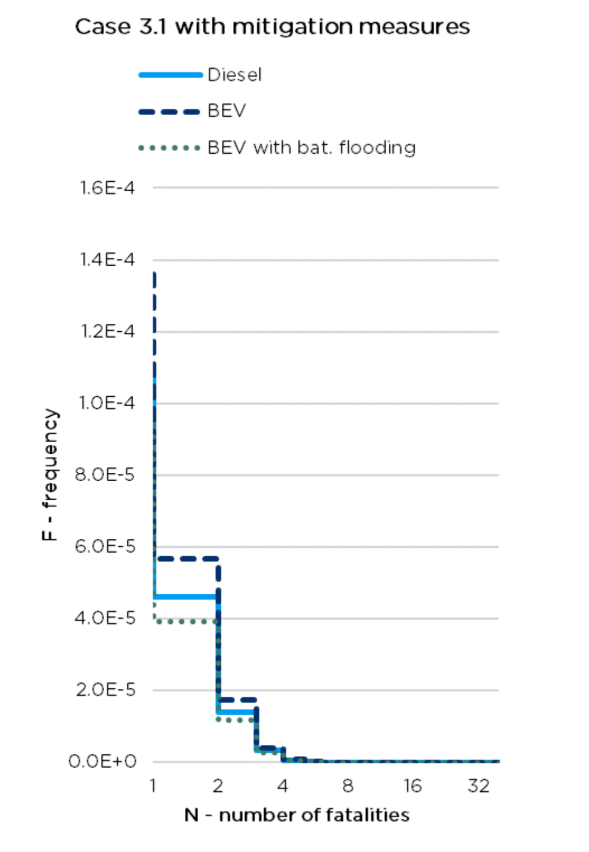
Access tunnel construction



Distribution zone construction

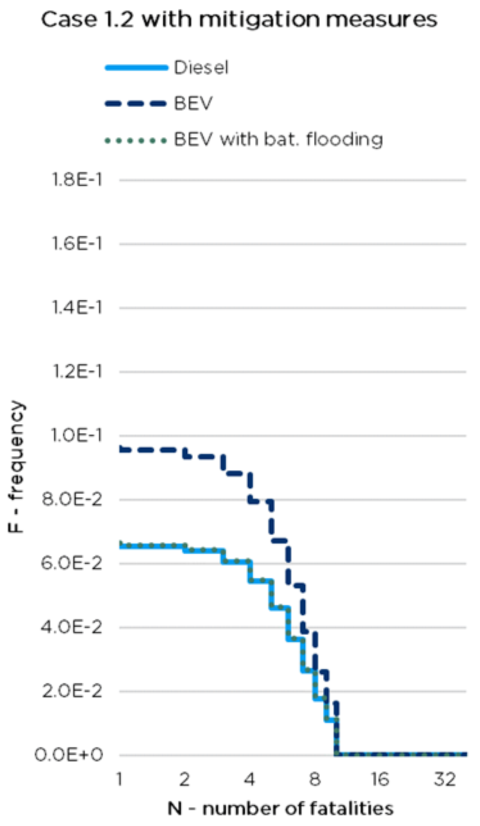


Motorway construction



Incidents in the access tunnel at the work front

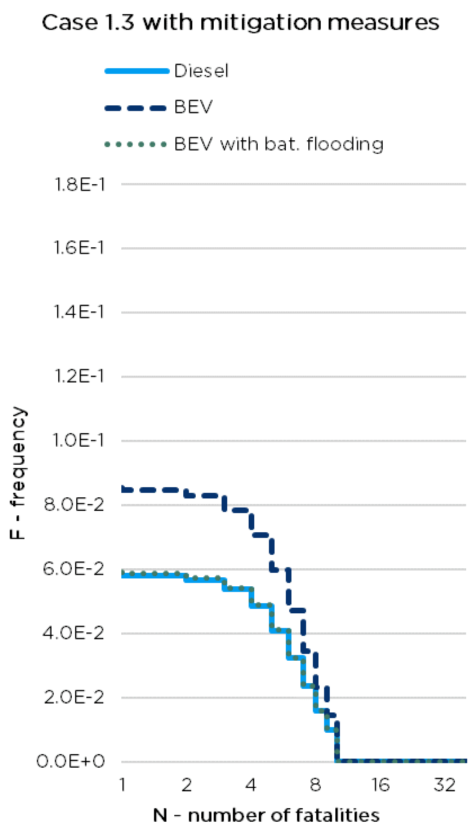
With mitigation measures available the BEV with battery flooding and diesel perform nearly identical.

Access tunnel construction	Distribution zone construction	Motorway construction
	*Not possible*	*Not possible*

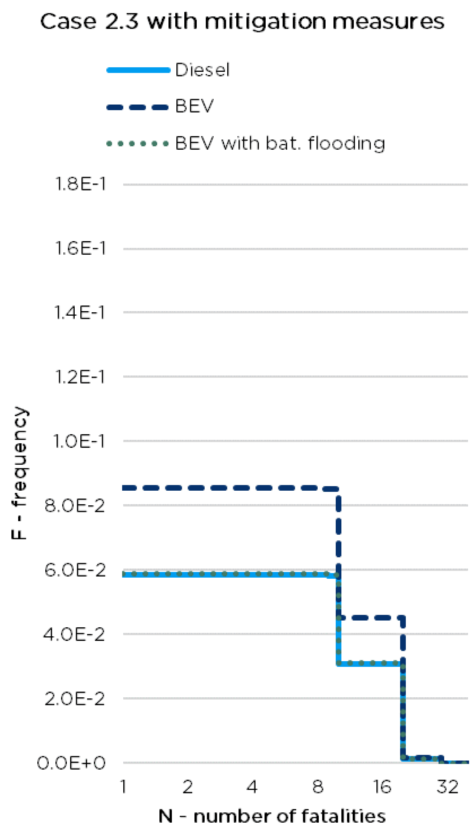
Incidents in access tunnel midway

Cases 2.3 and 3.3 are identical. With mitigation measures available the BEV with battery flooding and diesel perform nearly identical.

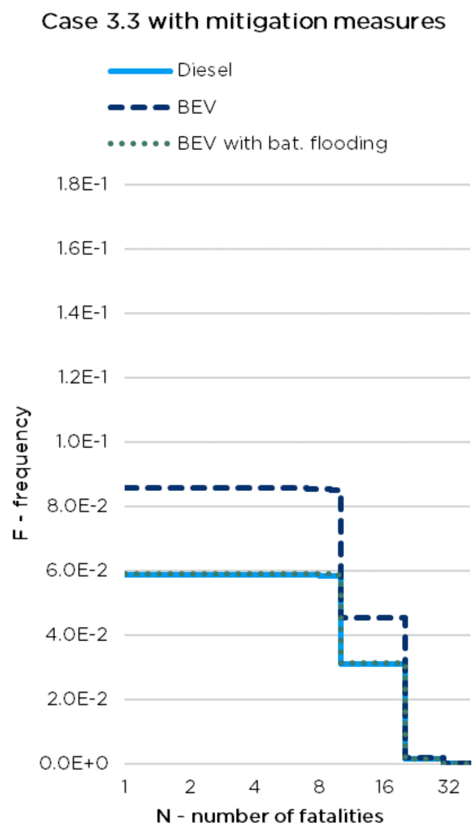
Access tunnel construction



Distribution zone construction

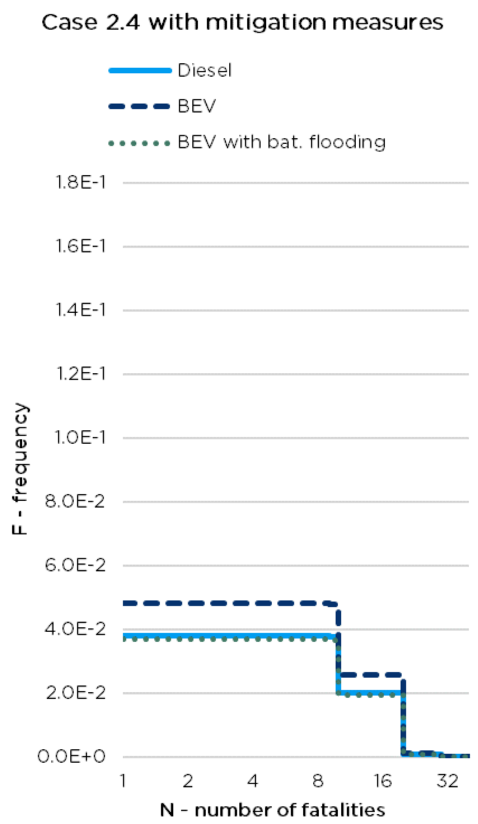
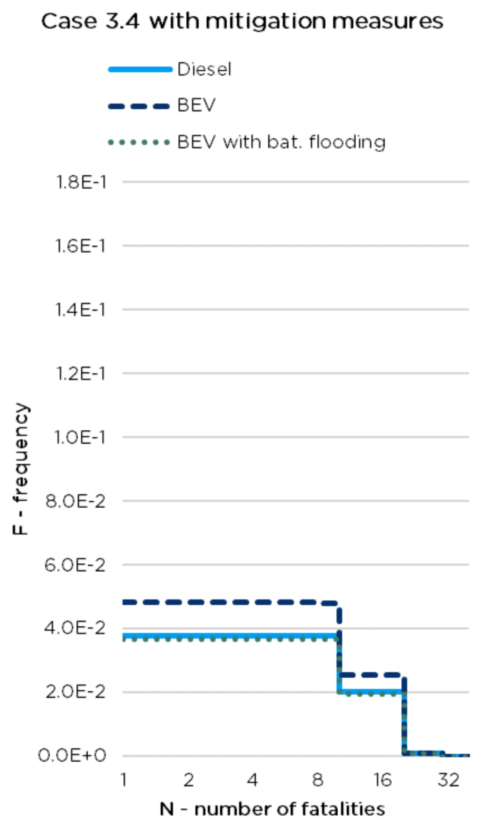


Motorway construction



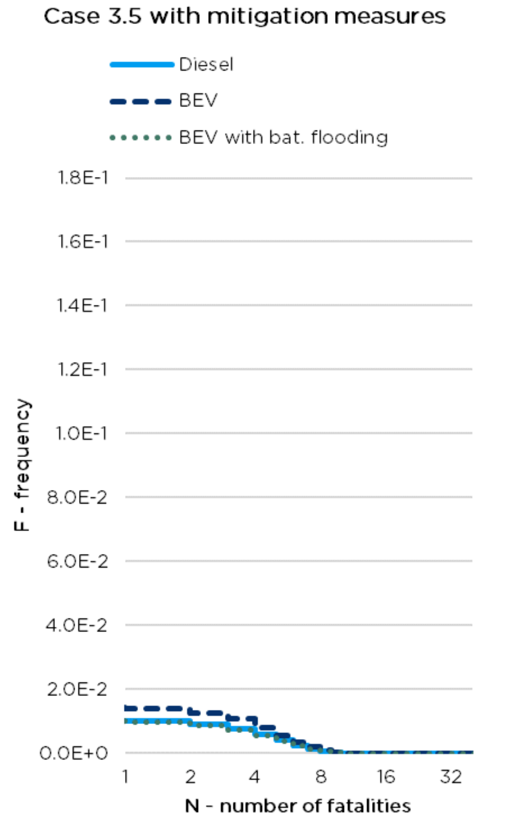
Incidents in the distribution zone

Cases 2.4 and 3.4 are identical. With mitigation measures available the BEV with battery flooding performs best.

Access tunnel construction	Distribution zone construction	Motorway construction
Not possible		

Incidents in the motorway tunnel

Again, the BEV with battery flooding performs slightly better than the diesel dumper, but considering uncertainties they can be regarded as equal.

Access tunnel construction	Distribution zone construction	Motorway construction
Not possible	*Not possible*	

Appendix 7
Details on batteries

Appendix 7.1 – Battery chemistry
Appendix 7.2 – BMS features
Appendix 7.3 - Information from interviews with battery manufacturers

Battery chemistry

Each chemistry has advantages and disadvantages and is more appropriate for one or another application. In the following, the main characteristics are summarized for the most used chemistries:

- NMC batteries are widely used in electric vehicles (EVs) and energy storage systems due to their high energy density, long cycle life, and relatively low cost. NMC batteries have higher specific energy (energy per unit mass) and specific power (power per unit mass) compared to other batteries (for example LFP). Also, cobalt and manganese are rare materials. Regarding thermal runaway (TR), they have low thermal stability compared to LFP.
- NCA batteries have a higher energy density than NMC batteries and are commonly used in high-end EVs such as Tesla. Disadvantages are the lower safety and higher cost in comparison to NMC and LFP batteries.
- LCO batteries offer higher thermal stability but more moderate specific energy than some other types of Li-ion batteries. The key benefits are high current rating and long cycle life, as well as enhanced safety and tolerance if abused.
- LFP batteries are known for their long cycle life, high thermal stability, and safety. They are commonly used in applications that require high power output and safety, such as power tools, electric bikes, and grid storage systems. LFP batteries have a lower energy density than NMC and NCA batteries, which means they are heavier.
- LTO batteries have a high cycle life, fast charging capability, and high safety. They are commonly used in applications that require high power output and fast charging, such as electric buses, aerospace, military, smart grid. However, LTO batteries have a lower energy density than other types of Li-ion batteries, which means they are heavier.

A summary comparison is provided in Figure A7-1.

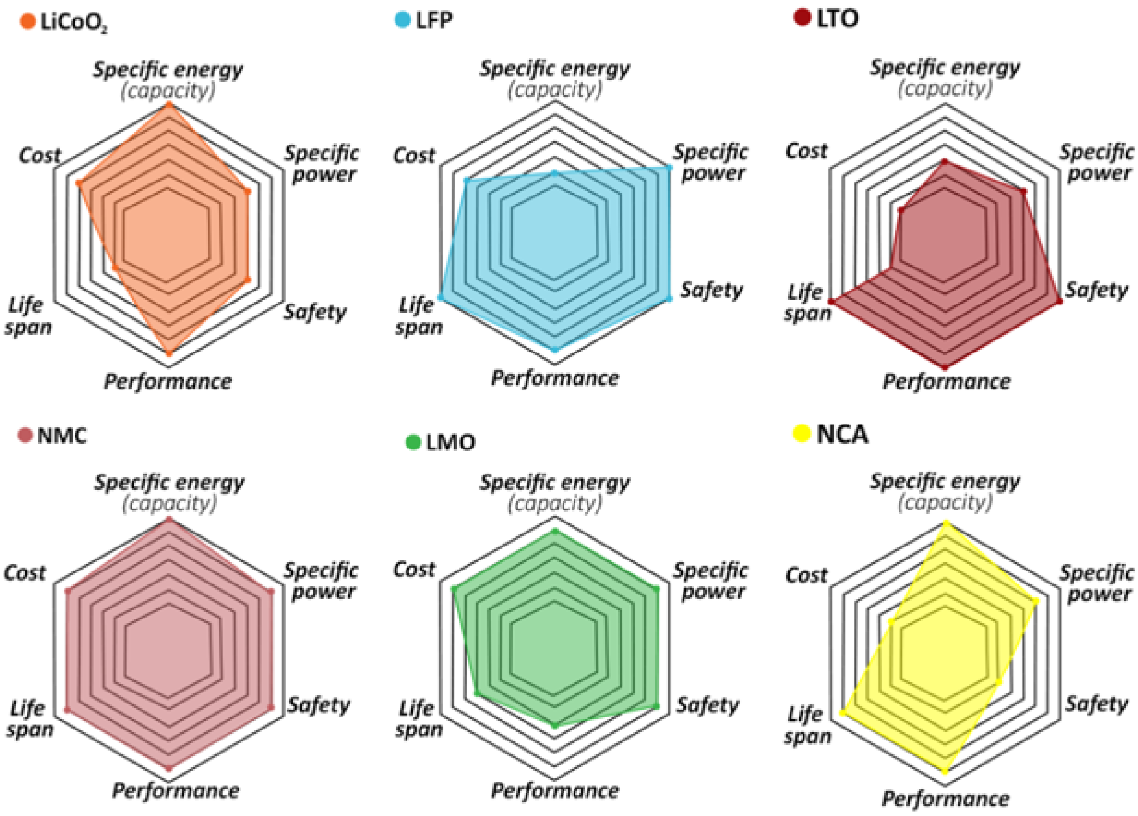


Figure A7-1 Li-ion battery chemistry characteristics comparison, ref. /8/.

BMS features

The primary function of a BMS is to ensure the safe and efficient operation of the battery pack. It performs several key tasks, including:

- State of Charge (SoC) Estimation: The BMS monitors the energy level of the battery and estimates its SoC, indicating how much capacity is remaining. This information is crucial for accurately determining the range or available energy in a battery-powered system.
- Cell Balancing: In a multi-cell battery pack, cells can have variations in their capacity or voltage due to manufacturing differences, aging, or other factors. The BMS equalizes the charge among individual cells by redistributing energy, thus maximizing the pack's overall capacity, and extending its lifespan.
- Overvoltage and Undervoltage Protection: The BMS safeguards the battery pack from operating outside safe voltage limits. It prevents overcharging, which can damage the battery or cause a safety hazard, as well as prevents excessive discharge, which can lead to cell damage or reduced performance.
- Temperature Monitoring: Batteries can be sensitive to temperature extremes. The BMS monitors the battery temperature and takes appropriate actions to prevent overheating or operating in extremely cold conditions, as these can impact battery performance and longevity.
- Current Monitoring: The BMS measures the current flowing into and out of the battery pack. It helps track energy usage, enables accurate SoC estimation, and ensures that the charging and discharging currents are within safe limits.
- Fault Detection and Diagnostic: The BMS detects any abnormalities or faults in the battery pack, such as short circuits, open circuits, or cell failures. It provides alerts or initiates protective measures to prevent further damage and ensure the safety of the system.
- Communication and Data Logging: Many BMS units offer communication interfaces, such as CAN (Controller Area Network), to exchange information with the overall system or external devices. Additionally, they may log data related to battery performance, including voltage, current, temperature, and fault history, for analysis and troubleshooting purposes.

Information from interviews with battery manufacturers

We have conducted two interviews with battery manufacturers Xerotech and Intercel Energie BV and in the following the main outcomes are reported.

Xerotech

Xerotech is a battery technology company that is working with industrial electrification. Xerotech buys cells and put them together into battery modules and packs and build their own BMS. The batteries are then sold to the automotive industry or Original Equipment Manufacturer (OEM). Xerotech is currently providing batteries to Normet. The range of battery is from 10 to 6000 kWh.

Types of battery chemistry Xerotech use and comparison in terms of safety and performance to other types of battery chemistry

The chemistry of the batteries that Xerotech use are LFP/NMC/NCA.

Safety is not solely related to chemistry, indeed a battery consists of four components, all of which influence battery safety:

1. Anode
2. Cathode (LTO, NMC, NCA, etc.)
3. Separator (solid state, etc.)
4. Electrolyte (organic/inorganic)

Additionally, battery safety is also influenced by other factors such as cell shape, the method of merging the cells to create modules and packs, the BMS, etc.

When speaking about chemistry, there is a strong correlation between energy density and stability. Higher energy density results in lower stability. From the most energy-dense to the least, the order is NCA > NMC > LFP > LTO. However, all these chemistries are flammable.

In terms of energy density:

- Diesel: 11,000 Wh/kg
- Battery: ~250 Wh/kg (value dependent on the chemistry)

The energy density varies depending on the battery cell chemistry. For example, 10 NCA cells would have a similar energy as 35 ml of diesel, while it would take about 20 cells (cylindrical) of LFP to achieve the same energy.

Application of Batteries in Dumpers: Deployment Locations, Quantities, Battery Size, Range, and Limitations

10 Volvo dumpers will be released at the end of June 2023 with a NMC 300 kWh.

However, LFP batteries are also investigated. The LFP is quite under the spot because Chinese companies are providing mostly LFP and thus driving the industry on this direction.

However, accordingly to Xerotech, comparing electric vehicles VS diesel, incident of fire or failure is 10 times lower for electric vehicles.

Installation Locations of Charger Infrastructure: Tunnels vs. Exterior Areas

According to Xerotech, the configuration can be very different. For smaller machines, the fast charging is often underground, whereas for tunnelling it can vary, because of the long distance of the tunnels.

Safety Measures for Preventing Battery Fires and Explosions in Battery Packs

The BMS has built in preventions: Prevent abuse condition, overvoltage, undervoltage, over temperature, undervoltage, short circuit, undercurrent (a lot of these are correlated).

However, a main problem with the battery fire is the reignition. For now, the main solution is to place the battery underwater for seven days. When the battery is on fire, or has been on fire, it is already too late for the BMS to do anything. Also, the BMS is external, with some measurements in the battery, so if something happens the BMS can disconnect the connectors, however, it can happen that something happens inside the battery and when the BMS recognise it, it is already too late. Some battery packs utilize cell-level fusing which make them intrinsically safe with regard to hard short circuits. To slow or prevent thermal runaways, there are methods where passive propagation resistant materials (such as foams or silicone potting compounds) are introduced as a barrier between battery cells. Same recommendation for all the battery pack chemistries, even though some are less energetic there are not distinctions in terms of recommendations for now.

Heat Release Rate (HRR) and HF Gas Perspective
HF gases: It depends on the extent of combustion, a battery fire can be very different, from a very slow fire to a full explosion, for now the first responder is to wear a mask.

According to Xerotech, the risk is for now seen more in the burning of the battery than in the gases.

Xerotech recommends using water to bring fire under control, submerge the battery under water and leave it there for seven days.

In terms of water: If the battery has a volume X, the volume of water should be between two and five times. An additional step is to put salt in the water, however, this can create galvanic actions.

Continuous Improvement and Innovation of Battery Packs

- *Swap batteries:*

The OEM is deciding how to use the battery. The pro of swap batteries is that they can charge slower, and thus avoid peaks in the local electricity grid. However, they add complexity and costs. It takes 3 to 4 minutes to swap batteries.

Considering in terms of costs, a typical dumper diesel machinery cost half million dollar whereas an electrical machinery costs 1.2-1.5 million.

However, there are Chinese companies with a very different strategy where the electrical machinery costs ~300000 dollars.

Looking at the battery price, if a battery swap is considered the price is not much influenced as it would be with electric vehicles (where the battery price can also be 40/50% of the total cost of the vehicle).

- *Battery lifetime:*

The optimal battery temperature to limit the degradation of the batteries is 25°C. Xerotech uses liquid-cooling, where the battery is cooled to keep operation around 25°C. However, the battery can operate up to 55°C, when the BMS will send signals that the temperature is too high.

In terms of lifetime, the LTO is the one with the longest time expectancy followed by LFP.

In general, a lifetime of 5-8 years is expected for electrical machinery. However, the battery lifetime is highly dependent on the calendar and cycling aging. Calendar aging is function of time, temperature and state-of-charge, this is always present, even if the battery is not used. The cycling aging is function of how the battery is used, charged and discharged, etc.

- *Other risks:*

With tunnel constructions there are a lot of other risks: noise, pollution, etc. which should be considered, where the battery electrical machinery will have a positive impact.

Remember that diesel burns as well, and at the moment the largest number of fires in machinery are caused by diesel.

Intercel Energie BV

Intercel Energie BV is a specialist in battery solutions. For over 35 years they have been supplying batteries for every possible application providing custom made solutions. Initially they were working with lead acid batteries, now they have a lot of different battery chemistries. Some years ago, they started looking into diesel machines to be electrified. Batteries are today going from 19 to 250 kWh per battery. However multiple batteries can be used together forming larger sizes. Today they are working on building a machinery with four batteries of 180 kWh, a total of 720 kWh. These batteries could be charged with one or multiple chargers, and making custom made solutions they investigate pros and cons for each.

A possibility for them is also to make redundant systems, with different power sources, so if there is a failure in one battery they can run on the other.

Their batteries can fast charge with offboard DC charger 1 MW and with 20 kW AC chargers. And if there are multiple batteries they can charge with multiple chargers.

Types of battery chemistry Intercel Energie BV use and comparison in terms of safety and performance to other types of battery chemistry

In the past, NMC were used. They are very popular because of the high energy density. LFP has evolved very fast during the last five years, with energy density between 160 and 180 Wh/kg for the LFP they are using. According to Intercel, today LFP cells can have a similar energy density of NMC. Safety is key and that is why they use LFP. The price is similar for the two.

Safety Measures for Preventing Battery Fires and Explosions in Battery Packs

For safety, there are multiple measures, here some examples:

1. Tests of cells: LFP cells are tested in the company before utilization. Safety events on the cell show that the cell starts to gas but not fire.
2. Grouping of cells by making sure that there is no possibility to escalate a fire, with separator and air gas between cells.
3. Fuses: Multiple fuses and contactors are utilized in the battery and can be opened in case of safety overreach.
4. BMS: BMS controls features are utilized to measure the temperature, the charging behaviour, etc.

Heat Release Rate (HRR)

Heat release is taken into consideration with the drive cycle of the specific vehicle to be designed, because it is very important for cooling. They analyse the design of the battery.

Continuous Improvement and Innovation of Battery Packs

- *Swap batteries* are also considered depending on the application. Cooling is a main topic to keep in mind in charging and discharging conditions and when batteries are custom made the need for cooling is investigated. Major risks of swap batteries are caused during swapping, where high voltage components need to be handled.
- *Custom made example of a battery produced for a hybrid train by Intercel:* The train is running inside a factory estate with a hybrid train battery+diesel. In regards to fire, the factory has its own fire department, additionally, with Intercel they have developed several safety options, such as the possibility of flooding the battery without removing the battery from the train. For this project, safety was the key factor.

Emergency service:
For now, Intercel's suggestion is to drown the battery for one week in water if a fire happens.