E39 ROGFAST PROJECT – SECTION E02

RISKS WITH BATTERY-ELECTRIC TRANSPORT VEHICLES IN TUNNEL EXCAVATION

Fire risk and process impact analysis

Statens vegvesen

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ABBREVIATIONS

ADT	Articulated Dump Truck
AEGL	Acute Exposure Guideline Level
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dosages
FIC	Fractional Incapacitating Concentration
GHG	GreenHouse Gas
GVW	Gross Vehicle Weight
HF	Hydrogen Fluoride
HRR	Heat Release Rate
HSE	Health, Safety and Environment
ICEV	Internal Combustion Engine Vehicle
LFP	Lithium-Iron-Phosphate
Li-ion	Lithium-ion
LMO	Lithium-Manganese-Oxide
NCA	Lithium-Nickel-Cobalt-Aluminium-oxide
NMC, NCM	Lithium-Nickel-Manganese-Cobalt
NMT	Norwegian Method of Tunnelling
NPRA	Norwegian Public Roads Administration (Statens vegvesen)
OEM	Original Equipment Manufacturer
RDT	Rigid Dump Truck
RTT	Road Tipper Truck
SoC	State of Charge
SoH	State of health
TLV	Threshold Limit Values

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Norwegian Public Roads Administration (NPRA), Statens vegvesen, has selected the Rogaland Fixed Link in the E39 as a pilot project for fossil-free construction sites. The contracts marketed for construction of Boknafjord tunnel already require static operations of heavy machinery to use cable-electric power. For the upcoming contract for section E02 (Rogfast E02), NPRA is aiming to further reduce greenhouse gas emissions by investigating the possibility for switching the trucks transporting rock from conventional diesel variants to battery-electric alternatives. Primary focus is to ensure health, safety and environment (HSE) and investigate risks related to battery-electric vehicle fires. In addition, NPRA wants to gain knowledge about the impact switching machinery could have on the Norwegian Method of Tunnelling.

NPRA has granted this risk analysis study to a project consortium consisting of ILF Consulting Engineers Norway joint by Søvik consulting (Norway), Graz University of Technology, Institute of Thermodynamics and Sustainable Propulsion Systems (Austria) and ILF Consulting Engineers Austria. The study has been based on currently market available battery-electric and equivalent diesel transport trucks. Based on the challenging characteristics at Rogfast E02 (long transport distances, steep uphill at Kvitsøy access and heavy-duty application) a battery-electric and a diesel variant of an Articulated Dump Truck (ADT), in 4X4 configuration with a loading capacity of 40 ton, have been selected.

Fire risk analysis has focussed on comparison of likelihood and consequences for possible fire scenarios for diesel ADTs to battery-electric ADTs, including thermal runaway of the batteries:

- In general, battery-electric vehicle fires can be estimated to be significantly less likely than conventional vehicle fires, as the main source of ignition (hot surface of combustion engine) is missing. In addition, potential underground use has been focus in fire safety development of battery-electric ADTs.
- Scenario-based fire curves developed reflect that fire of a battery-electric ADT can be up to 4 hrs, significantly longer than for a diesel ADT (up to 3 hrs) and needs to be considered for the rescue shelters. Detailed fire simulations for Rogfast E02 have indicated that the potential release of toxic gases by battery fires still lead to similar times to incapacitation for persons located in proximity of the fire as for a diesel ADT. Specific harmful substances typically associated with battery fires, in particular hydrogen fluoride (HF) concentrations, were found to be below critical threshold levels.
- Application of battery-electric ADTs at Rogfast E02 requires consideration in fire safety planning. Since battery fires are generally difficult to extinguish, battery-electric ADTs should be equipped with automated fire suppressions systems to allow quick intervention if electrical systems catch fire. The work force is to follow standard safety practices (protective clothing), extended by using face masks and eye protection in case of a fire (shield against HF exposure) and evacuate to the rescue shelters.
- Battery-electric ADTs should preferably have a hose connection, to allow battery pack flooding in case ample water is available. Infrastructure for recharging of the batteries should preferably be located outside the tunnel.
- In general, Rogfast E02 characteristics require careful consideration for both battery-electric as well as diesel vehicle fires due to possible remote fire locations and limited accessibility for rescue services.

Process impact analysis has focused on comparison of transporting rock by battery-electric ADTs to diesel ADTs by developing first order models to assess productivity and efficiency:

- Available battery-electric ADTs are of comparable loading capacity to their diesel equivalent, but could have a lower driving speed and thus affect productivity. Key benefit of such ADTs is less energy consumption while being more efficient, enhanced by partial battery regeneration along the downhill section at Rogfast E02. However, the currently used battery capacities still have a significantly lower effective energy content (roughly one third) than the equivalent diesel ADTs. This off-set is counter acted by the OEMs by equipping the battery-electric ADTs with battery swapping solutions.
- For both ADT-types, the long transport distances and steep uphill section make energy demands at Rogfast E02 high, forcing especially the battery-electric ADTs to rely on multiple battery swaps. This requires recharging strategies, which extends current loader-based transport planning.
- The more efficient but less productive battery-electric ADT studied could be switched out by a larger, more powerful battery-electric ADT to increase tonnage transported (practical feasibility needs to be checked). A hybrid solution, limiting battery-electric ADTs to only transport in the tunnel, would increase complexity by requiring a temporary storage location and more trucks.

Extending beyond the scope of the risk study but considering the information and knowledge revealed, some additional aspects to consider have been briefly presented:

- Warranting careful consideration are the limited number of OEMs and battery-electric ADT-types (intended for mining) currently available. This could make market availability an issue and in general restricts choices. Moreover, initial application in an already challenging project should be regarded as to increase complexity and uncertainties.
- A GHG Protocol estimation highlights the sustainability potential for reduction of greenhouse gas emissions by switching to battery-electric ADTs at Rogfast E02. These results can help to accelerate the application of sustainable trucks.
- The use of only (battery-) electric vehicles and machinery during construction could also influence the construction ventilation, if not intended for emergency operation. During normal operation the fresh air requirements would mainly be governed by the work force, with the electric vehicles and machinery not considered completely free of emissions.

The risk analysis study has concluded that potentially suitable battery-electric trucks for transporting rock at Rogfast E02, namely for most ADTs, are currently available on the market. Application of such trucks would have to be considered in fire safety planning (fire duration, harmful toxic gases) and excavation process planning (productivity, recharging strategies).

For Rogfast E02, challenging characteristics and scale suggest a trial (product development, application experience) could be better considered in a less demanding and more suitable application of the Norwegian Method of Tunnelling. As an option, sustainability-oriented requirements could be included in the contract for Rogfast E02, helping to promote stakeholder participation and aiming to stimulate development of innovations.

1 INTRODUCTION

1.1 Project scope and structure

The Norwegian Public Roads Administration (NPRA), Statens vegvesen, aims to halve greenhouse gas emissions by 2030 compared to 2005. In this context, NPRA is considering extending the use of electric construction machines in tunnel work to help in reaching its sustainability goals [1]. The currently under construction Rogaland Fixed Link in the E39, commonly referred to as the E39 Rogfast, has been designated by NPRA as a pilot project for fossil-free construction sites. This challenging and large scale project involves Boknafjord tunnel, which at a length of 26.7 km and a deepest point of 390 m under the sea will be the world's longest and deepest subsea road tunnel. A partial (or ultimately complete) conversion of diesel to electric machines especially in the scope of this particular project can however be regarded as a major change in tunnel construction. On this basis, an investigation into key areas of the construction process is warranted, aiming to obtain a first order assessment of possible risks involved.

Several contracts for E39 Rogfast have already been commissioned in which already requirements have been implemented for static operations of heavy machinery to use cable-electric power. For the upcoming contract for section E02, NPRA is aiming to further reduce the carbon footprint by considering the possibilities for conversion of the trucks transporting excavated rock material from conventional diesel to battery-electric alternatives. Before actual contract implementation, NPRA wants to investigate which possible effects this switch in truck types might have on their responsibility to ensure health, safety and environment (HSE). Primary focus are currently not sufficiently understood risks related to fire involving battery-electric machines [1]. In addition, NPRA wants to gain perspective on the potential impact changing transport trucks could have on the progress of the excavation process. Both are to be investigates through a detailed risk analysis study [1].

NPRA has granted a dedicated project consortium consisting out of ILF Consulting Engineers Norway joint by Søvik consulting (Norway), Graz University of Technology, Institute of Thermodynamics and Sustainable Propulsion Systems (Austria) and ILF Consulting Engineers Austria to conduct this risk analysis study. Considering the large scale project background, the goal of this risk study is a study primarily to analyse the main differences and potential risks in changing propulsion system for the transport trucks at E39 Rogfast project, section E02 (Rogfast E02). As main topics both fire risk and process impact, by comparing battery-electric trucks to conventional diesel trucks for transport at the project, will be studied in detail. The risk study has first to identify and select through market research possible battery-electric transport trucks suitable for application in the Norwegian Method of Tunnelling as (will be) used in the project. Representative trucks for both propulsion types are subsequent to define and use for detailed analysis. Fire risk analysis will focus on establishing the main fire scenarios and the resulting potential harmful toxic smoke and heat release for both truck types, highlighting key differences and provide risk mitigation measures. Process impact analysis will centre on establishing productivity and efficiency for both truck types, discussing key differences and present mitigation measures.

The risk analysis study is to focus on purely battery-electric trucks that are currently available on the market and are potentially suitable for intended use at Rogfast E02. Alternative solutions for sustainable propulsion of transport trucks such as a hydrogen fuel-cell technology or hybrid solutions, for instance diesel-hybrid, are therefore considered outside of the scope of this study. Furthermore, the risk study focusses on the assessment and comparison of the trucks with Rogfast E02 serving as case study. For this purpose, the truck characteristics and in particular the project layout simplified. Moreover, with the focus being on the truck comparison, the possible interaction with the actual E39 Rogfast project as well as the tunnel excavation process at Rogfast E02 are not part of the scope of this study.

1.2 Document outline

The main findings of the NPRA risk analysis study into battery-electric transport trucks for tunnel excavation at Rogfast E02 are presented in this report. In Chapter 2 a brief overview of the E39 Rogfast project and in particular section E02 is provided. Chapter 3 gives an overview of typically battery types which could be or are used in construction vehicles, followed by various fire suppression measures aimed at battery fires. The results from the market research and the selection of representative trucks for the study is presented in chapter 4. Subsequent is in chapter 5 the framework and methodology of the fire risk analysis outlined, followed by the main results and identification of possible risk mitigation measures. Chapter 6 focusses on the process impact analysis, outlining the framework and methodology, presenting the main results and discussing various mitigation measures. Chapter 7 discusses additional aspects that have emerged during the risk study and warrant consideration, The main findings and recommendations of the risk study are presented in chapter 8. Followed by the bibliography and the appendices, reflecting a list of OEMs contacted and a vehicle database based on the market research.

The project consortium, its various member organisations and their representatives, want to express their gratitude to NPRA for granting the opportunity to conduct this risk analysis study and express the desire for a future collaboration.

2 ROGFAST TUNNEL PROJECT

2.1 General

NPRA has provided some typical information regarding the E39 Rogfast project and in particular with respect to section E02; at a kick-off meeting, dated 14-04-2023 [2], an intermediate progress meeting, dated 19-06-2023 [3] and a project visit to the Mekjarvik construction site (north of Stavanger, Norway), dated 25-04-2023. The information provided has allowed to obtain a general overview of the E39 Rogfast project and essentially characterise section E02.

2.2 E39 Rogfast project

E39 is a national road connecting large parts of Norway's west coast and runs between Trondheim and Kristiansand, using at the moment several ferry crossings. A new connection named "Ferjefri E39", or ferry-free E39, is foreseen, which aims to eliminate or reduce existing ferry connections by replacing these with new roads, bridges and tunnels. The projects included are aimed to improve traffic flow and shorten travel times.

From the various sections planned, the road connection between the municipalities of Randaberg (near Stavanger) and Bokn is of particular interest. This section will replace the ferry across the Boknafjord by means of a subsea tunnel (see figure 2-1). This project, called Rogaland Fixed Link or E39 Rogfast, is currently under construction and includes the twin-tube Boknafjord tunnel. This tunnel will have a length of 26.7 km and a deepest point of 390 m under the sea, making it after completion the world's longest and deepest subsea road tunnel [4].

Boknafjord tunnel is divided into several contracts, with E02, E03 and E04 comprising the largest undertakings [4]. Sections E03 and E04 are currently under construction with the contract for E02 being commissioned in the near future [2]. In this context, the risk study will focus on section E02, serving as case study.

Figure 2-1: Overview of the currently under construction E39 Rogfast project, with the world's longest and deepest subsea road tunnel called Boknafjord tunnel [4]

2.2.1 Case study: E39 Rogfast, section E02

The middle section of Boknafjord tunnel is located in the area of Kvitsøy island and is designated as E39 Rogfast project, section E02, commonly referenced as Rogfast E02 [4]. This twin-tube tunnel section has a total length of about 9 km tunnel, extending an equal distance in both directions. The tubes to be constructed will have a maximum incline of 4.5% [4]. The connecting tunnel to the surface of Kvitsøy island is around 4.5 km long and has a gradient of up to 7% [4] (see figure 2-2).

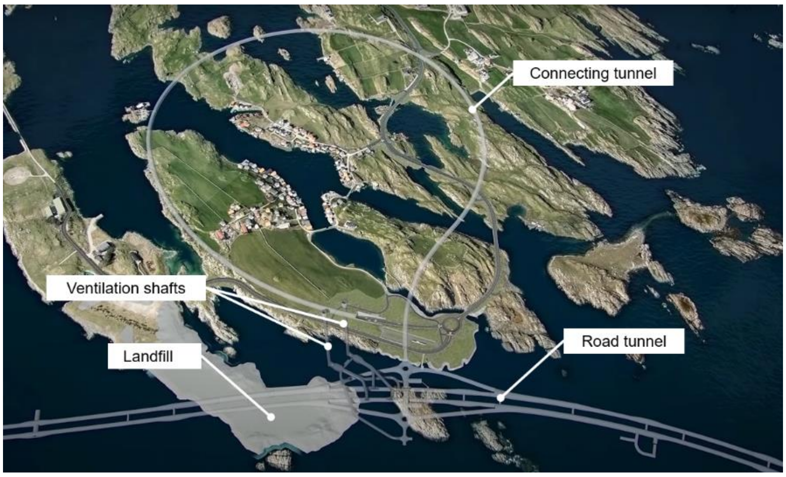


Figure 2-2: Detailed view of E39 Rogfast project, section E02 (Rogfast E02) at Kvitsøy Island, indicating the access tunnel to the main road tunnel (still taken from promotional video published by NPRA [5])

Each of the tubes has a tunnel profile of type T 10,5, in accordance with the Norwegian guideline for road tunnels [6]. This horseshoe profile has space for two traffic lanes with emergency walk ways on both sides. The base width is 10,5 m with the radius of the road being 4.79 m at a centre point 0.725 m horizontally offset from the centre line at a height of 0.664 m. The centre line crown radius is 5.95 m, situated at the same height. This reflects a total cross-sectional area of the road tunnel of 61 m^2. A schematic representation of tunnel type T 10,5, taken from the guideline [6], can be seen in the left picture of figure 2-3.

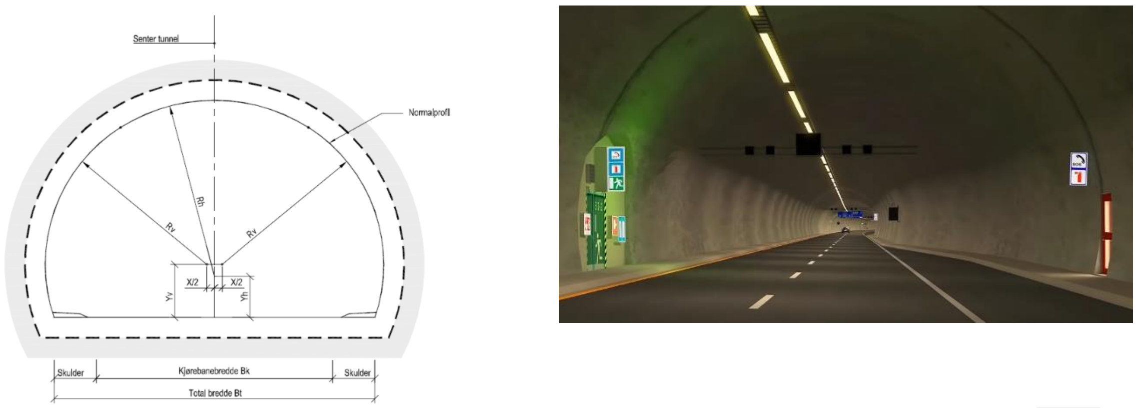


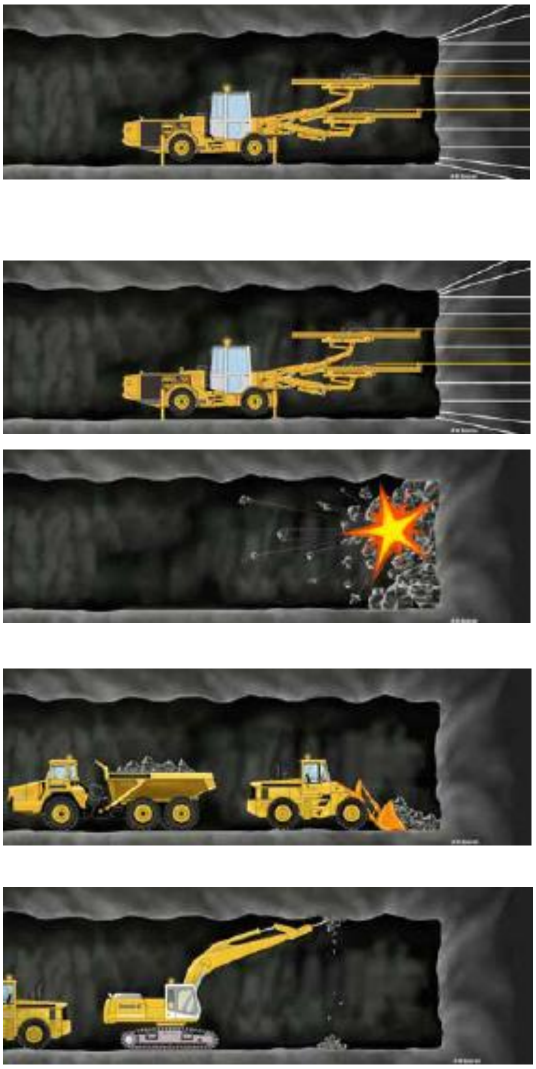
Figure 2-3: Schematic cross section according to the Norwegian guideline for road tunnels (left) [6] and impression of emergency exits and lay-bys in Boknafjord tunnel (right) (still taken from promotional video published by NPRA [5])

For reasons of safety, the tunnel has emergency lay-bys situated every 500 m and emergency exits (usually designed as cross passages between the two tunnel tubes) are planned every 250 m. Fresh air supply will be provided by two ventilation shafts (air inlet and outlet) with 10 m diameter and longitudinal fans positioned over the traffic lanes in the main tunnel tubes.

2.3 Norwegian Method of Tunnelling

2.3.1 General

In Norway, the conventional drill and blast method is frequently used for the construction of road and rail tunnels. This is commonly referred to as the Norwegian Method of Tunnelling Method (NMT) and is best suited for tunnelling through solid rock. The NMT includes procedures and timing between each work task, which ensure a cost-effective construction process. A typical cycle involves a series of sequential steps, which are schematically shown and explained in figure 2-4 (taken from [7] and also further detailed in [8]).



1. Pre-injection

Holes approximately 20 m long are drilled around the entire tunnel cross-section. Cement mass is pumped into the holes under high pressure. The purpose is to seal the cracks in the rock so that groundwater cannot penetrate.

2. Drilling and Charging

Drilling of holes about 5 meters long, which are filled with explosives. The blast pattern is selected according to the quality of the rock.

3. Blasting and Ventilation

To minimize surface vibrations, each blast is divided into series, which are fired in a quick sequence (duration of a few seconds). After blasting, dust and gases are removed by ventilation.

4. Displacement

The blasted material is loaded onto dump trucks or trucks. Depending on the landfill location, the rock is stored outside the tunnel or transported directly along a specified route to an approved landfill.

5. Scaling and securing

Loose rock is crushed and cleaning of the surface is performed. Depending on rock properties, tunnel ceiling and walls are secured with bolts, shotcrete, and/or reinforcing arches. After each blasting, geologists check and evaluate the securing.

Figure 2-4: Schematic representation of the various steps per drill and blast cycle in the Norwegian Method of Tunnelling (NMT), taken from [7]

2.3.2 Project application

Excavation at Rogfast E02 is assumed to be according to the NMT [2, 3]. After construction of the Kvitsøy access tunnel, the main tunnel tubes will be excavated in both directions. Each tube of the main tunnel is excavated with around a 0.65 m thick oversize, giving an excavated rock area of around 75 m^2. A typical excavation progress depth for each tube would be around 5 m per drill-blast cycle [2, 3]. The rock material excavated is to be transported by suitable trucks from the tunnel face to a landfill site (e.g. land reclamation), as seen in figure 2-2. Truck loading at the tunnel face is intended by a loader from AMV [2, 3] (see figure 2-5).

Figure 2-5: Some typical machinery of relevance to application of NMT at Rogfast E02, showing a Volvo articulated hauler (left) [9] and an AMV loader (right) [10]

2.3.3 Requirements for transport trucks

From the perspective of the NMT, the main relevant aspect to consider for the trucks is their ability to transport blasted or broken rock away from the tunnel face, also referred to as mucking. Typically, heavy-duty trucks would be selected that combine a high loading capacity with (very) good off-road abilities at speed. These typical requirements are extended for this particular study by including battery-electric propulsion.

Considering the underground working environment at Rogfast E02, the following typical requirements for the transport trucks have been stated:

- **Battery-electric drivetrain**: Trucks should have a battery-electric drivetrain, preferably an equivalent diesel variant is available. Of interest are also battery technologies, recharging solutions, fire prevention measures and productivity / efficiency. In addition, trucks should already be applied for such purposes.
- **High loading capacity**: Truck types suitable should have a sufficiently large loading capacity to allow for a timely and complete clearance of all the rock material produced in a single drill-blast cycle.
- **Good off-road capabilities**: Trucks would have to transport broken rock material in a tunnel excavation environment. The road surface will probably reflect a flat, but rough rock surface which could be muddy and wet. Most notably is the steep Kvitsøy access, which is assumed to be unpaved. To conclude, the trucks should have sufficient traction while transporting the rock material uphill.
- **Layout and design**: In general, the trucks should be powerful, reliable and robust to cope with the underground working environment.

3 BATTERY SOLUTIONS FOR CONSTRUCTION VEHICLES

3.1 General

A battery electric vehicle (BEV) is powered purely by electricity stored in a rechargeable battery. In contrast, an internal combustion engine vehicle (ICEV) uses a petrol or diesel propulsion system. BEVs are equipped with an electrified drivetrain that includes one or more electric motors and an inverter. The electric motor converts electrical energy from the battery into mechanical energy that drives the vehicle's wheels. The inverter controls the flow of electricity to the motor, allowing control of the motor's speed and torque.

The heart of a BEV is the battery, where the energy is stored electrochemically. The battery pack consists of a large number of individual battery cells, typically lithium-ion (Li-ion) cells, connected in series and parallel to achieve the specified voltage and/or capacity. The battery management system (BMS) is another important component that monitors and manages the state of charge (SoC), state of health (SoH) and temperature of the battery. It helps to prevent overcharging, over-discharging and overheating, ensuring the safety and longevity of the battery. BEVs often have regenerative braking, which captures some of the kinetic energy generated during braking and converts it back into electrical energy.

3.2 Types of batteries for heavy-duty application

3.2.1 General requirements and regulations

Batteries for heavy-duty applications must meet somewhat different requirements than those for passenger cars. First and foremost, it is about the vehicle's availability. The aim of a truck is to have as little downtime as possible during its lifetime. Construction machines are also often used in multi-shift operation (i.e., twenty-four-seven). The following differences must be taken into account:

- **Faster charging:** to ensure a high availability, a short charging time with high power is necessary. Swap systems can be used as an alternative, but again these should be charged as fast as possible (depending on the pool size).
- **Long cycle life:** the batteries in these vehicles must achieve a long lifetime in terms of the number of charging and discharging cycles.
- **Higher capacity:** especially trucks have to cover long distances and require batteries with a high capacity.
- **Higher power:** the power for the high-performance drivetrain engines as well as the power to supply the auxiliary electrical systems has to be provided.
- **More robustness:** particularly in the case of construction machinery, operation under difficult ambient conditions results in vibrations, impacts and shocks that can damage the battery. Therefore, the battery must be appropriately protected or designed to be robust.
- **Higher voltage:** batteries of passenger cars usually operate at a voltage level of 400V. Due to higher energy requirement and more powerful electrical systems, the trend for trucks is towards higher voltage classes, such as 800V.

Additionally, approval is needed if the vehicles are driving on public roads. For BEVs the UN ECE regulations 100 (Electric power trained vehicles) or 153 (Fuel system integrity and electric power train safety at rear-end collision) apply. In addition, national rules and regulations might be relevant. If no road approval is required, but the vehicles are intended to be placed on the European market, the Machinery Directive (Directive 2006/42/EC on machinery) must be complied with. Among other, this directive regulates basic safety requirements and CE marking.

3.2.2 Battery types

At the moment, the most commonly used traction battery type in automotive technology for electric vehicles are lithium-ion (Li-ion) batteries. This battery has prevailed over the other types due to its high energy density, relatively low self-discharge and long cycle life. Li-Ion batteries can be divided into several sub-types, which are often classified according to the cathode material. Important representatives are Lithium-Iron-Phosphate (LFP), Lithium-Nickel-Cobalt-Aluminium-oxide (NCA), Lithium-Manganese-Oxide (LMO) or Lithium-Nickel-Manganese-Cobalt (NMC, NCM). Some important properties of the mentioned types are graphically compared in the following chart (see figure 3-1).

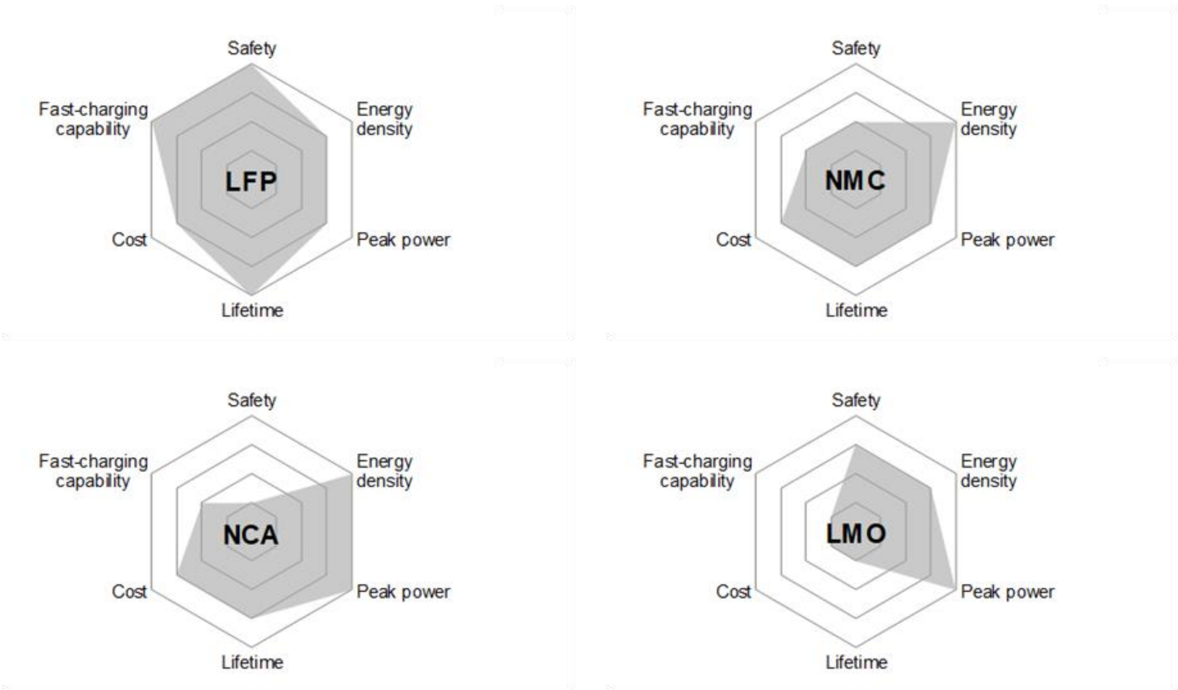


Figure 3-1: Characteristics of some Li-ion battery types [11]

Another type are solid-state batteries (without liquid electrolyte), which are very promising in terms of safety, energy density and service life. However, their use is still at the research and development stage; they are not yet used in series production.

A new, dedicated battery development for the specific requirements for heavy-duty application is in competition with economic reasons. From the current perspective, synergy effects from battery development can be adopted from the much larger passenger car market, which is already more mature and traction batteries have been used in series production for several years. However, in most cases the OEMs do not manufacture the battery themselves, but obtain them from suppliers or battery manufacturers. This is also the case for trucks and construction equipment, which obtains modules from the same battery manufacturers as supply the passenger car industry.

In general, it can be assumed from today's point of view that trucks and construction machinery use the same modules as used in passenger cars. However, due to the higher capacity and voltage required, a larger quantity of modules is used, which are connected to each other as required. A more powerful cooling system (or BMS), for example, must be taken into account for such battery systems. In the medium and long term, a development specifically for the requirements of trucks and construction machinery might bring its own battery types.

3.2.3 Comparison of LFP and NMC

An evaluation of available data sheets and feedback from OEMs shows that the same Li-ion battery types are used in construction vehicles as are used in cars. These are LFP batteries or NMC batteries. Some main important differences between these battery types are:

- **Energy Density:** LFP batteries typically have lower energy densities compared to NMC batteries
- **Power Density:** LFP batteries tend to have higher power densities than NMC batteries. Power density refers to the ability of a battery to deliver power quickly.
- **Cycle Life:** LFP batteries can typically endure more cycles before reaching the end of their useful life.
- **Cost:** LFP batteries tend to be less expensive than NMC batteries. This is primarily due to the simpler and less expensive raw materials used in LFP battery production.

In this context, the difference in terms of safety is particularly important to mention. **LFP batteries can be regarded to have better tolerance to high temperatures compared to NMC batteries**. They can withstand elevated temperatures without significant performance degradation or safety concerns. Additionally, **LFP batteries tend to have a higher thermal runaway temperature threshold, making them more resistant to overheating.** If a thermal runaway occurs, they have a lower risk of thermal propagation to neighbouring cells. This means that if one cell fails, the likelihood of the failure spreading to other cells in the battery pack is reduced.

3.3 Charging methods for practical use on construction sites

In principle, there are several ways to charge the vehicles' battery, or at least to support it with power supply during operation. Although not all systems are suitable for application on construction sites, and in particular in tunnels, a short description of all available systems will be given for the sake of completeness.

3.3.1 Charging stations

The simplest and most common option is to connect the battery to a charging station via a charging cable. Based on the charging speed, a distinction is made between **normal charging** and **fast charging**. This is normally expressed by means of C-rate:

$$C_r = \frac{I_{max}}{E}¶$$

Equation 3-1: charging speed as defined by the C-rate

The C-rate [h^{-1}] refers to the charging or discharging current I [A] relative to the battery's capacity E [Ah]. For example, at 1 C a fully discharged battery with a capacity of 1 Ah should be fully charged with 1 A within 1 hr. The following can subsequent be distinguished:

- Normal charging: up to a charging rate of 1 C
- Fast charging: the C-rate of fast charging depends on battery chemistry, manufacturer, and application; it ranges from 2 C to 5 C or even higher

Normal charging

To provide the energy required for charging several batteries at the same time, a suitable charging infrastructure is necessary. This takes into account, for example, a proper cooling system and a reliable power supply. In order to avoid bottlenecks in the power supply (particularly at construction sites in remote areas) and to compensate peaks in the grid, a battery energy storage system (BESS) is useful. Such mobile energy buffer systems consist of several batteries and an integrated battery management system. The system is charged externally and can then be connected to a battery that is to be charged as shown by examples in figure 3-2.

Figure 3-2: Battery charging via power cable (left, source: Epiroc) and example of a charging station (right, source: Caterpillar)

Fast charging

Not all lithium-ion chemistries accept fast charging, as it usually affects the functionality of the battery and accelerates its aging. To enable fast-charging, charging systems need to be designed to deliver the appropriate charging current and voltage within the safe operating limits of the specific battery chemistry. This requires monitoring and controlling factors such as temperature, voltage, and charging current to ensure the battery's health and safety.

Basically, both LFP and NMC batteries are capable of fast-charging. However, there are some differences in their performance characteristics in this perspective. **LFP batteries generally can handle higher charging rates**, without significant degradation or safety concerns. They have lower internal resistance, which allows them to accept a higher charging current without overheating. On the other hand, **NMC batteries usually require a more careful charging management**. More heat maybe generated during fast-charging as they might have a higher internal resistance. This heat generation can impact the overall battery performance and lifespan if not properly managed.

3.3.2 Battery swapping

In the concept of **battery swapping**, the empty vehicle battery is replaced by a fully charged battery at a charging station. This allows a quick battery change instead of waiting for the battery to charge. The process takes only a few minutes and is thus comparable to the refuelling process for a conventional diesel-powered vehicle.

However, the system has limited applicability because it is only suitable for vehicles with replaceable, accessible batteries. Currently, there are no uniform standards for such a system, deciding to use such a system would mean being dependent on a manufacturer. Each OEM uses its own battery packs with different battery designs (size, shape, connection), making it difficult to implement a widespread battery swapping system (see figure 3-3).

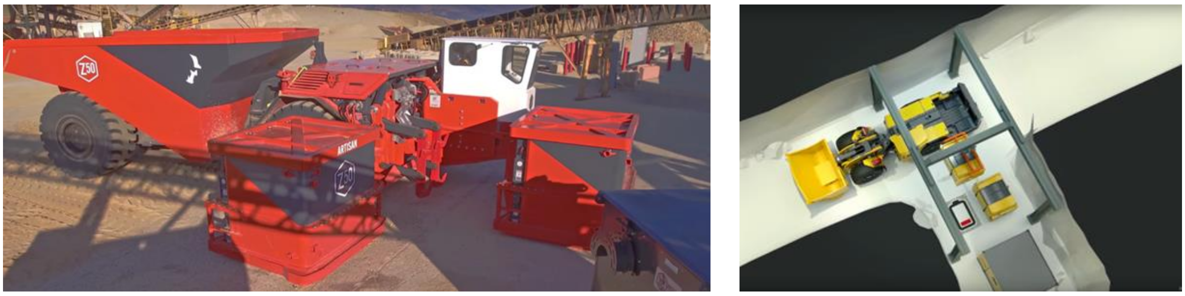


Figure 3-3: Examples of charging systems using battery swapping by a vehicle-based mechanism (left, source: Sandvik) and using a n overhead crane (right, source: Epiroc)

3.3.3 Trolley system

Another possibility is (partial) charging by power lines, called a **trolley system** as shown in figure 3-4 by several examples. For this purpose, power lines are installed on main transport routes, and the vehicles are equipped with current collectors. Particular case are areas of high gradients, for which the overheard cables can be used to support the higher energy demand and to save the battery. Energy can also be recuperated into the network in the opposite direction.

The installation effort is manageable for long-term construction projects, but the issue of safety due to exposed live parts is a major drawback of this system. Such a system is currently being implemented in some pilot projects on roads as well as in mines. An application in underground mining is not known at present.

Figure 3-4: Examples of a trolley system already realised for road trucks (left, source: SCANIA CV AB) and for mining application (right, source: Liebherr [12])

3.3.4 Inductive charging

Inductive charging enables vehicle batteries to be charged without wires or open power lines. The battery is charged via an induction coil connected to a charging station in the ground. Such system is also implemented only in rare research projects (see figure 3-5).

Figure 3-5: Induction coil in the ground [13]

3.4 Thermal runaway

A thermal runaway in lithium-ion batteries refers to a self-reinforcing process, that leads to a rapid increase in temperature, illustrated by figure 3-6. It is a heat generation due to reactions within the cell, which leads to faster reaction rates, higher temperatures and more exothermic reactions, which in turn further intensify this process. Only massive and targeted cooling can slow down the reaction.

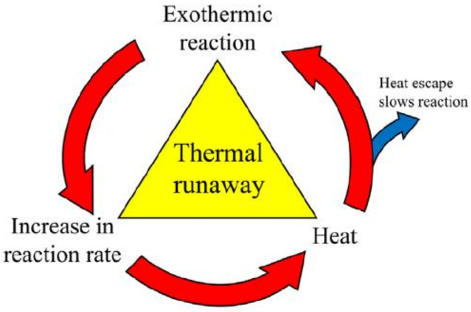


Figure 3-6: Loop of a thermal runaway, taken from [14]

There are several reasons for such a reaction to be triggered.

- Damage to the separator between the electrodes can cause direct contact between the cathode and anode, leading to an **internal short circuit**.
- Exposure to high temperatures or an **external heat**, such as a nearby fire, can cause the battery to heat up.
- **Overcharging** a battery beyond its capacity or **over-discharging** can lead to instabilities in the chemistries, contributing to thermal runaway.
- **Physical damage** due to mechanical stress, punctures, or impacts can damage the battery's structure, initiating chemical reactions that generate heat.
- The state of health (SoH) of a battery is a measure of its overall condition. If the SoH decreases with **aging**, the battery becomes less reliable and more vulnerable to unexpected behaviour.

In summary, it can be said that the separator of the cell plays a crucial role. It is a thin plastic film that ensures the separation of the electrodes. If the separator is damaged due to the previously mentioned reasons, a short circuit causes the cell to heat up. The initial temperature depends on the cell chemistry.

A thermal runaway can be noticed by various signs / potential hazards:

- **Heat release:** a thermal runaway releases heat due to the decomposition reactions
- **Release of gases and aerosols:** these substances can be both flammable and toxic, gases detected are CO, CO_2, H_2, HCs (CH_4, C_2H_4, C_2H_6). Via intermediate compounds, hydrofluoric acid (HF) can also be formed by the electrolyte usually used. HF is of particular importance because it poses a serious risk to health and safety. It has a corrosive effect which can quickly damage the skin, eyes and respiratory tract. If in-haled, it can cause respiratory irritation, bronchitis, pulmonary edema and other severe respiratory disorders. Besides, the smoke can contain metals such as lithium, nickel, cobalt, manganese.
- Formation of **jet flames** or **rupture** of cells
- **Leakage of liquid electrolyte:** often a lithium salt solution is used as electrolyte, specifically lithium hexafluorophosphate ($LiPF_6$), which is harmful to health and can cause skin irritation or eye irritation on contact.

3.5 Extinguishing methods for battery fires

Basically, it is not possible to extinguish a fire of a Li-ion battery cell. Due to the large temperatures generated during the thermal runaway, an enormous cooling effort would be necessary to dissipate heat from the failed cell. The primary goal is therefore to prevent the propagation of this thermal runaway to other cells.

There are two main characteristics of a lithium-ion battery fire:

- Difficult to extinguish because water must be applied directly to the battery. This can require a large amount of extinguishing water.
- Longer fire duration due to sequential ignition of battery modules. In addition, re-ignition of cells must be taken into account.

In principle, several strategies are possible for cooling, although not all of them can be considered useful for the requirements considered in this report. In the following the operation of the extinguishing method as well as a short assessment are presented.

3.5.1 Conventional cooling

The battery is cooled by a large amount of water applied to outside of the battery housing. The battery is well protected by a housing from damage caused by external impacts. This makes extinguishing the fire a challenge (as shown in figure 3-7), because the cooling effect of the water applied has difficulties in reaching the inside of the battery or the damaged cell. This explains the huge amount of extinguishing water required for this purpose.

Figure 3-7: Conventional cooling of a battery pack mounted in the car's underbody [15] (left) and fire container of a Norwegian fire department [16] (right)

3.5.2 Fire container

The damaged vehicle is moved into a special fire container (for example, see figure 3-7), which is then flooded with water until the battery is submerged. The vehicle remains there until there is no longer any danger posed by the battery. This can take up to several days.

This strategy is not manageable for large vehicles, compounded by space limitations inside a tunnel. Alternatively, only the sub-pack could be placed in the container. For this, it would have to be possible to remove the battery (or battery swap), but this variant is also not really practicable.

3.5.3 Fire blanket

Applying a large fire blanket covering the burning vehicle can reduce the spread of smoke in the first few minutes, as shown in figure 3-8. A fire blanket for large construction vehicles is however not available. In addition, it does not cool the damaged battery cells and thus does not prevent further propagation of the thermal runway.

Figure 3-8: Application of a fire blanket on a burning BEV (source: TU Graz, BRAFA project)

3.5.4 Extinguishing lance

A steel lance is driven into the burning battery pack and extinguishing water enters the interior of the battery through openings at the lance tip. Several examples can be seen in figure 3-9. This strategy is extremely effective in getting the extinguishing water into the battery's interior in a targeted manner. There are several models on the market (manual driving or pneumatic), although activating the system from a distance is preferred. Detailed instruction and training of firefighters is mandatory, as there are hazards from the high voltage system. It is also necessary to know the exact position of the battery in the vehicle.

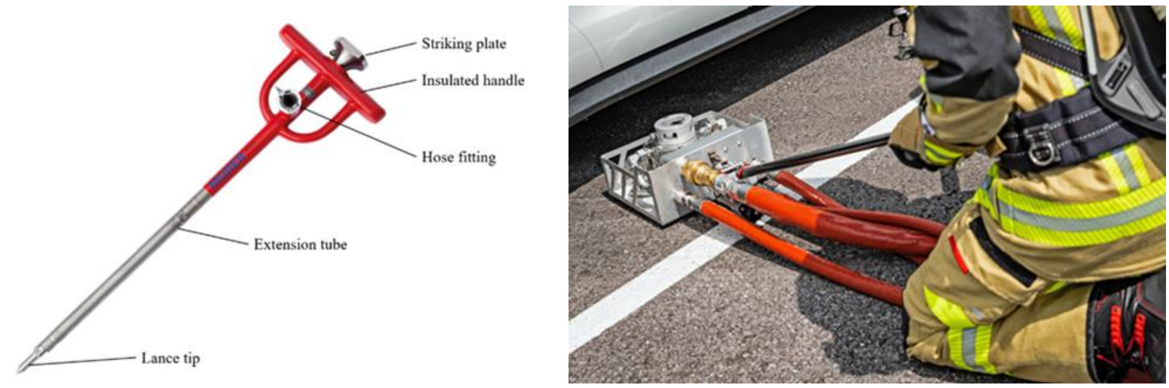


Figure 3-9: Two different types of extinguishing lances (source left: Murer Feuerschutz, source right: Rosenbauer)

3.5.5 Mobile fire suppression system

This fire extinguishing system is permanently installed on the vehicle and triggers automatically or manually by the driver. It has already been established for years in conventional construction vehicles (see figure 3-10) and can also be used for BEVs in principle. However, it is usually an extinguishing system with nitrogen (N_2), with the aim to smother a fire in the vicinity of the battery like a fire in the electrical box or a cable fire. **It's per se not to suppress a thermal runaway inside the battery**. Especially for construction vehicles with several sub-packs distributed in the vehicle, installation is costly. However, the probability of a fire spreading to the battery can be reduced.

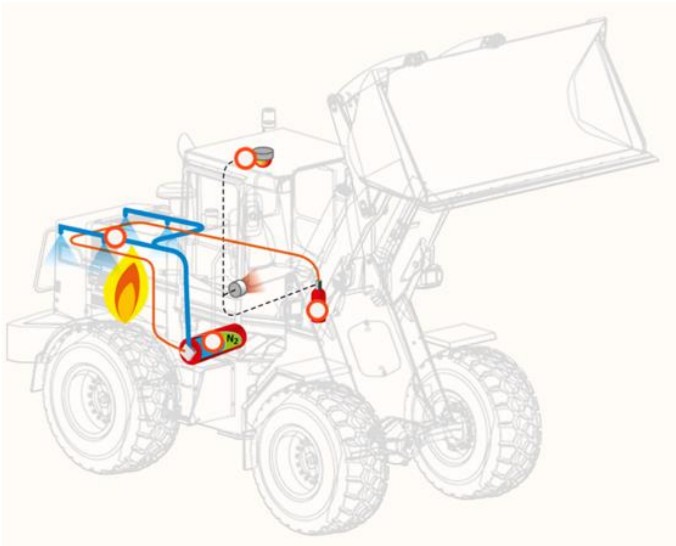


Figure 3-10: Example of a mobile fire suppression system mounted on an excavator by Fogmaker [17]

3.5.6 Fire hose connection

A hose connection is attached to the outer casing of the vehicle, as shown in figure 3-11. Extinguishing water is routed inside to the individual battery sub-packs, flooding the battery cells. This provides emergency personnel, as well as workers, the ability to effectively cool the battery pack with water. The hose remains connected as long as it is needed.

With little effort, emergency personnel can flood the battery very effectively. Water consumption is significantly lower than cooling the pack conventionally. Due to the very simple handling, if used in time, it is also possible for construction workers to use it themselves.

Figure 3-11: Fire hose connection on an electric construction vehicle (source: Epiroc)

3.6 Main findings

3.6.1 Battery technologies and charging solutions

The main types of lithium-ion batteries currently being used by OEMs for trucks and construction machinery are LFP and NMC. LFP batteries typically have lower energy densities, tend to have higher power densities, can typically endure more cycles before reaching the end of their useful life and tend to be less expensive than NMC batteries.

A thermal runaway in lithium-ion batteries refers to a self-reinforcing process that leads to a rapid increase in temperature. Possible reasons being internal short circuit, external heat, overcharging, over-discharging, physical damage and/or aging. In this context, LFP batteries tend to have a higher thermal runaway temperature threshold, making them more resistant to overheating.

Several possibilities of charging the vehicles' batteries have been presented. Due to the necessity of a high availability of the construction vehicles, a rapid charging of the high-capacity batteries is required.

Considering Rogfast E02, two charging methods are relevant taking the current state of the art into account:

- Special **charging stations** allow charging with high currents and represent a kind of buffer storage for charging the vehicle's battery. The connection to the vehicle is provided by cables. Due to safety concerns (e.g., problems when charging the battery), the stations are preferably located outside of the tunnel.
- The concept of **battery swapping** is already in use. Instead of waiting for the charging time at the charging point, the empty battery can be replaced by a full one within a few minutes. There are different systems on the market, however, they are not compatible with each other.

3.6.2 Extinguishing methods for battery fires

A malfunction of the battery, i.e., within the battery cell, can trigger a thermal runaway. This reaction can lead to heat release, release of gases and aerosols, jet fires or even explosions. However, the form and degree of this reaction depends on several parameters, such as the cell chemistry used or the state of charge of the battery. The higher the number of battery cells, the higher the probability of a malfunction. This should also be considered for battery-powered construction vehicles, which are equipped with large-capacity batteries.

The thermal runaway itself cannot be extinguished, but the aim of extinguishing measures is to prevent the reaction from spreading to other neighbouring cells. Several extinguishing techniques have been described for this purpose. In the case of extinguishing a fire in an underground construction site, challenging environmental conditions are added, primarily due to the limited amount of space available as well as continuous (high volume) water supply.

For Rogfast E02, reasonable firefighting could be provided by two techniques:

- **Mobile fire suppression system:** permanently installed fire suppression system on the vehicle. Such systems have been used for years on conventional vehicles, and in the case of battery electric trucks it is designed to prevent the fire from spreading to the battery (e.g., fire in the electrical box or a cable fire). **These systems are not aimed at suppressing a thermal runaway.**

- **Fire hose connection:** by means of a hose connection, the faulty battery can be flooded directly. This solution is therefore beneficial against a thermal run-away. Based on the simple application, the system could also be used by for instance operators, who can keep the fire under control even before the arrival of the emergency services. However, this does require the availability of a continuous water supply.

4 TRUCKS FOR TRANSPORTING EXCAVATED ROCK

4.1 General

Both fire risk and process impact analysis are to be based on representative battery-electric trucks that could be used for rock transport at Rogfast E02. Since no actual trucks have been selected beforehand, a market research into available and suitable trucks has been conducted. The goal of this market research is to establish a database of battery-electric trucks, categorised into different vehicle classes. In case of market availability of suitable battery-electric trucks, equivalent and/or typical diesel trucks are to be identified for reference. Subsequent are based upon project demands and constraints representative diesel and battery-electric trucks selected to be used in both studies.

In this chapter an overview is provided of battery-electric and equivalent diesel trucks that are currently available on the market and could be used for transport application in tunnelling. The goal is to provide per vehicle class typical examples of trucks with summarised the main characteristics of relevance to the study. Based on the project demands and constraints the vehicles classes are qualitatively assessed and representative diesel and battery-electric trucks selected. The chapter is concluded with some main findings regarding the current market availability of battery-electric trucks for transport application in tunnel excavation.

4.2 Selection of vehicle classes

Primary focus for the market research has been battery-electric trucks that are currently available and of relevance with respect to the application intended at Rogfast E02. Various of the Original Equipment Manufacturers (OEMs) that currently have potentially suitable trucks in their product line-up have been contacted to obtain more detailed information. An overview of these OEMs can be found in appendix I.

Hybrid solutions, both as part of the trucks propulsion system as well as by different truck types supplementing each other, have not been considered. The presented trucks all have a purely battery-electric or a conventional diesel drivetrain.

4.2.1 Vehicle classes

The battery-electric and diesel trucks have been categorised using three distinct vehicles classes that reflect typical transport trucks that could be used on construction sites, in tunnel excavation and in general for off-road transport application. The vehicle classes are defined as follows:

- **Road Tipper Truck (RTT)**: truck mainly offered by mainstream road truck OEMs that has limited to good off-road capabilities with its maximum loading capacity in case of road use based on road legal axel loads. Vehicle layout can be as truck with tipper or tractor with tipper trailer.
- **Articulated Dump Truck (ADT)**: truck using an articulated lay-out, intended for heavy-duty application, possibly in underground excavation, has good to very good off-road capabilities and a preinstalled box with high loading capacity.
- **Rigid Dump Truck (RDT)**: truck intended only for off-road use, focussed on high to very high box loads, often used in open-pit mining

The various vehicle classes and the trucks identified and selected are described in some detail hereafter with the primary focus on the propulsion system, drivetrain and main characteristics of relevance for construction application. An overview of the vehicle classes and the various trucks can be found in the vehicle database in appendix II.

4.3 Overview of road tipper trucks

4.3.1 Market available battery-electric trucks

Various well-known OEMs already have battery-electric drivetrains for road trucks in their product line-up. These electric drivetrains are continuously in development with improvements as well as new applications emerging. General perception is that electric-drivetrains are not specially developed and designed for use in road tipper trucks (RTTs), but rather implemented to already available product solutions with modifications if required.

Battery-electric drivetrain application focusses mainly on road use, in the light to medium range and/or duty. Furthermore, battery-electric trucks tend to be heavier than the equivalent diesel trucks, with the battery packs using more space than a typical diesel tank would. For OEMs safe and reliable use is key, reflected in special safety measures such as battery pack management (charging status, temperature etc.), emergency cut-offs and hand-held fire extinguishers. These OEMs offer special services to aid and assist in battery management and truck scheduling. Some typical relevant examples are given to illustrate electric drivetrain development and application possibilities.

Volvo Trucks

The electric drivetrain is fitted to the truck chassis with the electric motors carried in between the main chassis girders and the battery packs positioned on either side of the chassis [18]. This battery-electric drivetrain is used to power amongst others the construction focussed FMX series [19]. Figure 4-1 provides some examples to illustrate truck application and battery-electric drivetrain layout. For this product series power is provided by two or three electric motors with a combined output of 180 – 490 kW. The four or six battery packs have a total energy capacity 450 – 540 kWh [19]. Possible RTT configurations currently being offered are for instance 6X4 [20] or 8X4 with tridem [21]. Based on axel configuration, the 8X4 variant would have to comply with a typical road legal Gross Vehicle Weight (GVW) of 32 ton, giving an estimated loading capacity of 15 ton.

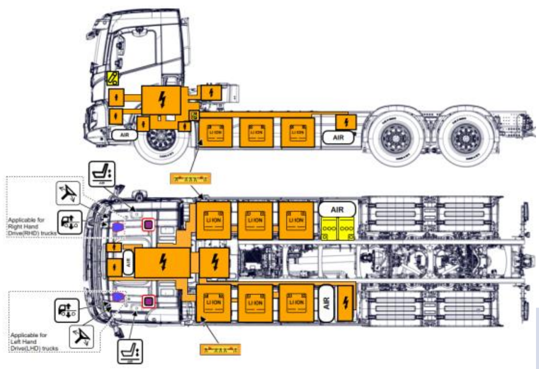


Figure 4-1: Example of a Volvo battery-electric FMX [22] (left) with a schematic representation of an electric drivetrain assembly from Volvo [18] (right)

Alternative construction application could be to use the general purpose FH series [23] in 4X2 configuration [24] as a tractor for a three-axel tipper trailer. The drivetrain has three electric motors proving 490 kW being supplied by the battery packs [18, 23]. Tractor and trailer would have to comply with a road legal GVW of 40 ton, giving a loading capacity of around 23 ton.

Volvo lists the possibility for fast charging up to 250 kW, taking around 2.5 hr for a full-recharge [19, 23]. It is noted that electric production (in small series) has started in 2022, with the first RTTs being used, for instance in Sweden [22] and the Netherlands [25].

Mercedes Benz Truck

Battery electric trucks use a by Mercedes Benz specially developed axel which incorporates an electric motor with a power output of 330 kW [12]. Energy is provided by three or four battery packs attached to the chassis with each an energy capacity of 112 kWh, dependent on truck configuration and needs [12]. Maximum recharging capacity is given at 160 kW [12].

Current configurations on offer are limited to for instance 6X2 eActros [12, 26] with an 8X4 eArocs intended for construction applications in development as demonstrated by a prototype at the BAUMA 2022 [26, 27]. As tractor for a tipper trailer a 4X2 eActros longhaul [12, 26] could be used as shown in the left picture of figure 4-2.

Production is reported to start end of 2023 (eActros and eArocs) and end of 2024 (eActros longhaul) [12].

Figure 4-2: Examples of battery-electric trucks used in construction transport application from Mercedes Benz, showcase vehicle at the BAUMA 2022 (left) [26] and from BYD in 8X4 configuration (right) [28]

BYD

An embedded electric motor in the axel is also adopted by BYD, as for instance in their construction oriented 8X4 T10 cab chassis [29, 28] as seen in the right picture of figure 4-2. The electric drivetrain consist out of two electric motors with each 180 kW and 435 kWh LFP-battery capacity [29, 28]. Charging time is reported to be around 2 hrs [29, 28]. Availability and compliancy with European road legalisation is to be checked.

4.3.2 Typical diesel transport trucks

Based on the broad range of possible diesel RTTs, two typical trucks have been selected to serve as reference for the risk analysis study. As mentioned, similar RTTs can be obtained from other OEMs.

As typical RTT a 8X4 Mercedes Benz Arocs is chosen, having a 330 kW diesel engine and a 300 litre diesel tank [30, 31]. Based on the axel configuration the GVW would be limited to 32 ton, giving a road legal loading capacity of around 17 ton.

As tractor for a three axel tipper trailer a Mercedes Benz Arocs 4X2 with a 375 kW diesel engine and 390 litre diesel tank could be used [32, 33]. For this layout, the GVW-based loading capacity would be estimated as 25 ton.

4.4 Overview of articulated dump trucks

4.4.1 Market available battery-electric trucks

The market for battery-electric articulated dump trucks (ADTs) is mainly aimed at underground mining application and consist primarily out of two OEMs; Epiroc and Sandvik. It is however noted that Epiroc and other third parties, such as eMining who is currently working on a diesel ADT [34], are offering retrofitting of diesel equipment.

Epiroc

For various heavy-duty construction equipment types, Epiroc has one or more battery-electric alternatives in their line-up; for example various drill rigs, a loader, and an ADT [35]. This battery-electric ADT has a loading capacity of 40 ton with in each of the two axels an electric motor with a power of 200 kW providing a 4X4 configuration (see figure 4-3) [36]. Energy is proved by five NMC battery packs with a combined energy capacity of 450 kWh, located next to the driver cabin [36]. The battery packs can be offloaded for recharging and switch for fully-recharged ones using an overhead crane, commonly referred to as battery swapping [36, 37].

Figure 4-3: Epiroc battery-electric 40 ton ADT [36] (left) with examples of Epiroc battery packs [37] (right)

Considering the intended working environment, Epiroc has given much attention into developing robust and safe battery packs for use [38]. In short, the battery packs have preinstalled measures to prevent a thermal runaway, software management to safeguard during use, a robust design to prevent damage and various fire suppression measures such as a hand-held fire extinguisher, an automated fire suppression system and a hose connection for battery pack flooding [38].

Epiroc offers both ADTs and battery packs as well as various other equipment and services such as swapping and recharging infrastructure. In addition, services are provided for battery management and truck scheduling [37]. The ADTs are currently in production with examples of use in mining transport application, such as for instance in Sweden [39] and Canada [40].

Sandvik

Battery-electric mining equipment is also offered by Sandvik [41]. Besides multiple loaders, also two ADTs, having a loading capacity of 50 ton [42] and 60 ton [43] respectively, are present in their product line-up. The 50 ton ADT in 4X4 configuration has four electric motors, each in one of the wheels hubs, with a combined power of 720 kWh [42]. The two battery packs are of type LFP with an energy capacity of 354 kWh, reported to possibly be extended to 482 kWh [42].

Battery packs can be offloaded and picked-up using a special lifting mechanism on the ADT [44] (see figure 4-4). Sandvik lists batteries as in compliance with various safety related legislation and offers both recharging stations and batteries as well as aids in battery management and truck scheduling [45].

Figure 4-4: Sandvik battery-electric 50 ton ADT [42] (left) and example of the battery offloading mechanism at the recharging station [44] (right)

4.4.2 Typical diesel transport trucks

Typical diesel ADTs often used for off-road transport in construction projects are Volvo articulated haulers, however similar trucks from other OEMs could also be used.

Volvo construction equipment provides a broad range of ADTs, categorised based on (off-road) loading capacity. From this product line-up as typical diesel ADTs a 30 ton [46] and a 40 ton [47] truck were selected. Both these ADTs have a 6X6 configuration with a 265 kW or 350 kW diesel engine and a 380 litre or 480 litre fuel tank. The 40 ton variant is shown in the left of picture of figure 4-5.

Figure 4-5: Diesel powered Volvo 40 ton ADT [47] (left) and Epiroc 40 ton ADT [48] (right)

Considering that the battery-electric ADTs are in essence based on a diesel equivalent, for each of the OEMs a diesel ADTs was additionally selected; for Epiroc the 40 ton ADT with a 400 kW diesel engine and a 580 litre fuel tank [48] and for Sandvik the 50 ton ADT with a 515 kW diesel engine and a 840 litre fuel tank [49].

4.5 Overview of rigid dump trucks

4.5.1 Market available battery-electric trucks

Rigid dump trucks (RDTs) are typically used for open pit mining in which loading capacity is of most importance. This reflected in the truck sizes available, most are far too large to be considered for use in tunnel excavation. In addition, battery-electric development seems to mainly focuses on hybrid solutions with an electric drivetrain supplementing the conventional diesel engine. An example is a diesel-hybrid RDT currently in development by Liebherr at the Erzberg mine in Austria [50]. This ADT relies on downhill loaded transport to optimise energy consumption, possibly extended by a trolley system.

The market research did however reveal a purely battery-electric RDT. This truck is a prototype and has been developed by eMining (part of Lithium System) in collaboration with Kuhn (see figure 4-6) using a retrofitted Komatsu diesel RDT [51, 52].

Figure 4-6: Kuhn / eMining prototype of a retrofitted Komatsu HD605-7 to battery-electric drive [52]

4.5.2 Typical diesel transport trucks

Based on the battery-electric prototype RDT, the original base truck would serve a diesel reference. This Komatsu has a loading capacity of 55 ton with a 575 kW diesel engine [53].

4.6 Representative vehicles selected for study

4.6.1 Vehicle class assessment and selection based on project application

The suitability for application at Rogfast E02 is based on assessment of the transport requirements for each of the vehicle classes and the truck selected. Recalling from the chapter 2.3.3, the transport trucks would have to combine a battery-electric drivetrain with a high loading capacity and good off-road capabilities as well as being generally powerful, reliable and robust.

Each of the vehicle classes has been assess accordingly:

- Road Tipper Truck (RTT): battery-electric trucks with tipper start to become available, but construction focused products more limited and/or in development. Moreover, use is intended for more basic and less heavy-duty transport applications. Considering project scale and characteristics deem currently available RTTs not a practical or first choice. Tractor with trailer is considered not feasible, since rock-based road surface at in particular the Kvitsøy access would require more axles with traction.
- Articulated Dump Truck (ADT): mining based battery-electric trucks have a layout and design as well as off-road capabilities and tonnage which would allow project consideration. It should be kept in mind that these truck are similar to typical conventional diesel ADTs, but would still require project adaption to a new vehicle type.
- Rigid Dump Truck (RDT): impractical trucks sizes and mainly diesel hybrid solutions has made RDTs not feasible for the purpose of this study

Vehicle class selected for the risk analysis study: articulated dump truck (ADT)

It should be noted, that during assessing market availability of battery-electric ADTs, no use in an actual tunnelling project has been found. The application of such ADTs should therefore be seen as technology that has not yet proven itself in a tunnel excavation environment.

4.6.2 Selected vehicles for study: articulated dump trucks

In order to promote a direct comparison of a battery-electric ADT to a diesel ADT, while also considering the limited ADT-types currently available, **it has been chosen to focus the study on the Epiroc 40 ton ADT.**

For this particular ADT-type, both variants use in essence the same basic truck layout with the drivetrain being the main differentiating aspect. In addition, sufficient data has been obtained to form the basis for both fire risk and process impact analysis.

An overview of the main parameters characterising the diesel and battery-electric ADTs selected is shown in table 4-1. Some of the parameters have been rounded for study purposes.

Vehicles selected	Articulated Dump Truck	
	Diesel reference	Electric alternative
Drivetrain	ICEV	BEV
Vehicle class	Articulated Dump Truck	Articulated Dump Truck
Application	Off-road	Off-road
Load capacity (off-road)	40 ton	40 ton
Propulsion type	Diesel combustion	Li-Ion
Layout and configuration	4X4	4X4
Number of motors	1	2
Power per motor	400 kW	200 kW
Total power of drivetrain	400 kW	400 kW
Number of forward gears	8	1
Capacity diesel tank	500 l	
Capacity per battery pack		90 kWh
Number of battery packs		5
Energy density	Diesel: 9.72 kWh/l	LFP: 0.09-0.12 kWh/kg NMC: 0.15-0.28 kWh/kg
Total energy of drivetrain	4 860 kWh	450 kWh
Refuelling time	10 min	
Battery swapping time		10 min
Battery recharging time		150 min
Drivetrain efficiency	20%	80%
Range of utilisation (SoC)	5-100%	5-90%
Total effective energy of drive train	923 kWh	306 kWh
Regenerative braking system	No, engine breaking	Yes, battery recharging
Loading capacity	40 ton	40 ton
Vehicle weight - empty	30 ton	40 ton
Vehicle weight - loaded	70 ton	80 ton
Max. speed flat / downhill - empty	40 km/h	20 km/h
Max. speed uphill 4.5% - empty	40 km/h	20 km/h
Max. speed uphill 7% - empty	30 km/h	20 km/h
Max. speed flat / downhill - loaded	40 km/h	20 km/h
Max. speed uphill 4.5% - loaded	20 km/h	20 km/h
Max. speed uphill 7% - loaded	15 km/h	18 km/h
Total vehicle length	11 m	11 m
Total vehicle width	3 m	3 m
Total vehicle height	3.5 m	3.5 m
Box height (load height)	2.5 m	2.5 m
Box dump height (max. height opened)	5.75 m	5.75 m
Loading time	4 min	4 min
Dumping time	1 min	1 min

Table 4-1: Overview of the main parameters for characterisation of the representative diesel and battery-electric ADTs selected

4.7 Main findings

4.7.1 Overview potentially suitable battery-electric trucks:

Based on market research and various OEMs contacted, the following can be concluded per vehicle class:

- Road Tipper Truck (RTT): various well-known OEMs are developing battery-electric drivetrains for road trucks, application mainly for road use, light to medium range and/or duty
- Articulated Dump Truck (ADT): development from diesel-equivalent, focusing on safe and efficient heavy-duty applications, limited number of full-electric ADT-types currently on the market, focus mainly on mining
- Rigid Dump Truck (RDT): trucks are developed for open-pit mining and become quickly not practical for tunnel excavation, diesel-electric hybrid solutions incorporating regeneration

4.7.2 Transport truck selected for study: articulated dump trucks

Considering the intended application of transport trucks at Rogfast E02, various main requirements have been formulated such as battery-electric drivetrain, high loading capacity, good off-road capabilities and in general being powerful, reliable and robust.

Battery-electric ADTs can be considered the first choice for transport during tunnel excavation at Rogfast E02, combining a high loading capacity with good off-road capabilities and a heavy-duty focussed layout and design. This would such ADTs to clear out the rock material produced at the tunnel face by transporting it across a rock-based road surface through the tunnel, along the steep Kvitsøy access to the landfill site.

Development of battery-electric RTTs do include construction applications of which only truck with tipper could be considered for Rogfast E02. Product development focuses on however on less heavy-duty transport, making currently available RTTs not a practical or first choice.

Representative vehicles selected: ADT with 40 ton loading capacity and 4X4 battery-electric drivetrain to equivalent diesel powered ADT

The market research revealed additional aspects to consider with respect to application of battery-electric ADTs:

- Limited number of OEMs / ADT-types currently available restricts choices and potentially actual product market availability
- Trucks are starting to be used for underground mining, no actual tunnelling project found
- Application of battery-electric ADTs in established NMT would require more practical information and/or trials

5 FIRE RISK ANALYSIS

5.1 General

A conversion of diesel to electric trucks used in the transportation of the excavated rock can be regarded as a major change in tunnel construction. On this basis, an investigation to obtain a first order assessment of possible risks involved has been conducted. The main focus was to pinpoint, analyse and assess risks tied to workforce safety of onsite personnel, emergency response operations, and the structural integrity of the tunnel itself.

In this chapter an overview is given of the fire risk analysis, elaborating the framework, methodology, and results. In addition, insights are provided into the intricate nature of the process and its crucial considerations.

5.2 Framework and Methodology

The fire risk analysis has been conducted following established methodologies, particularly adhering to the procedural outline illustrated in figure 5-1.

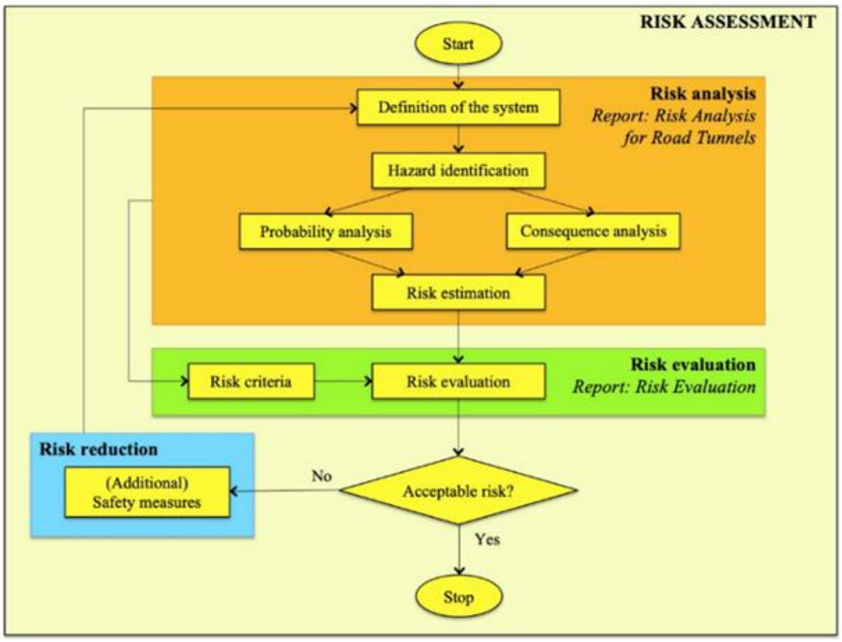


Figure 5-1: Generalized risk-assessment flow-chart, according to PIARC Working Group No. 2 "Road Tunnel Safety" of the Technical Committee C.4 -"Road Tunnel Operation [54]

This risk assessment methodology considers the following phases as elaborated hereafter:

- The initial phase involves the definition of the system, with particular emphasis on delineating the system boundaries. Within this defined framework, pertinent hazards have been systematically identified.
- For each individual hazard, risk in terms of probability and consequences has been evaluated. In the context of this specific fire risk assessment, the probability analysis has been executed qualitatively. In contrast, the analysis of consequences, particularly concerning fire-related impacts on tunnel workers, has been quantitatively addressed. This quantitative analysis involved the

utilization of representative fire scenarios analysed by means of computational fluid dynamics (CFD) simulations. The outcome of these simulations facilitated the evaluation of toxicity levels in the proximity of potential fire sites.

- To evaluate risk, a comparative approach has been applied. Therefore, risk differences due to the use of BEV machinery to ICEV machinery were identified by comparing probabilities and consequences for the respective energy-storage technologies.
- For those hazards and scenarios, where risk comparison showed a potentially significant risk increase, mitigation measures have been discussed

The following sections elaborate and extend each of these assessment stages, providing a thorough understanding of the underlying dynamics of fire risk and the methods utilised to efficiently address them.

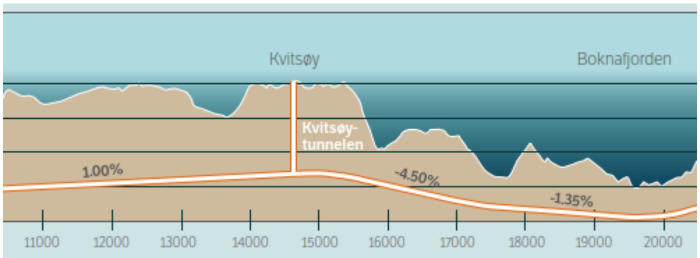
5.3 Definition of the system

The scope of the fire risk analysis pertains exclusively to those risk factors that exhibit potential distinctions between battery electric transport vehicles utilised in tunnel excavation and conventionally propelled counterparts. This selective approach ensures a focused evaluation of areas unique to battery electric vehicles within this specific context of this study.

For reference, the analysis considers ADTs due to their suitability for this kind of transport applications in tunnel projects, their availability as both BEV variant and equivalent conventional diesel powered ICEV, and the availability of ample quantitative data for analysis.

The analysis of both ADT types is conducted as a case study set out for the excavation process at Rogfast E02. Of relevance to the fire risk analysis are notably the cross-sectional geometry, longitudinal profile, and distinct segment lengths, with figure 5-2 showing the overarching layout of the construction section. The cross-sectional geometry remains predominantly consistent across the section to be constructed. However, it's feasible to distinguish two sub-sections characterized by differing inclinations:

- Main tunnel: an almost horizontal section covering a maximum of about 4.5 km in either direction, having an inclination of around 1% and -4.5% respectively. Both subsections' lengths expand as tunnel excavation advances.
- Kvitsøy access: a steep section giving access to the main tunnel, spanning approximately 4.5 km, characterised by a roughly 7% gradient.



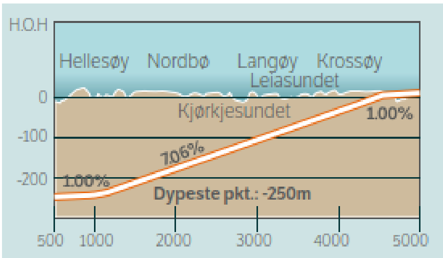


Figure 5-2: Longitudinal sections at Rogfast E02, showing the general geometrical layout for the main tunnel (left) and the Kvitsøy access (right) [4]

Additionally, a general construction ventilation system, designed to provide fresh air in areas where excavation activities occur, is assumed to be operational before fire ignition. However, **it is not assumed that this construction ventilation system is actively employed for fire ventilation purposes in the incident tube**, as these systems are not typically designed for such use.

Fire risk analysis furthermore **presumes the presence of fire shelters or equivalent systems that offer a haven for a defined duration**. In addition, **procedures for secure evacuation in smoke-filled tunnels are assumed incorporated**. It's noteworthy that specific details about the fire safety and emergency concept are not assumed as such within the fire risk analysis. These particulars are expected to be developed in subsequent stages of the construction planning project, as an integral part of the tunnel construction safety concept.

5.4 Hazard identification

Several hazard types have been discerned as pertinent to the comparative analysis between battery-electric and conventional transport vehicles in tunnel excavation. These hazard types encompass the following.

5.4.1 Fire hazard

The significance of fire hazards stems from societal awareness surrounding battery fires, amplified by the potential for catastrophic outcomes in tunnel (and tunnel construction site). In the context of BEVs, the primary distinction in fire hazards compared to ICEVs is attributed to the phenomenon of thermal runaway in Li-Ion batteries.

Thermal runaway can initiate from two main scenarios, an engulfing fire that originates elsewhere in the vehicle or as a result of battery malfunctions (penetration, overcharging, aging effects, etc.) where it becomes the source of the fire itself. During a thermal runaway the chemical constituents within the battery, such as electrolytes and Anode/Cathode materials, undergo decomposition and vaporization. The subsequent venting of these toxic and flammable gases from the battery, whether abruptly or in a controlled manner, raises significant concerns. Central amongst which is the potential formation of an explosive atmosphere. Furthermore, the **formation of Hydrogen Fluoride (HF)**, stemming from the fluoride components of the electrolyte, stands as a major toxic substance to contend with.

The intricate dynamics of these fire hazards, exploring their implications and potential consequences within the tunnel excavation environment have been analysed in detail as presented in section 5.4.6.

5.4.2 Venting of toxic and / or flammable gases

During a **thermal runaway** event, heat within the battery cell escalates with the decomposition and vaporization of chemical components generating flammability and toxicity gases that accumulate with pressure building up. The subsequent release of these gases can occur through cell rupture or via overpressure vents and is termed as "**venting gases**".

Experiments conducted on battery cells at a smaller scale have revealed that, the heat generated during thermal runaway of individual cells may not always reach levels sufficient to ignite the produced gases. In instances where ignition does not occur, the venting gases are discharged without undergoing combustion and would be carried along the tunnel through the longitudinal airflow. The level of toxicity is contingent upon cell chemistry, with fluoride being a common component. Consequently, the presence of HF is a significant concern within non-ignited venting gases. This mainly applies to the **immediate vicinity of the vent opening (whether through design or cell rupture), at which toxicity levels can be elevated.** Localised concentrations in close proximity to the battery theoretically can pose challenges.

The risk associated with the venting of non-ignited battery cells is projected to be notably lower than the risk linked to ignited releases. This seemingly discrepancy is firstly based on the improbability that a majority of cells within the battery simultaneously undergo thermal runaway, thus limiting the volume of gases vented at any instance. **During battery fires however, the potential for multiple cells undergoing thermal runaway simultaneously is greater with the higher volumes of gases expelled being (partially) ignited**. Furthermore, the nature of excavation sites necessitates a baseline airflow within the tunnel which combined with the restricted volume of vented gas is anticipated to result in minimal concentrations. However, during battery fires such a ventilation may not function optimally.

Additionally, the **dissolution of HF in water can lead to the deposition of hydrofluoric acid** on nearby surfaces, including the battery casing, vehicle, tunnel floor, and tunnel walls. Hydrofluoric acid is toxic itself and can be absorbed through the skin.

5.4.3 Electrical strokes

Electrical strokes represent a distinctive hazard typically associated with BEVs, including those employed in tunnel construction. These hazards can materialise as a consequence of collisions or malfunctions occurring during the charging process, being in particular of relevance in case of high voltage systems. In the event of a collision, the potential for electrical components to sustain damage exists, leading to short-circuit scenarios and subsequent electrical strokes. During the charging phase, issues like overcharging or malfunctions in the charging infrastructure can precipitate electrical strokes. The implications of electrical strokes encompass a range of concerns. Most notably, these events can induce the ignition of surrounding flammable materials, potentially leading to fires. Moreover, electrical strokes can pose direct harm to personnel present in the vicinity, given the potential for electric shock and subsequent injuries.

Tunnel environments amplify risks posed by electrical strokes due to the enclosed space restricting the dispersion of released energy, leading to higher probabilities of electrical contact with conductive surfaces, machinery, or personnel. Within the context of tunnel excavation, the presence of both personnel and machinery in close proximity further compounds the potential for electrical strokes. Other factors such as the elevated levels of dust, humidity, and potential water ingress characteristic of tunnel environments can aggravate the risk of electrical short-circuits.

For emergency responders, including tunnel personnel and emergency services, situations involving collisions or fires introduce specific challenges. If an electrical shortcut between the battery and the vehicle body exists, these responders face an elevated risk due to potential contact with electrified components. In emergency scenarios, quick and efficient actions are crucial, but the presence of electrified surfaces compounds the complexity of rescue and firefighting efforts.

Modern battery safety technologies are designed to mitigate such risks. These safety measures are strategically employed to prevent electrical shortcuts, consequently limiting the hazard of electrical strokes. Among these safety mechanisms, insulation and isolation techniques are prominently featured. Battery systems often integrate barriers and insulation layers that isolate conductive elements, minimizing the possibility of inadvertent electrical contacts. Additionally, advanced battery management systems are employed to monitor and regulate the charging and discharging processes, proactively identifying anomalies that could lead to electrical shortcuts.

To additionally **minimize potential consequences, BEV should be recharged** (higher probability of thermal runaway) **while being parked outside the tunnel in well-ventilated areas**. Also, **the possibility of toxic and flammable venting gases should be considered in the construction-ventilation design, to ensure a minimum airflow** is given at all times during operation, in all areas where BEV are operated.

5.4.4 Environmental hazard

A notable concern stemming from the integration of BEVs in tunnel construction projects is considered to arise from water used for fire-fighting purposes of Li-Ion battery fires causing environmental issues. The water used to suppress or extinguish such fires becomes contaminated with the chemicals released from the battery. This contamination of fire-fighting water with heavy metals and other battery-specific substances necessitates special wastewater management and treatment, in particular challenging during tunnel construction.

Tunnel construction projects inherently involve wastewater management due to water utilization during drilling and other processes, often designed with rock water in mind. However, conventional wastewater treatment facilities are generally not equipped to address the specific pollutants introduced by battery fires. To mitigate these environmental risks, a proactive approach could be to equip wastewater management and treatment systems with the capacity to accommodate battery-specific substances like heavy metals. A crucial strategy to minimise the environmental impact is to create provisions for extracting wastewater from the treatment system for specific aftertreatment in case of a BEV fire.

5.4.5 Other hazards

BEVs also introduce other environmental hazards that extend beyond the construction site itself. These hazards are, however, not related to tunnel construction processes directly but are rather general issues arising from the transition from fossil fuels to electrical batteries as energy storage technology:

- Mining and resource extraction: the production of batteries requires the extraction of raw materials, such as lithium, cobalt, and nickel. These materials are often sourced from mining operations that can have significant environmental impacts
- Energy source and production: while battery-electric vehicles produce zero tailpipe emissions, the environmental impact of these vehicles also depends on the source of the electricity used for charging. If the electricity is generated from non-renewable sources, it can contribute to air pollution and greenhouse gas emissions.
- Battery disposal and recycling: at the end of their life cycle, batteries need to be properly disposed or better recycled. Improper handling of these batteries can lead to the release of hazardous materials into the environment

5.4.6 Summarised findings

Among the range of identified hazards discussed in the previous section, those related to fires involving tunnel construction vehicles appear to be particularly significant. As a result, a comprehensive risk analysis, focusing on these hazard types, has been conducted. This analysis encompasses both a qualitative probability analysis and a thorough examination of potential consequences. The methods used as part of the fire risk analysis as well as the obtained results are presented in the following.

5.5 Fire probability analysis

5.5.1 Assessment approach

The central objective of the probability analysis was to establish the main differentiation between BEVs and ICEVs concerning their likelihood of encountering fires during tunnel construction. As reliable statistical data are scarce and in particular not readily available, establishing absolute probabilities of such incidents occurring is currently not feasible. The probability analysis is therefore based on a qualitative discussion and informed by interpretation of the available quantitative data.

5.5.2 Qualitative discussion

During tunnel construction, the prevalent fire sources often stem from small leakages of diesel or hydraulic oil igniting upon contact with hot surfaces [55]. For construction vehicles equipped with internal combustion engines, the engine itself generates these hot surfaces, positioning it as the principal source for igniting fires. Contrastingly, BEVs lack a combustion engine and the associated hot surfaces. **While BEVs still possess potential sources of hot surfaces like axles or malfunctioning brakes, the occurrence of fire from these sources is anticipated to be less frequent.** This divergence arises due to the necessity for concurrent instances, such as hydraulic oil leakage with for ICEVs the perpetually present hot surface from the engine simplifying ignition.

BEVs introduce an additional potential ignition source in the form of battery thermal runaway. Such thermal runaway can be induced by factors such as internal battery shortcuts due to failure, external shortcuts triggered by rockfall or collisions, or even charging-related failures and misuse. The likelihood of thermal runaway is intrinsically linked to battery safety design elements, encompassing factors like cell chemistry, battery management systems, and battery enclosures. Contemporary automotive batteries adhere to much more stringent safety standards than older batteries, thus reducing the likelihood of fires stemming from thermal runaways. Therefore, despite this additional ignition mechanism, it can be estimated that batter-electric construction vehicles should experience a lower probability for catching fire than construction vehicles relying on an internal combustion engine.

5.5.3 Quantitative data

Collectively, it can be regarded that the probability of a fire occurring during BEV operation is notably lower compared to ICEVs. This assertion is supported by fire data provided by different sources.

The Norwegian Directorate for Civil Protection's records between 2016 and 2022 reveal a higher count of vehicle fires among ICEVs than BEVs [56] . Although precise exposure metrics such as total travel kilometres are unavailable, the relative fire probabilities can be inferred from the proportion of each vehicle type in the Norwegian fleet, as reported in [57]. This analysis, considering the number of fires per vehicle / energy carrier, indicates a roughly 8-fold lower relative fire frequency for BEVs compared to ICEVs [57], (see figure 5-3).

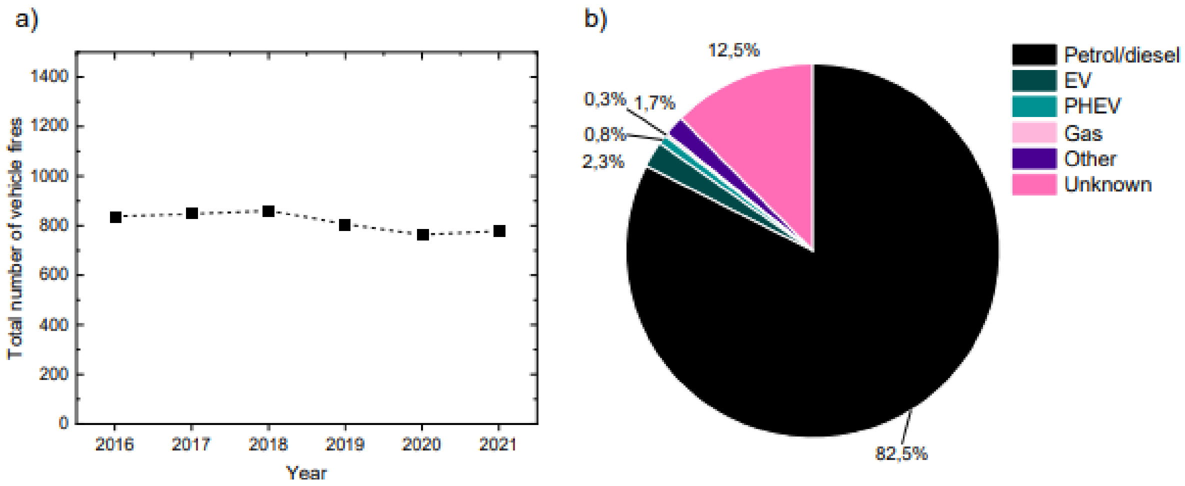


Figure 5-3:a) Total number of vehicle fires in Norway between 2016 – 2021 and b) total number of passenger vehicle fires in Norway between 2016 and March 2022, divided by the type of energy carrier, taken from [57]

This approximately one order of magnitude difference is also supported by Swedish fire frequency data from the civil contingency agency (MSB) as reported in [57] and shown in figure 5-4. Please note that the data for electric vehicles (EVs) also includes Plug-in Hybrid Electric vehicles (PHEVs).

Year	Number of EVs and PHEVs	Number of EVs and PHEVs fires	Relative frequency of fires	Number of ICEVs	Number of ICEV fires	Relative frequency of fires
2018	156 500	8	5 x10-5	4 900 000	3800	80 x10-5
2019	214 500	6	2 x10-5	4 900 000	3400	70 x10-5
2020	308 500	20	6 x10-5	4 950 000	3400	70 x10-5

Figure 5-4: Total number of passenger vehicles in Sweden (2018 – 2020) and the relative frequency of fire per energy carrier, data from Swedish civil contingency agency (MSB) and taking from [57].

In addition, also data from the United States indicate a similar relative difference in the probability of fires between BEVs and ICEV, as reflected by fire data provided by Tesla for the period between 2012 and 2021 (see figure 5-5). According to this dataset, approximately one Tesla vehicle fire occurred for every 210 million miles travelled. In contrast, data from the National Fire Protection Association (NFPA) and the United States Department of Transportation (DOT) reveals that there is a vehicle fire for every 19 million miles travelled within the United States. While this approximate tenfold difference in fire likelihood is Tesla-specific and not directly applicable to all electric vehicles, it underscores a substantial distinction.

Figure 5-5: Comparison of vehicle fire probabilities for TESLA vehicles and average U.S. vehicles [58]

It's important to note that these datasets mostly encompasses the entire vehicle fleet, including older vehicles and petrol-driven vehicles which are known to have a particularly higher fire probability than diesel vehicles, while the electric vehicles represent more modern automobiles.

This significant variation bolsters the estimated relationship of in general BEV experiencing a significantly lower fire probability than ICEV, which can be expected to also hold for vehicles used during tunnel construction.

5.5.4 Limitations in current data

Similar findings (approximately one-order of magnitude difference) for the relative difference in fire probability between BEV and ICEV strengthen the deduced estimation. However, the interpretation of statistical data regarding fire frequencies of battery-electric vehicles (BEVs) must be approached cautiously due to several limitations:

- **Limited data availability:** BEVs are relatively new, leading to a scarcity of historical fire incident data for accurate analysis.
- **Incomplete exposure metrics:** often, precise exposure metrics such as total travel distances or kilometres for BEVs are missing, making it challenging to calculate fire probabilities with precision.
- **Diverse vehicle age and safety equipment:** the dataset includes mostly new BEVs with advanced safety features, while internal combustion engine (ICE) vehicle data encompasses a wider age range, including older models that may have a higher fire frequency.
- **Applicability of passenger car data:** currently available data primarily pertains to passenger cars, posing challenges in directly extrapolating findings to larger vehicles and even more so for actual applications such as construction.
- **Fuel type variations:** ICE vehicle fire data includes both petrol and diesel vehicles, while large (construction) vehicles predominantly use diesel. Given the higher fire frequency of petrol vehicles, this could introduce distortion in the fire probability comparison.

- **Impact of vehicle size:** general trends suggest that larger vehicles have a higher fire probability. It remains uncertain whether this holds true for the relationship between small and large BEVs, potentially magnifying the disparity between BEVs and ICEVs in fire probability.

5.6 Fire consequence analysis

5.6.1 Fire simulations and fatality assessment

The focal objective of the consequence analysis is to analyse the principal distinctions between BEVs and ICEVs concerning the potential impacts on the health and safety of individuals within the tunnel in the event of a construction vehicle fire.

To achieve this goal, comprehensive fire simulations were conducted to evaluate representative fire scenarios at various fire locations at Rogfast E02. These locations were selected to acknowledge diverse geometrical boundary conditions and varying flow dynamics within the tunnel tube. Fire due to construction and loading activities at the tunnel face would take place in a tunnel section with a shallow gradient. This location is considered worst case, since this would experience one-sided enclosure with smoke accumulation, possibility influenced by open and perhaps actively ventilated cross-passage connections to the parallel tube. Fire at the Kvitsøy access anticipates to exert the highest engine load on a transport vehicle due to the steep gradient. This location would feature open tunnel tube boundaries on both sides, respecting a large available tunnel volume further downhill of the fire location. The fire locations are defined accordingly (see figure 5-6):

- **Fire location A**: situated at the tunnel face of the main tunnel with the shallow gradient
- **Fire location B**: positioned at the Kvitsøy access in the midst of this steep section

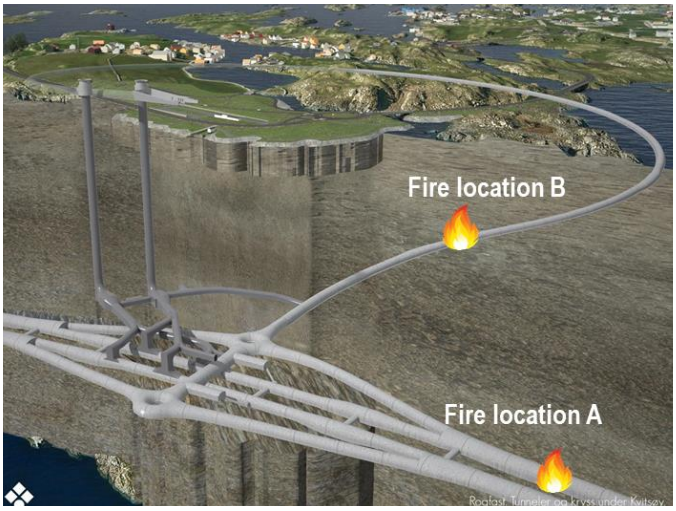


Figure 5-6: Position of fire location A and fire location B specifically considered in the fire risk analysis

At each of these fire locations multiple fire scenarios have been investigated. These scenarios encompassed for the diesel ADT a typical fire progression starting from a diesel pool. For the battery-electric ADT two scenarios emulating fire developments linked to distinct ignition mechanisms, namely the ignition of hydraulic oil on a hot surface and the ignition inside the battery due to thermal runaway have been considered:

- **Fire scenario I**: Diesel ADT fire following ignition of a diesel pool
- **Fire scenario II**: Battery-electric ADT fire following ignition of hydraulic oil on a hot surface
- **Fire scenario III**: Battery-electric ADT fire following a thermal runaway by ignition of the battery

The fire scenarios and the development of the resulting fire curves will be elaborated in sections 5.6.2 to 5.6.6 hereafter.

In total six fire and smoke propagation simulations (three fire scenarios at two locations) have been performed utilising Fire Dynamics Simulator (FDS) version 6.7.7. This transient three-dimensional Computational Fluid Dynamics (CFD) software specialises in simulating smoke propagation and fire dynamics, making it a primary tool for numerically modelling tunnel fire dynamics. FDS operates based on a low Mach number approximation of the Navier-Stokes equation, employing a Large-Eddy Simulation formulation optimized for buoyant flows [59].

The outcomes of the 3D-CFD simulations were harnessed to assess survivability conditions in close proximity to the fire events. This evaluation entailed the assessment of smoke and temperature conditions at face-level, followed by further processing through a survivability model. This model calculated the time to incapacitation for every position within the simulated 3D domain, defined by 1 km.

Details about the survivability model and the criteria used to define time to incapacitation are elaborated in section 5.6.7.

5.6.2 Fire scenario description

To enable a comprehensive assessment, plausible and representative fire progressions were established for each of the three fire scenarios. These qualitative scenario descriptions provided the foundation for constructing fire curves, representing the development of the heat release rate (HRR) over time. The base for establishing these fire curves has been the “Exponential Design Fire Curve Method with Superposition” as elaborated in [60]. This model employs the superposition of time-staggered fire curves for separate components to describe the heat release rate of the entire vehicle at any given moment (as delineated by Equation 5-1).

$$\dot{Q}(t) = \sum_{Component\ i} \dot{Q}_i^{max} \cdot n_i \cdot r_i \cdot \left(1 - e^{-k_i \cdot t}\right)^{n_{i-1}} \cdot e^{-k_i \cdot t}$$

Equation 5-1: Exponential Design Fire Curve Method with Superposition [60]

Values for model parameters of n_i, $r_i$and k_i can be estimated based on fundamental fire parameters such as the maximum heat release rate ($\dot{Q}_i^{max}$), the total calorific content (E_i^{tot}) and the time to maximum HRR (t_i^{max}), for details see chapter 6.3 in [60].

The fundamental fire parameters were estimated for distinct vehicle components, which were the cabin/cab, energy storage (diesel tank, Lithium-Ion battery), hydraulic oil, wiring and hoses, and tires. The input parameters used for the analysis are compiled in table 5-1. The values for conventional energy storage and other vehicle components shared with conventional dumper trucks were derived from well-established fire science sources, leveraging values from literature for analogous components. In contrast, values for battery-electric vehicles were derived from findings obtained in full-scale fire tests conducted on dumper truck batteries within a dedicated fire test facility.

Component	E_i^{tot}	$\dot{Q}_i^{max}$
Cab	3 500 MJ	1.5 MW
Energy Storage (500 L Diesel)	18 000 MJ	14.0 MW
Energy Storage (450 kWh electrical battery)	21 825 MJ (5 sub-packs)	3.0 MW (per sub-pack)
Hydraulic Oil	7 200 MJ	2.7 MW
Tires	43 200 MJ (4 tires)	3.0 MW (per tire)
Wiring and hoses	1 500 MJ	0.8 MW

Table 5-1: Fire parameters with respect to major vehicle components of articulate dumper trucks

The qualitative scenario descriptions, coupled with the fire curves resulting from the application of the aforementioned fire development model, are detailed in the subsequent text.

5.6.3 Fire scenario I: Diesel ADT fire – ignition of a diesel pool

For diesel ADTs, the typical fire scenario established hereafter is in line with literature, for instance reported in [55]. A diesel leakage precipitates a pool of flammable liquid, subsequently igniting on a hot surface, often the engine compartment. The fire subsequently propagates to the fuel tank, then advances to one of the tires. Progressively, the fire extends to the cabin, hydraulic oil, wiring, hoses, and the remaining tires. Using the fire development model the resulting fire curve shown in figure 5-7 has been derived.

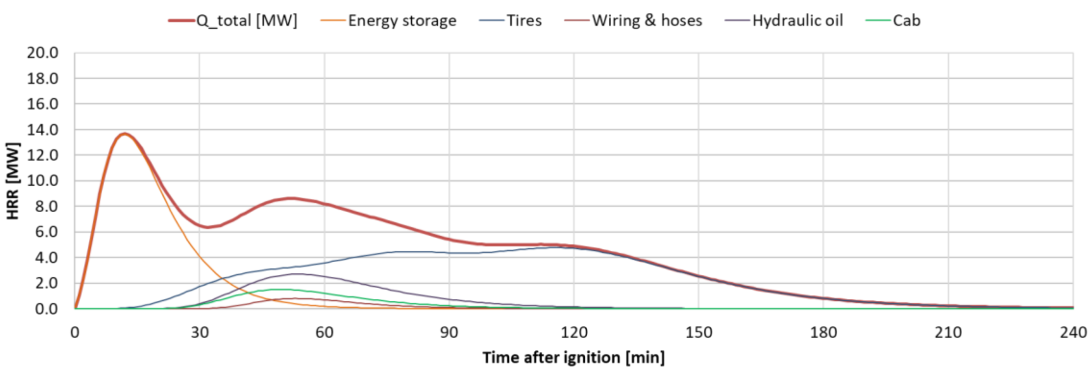


Figure 5-7: Fire curves for fire scenario I: diesel ADT fire – ignition of a diesel pool fire, reflecting overall development and for constituent components

5.6.4 Fire scenario II: Battery-electric ADT fire – ignition of hydraulic oil on hot surface

The primary battery-electric ADT fire scenario is considered to have a fire sequence comparable to the diesel ADT. A hydraulic oil leakage causes a pool of flammable liquid that ignites on a hot surface. The fire then extends to a tire, and subsequently to the wiring and hoses. Key difference however with the diesel ADT, it takes roughly 30 – 40 min later before the battery becomes embroiled in the fire, compounded by its higher energy content. Given the considerable engulfment of the entire battery by the fire, all sub-packs are envisaged to become involved nearly simultaneously. The fire continues to spread to the remaining tires and the cabin. The corresponding fire curve is displayed in figure 5-8.

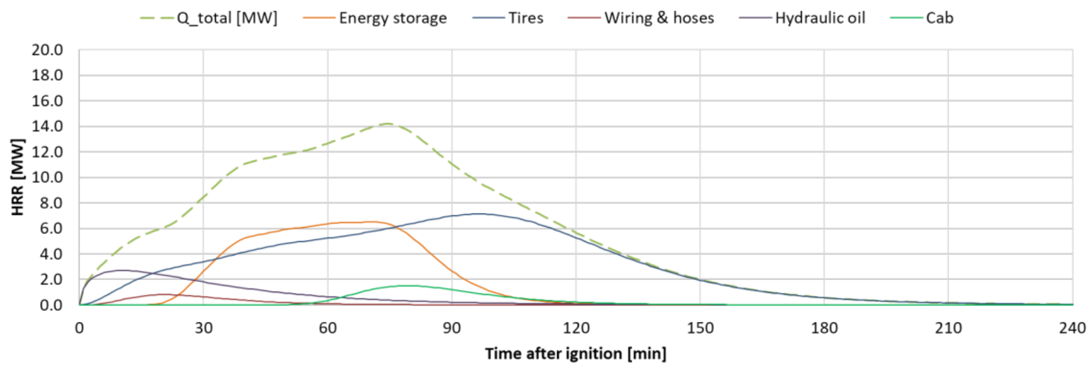


Figure 5-8: Fire curves for fire scenario II: battery-electric ADT fire – ignition of hydraulic oil on hot surface, reflecting overall development and for constituent components

5.6.5 Fire scenario III: Battery-electric ADT fire – battery ignition (thermal runaway)

For the second battery-electric ADT fire scenario, the fire sequence focusses on a thermal runaway. The initiation of a thermal runaway in one of the sub-packs starts a fire. Fire then propagates within the battery, encompassing all sub-packs over time. Given that fire propagation within the battery is typically impeded by battery safety designs, the fire curves of individual modules are anticipated to exhibit significantly less temporal overlap than in the first battery-electric ADT fire scenario. With the propagation between sub-packs, the fire extends to the hydraulic oil, wiring, and hoses. Subsequently, the fire advances to the cabin and the first tire, eventually affecting all tires. The corresponding fire curve is presented in figure 5-9.

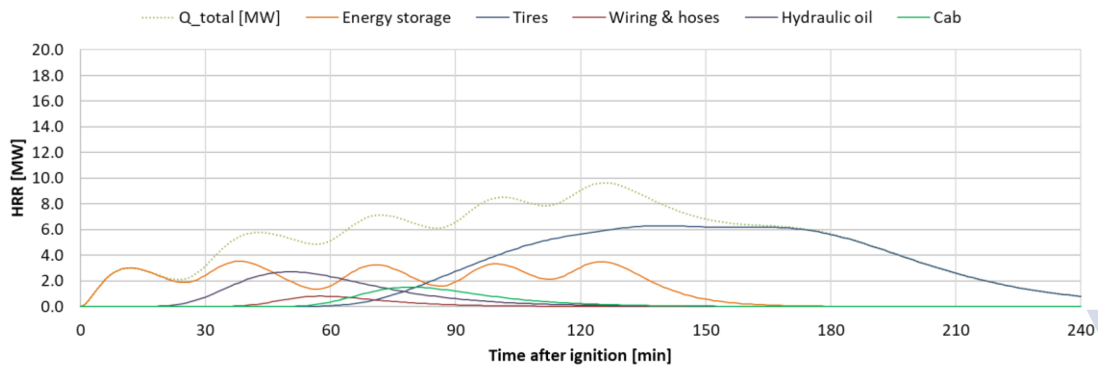


Figure 5-9: Fire curves for fire scenario III: battery-electric ADT fire – ignition of the battery, reflecting overall development and for constituent components

5.6.6 Comparison of scenario-based fire curves

The primary distinctions among the three fire scenarios lie in the maximum HRR, fire growth rate, and total combustion duration (see figure 5-10). The diesel ADT scenario is characterized by the most pronounced increase in HRR, attributed to the rapid release of a substantial quantity of flammable liquid, e.g. the content of the diesel tank. The battery-electric ADT scenario with hydraulic oil ignition possesses the highest overall HRR, albeit only marginally surpassing the maximum HRR of the diesel ADT scenario. Notably, the scenario involving a thermal runaway causing ignition within the battery is envisioned to have the longest fire duration due to the gradual fire propagation within the battery.

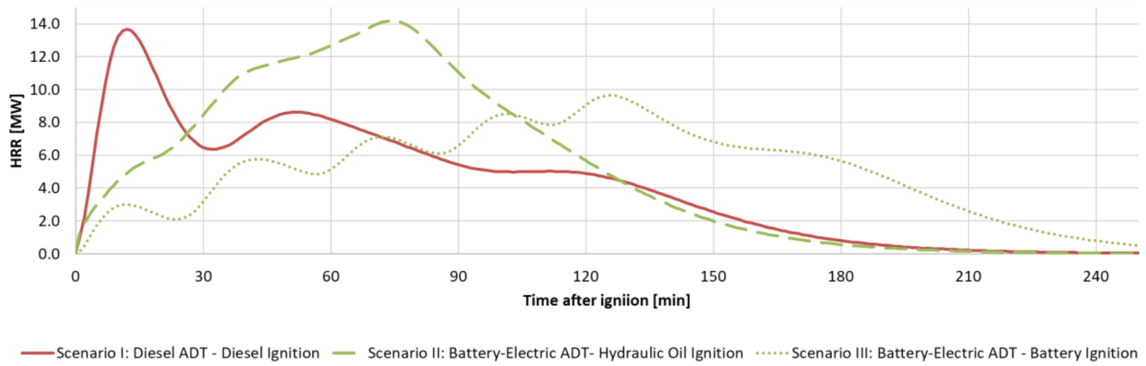


Figure 5-10: Comparison of developed diesel ADT fire scenario to battery-electric fire scenarios

5.6.7 Fatality criteria

The assessment of differences in consequences for individuals exposed to vehicle fires within the tunnel involves the application of the FED/FIC approach developed by Purser and McAllister [61]. This model comprehensively considers major hazards associated with human exposure to fires, encompassing hyperthermia from heat exposure, asphyxiation due to inhalation of CO, CO_2, and HCN, and irritation of the eyes and respiratory tract. The model operates through an accumulation-based intoxication concept for asphyxiant gases, a concentration-based framework for irritating gases, and an accumulation-based approach for evaluating the effects of elevated temperatures on the human body.

In a concentration-based model, the real-time concentration of a specific gas species along the evacuation path of an individual is compared to a predetermined threshold. If the concentration surpasses the defined threshold, the evacuee is considered incapacitated, with the success or failure of the evacuation solely contingent on the prevailing concentrations at a given time. The Fractional Incapacitating Concentration (FIC), hinging solely on the concentration at the present time step, is used for irritating gases.

Conversely, an accumulation-based model calculates the absorbed dosage throughout an evacuee's egress route and contrasts it with a dosage-based threshold. Here, the success of evacuation depends on both the concentrations along the escape route and the duration of exposure to these concentrations. Fractional Effective Dosages (FED) for asphyxiation, hypothermia, and CO_2 are founded on dosage-based thresholds, contingent upon the accumulated dosage over time.

Within the FED/FIC approach, an evacuee is classified as incapacitated if one or more of the following criteria are met at any moment during the fire event:

$$FED_{Asyphyxiation}(t) \geq 1.0,$$
$$FED_{Hypothermia}(t) \geq 1.0,$$
$$FED_{CO_2}(t) \geq 1.0,$$
$$FIC_{Irr}(t) \geq 1.0.$$

Equation 5-2: Incapacitation criteria as defined in the FED/FIC approach [61]

Details about the mode and how the individual contributions are calculated can be found in [61]. It is, however, essential to recognize that to apply the FED/FIC model, knowledge of the concentrations of combustion products as functions of time along the tunnel is imperative. These concentrations can be acquired via FDS simulations, provided the respective yields (release rates of combustion products in grams per second) are known. Thus, the yields for significant combustion products anticipated to be released from distinct vehicle components during fires of both ADT types have been compiled and applied in accordance with the context. The values utilised are summarized in table 5-2, drawn from literature sources such as [60], [62], and [63], or estimated based on expert insights. To incorporate these values into the analysis, they were converted into release rates based on the total calorific content and the weight of the corresponding vehicle component. This approach ensures the accurate representation of combustion product release rates.

Component	CO [kg/MJ]	CO_2 [kg/MJ]	HF [kg/MJ]
Cabin	0.0030	0.0740	-
Energy Storage (500 L Diesel)	0.0005	0.0500	-
Energy Storage (450 kWh electrical battery)	0.0006	0.8350	0.0002
Hydraulic Oil	0.0010	0.1000	-
Tires	0.0011	0.0520	-
Wiring and hoses	0.0029	0.0370	-

Table 5-2: Toxic gas release rates from combustion product yields applied in the FDS model

In addition, HF concentrations, a potential toxic combustion product typically formed in case of thermal runaway from the fluoride components of the electrolyte, have been assessed using acute exposure guideline levels (AEGLs) [64]. These threshold levels describe the human health effects from once-in-a-lifetime, or rare, exposure to airborne chemicals. AEGLs are used by emergency planners and responders worldwide as guidance in dealing with rare, usually accidental, releases of chemicals into the air. Various levels are given, of which level 2 values are used to indicate irreversible or other serous, long-lasting adverse health effects or an impaired ability to escape. Level 3 is associated with life-threatening health effects or death.

5.6.8 Simplifications and assumptions

The fire consequence analysis entails certain limitations and assumptions that warrant consideration briefly discussed herafter:

- **Simplified geometry:** the analysis relies on simplified geometric representations, focusing on key factors, while geometrical intricacies are not fully captured.
- **Fire development:** fire scenarios and curves have been estimated based on plausible chains of events. However, the actual fire development in a real construction vehicle fire may differ from the assumed fire duration, maximum heat release rate, and total heat released.
- **CFD uncertainties**: Computational Fluid Dynamics (CFD) models inherently involve uncertainties and simplifications. The application of CFD tools in a coarse manner introduces further approximation, making the results indicative rather than precise.
- **Assumed toxic gas releases**: toxic gas release rates are assumed based on available data, yet this data remains limited and doesn't specifically cater to articulated dump trucks. The actual release rates in real fire scenarios could deviate from these assumptions.

5.7 Fire risk analysis

The fire risk comparison between battery-electric construction vehicles and diesel construction vehicles is based on the assessment of both fire frequencies and fire consequences. The analysis takes into account the differences in fire hazards, ignition sources, and fire dynamics discussed in the previous sections.

5.7.1 Comparison of fire frequencies

As established in the probability analysis, the likelihood of a fire occurring during the operation of BEVs is notably lower compared to ICEVs. Although the fire likelihood discussed strongly relies on (still) limited data, it underscores a significant distinction in the fire occurrence probability between BEVs and ICEVs. **While precise quantitative values may not be extrapolated directly, a substantially lower fire frequency for BEVs, likely in the range of one order of magnitude, can be assumed**.

It is important to consider that specific factors related to larger BEVs (larger size, drivetrain development and application) as well as the layout at Rogfast E02 (long travel distances, steep gradients) may influence fire likelihood. Those factors might have a similar influence on battery-electric drivetrains and diesel drivetrains in terms of tendency but are (yet) unknown.

5.7.2 Comparison of fire consequences

The assessment of fire consequences for both vehicle types is based on the comparison of calculated times to incapacitation and exposure to hazardous combustion products. The focus lies on the impact of fire dynamics, toxicity, temperature, and irritability on the health and safety of individuals within the tunnel.

For the analysis of time to incapacitation, a stationary evaluation of criticality levels for toxicity, temperature, and irritability was conducted for each position within the simulated 3D domain of the tunnel. While no distinct egress model was applied for this risk study , the results provide insights into the duration during which individuals that remain in place would be conscious if exposed to the fire. Moreover, it should also be noted, that concentrations have been evaluated at a reference height of 1.6 m and that concentrations could be higher closer to the tunnel ceiling in areas where smoke is strongly stratified. Furthermore, the obtained concentrations at reference height might be influenced by boundary conditions and numerical CFD parameters and can in principle also very if the scenario parameters are changed. Taking these uncertainties and the uncertainties of the simplified CFD analysis into account, the consequence analysis should be interpreted as first order estimation of the potential differences rather than an exact in depth determination.

The comparison of times to incapacitation across different fire scenarios and locations shows that the times are generally similar between battery-electric-vehicle and diesel-vehicle fires. At both fire locations A (figure 5-11) and B (figure 5-12), the time to incapacitation is comparable for all three fire scenarios, albeit longer for fire location B due to higher airflow velocities. **These findings indicate that the egress conditions, in terms of expected time to incapacitation, are independent of the vehicle type (BEV or ICEV).**

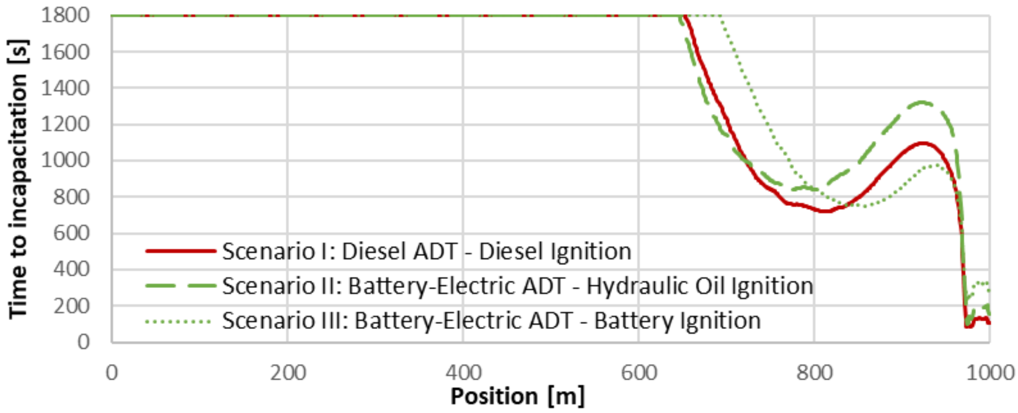


Figure 5-11: Time to incapacitation for fire location A – fire position in the figure is 980 m

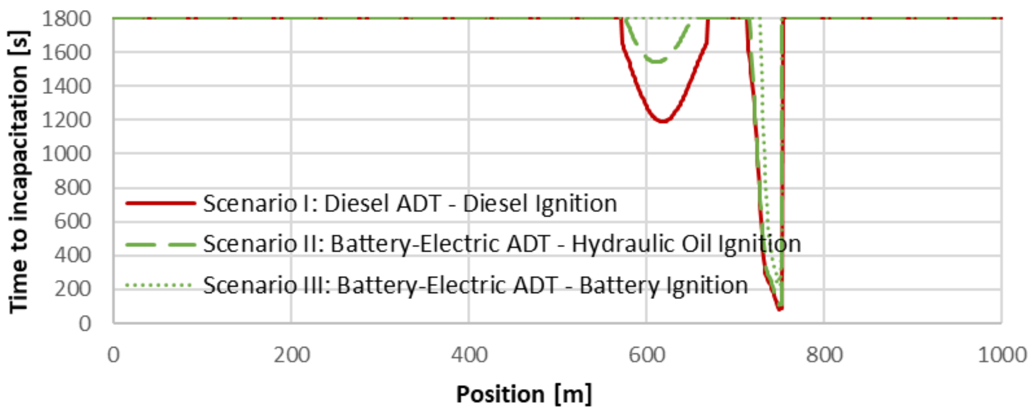


Figure 5-12: Time to incapacitation for fire location B – fire position in the figure is 750 m

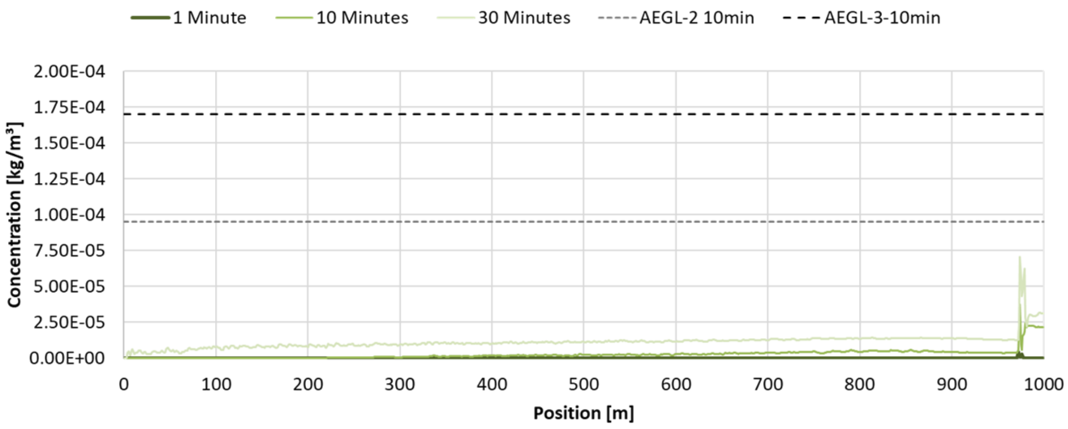


Figure 5-13: HF concentrations at different times after fire ignition for fire location A – comparison to AEGLs

Figure 5-13 and figure 5-14 shown the assessment of HF concentrations. HF concentrations are well below both 10-minute-exposre AEGL limits (level 2 and level 3). This is due to large dilution effects. Concentrations for fire location A are significantly higher than for fire location B because of the higher air velocity in the steep tunnel section. **As a result, HF can be assessed as not relevant in the considered scenarios**.

However, the formation of hydrofluoric acid (dissolution of HF in water) in general and very localized HF concentrations in the direct vicinity of the fire location are not covered by the model and therefore have to be taken into account in the definition of the safety concept in case BE construction vehicles are used.

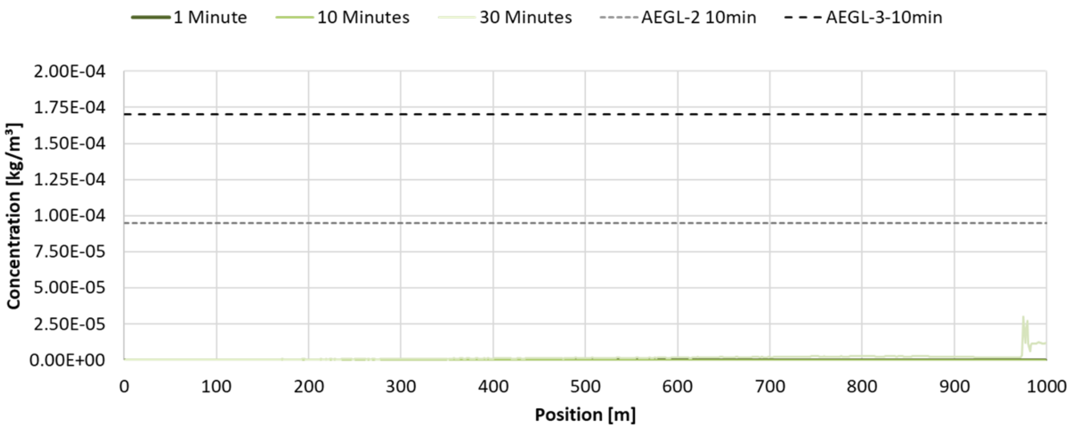


Figure 5-14: HF concentrations at different times after fire ignition for fire location B – comparison to AEGLs

5.7.3 Summarised findings

Considering both fire frequencies and fire consequences, the results of the fire risk comparison suggest that the main difference in fire risk between BEVs and ICEVs during tunnel construction is related to the different fire probabilities, the fire dynamics associated with the thermal runaway of the Li-ion battery and the release of HF as a product of the thermal runaway.

While the actual fire frequencies are notably lower for BEVs, the consequences in terms of incapacitation times and toxic exposures are similar to slightly higher for BEVs compared to ICEVs. The potentially higher consequences for tunnel workers are estimated to be relatively minor in the context of the overall fire risk assessment.

The different fire dynamic is also one of the main concerns for the fire brigade. **The fire duration in case of BEV fires can be significantly longer than for conventional vehicle fires. However, without offensive extinguishment, the energy in the battery is likely to be consumed by the fire within several hours.** According to actual battery-fire tests, extremely long fire durations and re-ignition are only an issue if the fire is to be extinguished, after the thermal runaway has already started [65].

The main concern with respect to structural safety is also the different fire dynamic. Fire duration in case of BEV fires can be significantly longer than for ICEV fires, with the total heat released being comparable. The fire load can be slightly higher for BEVs compared to ICEVs. The differences in maximum HRR or fire duration are supposed to not make any significant difference with respect to structural safety during construction since the tunnel at Rogfast E02 is constructed in solid rock.

5.8 Possible fire risk mitigation measures

Four different hazard types have been identified as significant factors in the comparative analysis between BEVs and ICEVs used for transport during tunnel excavation. The preceding section delved into detailed risk analysis for each of these hazards and also touched upon specific risk mitigation measures addressing the respective hazards. To provide a cohesive overview, the following summary encapsulates the mentioned measures, encompassing various aspects of safety and mitigation strategies for each hazard type.

5.8.1 Fire hazard mitigation

The primary concern with fire hazard is the generation of HF and the distinct fire dynamics associated with BEVs. To mitigate risks related to HF exposure, the following is advised with respect to the work force and emergency responders:

- Tunnel workers should follow standard safety practices, such as wearing appropriate clothing like long sleeves and trousers. Additionally, **face masks and eye protection should be readily available in case of a fire to shield against HF exposure**.
- **Tunnel workers should evacuate the fire site immediately and head to a designated safe area**, avoiding attempts to extinguish the fire.
- **The work force is advised to only operate the onboard fire suppression systems in the battery-electric vehicle.** No other attempt to extinguish a battery fire should be undertaken, since this is generally ineffective and exposes workers to prolonged hazards.
- Emergency responders must be equipped with breathing apparatuses and protective gear designed to withstand HF exposure.

With respect to the battery-electric vehicles, the following measures are advised to mitigate risks related to fire events:

- **The battery-electric vehicles should be equipped with onboard fire suppression systems, employed to extinguish fires before thermal runaway occurs.**
- Additionally, **BEV design should consider direct fire-fighting access to the battery and onboard fire suppression systems** with ample water supply to prevent thermal runaway.
- Battery recharging of BEVs should preferably be done at charging points located outside the tunnel to enable direct intervention in case of problems (e.g. battery malfunction, short circuit, overcharging etc.)
- Due to the potential for longer fire durations in BEV fires, **fire safety concepts should be adjusted to respect longer fire durations**. Rescue shelters and safe areas might need to accommodate extended operating times.

5.8.2 Toxic gas venting

Unignited venting of toxic gases is of concern. To minimize this risk, **BEVs should be parked and recharged outside the tunnel in well-ventilated areas**.

The construction-ventilation design should account for the potential of toxic and flammable gases, ensuring a continuous minimum airflow during BEV operation.

5.8.3 Electrical stroke prevention

To reduce the probability of electrical strokes, where the battery is shortcut with the vehicle body, BEVs should be equipped with an automatic voltage shutdown mechanism.

Rescue services should receive adequate training and information from vehicle and battery manufacturers to handle these scenarios correctly.

5.8.4 Environmental risk mitigation

Precautionary measures for separate aftertreatment of tunnel wastewater contamination by firefighting water after a BEV fire can help minimize environmental risks.

5.9 Main findings

5.9.1 Main differentiating aspects

Main fire source during tunnel construction is diesel or hydraulic oil from small leakage igniting on hot surface (engine), which is missing for battery electric vehicles and makes fires more unlikely. Malfunction of brakes or other mechanical parts could also serve as point of ignition but is much more unlikely. Therefore fires of battery electric construction vehicles is expected to be less likely than for diesel driven vehicles.

The primary concern with fire hazard of BEVs is the generation of hydrogen fluoride (HF) and the distinct fire dynamics associated with BEVs. Other hazards to consider in case of using battery electric vehicles are venting of toxic and/or flammable gases, electrical strokes due to malfunction/damage, environmental hazard due to water contamination.

Fire duration in case of battery electric ADT fires can be significantly longer than for diesel ADTs fires (up to 4 hrs resp. up to 3 hrs). The difference in fire scenario is expected to be limited to order of magnitude of hours if battery is left to burn freely (no fire-fighting interaction) after start of thermal runaway. The total heat release rate is comparable for both vehicle fires.

Simulation of fire scenarios (smoke/toxic gases) considering Rogfast E02 characteristics showed, that the time to incapacitation is similar for battery electric and diesel ADT fires. HF concentrations in case of battery-electric ADT fires are below critical threshold levels (AEGLs). However, localised HF and hydrofluoric acid (dissolution of HF in water) concentrations can be elevated in the vicinity of the fire or in the hot smoke layer.

5.9.2 Main measures to limit fire safety impact

Battery electric vehicles should be equipped with automated fire suppression systems, specifically designed for scenarios like cable fires, in order to prevent the initiation of thermal runaway within the battery due to an engulfing fire. It is not recommended for operators or workers to attempt intervention using alternative methods.

In the event of a fire, rescue services' ability to respond effectively is enhanced if battery electric vehicles are outfitted with a hose connection for the purpose of flooding the battery pack.

Infrastructure for recharging of batteries should preferably be located outside the tunnel to allow direct intervention, in particular for fire services in case of fire.

6 PROCESS IMPACT ANALYSIS

6.1 General

The battery-electric and diesel ADT have the same truck layout and loading capacity with key difference being the drivetrain, e.g. electric motors and battery packs or a diesel engine with a fuel tank. Looking at current developments in automotive engineering and in particular for road truck manufactures, the focus for battery-electric drivetrains is primarily on safe, reliable and efficient use. The manufactures of battery-electric ADTs follow a similar approach, in which their off-road use and possible application in underground mining are key factors reflected in the overall truck and battery-electric drivetrain design. Product development centres on establishing equivalent battery-electric trucks which are comparable or better in terms of productivity and efficiency to typical (standard) diesel trucks.

The framework and methodology selected for the process impact analysis follows the same principles. The diesel and the battery-electric ADT selected are compared in terms of productivity and efficiency, focussing on energy capacity and energy consumption by the respective drivetrains. In this chapter, the framework and methodology adopted for comparing material transport and energy consumption for trucks used in tunnel excavation transport application are described. The first order models developed are subsequently applied to analyse which possible process impacts changing ADT-type respectively propulsion type could have on Rogfast E02. Thereafter, possible process impact mitigation measures are identified and analysed. The chapter is concluded by presenting the main findings.

6.2 Framework and methodology

6.2.1 Selection of relevant criteria

The representative ADTs selected are in essence the same base truck, which is designed for off-road use in heavy-duty applications. These particular ADTs are mainly used in (underground) mining, as is reflected in the overall truck design and battery-electric drivetrain development, Keeping in mind that actual tunnel excavation application requires careful consideration, for the purpose of this study are possible differences between mining and tunnelling not seen as key-differentiating aspects to serve as basis for the process impact analysis.

Assuming that both ADT-types are suitable for tunnel excavation transport application, the transport task itself becomes the primary focus. The ability to transport material can be expressed through general key criteria such as **productivity and efficiency**. These criteria reflect both the rate at which the material is transported as well as to which extent resources have been consumed. Both can be expressed per vehicle and/or trip, per progress at the tunnel face or for the overall tunnel excavation project. **In this study, the focus is on differentiation between ADT-types and therefore only the progress at the tunnel face at various points along the axis for one of the main tunnel tubes at Rogfast E02 is analysed. The impact on and interaction with the overall tunnel excavation process are not considered.**

These process impact criteria can be described in more detail as summarised below:

- **Criteria 1 – productivity**: typically transport trucks have similar characteristics, defining unloaded and loaded transport. As such, productivity can be expressed using the amount of material transported per time interval. In this case [ton/hr] is chosen, reflecting a higher productivity in case more tonnage is transported per hour.

- **Criteria 2 – efficiency**: since the diesel and battery-electric drivetrains use different energy sources, energy as a general quantity or unit is used as basis for comparison, expressed in [kWh]. Efficiency can subsequently be expressed as [ton/kWh], with a higher efficiency thus representing less energy consumption per ton being transported.

6.2.2 Modelling approach

Both productivity and efficiency are analysed using separate 1D-models in which key characteristics for trucks transporting material are incorporated. These models are subsequently applied for both ADT-types selected for the risk study at Rogfast E02.

Analysing productivity aims to match the project demands with a number of appropriate transport trucks, in this case the representative ADTs selected. This requires determining the total amount of material to be transported and the loading capacity of a truck, the transport route between the loading and dumping area as well as the operations at these locations. This can be described using **a first order method to determine truck movement and scheduling for transporting material produced by a single tunnel excavation cycle.**

Energy efficiency relies mainly on the respective diesel and battery-electric drivetrains. The principle can be summarised by transforming the energy capacity available by the diesel engine or electric motors into power that drives a truck forwards. This requires determining the amount of stored energy onboard of a truck, knowledge of the respective drivetrain efficiency in energy utilisation, as well as estimating the energy required to drive a truck along the transport route. This can be described using **a first order method to determine energy demands and management required during truck movement for transporting material produced by a single tunnel excavation cycle.**

6.3 Productivity – transport comparison

6.3.1 Model description

The productivity analysis first considers a single trip for a truck from the loading area at the tunnel face to the dumping location. The total time for a single trip can be determined from the transport route and the driving speed as well as additional loading and dumping times. This requires determining the following main parameters:

- **Transport distance and time**: total distance for a truck to travel across each of the route sections. The time required is based on the driving speed, considering off-road terrain conditions and loading status.
- **Loading and dumping time**: additional time for loading a truck, depending on truck loading capacity and loading operation (e.g. loader type, bucket size, efficiency). A reference time is used for emptying the box, dumping.
- **Total time for 1 trip**: time for a single trip, combining the transport time with the loading and dumping time.

Subsequently, **truck demands are determined based on assuming as a general aim a continuous loading operation at the tunnel face**. The total time required to transport all material produced in a single excavation cycle can be determined from considering the number of trucks and their transport times necessary to achieve the total number of trips needed. The following parameters are required:

- **Total tonnage and number of trips**: amount of material to be transported from the tunnel face, depending on cross-sectional shape and progress depth. The transport capacity of a truck determines the number of trips needed.
- **Truck numbers and trips**: continuous loader operation is defined by determining the number of trucks that can be loaded during a single trip of a truck. In addition, for practical reasons a maximum number of trucks available is assumed, even if that causes the loader to pause for some time. The number of loading cycles reflect the maximum number of trips for a truck.
- **Total time for 1 excavation**: based on the total time for a single trip extended to all trips with in addition the time to subsequently load all trucks

6.3.2 Simplifications and assumptions

The model described simplifies the transport process to a 1D route consisting of continuous sections along which a truck drives at a driving speed given the terrain conditions and loading status. **Trucks are not interrupted during their trips by other tunnel processes**, nor is the actual tunnel geometry along the route explicitly taken into account.

Loading a truck at the tunnel face is simplified to considering the type of loader and taking a standard loading time, not taking explicitly the actual confined loading environment into account. The cyclic nature of the loading process is included through assuming all trucks available are loaded in series until all material produced has been transported. **Loading is assumed continuous as long as trucks are available by having returned from their trip**.

6.3.3 Project application

The transport route for the ADTs at Rogfast E02 is simplified into 1D-sections according to basic project data [2, 3, 4]; **from the landfill to the Kvitsøy access, along the Kvitsøy access and through the tunnel tube to the tunnel face and vice versa** (see table 6-1). To illustrate the resulting long transport distances, for example with the tunnel progressed at a depth of 2,5 km, a single trip of a truck represents a transport distance of 16 km.

All sections are assumed to be off-road for which a typical maximum construction site driving speed of 30 km/h holds.

Rogfast E02	Section 1	Section 2	Section 3
Start	Landfill	Kvitsøy access	Tunnel
End	Kvitsøy access	Tunnel	Tunnel face
Road surface	Off-road	Off-road	Off-road
Length	1.0 km	4.5 km	Max. 4.5 km
Gradient	0%	-7%	0% / -4.5%
Max. on site driving speed	30 km/h	30 km/h	30 km/h

Table 6-1: Overview of project schematisation at Rogfast E02

The cross-section of each tube at Rogfast E02 will be of type T 10,5 [6]. Tunnel excavation will adopt the NMT [66], in which rock material is produced at the tunnel face using drill-blast cycles. Considering granite as representative rock material, weight or tonnage is more relevant than volume.

Hence, based on the cross-sectional shape, the typical progress depth of 5 m, the density of granite and a factor reflecting the transport of blasted or broken rock material [67] allows to determine the total tonnage to be transported (as detailed in table 6-2). **For each drill-blast cycle in total ca. 1900 ton is to be transported away from the tunnel face**.

Excavation process	Parameter
Type of progress	Drill-blast
Tunnel cross-section	T 10,5
Cross-sectional area	75 m^2
Excavation depth	5.0 m
Rock volume per blast	375 m^3
Transport factor broken rock	1.8
Density rock (granite)	2750 kg/m^3
Total rock mass for transport (rd.)	1900 ton

Table 6-2: Overview of the tonnage per drill-blast cycle at Rogfast E02

The battery-electric [36, 42] and diesel equivalent [48, 49] **ADTs selected have a representative loading capacity of 40 ton.** Based on the total tonnage to be transported per drill-blast cycle, the total number of trips can be determined. **In total 50 trips are needed to transport all excavated rock produced per cycle away from the tunnel face.**

Depending on the type of battery-electric ADT, the driving speed could be lower than the equivalent diesel ADT, but seems then less influenced by terrain inclination and loading status. **Based on the representative ADTs selected, the battery-electric ADT is considered to have in general a lower driving speed than the diesel ADT.** The various driving speeds depending on terrain conditions and loading status can be taken from table 6-3.

ADT selected - driving speed	Loading status	Diesel	Battery-electric
Max. speed flat / downhill	Empty	40 km/h	20 km/h
Max. speed uphill 4.5%		40 km/h	20 km/h
Max. speed uphill 7%		30 km/h	20 km/h
Max. speed flat / downhill	Loaded	40 km/h	20 km/h
Max. speed uphill 4.5%		20 km/h	20 km/h
Max. speed uphill 7%		15 km/h	18 km/h

Table 6-3: Overview of driving speeds dependent on terrain conditions for the ADTs selected

At the tunnel face based on space restrictions the trucks are loaded using a typical AMV-loader [10], having a bucket size of around 5.0 m^3 or 7.6 ton of broken granite (assumed rock material) per pass. A loading time of around 4 min at an efficiency of 95% in reaching the maximum loading capacity of the ADT (effective ADT-tonnage = 38 ton) is assumed. Dumping of an ADT at the landfill site is assumed to take around 1 min.

6.4 Efficiency – energy comparison

6.4.1 Model description

Energy consumption for a single trip of a truck can be described using Newton's second law which states equilibrium of forces acting on the acceleration of a mass and takes the following form [68, 69]:

$$F_t(t) = m_v \frac{d}{dt} v(t) + F_r(t) + F_g(t) + F_a(t) + \overbrace{F_d(t)}^{\approx 0}$$

Equation 6-1: equilibrium of forces acting on the acceleration of the mass of a truck [68, 69]:

For a truck moving along a route in time (t) the energy stored in the diesel tank respectively the battery packs is used by the diesel engine or the electric motors to gain kinetic energy representing forward traction, expressed by (F_t). Energy is transformed by the drivetrain to acceleration the mass of a truck (m_v) up to a driving speed (v) which is subsequent maintained. Along a route resistance forces act on a truck, such as rolling friction (F_r) aerodynamic drag (F_a), continuously draining energy from the system. In addition, potential energy is gained with altitude based on the gravitational (g) weight of a truck (F_g). Other resistance force might also act on the truck (F_d). Schematically this can be represented using a free-body diagram as can be seen in figure 6-1 [68, 69].

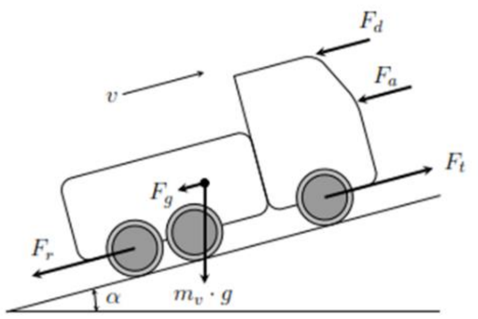


Figure 6-1: Schematic representation of the forces acting on a truck in motion [68, 69]

Energy consumption by the traction force (E_t) is subsequent determined based on the work done by the respective force along the route (s). Hence, the total energy required can be expressed through [68, 69]:

$$E_t = \int_{t_1}^{t_2} F_t(t) v(t)\, dt \approx F_t s$$

Equation 6-2: work or energy consumed by the traction force of a truck in motion

In addition to the traction force, also other processes could require energy such as auxiliary systems used by the drivetrain or by the operator in the cab etc. For the purpose of this study, these additional energy drains are assumed part of the overall efficiency of the drivetrain and are therefore not considered separately.

Single not traction related energy drain considered is emptying of the box / dumping at the landfill site. This requires lifting the load with no energy recuperation assumed by lowering the box.

Based on the transport route, first the various energy consumptions required for a single trip of a truck are determined according to the following:

- **Rolling resistance**: energy required to overcome the terrain resistance along the route considering off-road use
- **Gravitational resistance**: energy required to overcome gravitational forces in case a truck moves up an inclination. This energy contribution can be recuperated in reverse operation, e.g. engine breaking or battery recuperation.
- **Aerodynamic drag**: energy required to overcome the air resistance for a truck moving at speed. The contribution of this factor highly depends on the driving speed
- **Acceleration / deceleration**: energy required to increase the speed of a truck. This energy contribution can be recuperated in reverse operation, e.g. engine breaking or battery recuperation.
- **Dumping**: energy required to empty the box, considering the gravitational resistance of the material transported

Subsequently, the available energy for a truck is determined considering the (nominal) energy stored in the diesel tank or the battery packs. The utilisation of the energy stored requires the conversion by the diesel engine or the electric-motors to actual traction of a truck and as such reflects power output vs. energy consumption. This drivetrain characterisation is simplified to assuming that sufficient power is available and that the energy conversion can be represented by the efficiency of the drivetrain. **Based on manufacturer data regarding driving speeds dependent on terrain conditions and loading status, an assumed constant drive train efficiency is used to determine the energy consumption**. According to these principles the following parameters are determined:

- **State of Charge (SoC)**: defines the nominal energy available relative to the total energy capacity, commonly used for the (re)charge level of battery packs. In this study also used for the level of diesel fuel in the tank of a truck.
- **Drivetrain efficiency**: reflects heat and friction losses mainly for the diesel engine and to a lesser extent for the electric motors. In this study, the efficiency is used to characterise the drivetrain and not the actual power output vs. energy consumption at a driving speed given.
- **Effective and needed energy capacity**: combining the nominal energy capacity stored on a truck and the drivetrain efficiency reflects the actual or effective energy available for a truck. Overall or actual energy consumption defines the energy needed.
- **Recharging method and time**: battery management for a truck can involve battery charging onboard or battery swapping. The time for battery charging is based on reaching a maximum SoC with for practical reasons no full-charging is considered.

6.4.2 Simplifications and assumptions

Based on the transport comparison, the model described simplifies energy demands to a comparison of consumption to capacity. **Energy consumption considers the same 1D route sections and assumes a continuous and linear development of the various resistance forces acting on a truck**. In addition, it is assumed that at the start of each section a truck accelerates up to the driving speed given and brakes to a complete stop at the end. This approach considers a distinct change in the transport route at the start or end point as well as in between sections by change in direction.

Traction generated by a truck could take the form in determining the power output generated, driving speed attained and energy consumed. However, with limited detailed data actually available to determine these relationships, in this study a more simplified approach has been adopted. It **is assumed that the diesel or battery-electric drivetrain of a truck has sufficient power** to provide for continuous traction to overcome resistance at the driving speed given**.** In addition, the **energy conversion is not based on actual fuel or electricity consumption by the respective drivetrain, but on an assumed constant drivetrain efficiency**. This approach considers a more general drive train efficiency, typical for a diesel engine or electric-motors and does not consider changes based on for instance rev count or (continuous) straining due to terrain conditions and loading status.

Battery recharging is assumed to be linear with time which for the most part of the battery capacity up to reaching SoC-levels representing full recharging is sufficiently accurate considering the scope of this study.

6.4.3 Project application

Energy management focusses on determining the energy consumption in reference to the energy capacity during a trip of a truck, in this case an ADT driving along the transport route at Rogfast E02.

Energy consumption reflects the motion of an ADT based on the traction to accelerate its mass and to overcome the resistance forces. An overview of the various energy requirements is shown in table 6-4. From this table it becomes apparent that, **loaded transport along the Kvitsøy access requires considerable efforts for both ADT-drivetrains, based on the length and the elevation/inclination. This adds to the energy required to overcome the rolling resistance, which increases with progressing tunnel length** at an assumed 3% of the vehicle weight.

Other energy requirements, such as acceleration and aerodynamic drag, consume comparably limited amounts of energy and reflect the relative low driving speed of such ADTs.

For both the declaration and especially the gravitational (downhill) energy, the efficiency for energy recuperation has been considered by assessing the drivetrains of the ADT-types:

- **The battery-electric ADT can recuperate the battery packs and partially restore energy consumed** at an assumed efficiency of 80%. This in particular holds during downhill transport of an ADT, returning from the landfill site.
- **For the diesel ADT only engine breaking or hill-descent would be present** at an assumed efficiency of 20%, limited by the constraint that no actual energy recuperation occurs but rather less energy is consumed.

Parameters		Articulated Dump Truck (ADT)											
		Diesel reference						Battery-electric alternative					
Sections		1	2	3	3	2	1	1	2	3	3	2	1
Start		Landfill	Kvitsøy access	Tunnel	Tunnel face	Tunnel	Kvitsøy access	Landfill	Kvitsøy access	Tunnel	Tunnel face	Tunnel	Kvitsøy access
End		Kvitsøy access	Tunnel	Tunnel face	Tunnel	Kvitsøy access	Landfill	Kvitsøy access	Tunnel	Tunnel face	Tunnel	Kvitsøy access	Landfill
Road surface		Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road
Length		1 km	4,5 km	4,5 km	4,5 km	4,5 km	1 km	1 km	4,5 km	4,5 km	4,5 km	4,5 km	1 km
Gradient		0%	-7%	0%	0%	7%	0%	0%	-7%	0%	0%	7%	0%
State		Empty	Empty	Empty	Loaded	Loaded	Loaded	Empty	Empty	Empty	Loaded	Loaded	Loaded
Vehicle weight		30 ton	30 ton	30 ton	70 ton	70 ton	70 ton	40 ton	40 ton	40 ton	80 ton	80 ton	80 ton
Driving speed		30 km/h	30 km/h	30 km/h	30 km/h	15 km/h	30 km/h	20 km/h	20 km/h	20 km/h	20 km/h	18 km/h	20 km/h
Energy required for	Rolling resistance	2.5 kWh/km	2.5 kWh/km	2.5 kWh/km	5.7 kWh/km	5.7 kWh/km	5.7 kWh/km	3.3 kWh/km	3.3 kWh/km	3.3 kWh/km	6.5 kWh/km	6.5 kWh/km	6.5 kWh/km
	Gravitional resistance		-1.1 kWh/km			13.3 kWh/km			-6.1 kWh/km			15.2 kWh/km	
	Aerodynamic drag	0.1 kWh/km	0.1 kWh/km	0.1 kWh/km	0.1 kWh/km	0.0 kWh/km	0.1 kWh/km	0.0 kWh/km	0.0 kWh/km	0.0 kWh/km	0.0 kWh/km	0.0 kWh/km	0.0 kWh/km
	Acceleration	0.3 kWh	0.3 kWh	0.3 kWh	0.7 kWh	0.2 kWh	0.7 kWh	0.2 kWh	0.2 kWh	0.2 kWh	0.3 kWh	0.3 kWh	0.3 kWh
	Deceleration	-0.1 kWh	-0.1 kWh	-0.1 kWh	-0.1 kWh	0.0 kWh	-0.1 kWh	-0.1 kWh	-0.1 kWh	-0.1 kWh	-0.3 kWh	-0.2 kWh	-0.3 kWh
	Dumping						0.2 kWh						0.2 kWh

Table 6-4: Overview of the main parameters describing energy demands for a truck transporting excavated rock at Rogfast E02

The energy capacity available for an ADT is determined by considering the energy stored onboard and the actual effective energy that can be used:

- The battery packs of the battery-electric ADT have an assumed representative capacity of 450 kWh [36, 42], of which nominally 85% can be used. Typically, the efficiency of electric drivetrains can be assumed high, taken at 80% [70]. This gives a total effective energy capacity of 306 kWh.
- For the diesel-ADT, energy is based on the fuel tank having a capacity of 500 l diesel [48, 49] at an energy density of 9.72 kWh/l [70] of which assumed 95% can nominally be used. Considering a rather limited efficiency for the diesel engine, assumed to be 20% [70], gives an effective energy capacity of 923 kWh.

The drivetrain characteristics reflect that, **the battery-electric ADT has roughly one third of the effective energy capacity compared to the equivalent diesel ADT**. Noteworthy is also that the diesel ADT consumes more resources as the **efficiency deficit assumed for the diesel ADT compared to the battery-electric ADT would result in a four times higher energy consumption**. An overview of the various parameters required governing energy management can be taken from table 6-5.

ADTs selected - drivetrains	Diesel	Battery-electric
Total energy capacity	4860 kWh	450 kWh
Efficiency	20%	80%
Range of utilisation (SoC)	5-100%	5-90%
Total effective energy capacity	923 kWh	306 kWh
Battery swapping time		10 min
Energy recuperation	Engine breaking	Battery recharging
Refuelling / recharging rate	11 %/min	0.57 %/min

Table 6-5: Overview of typical drivetrain energy characteristics for the ADTs selected

6.5 Process impact analysis

6.5.1 Analysed scenarios

The models described have been used to analysis the process impact of changing from the reference diesel ADT to the battery-electric ADT. In these analyses transport times, energy demands, productivity and efficiency have been determined, considering especially the following basic scenarios:

- **Process scenario 0 (benchmark)**: battery-electric ADTs using battery swapping
- **Process scenario 1**: battery-electric ADTs are not using battery swapping

6.5.2 Process scenario 0 (benchmark): battery-electric ADTs using battery swapping

Energy consumption per ADT-type during excavation of a section located 2.5 km into a flat tunnel are shown in figure 6-2. In this particular case, both ADT-types make five trips, from the tunnel face to the landfill site, with the reduced driving speed of the battery-electric ADT resulting in a longer transport time of around 5 hr, in comparison to around 4 hr for the diesel ADT.

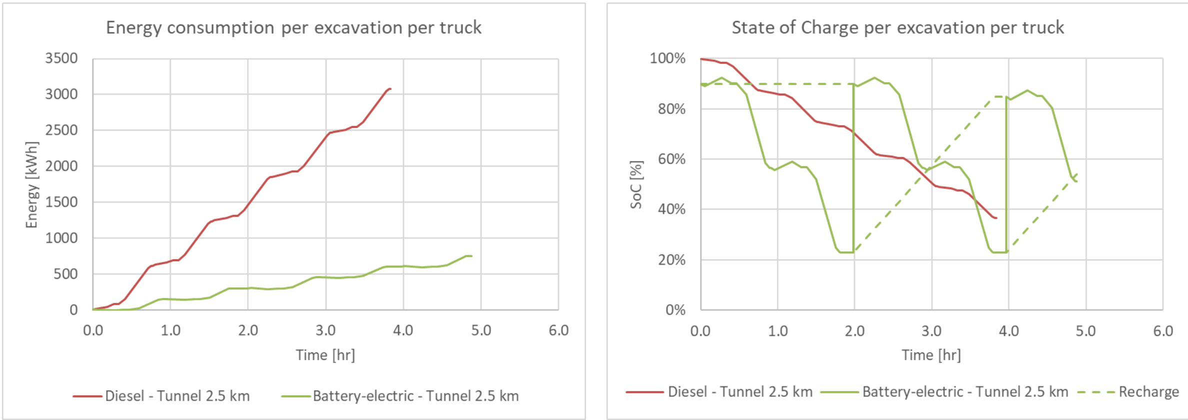


Figure 6-2: Energy consumption (left) and SoC-levels (right) per diesel and battery-electric ADT during transport of rock from the tunnel face at 2.5 km along a flat tunnel to the landfill site

Each diesel ADT consumes far more energy, around 3000 kWh, compared to the battery-electric ADT consumption of around 750 kWh. This clearly highlights the (assumed) limited efficiency of the diesel engine. In contrast and key aspect to consider is the reduced energy capacity of the battery-electric ADT which require battery swapping after each 2 trips, assumed to take place at the landfill site. The impact of the recharging time is however less critical, since the ADT is kept in operation by using an readily available battery that is already fully charged. For the diesel ADT the tank is drained to around 40%, and thus no intermediate refuelling is required. Please note that the ability of the battery-electric ADT for battery regeneration during downhill transport along the Kvitsøy access can be seen as energy gain in both graphs.

In case of excavation at a section in a tunnel with an inclination of -4.5%, with the distance of tunnel face being the same, energy demands due to loaded uphill transport increase as can been seen from figure 6-3. However, in this particular case there is no direct influence on the battery swapping strategy.

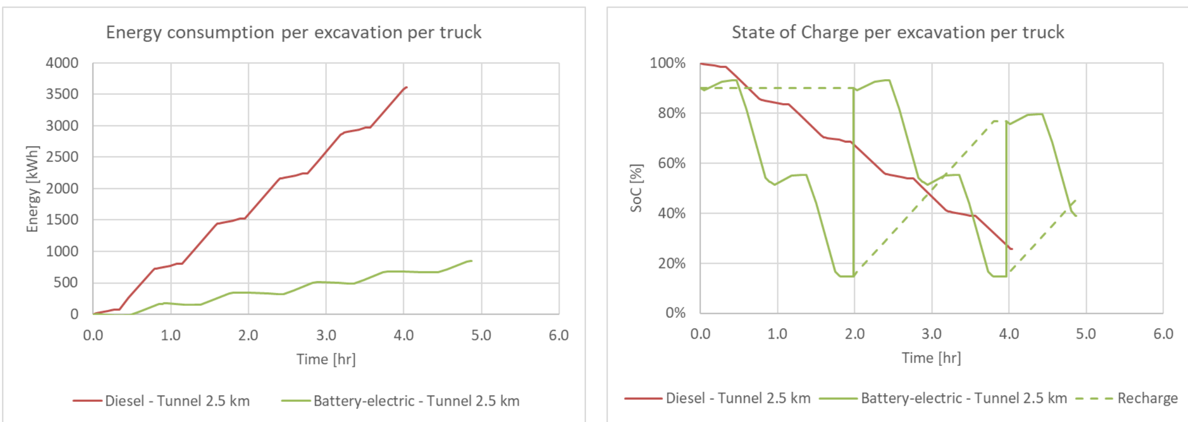
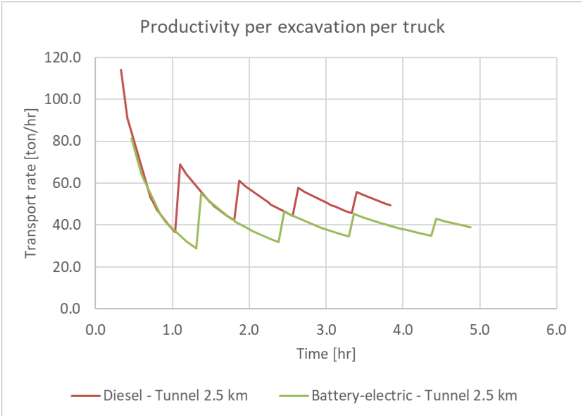


Figure 6-3: Energy consumption (left) and SoC-levels (right) per diesel and battery-electric ADT during transport of rock from the tunnel face at 2.5 km along a tunnel with an incline of -4.5% to the landfill site

Both cases highlight that **by using battery-electric ADTs in tunnel excavation, truck scheduling is not only to be based on sustaining loading operation, but also (re)charge strategies, such as battery swapping, become an essential part.** Due to the cyclic routine, each truck would have similar energy demands and thus would require its own recharging infrastructure to sustain loading operation. In this context, swapping infrastructure, if needed, could be shared. **This enhances complexity and requires additional efforts and considerations not yet present in the NMT**.

From the transport time and energy consumption, productivity and efficiency can be determined respectively (see figure 6-4). In both graphs the saw-tooth shape stems from the definition, in which hours and energy develop continuously, but tonnage reflects only the loading status. The reduced driving speed of the battery-electric ADT results in a lower productivity or transport rate, being around 40 ton/hr compared to the 50 ton/hr for the diesel ADT. A more distinctive difference can be seen in the efficiency rate. This is caused by the diesel engine being less efficient and consuming more energy and thus resulting in lower energy rates.



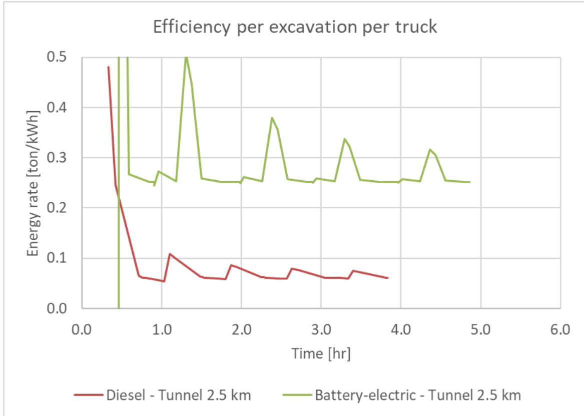
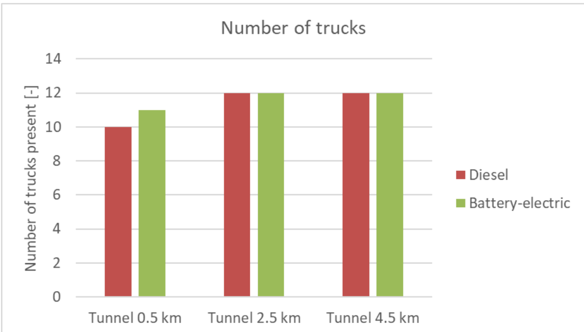


Figure 6-4: Productivity (left) and efficiency (right) per diesel and battery-electric ADT during rock transport with a flat tunnel progressed to 2.5 km

Additional key characteristics taken from the process impact analysis for various sections along a flat tunnel are shown in figure 6-5. Firstly, the relative long transport distances (based on both tunnel length and route to the landfill site) would require for both ADT-types a large number of trucks in order to sustain loading operation at the tunnel face. The typical higher driving speeds dependent on terrain conditions of the diesel ADT are in this case an advantage, but are partially counteracted by the maximum driving speed on the construction site of assumed 30 km/h.



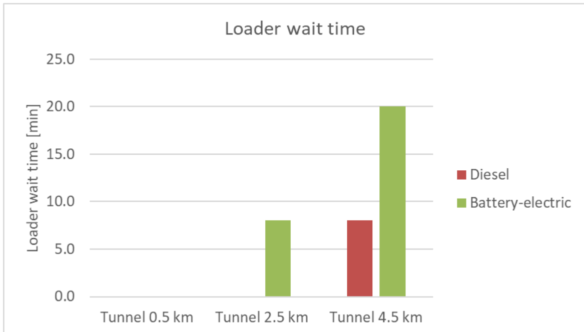


Figure 6-5: Number of trucks (left) and loader wait time (right) by using diesel or battery-electric ADTs during rock transport with a flat tunnel progressed at various lengths

In addition, the maximum number of trucks is assumed to be limited for reasons of feasibility and practicality. As such, with progressing tunnel length and by limiting to an assumed maximum number of 12 trucks, the loader is forced to wait at longer tunnel lengths / longer transport times, most notably in case of battery-electric ADTs. Figure 6-6 shows that for these sections the total transport time can range from six to nine hrs, with all trucks combined covering a total transport distance from 600 km to 1000 km respectively, depending on tunnel length. Such efforts are in general reflected by total energy demands, but with the diesel ADTs consuming far more energy, up to 35 MWh, compared to around 9 MWh for the battery-electric ADTs.

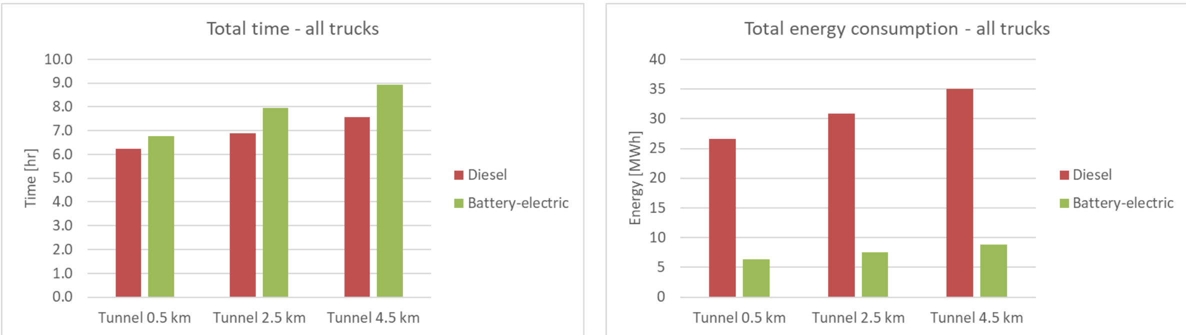


Figure 6-6: Total transport time (left) and total energy consumed (right) by using diesel or battery-electric ADTs during rock transport with a flat tunnel progressed at various lengths

6.5.3 Process scenario 1: electric ADTs are not using battery swapping

In case battery swapping is not possible or no additional batteries are available, recharging can only occur with the battery-electric ADT remaining at the recharging point, assumed located at the landfill site. This forced wait time will have a considerable influence on the productivity and efficiency of such ADTs, as illustrated by the following recharging strategies.

Figure 6-7 shows the influence of completely recharging the battery packs onboard of the battery-electric ADT when needed, meaning no new trip is possible. In this case, the ADT is forced to wait after just two trips for around 2 hrs while the batteries are recharging. This makes **full-recharging of the batteries not a practical solution and would require a faster recharging method to become a feasible alternative to battery swapping**.

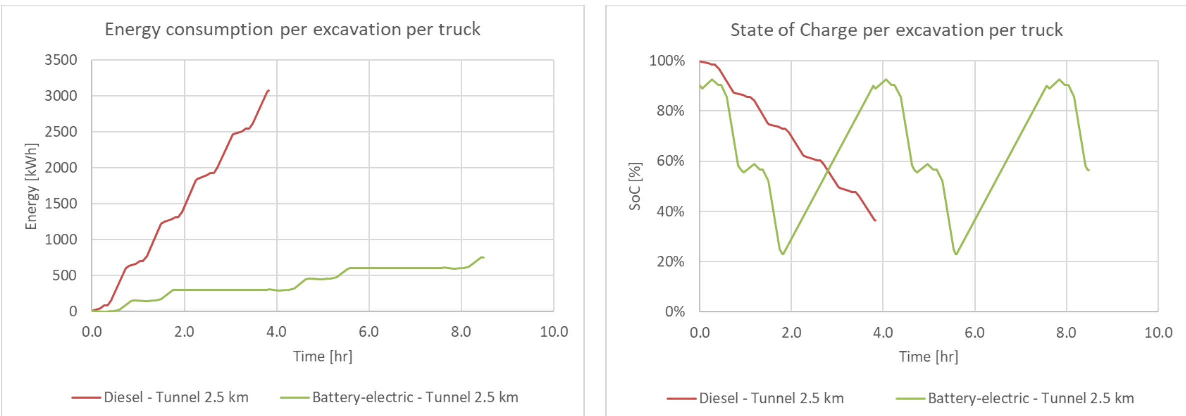


Figure 6-7: Impact of onboard full-recharging of the batteries for a battery-electric ADT in comparison to a diesel ADT during rock transport with a flat tunnel progressed to 2.5 km

A possible improvement could be to recharge the batteries based on actual needs, for instance recharging just enough to only allow for the next trip. This requires increased monitoring and planning based on SoC-needs and would increase complexity. Since the number of trips required remain the same, this can only give a slight improvement as can be seen from figure 6-8. Hence, with presently available recharging techniques, also **partial recharging strategy is considered impractical, since the excavation process relies on continuous and timely clearance of all rock material away from the tunnel face**.

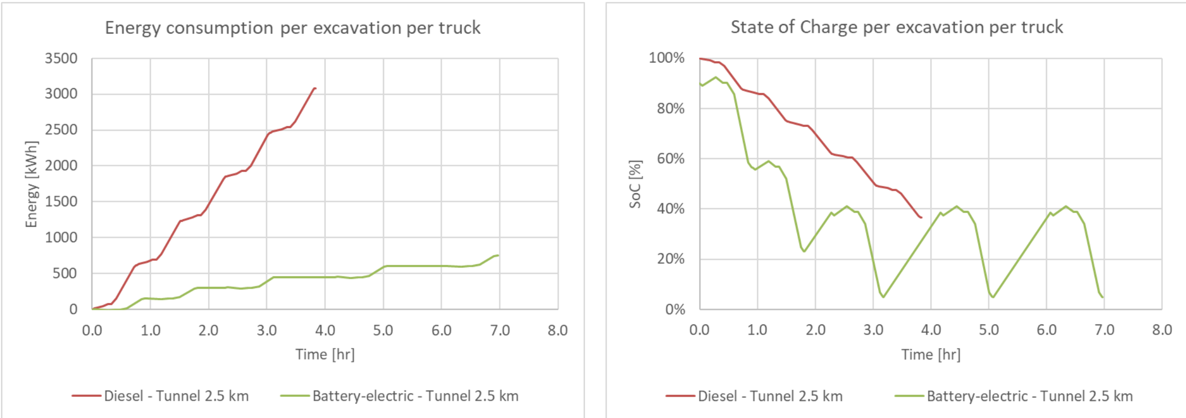


Figure 6-8: Impact of onboard partial recharging of the batteries based on SoC-needs for a battery-electric ADT in comparison to a diesel ADT during rock transport with a flat tunnel progressed to 2.5 km

6.5.4 Summarised findings

The following can be concluded from the process impact analysis, considering the ADT selected (keeping in mind the limited number of battery-electric ADTs available):

- For the battery-electric ADT selected; loading capacity is comparable, driving speed is lower than typical diesel ADT
- Effective energy capacity of the battery packs is far smaller than for a typical diesel tank, which together with a more efficient drivetrain still results in ca. 1/3 effective energy capacity compared to typical diesel ADT

The possible impact on Rogfast E02s excavation process can be summarised as follows:

- Battery-electric ADTs use less energy while being more efficiently compared to equivalent diesel ADTs, enhanced by the downhill section allowing for partial battery regeneration
- Battery swapping enables battery-electric ADTs to remain in operation and partially overcome energy capacity limitations. Onboard recharging methods are considered not practical/feasible for continuous transport application, since these would force battery-electric ADTs to wait.
- Reduced driving speed could result in higher battery-electric ADT-demands to sustain loading operation at the tunnel face
- Battery recharging requires strategy, scheduling and infrastructure, which increases complexity in the excavation process

From a perspective of process impact mitigation, measures could be investigated that enhance the productivity (e.g. transport times, tonnage transported) of the battery-electric ADTs and make them comparable to typical diesel ADTs. It should however be noted, that the limited number of battery-electric ADTs currently available on the market limits choices. In addition, the possible impact on the excavation process could also be mitigated by limiting the application of the battery-electric ADTs at Rogfast E02 to only transport in the tunnel.

6.6 Mitigation measures

6.6.1 Analysed scenarios

The limited number of market available ADTs limits the number of alternatives to investigate. Strictly speaking, the only alternative to consider and thereby to potentially mitigate the process impact of battery-electric ADTs is a larger, more powerful battery-electric ADT; with a loading capacity 50 ton while having a similar driving speed as the reference diesel ADT. In other words, **changing from the battery-electric Epiroc 40 ton to the Sandvik 50 ton**. This ADT-type would enhance productivity, could however become impractical based on vehicle dimensions. Alternative process impact mitigation measure could be to limit the application of the battery-electric ADTs to only transport in the tunnel, from the tunnel face to a temporary storage area. Both scenarios are defined hereafter:

- **Process scenario 2**: changing battery-electric ADT – higher tonnage, similar driving speed as the diesel ADT, e.g. improved productivity
- **Process scenario 3**: project constraint – only transport in tunnel

6.6.2 Process scenario 2: changing battery-electric ADT – improved productivity

Increasing tonnage and driving speeds of the battery-electric ADTs enhances their productivity as is shown in figure 6-9 for excavation of a section at 2.5 km along a flat tunnel. By increasing the driving speeds of the battery-electric ADT to similar values as defined for the diesel ADT, the transport times for both ADT-types become comparable. If in addition the loading capacity or tonnage also increases, the productivity of the battery-electric ADT could even become better than that of the diesel ADT. In this case, the battery-electric ADTs make one trip less than the diesel ADTs, giving a total transport time of around 3 hrs. The larger truck weight does increase energy demands, but this has no direct influence on the battery strategy, the battery-electric ADTs still have to swap batteries after two trips.

Improving the driving speed of the battery-electric ADT does reduce the time available for recharging of the batteries. This could in return influence the excavation process by forcing the ADTs to wait at the recharging station in case the batteries have not been sufficiently recharged. However, in this particular case, no additional battery swap is needed and the charging could continue beyond the transport time.

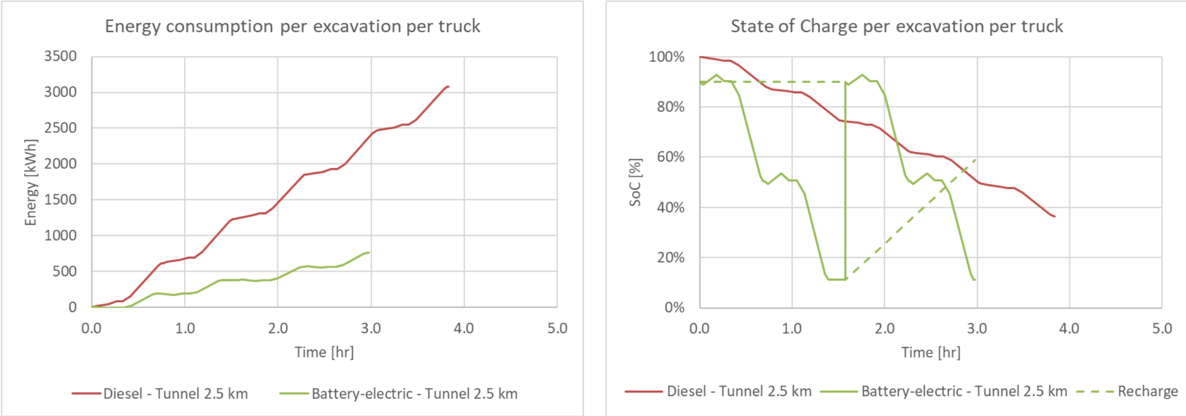


Figure 6-9: Energy consumption (left) and SoC-levels (right) using battery-electric ADTs with a higher tonnage and similar driving speed as the diesel ADTs for rock transport, flat tunnel progressed to 2.5 km

The higher tonnage and driving speeds of the battery-electric ADTs is also reflected in the number of trucks and their trips needed as can be seen figure 6-10. The improved productivity is reflected in sustained loading operation at the tunnel face up to the maximum tunnel length of 4.5 km. **These cases indicate the influence truck selection can have on the excavation process. It should however be noted that, by considering a larger truck also other aspects such as dimensions, manoeuvrability, availability etc. should be considered.**

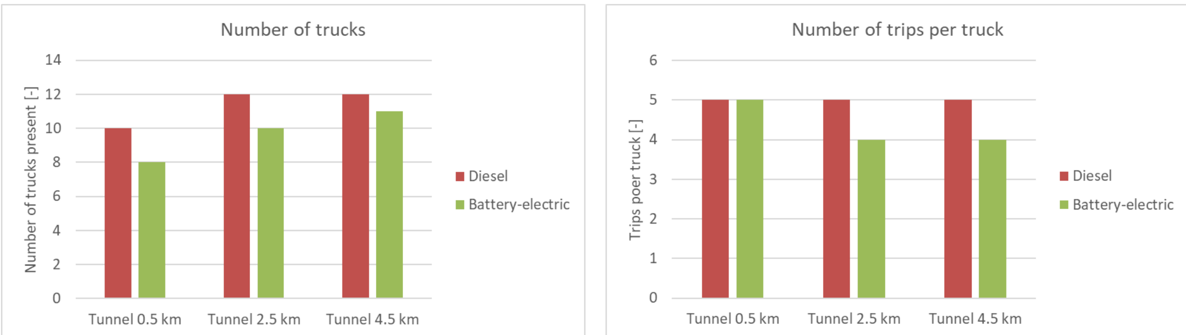


Figure 6-10: Number of trucks (left) and number of trips (right) using battery-electric ADTs with a higher tonnage and similar driving speed as diesel ADTs for rock transport, flat tunnel at various lengths

6.6.3 Process scenario 3: project constraint – only transport in tunnel

Process impact reduction with respect to the ADTs could also be achieved by limiting the use of the battery-electric ADTs to only transport in the tunnel. This would reduce energy demands and could reduce recharge complexity. It should be noted, that this would require a temporary storage area, assumed situated near the Kvitsøy access and also require trucks to further transport the rock material from the temporary storage area to the surface. In case of battery-electric solutions, the energy demand considerations as outlined in this chapter would then have to be extended to these trucks as well.

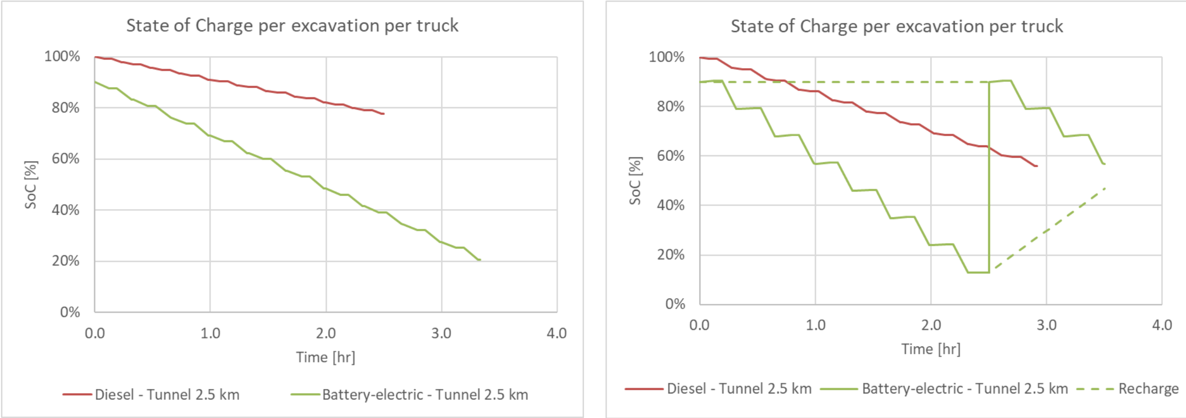


Figure 6-11: SoC-levels per diesel and battery-electric ADT, considering only rock transport in a flat tunnel (left) or a tunnel with an incline of -4.5% (right) to a storage area, tunnel progressed to 2.5 km

In case of transport along a flat tunnel, the energy capacity of the battery-electric ADTs is shown to be sufficient and no intermediate recharging is needed (see left graph of figure 6-11). The impact on the excavation process is shown in figure 6-12). Based on the shorter transport distances, truck demands reduce with each truck making more trips. However, the reduced driving speed of the battery-electric ADTs still would require more trucks and result in a higher transport time as would be the case for diesel ADTs.

In case excavation along an inclined tunnel section is assumed, the higher energy demands for uphill transport still would require the battery-electric ADTs to swap batteries. In this particular case, for a section at 2.5 km into the tunnel, battery swapping would be needed after seven trips with in total ten trips needed. This would require swapping and possibly recharging infrastructure to be available in the tunnel. Alternatively, the trucks could travel to the surface for battery swapping, which would require more time but reduce the probability of battery malfunction during recharging / swapping as suggested in the fire risk analysis (see section 5.8).

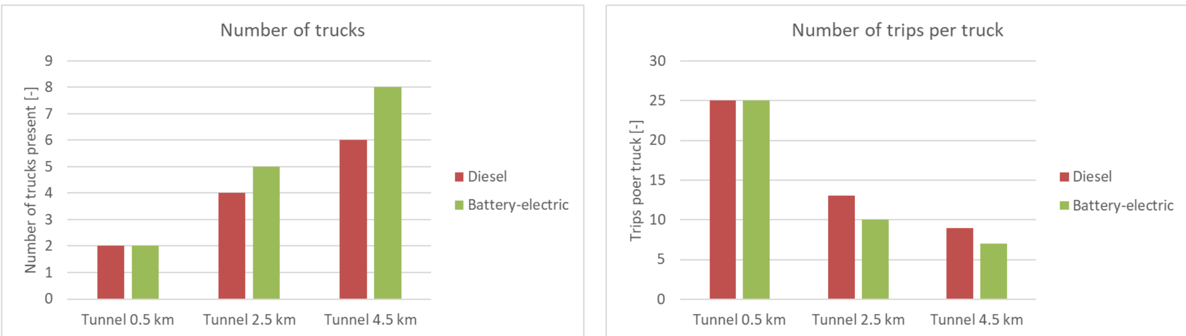


Figure 6-12: Number of trucks (left) and number of trips (right) using diesel or battery-electric ADTs during rock transport only along a flat tunnel to a storage location in the tunnel

6.6.4 Summarised findings

Various measures to mitigate a possible impact on the excavation process using battery-electric ADTs at Rogfast E02 have been analysed. The following can be concluded:

- Battery-electric ADTs with a higher loading capacity and/or driving speed could be used to increase productivity; additional aspects to still consider are practical limitations (larger vehicle size), availability and feasibility of truck demands, (re)charging and swapping infrastructure etc.
- Using battery-electric ADTs only for transport in the tunnel (tunnel face to temporary storage area) could help reduce their process impact. However, this would increase process complexity and energy management, in case of battery-electric transport trucks for further transport are used.

6.7 Main findings

6.7.1 Methodology adopted

For the process impact analysis two first order models have been developed that focus on transport and energy comparison for which the following can be stated:

- The process of a truck transporting material can be determined by distinct 1D route sections, considering continuous driving speeds based on terrain conditions and loading status. Goal should be to sustain loader operation at the tunnel face, allowing for continuous loading of trucks.
- Energy demands can be based on determination of the traction needed to overcome the resistance forces acting on a truck in motion. Drivetrain characteristics can be simplified by assuming sufficient power output with the diesel fuel and battery-electric energy conversion represented as drivetrain efficiency.
- The transport process comprises of a single drill-blast cycle and is assumed standalone. Moreover, truck movement is not interrupted by or interfering with other construction processes.
- More information enabling to characterise the efficiency of the drivetrain and relate power output to energy consumption could allow to improve energy demand assessment used in the first order models developed

6.7.2 Main differentiating aspects

From process impact analysis the following main aspects can be concluded with respect to the battery-electric and equivalent diesel ADTs selected:

- Available battery-electric ADTs are of comparable loading capacity (tonnage) and off-road abilities but could have a lower general driving speed with then less distinction between loaded-unloaded travel
- Available battery capacity combined with a more efficient drivetrain still give battery-electric ADTs one third of the effective energy capacity compared to equivalent diesel ADTs

- Battery regeneration (e.g. during braking; hill-descent) and in particular battery swapping enables battery-electric ADTs to remain in operation and partially overcome energy capacity limitations
- Application of battery-electric ADTs requires additional infrastructure (e.g. for swapping/recharging), strategy and scheduling, which add complexity to current excavation process and would require consideration in respect to NMT
- With the electric drivetrain being significantly more efficient than the diesel drivetrain, overall energy consumption could be significantly reduced by switching from diesel ADTs to their battery-electric equivalents.

In addition, main aspects specific to Rogfast E02:

- Long transport distances at typical reduced driving speeds of battery-electric ADTs compared to equivalent diesel ADTs add to already increased vehicle demands to sustain loader productivity at the tunnel face
- Long downhill section allows partial battery regeneration and improves battery-electric ADT efficiency compared to diesel ADT; for both ADT-types loaded uphill transport require considerable efforts

6.7.3 Main measures to limit process impact

Various measures have been analysed which could help to reduce the impact of battery-electric ADTs on the excavation process:

- Use battery swapping and allow for sufficient recharging time to avoid that battery-electric ADTs are forced to wait or have to frequently swap batteries
- Use battery-electric ADTs with a higher loading capacity and/or driving speed to increase productivity, considering in addition aspects with practical application (larger vehicle size etc.)
- Using battery-electric ADTs only for transport in the tunnel thus provides a less energy demanding application. However, a storage location and additional trucks for further transport would require additional planning and scheduling, especially, if battery-electric trucks are to be used.

7 ADDITIONAL ASPECTS TO CONSIDER

7.1 General

The scope of the risk study has primarily been on analysing fire risk and process impact for battery-electric and diesel ADTs at Rogfast E02. These topics reflect key areas of interest to NPRA. In the course of this study several other aspects have emerged which are of relevance and warrant consideration in case battery-electric trucks are implemented. These topics fall outside of the main scope of this risk study, but some remarks to highlight their relevance and elaborate some key aspects are in place.

In this chapter several of these additional aspects are briefly discussed and more detailed considerations would be necessary. Addressed are the following aspects. the limited number of potentially suitable transport trucks, the reduction in carbon footprint possibly attained by switching vehicle type, general fire safety considerations and possible optimisations in the tunnel ventilation used during construction.

7.2 Vehicle availability and project suitability

The limited number of OEMs and battery-electric ADT-types currently available warrant separate consideration. The restricted choice in truck type with the main focus on underground mining and practical experience currently being gathered should be considered as a factor that increases complexity and uncertainties. Moreover, actual market availability of these trucks, either directly from the OEMs or a third party supplier, could form an issue which should be considered beforehand as well.

These aspects are compounded by the challenging characteristics and project scale at E39 Rogfast. The length of Boknafjord tunnel, its depth and for section E02 the restricted access via Kvitsøy should be regarded as already demanding factors for application of the well-established NMT. Introduction of not yet proven key machines in the excavation process would require careful consideration, not just for the ability in transporting rock material but also the risks that might be associated by changes in a time-critical process component. Moreover, changes to the excavation process stipulated in the contract requirements warrant special consideration, for these could pose risks to project time and cost.

Approaches for application

Starting from the battery-electric ADTs selected, it could be investigated if trial application for the purpose of product development and if gathering practical experience specific to the NMT is possible. Such an approach is often adopted, also in Norway, to develop new technology through collaboration between research organizations, contractors and manufacturers. However, this would not overcome key challenging characteristics present at Rogfast E02 (e.g. high energy demands, large-scale project).

To still promote sustainability and to gain speed in conversion of the transport trucks, an initial application in a less energy demanding and challenging tunnelling project could prove worthwhile. Selection of an appropriate tunnel project should preferably allow more for loaded downhill operation to promote battery regeneration. Moreover, a more straightforward application of the NMT with preferably a less time critical application of the trucks could provide possibilities for monitoring and adjustment potentially necessary during implementation of innovations. Such a project could also allow to consider battery-electric road trucks for more general transport tasks, if within the range of their product applications. This would extend truck choices and promote gathering experience relevant for the NMT.

The sustainability goals themself could also be included in the E02 contract through a bonus-based approach. This could counter act the limited OEMs and ADT-types and stimulate contractor participation and product innovation by industry. As such, not the specific vehicle type to be used is stated, but rather sustainability requirement for the transport process are stipulated. This would broaden the scope of the contract and bring the requirements more in line with the sustainability goals set out by NPRA. Product development and innovations could be rewarded which might help to share and address risks to project time and cost as well.

7.3 Sustainability and carbon foot print

Reflecting on the goal defined by NPRA to cut greenhouse gas emissions, a first order estimate of the possible impact by switching transport trucks at Rogfast E02 has been made. Use has been made of the GHG Protocol developed by World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) [71]. This calculation methodology provides guidance for making GreenHouse Gase (GHG) emissions calculations based on considering direct and indirect dependencies associated with an activity. Typically three different scopes are considered; scope 1 - stationary and mobile combustion, scope 2 - purchased electricity and scope 3 – transportation (distribution and supply). Emission factors are used to specify the quantity of GHGs emitted per unit of producing activity, expressed in the dominant GHG – carbon dioxide – through [$kgCO_2$]. Alternatively, other GHGs, such as methane, can be included through equivalencies defined by [$kgCO_2eq$].

Application GHG Protocol

Establishing the basis on which these emission factors have been formulated is key, since most activities are not standalone but part of larger processes that can have different origins, reflecting interactions, varying life cycles, etc. This is partially counter acted in literature by determining the emission factors for more generalised activities as discussed hereafter for both propulsion types considered in this study. The focus is on solely comparing the GHGs emitted by energy consumption of the battery-electric ADTs to the equivalent diesel ADTs at Rogfast E02. Other sources of GHGs emitted, such as by raw material production (for instance for the batteries), production and supply of the ADTs, additional equipment etc., are not considered.

Mobile diesel combustion is based on data of a heavy-duty vehicle that stems from the GHG Protocol, which in turn bases their calculations on emission factors published by the United States (US) Environmental Protection Agency (EPA). For combustion of diesel fuel by a medium- or heavy-duty vehicle an emission factor of 10.22 $kgCO_2eq/gal$ (US) as part of scope 1 is given [72]. Considering the energy density of diesel fuel, this translates to 0.28 $kgCO_2eq/kWh$. Kindly note that this value can be regarded as an underestimate, since the production and supply of diesel fuel are not considered.

The emission factor for a non-combustion battery-electric vehicle can be based on considering the emission factor associated with the national electricity grid. Several institutions use different methodologies for estimating such emission factors, with the differentiation as a may be quite large which increases uncertainty. For this study, the country specific emission factors provided by Nowtricity have been used, since these rely on electricity data published by the European Network of Transmission System Operators for Electricity (Entsoe) and emission data published in reports by amongst other United Nations Economic Commission for Europe

(UNECE) and Intergovernmental Panel on Climate Change (IPCC). Moreover, these emission factors account for GHGs other than exclusively CO_2. For Norway, based on the large share of hydropower in comparison to other EU-countries, a considered relative low value of 0.03 $kgCO_2eq/kWh$ for the year 2022 is given [73]. This factor accounts for direct and indirect emissions associated with the electricity grid in Norway and falls in scope 2.

Figure 7-1 shows the carbon footprint based on considering the application of battery-electric and equivalent diesel ADTs at Rogfast E02, specific process scenario 0 (benchmark, see chapter 6.5.2). The internal combustion engine of a diesel ADT naturally emits GHGs, as reflected by the considerably larger GHG emissions per drill-blast cycle at Rogfast E02. The GHG emissions for battery-electric ADTs, associated with the electricity grid, can in this respect be regarded as limited. The large difference is further explained by the emission factors adopted for both ADT-types (varying by a factor of ten) and the diesel ADTs being less efficient and consuming more energy (around four times more). Combination of these values gives roughly a forty times higher carbon foot print for the diesel ADTs compared to the battery-electric ADTs.

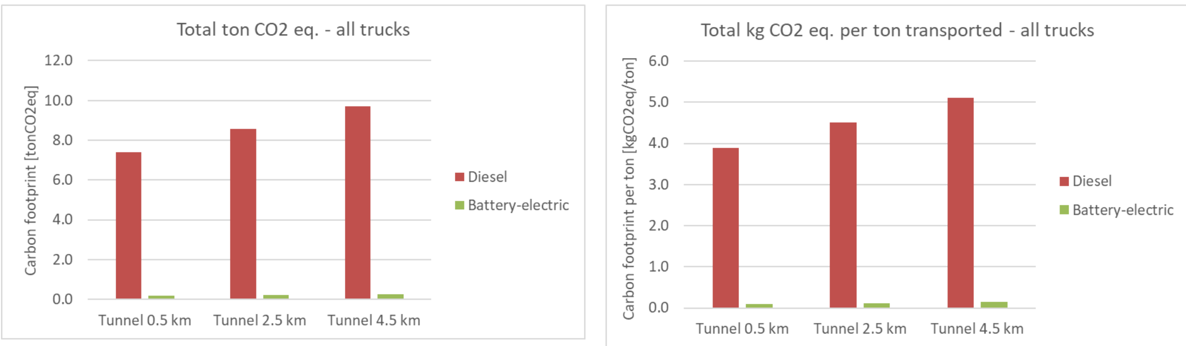


Figure 7-1: Total carbon foot print as absolute values (left) and per transported ton rock material (right) by using diesel or battery-electric ADTs, flat tunnel progressed to various lengths

The same holds for the carbon footprint per transported ton, since the tonnage is determined by the drill-blast cycle. For a typical drill-blast cycle at Rogfast E02 roughly 4.5 $kgCO_2eq$ is produced by the diesel ADTs per ton of material transported. Battery-electric ADTs would account for just a fraction, around 0.15 kgCO2eq/ton of transported rock material.

The results obtained highlight the sustainability gains that can be made by conversion of an energy and natural resources demanding process component. This in particular holds for Norway, with sustainable hydropower produced electricity boosting the benefits of the more efficient battery-electric ADTs. It should be noted that the GHG-comparison should not just be based on energy consumption, but also include product life cycle considerations.

7.4 General fire safety considerations

The scope of this report has primarily focused on the challenges stemming from the transition from diesel- to battery-electric vehicles, in the context of transporting excavated rock at Rogfast E02. Throughout this report, specific considerations regarding this transition have been highlighted. However, it's essential to recognize that the broader fire safety concept must encompass more general safety and fire risk aspects that extend beyond the unique characteristics of battery-electric vehicles, especially considering the challenging characteristics at Rogfast

E02. While the comprehensive fire safety concept is beyond the immediate scope of this report, the subsequent points highlight key aspects that should be considered, with a specific emphasis on the characteristics of the Rogfast E02 tunnel section.

Emergency egress and evacuation

Ensuring the safe egress of tunnel workers is of paramount importance. The overarching tunnel safety concept should outline clear and ideally well-marked emergency egress routes leading to safe zones away from fire hazards. This becomes especially challenging in deep subsea tunnels like Rogfast E02, where substantial distances between the tunnel face and portal may exist, potentially without cross-passages. Therefore, devising effective strategies for emergency egress over such distances is critical.

Rescue shelters

In the context of this risk study, rescue shelters have been discussed as a potential means to establish designated safe areas. Rescue shelters play a vital role in tunnel construction projects, serving as intermediate safe locations where personnel can seek refuge during fire or emergency situations [74]. These shelters can be strategically positioned along the tunnel and constructed using fire-resistant materials to withstand fire and heat effects. Equipped with effective ventilation systems, rescue shelters ensure a constant supply of fresh air and prevent smoke and toxic gas build-up. Communication systems within the shelters enable individuals to stay connected with external emergency response teams.

Construction ventilation

The ventilation systems available during tunnel construction are typically designed to create appropriate conditions for workers but may not be optimized for active emergency ventilation in case of fires within the construction area. However, these existing ventilation systems can still be integrated into the overall fire safety concept to enhance egress conditions. For instance, parallel tunnels could be maintained smoke-free by utilising construction ventilation, providing a safe egress route. Nonetheless, active smoke control within the incident tunnel using construction ventilation is typically not feasible. Additional information regarding this topic is discussed in section 7.5.

Emergency response plan

The emergency response plan forms a pivotal component of the overall fire safety concept. This plan outlines the coordination of all fire safety measures, roles, and responsibilities of involved parties during fire events. It incorporates communication protocols, an incident command structure, coordination with external response teams, and detailed guidance for tunnel personnel, emergency services, and relevant authorities.

Fire drills and fire-fighting training

Handling fires within tunnel environments presents unique challenges for both emergency responders and tunnel workers. As outlined under emergency response plan, actions specified should be regularly practiced through fire drills and fire-fighting training. These exercises encompass testing and maintenance of fire safety equipment, including fire detection and fire-fighting systems, communication networks, and public alert systems. By actively training for these scenarios, responders and workers ensure that they are prepared to effectively manage fire incidents in tunnel settings.

7.5 Tunnel construction ventilation

In the context of electric machinery, the ventilation during the construction phase is also of relevance (see figure 7-2). For operation of the tunnel ventilation during construction, distinction can be made between normal operation and emergency operation. The specific requirements of the ventilation modes are defined in the HSE-plan.

Figure 7-2: Exemplary representation of a construction ventilation with ducts (source: Statens vegvesen)

Normal operation

Usually, national guidelines specify minimum requirements for air quality in a tunnel during construction. The general ventilation objectives aim to provide the workers with good air conditions at all times and at every location. This can be summarised as follows:

- Ensuring the standard oxygen content of the air breathed
- Compliance with the threshold limit values (TLV) with regard to gaseous pollutants from the rock (methane, hydrogen sulphide, carbon dioxide, radon)
- Compliance with TLVs for gaseous pollutants and particulate matter from construction machinery and equipment (diesel engine emissions, soot, carbon dioxide, carbon monoxide, nitrogen oxides)
- Compliance with TLVs for inert dusts (concrete dusts resulting from the application of shotcrete and other concrete work, rock dusts resulting from excavation and transport)
- Protection of the workers from toxic blasting vapours
- Preventing the accumulation and stratification of explosive or toxic gases in sinks and vaults (methane, carbon dioxide, radon)
- Ensuring a tolerable working environment in terms of humidity and temperature

The ventilation design to achieve these objectives is based on (1) air volumes per person and (2) air volumes per unit of power of the diesel machinery. Typical threshold limits are 2m³/min per worker and 4m³/min per horsepower, as defined in for instance Switzerland by SIA 196 [75]. If only (battery-) electric vehicles and machines are used, only the minimal air requirements for the work force would remain. However, the contribution of the battery-electric vehicles should not be completely excluded in the fresh air requirement calculations, since such machines could still produce some form of heat, pollutants and dust by their use. In any case, in order to guarantee a good air quality, a fresh air supply would still be necessary. As the amount of air required by machines is usually much higher than that required by the work force, the required fan capacity could still be reduced.

Emergency operation

Dependent on the HSE-plan, the construction ventilation may have to fulfil functions in the event of an emergency as well. This depends on the specific ventilation concept and is planned and designed for the specific needs and possibilities of the construction site.

In case the construction ventilation has a role in the event of an emergency, the basic goal is to ensure best conditions for the worker's self-rescue. This is done by making sure that the ventilation system provides:

- A smoke-free or smoke-reduced tunnel area, and
- A fresh air supply to safe areas of the tunnel system

At Rogfast E02, considering a long, twin-tube tunnel presumably build in parallel, a feasible solution could be a supply/return construction ventilation system. In such a system, an active ventilation is provided in one of the tubes, usually by bringing in fresh air. The adjacent tube has no active ventilation and polluted air leaves through this tube to the outside environment. In the case of such a system, there is usually no emergency ventilation. In fact, if a fire occurs in one tube, the ventilation is shut down and the type of vehicle used is not expected to have any influence on the design of the ventilation.

7.6 Main findings

While conducting the risk study various additional aspects to consider have been identified that fall outside of the scope but should be considered.

The restricted choice in OEMs and battery-electric ADTs warrants careful consideration, in particular for a challenging project such as Rogfast E02. Considering the sustainability goals set-out by NPRA, various approaches can be outlined:

- Initial application in another, more suitable project (less energy demanding and challenging) would still allow to gain speed in the transition and gather practical experience but involve less risk
- Alternative approach could be to include sustainability focused bonus-based requirements in the contract, to promote stakeholder involvement and stimulate innovation.

A first order estimate of GHG emissions (equivalent CO_2 emissions) using the GHG Protocol by switching propulsion type for the ADTs at Rogfast E02 has been made. The results obtained can provide insights into the extent this can contribute to help NPRA reach their sustainability goals:

- The diesel ADTs naturally emit GHGs compared to the electricity grid based GHGs for the battery-electric ADTs
- Diesel combustion naturally emits more GHG per unit of fuel combusted, extended by the diesel ADTs consuming more energy. In contract, the benefits of the more efficient battery-electric ADTs are extended for Norway by hydropower being the main source for electricity produced.

In order to mitigate the potential consequences of fires, the formulation of an appropriate fire safety strategy should encompass the recognition of prolonged fire durations that may be characteristic of battery electric vehicles. Furthermore, consideration must be given to the possibility of toxic gases being emitted from battery fires:

- The work force should be directed to designated fire safety shelters (if such are available), taking into account the shelters' operational timelines
- Direct (skin) contact with toxic gases released by batteries is to be avoided. This can be achieved by utilising suitable working clothes and protective equipment.

The ventilation during the phase of tunnel construction depends on the characteristics of the construction site. Thus, the ventilation design has to be done individually for each project, considering the safety concept in the HSE-plan:

- During normal operation and by only using electrically powered vehicles and machinery, the fresh air requirements would mainly be governed by the work force, with the operation of the electric vehicles and machines not completely considered as emissions free. A lower power of the fans could still be a result.
- For emergency operation, construction ventilation might be considered. However, presuming a parallel construction of both tubes could make a supply/return system per tube a feasible solution as construction ventilation. Such a system can be considered not active in the event of an emergency, either by being shut down or not functioning anymore.

8 CONCLUSION AND RECOMMENDATIONS

The risk study has been conducted as part of the construction of the Rogaland Fixed Link in the E39, commonly referred to as the E39 Rogfast project. The primary focus are the main differences and potential risks in changing propulsion system for the transport trucks used in excavation of section E02 of Boknafjord tunnel. The main conclusions and recommendations of this study are intended to provide NPRA with detailed information regarding possible effects this switch in truck type might have on health, safety and environment (HSE) at E39 Rogfast project, section E02 (Rogfast E02).

8.1 Conclusions

The risk study has focused on the application of currently available battery-electric trucks to conventional equivalent diesel trucks for transport of rock produced in tunnel excavation at Rogfast E02. The main conclusions with respect to the various topics studied are as follows.

Battery solutions and vehicles

Market research has identified potentially suitable transport trucks, categorised in three distinct vehicles classes:

- Road Tipper Truck (RTT): various well-known OEMs for road trucks are offering battery-electric products with potential use in construction application. From these, only trucks with tipper could be considered, but current product development focuses mainly on less heavy-duty transport, making currently available RTTs not a practical or first choice.
- Articulated Dump Truck (ADT): only a limited number of battery-electric ADT-types from mainly two OEMs are currently available, with application focused on (underground) mining. Layout and design as well as off-road capabilities and tonnage would allow consideration at Rogfast E02.
- Rigid Dump Truck (RDT): trucks are commonly used for open-pit mining and most would be considered not practical for tunnel excavation. In addition, development seems to focus on diesel-electric hybrid solutions. These trucks have therefore not been considered in this study.

Based on the limited number of electric ADTs available, the risk analysis study has been conducted using a battery-electric ADT to an equivalent diesel ADT, both in 4X4 configuration with a loading capacity of 40 ton.

Fire risk analysis

Fire risk analysis has compared possible fire scenarios for diesel ADTs to battery-electric ADTs, including thermal runaway of the batteries. Scenario-based fire curves have been developed for both ADT-types:

- Resulting fire of a battery-electric ADT can be up to 4 hrs, significantly longer than for a diesel ADT (up to 3 hrs)
- The total heat release rate is comparable

Fire risks are typically based on combination of likelihood and consequences. In general, battery-electric vehicle fires can be estimated to be significantly less likely than conventional vehicle fires, as the main source of ignition (hot surface of combustion engine) is missing. In addition, potential underground application has been focus in fire safety development of battery-electric ADTs.

Fire simulations considering Rogfast E02 involving smoke and toxic gases indicate that the time to incapacitation for persons located in proximity of the fire is similar for both ADT-types. Harmful substances typically associated with battery fires, in particular hydrogen fluoride concentrations, were found to be below critical threshold levels.

Process impact analysis

Process impact analysis has focused on possible influences on productivity and efficiency in transporting excavated rock by means of battery-electric ADTs. First order models have been developed to analysis truck movement and loader-based scheduling as well as energy demands and recharging strategies:

- Available battery-electric ADTs are of comparable loading capacity to diesel equivalent, but could have a lower driving speed and thus affect productivity
- Following the general trend of electric vehicles, battery-electric ADTs use less energy while being more efficiently compared to equivalent diesel ADTs. Efficiency is enhanced by the downhill section allowing for partial battery regeneration.
- Currently used battery capacities still have a significantly lower effective energy content (roughly one third) than equivalent diesel ADTs

Battery-electric ADTs rely on battery swapping to remain in operation and thus require recharging infrastructure and strategies. Onboard recharging solutions are considered not practical, since these would force a prolonged wait for battery-electric ADTs.

Long transport distances and steep uphill section make energy demands at Rogfast E02 high for both ADT-types. This makes application of battery-electric ADTs due to their more limited effective energy capacity less suitable.

Additional aspects to consider

The limited number of OEMs and battery-electric ADT-types currently available could make market availability an issue. Moreover, the restricted choice in trucks with does far primarily experience gained in underground mining requires careful consideration and planning in detail in respect to the established NMT at the challenging Rogfast project.

Switching propulsion type for the ADTs contributes to reducing the carbon footprint at Rogfast E02. The main use of hydropower produced electricity in Norway would increase the benefits by the already more efficient and less energy consuming battery-electric ADTs.

The type of tunnel ventilation used during construction depends on the characteristics of the construction site and is planned project dependent as part of the HSE-plan:

- By only using electrically powered vehicles and machinery, the fresh air requirements during normal operation would mainly be governed by the work force, not completely excluding the electric vehicles and machinery.
- The configuration at Rogfast E02 could make a supply/return tube construction ventilation system a feasible solution. Such a system can be considered not active in the event of an emergency, either by being shut down or not functioning anymore.

8.2 Recommendations

Based on the various analyses and additional considerations, several mitigation measures and other more general contemplations have been formulated. The main recommendations are stated below.

Battery solutions and vehicles

The limited number of OEMs and battery-electric ADTs types restricts practical information and potentially actual product market availability.

Gathering more information and/or conducting trials should be considered for application of battery-electric ADTs in established NMT.

Fire risk analysis

Typically vehicular battery fires are difficult to extinguish and require special tactics (e.g. targeted flooding using extinguishing lance or vehicle submerging in fire container). Battery-electric ADTs should therefore be equipped with automated fire suppressions systems, other types of intervention are not advised.

In general, the work force is to evacuate to the fire safety shelter and avoid contact to harmful gases expelled by the batteries by wearing appropriate protection to avoid direct skin contact.

Battery-electric vehicles are preferably equipped with a hose connection for battery pack flooding, with actual use only feasible if continuous water supply is available. Recharging infrastructure is preferably to be located outside the tunnel, as precautionary measure and to allow direct intervention.

Rogfast E02 characteristics require careful consideration for both battery-electric as well as diesel vehicle fires due to possible remote fire locations and limited accessibility for rescue services.

Process impact analysis

Productivity and energy efficiency could be improved by aiming to reduce transport times and/or trip numbers by selection of an ADT-type with higher loading capacity and/or driving speed. It should be considered that bigger trucks might not be practical.

Hybrid vehicle solutions with battery-electric ADTs only used for transport in the tunnel would help reduce energy demands for these vehicles. However, this would increase complexity of the excavation process by requiring a temporary storage location and additional trucks for further transport.

Development of the first order process impact analysis models is to aim at establishing simplified relationships between power output and energy consumption, characterising the efficiency of the drivetrain.

Additional aspects to consider

Initial application in a less challenging tunnelling project (shorter distances, less trips, lower gradients), preferably allowing more for battery regeneration (loaded downhill operation) would be more suitable and less risky.

Using a new technology (not proven yet in tunnelling) for the first time increases complexity of the excavation process and adds additional uncertainty to an already challenging and large scale Rogfast project. Close cooperation with various stakeholders, such as OEMs and possibly contractors, is for product development often used to gather practical information and / or conduct trials and could be considered for this or another project.

The large sustainability gains that can be made by conversion of process components in tunnel excavation warrant further pursuing this goal and highlighting their potential can help to speed up this transition.

A bonus-based approach focused on sustainability goals could counter act the limited OEMs and ADT-types as well as stimulate contractor participation and product innovation.

The formulation of an appropriate fire safety strategy should encompass the prolonged fire durations that may be characteristic of battery electric vehicles as well as the possibility of toxic gases being emitted from battery fires.

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Appendix I: overview contacted OEMs and third parties

Contacted OEMs and third parties	Date of meeting	Remarks	Reference
MDU University, Sweden Epiroc	12-05-2023	Details Epiroc battery solutions and product line-up, specifics battery-electric ADT	[38]
Volvo Trucks	25-05-2023	General Volvo Trucks sustainable drivetrains, main characteristics electric product line-up	
eMining (part of Lithium System)	13-06-2023	Basic approach truck retrofitting, examples prototype RDT and current ADT project	[34]
AMV	16-06-2023	Innovations in industry / equipment Focus on NMT	
Mercedes Benz Trucks	23-06-2023	Key features Mercedes Benz Trucks sustainable drivetrains, specifics electric product line-up	[12]
Scania	-	No response	
Sandvik	-	No response	

Table I-1: Overview of contacted OEMs, dates of meetings and/or remarks

Appendix II: vehicle database

Sovik Consulting, TU Graz & ILF Consulting Engineers

Project:	Risk with battery operated transport vehicles in tunnel excavation
Projectnr.:	15958
Client:	Statens vegvesen
Service:	Risk analysis of electric vehicles transporting excavated rock
Document:	Vehicle database - Road Tipper Truck
1. Date:	14.06.2023
Revision:	-
Date:	-
Processed by:	BL, OH, PF

Vehicle Database		Diesel			Battery-electric			
		Road Tipper Truck (RTT)		Diesel reference Road Tipper Truck	Road Tipper Truck (RTT)			Electric alternative Road Tipper Truck
								
General								
Vehicle: brand & type		Mercedes Arocs 4145K	Mercedes Arocs 1851 LS		BYD T10 ZT	Volvo FMX 84R TE	Volvo FH 42T E	
Tipper: brand & type		EMPL tipper	Meiller tipper trailer		TBD	TBD	Meiller tipper trailer	
Drivetrain		ICEV	ICEV	ICEV	BEV	BEV	BEV	BEV
Vehicle class		Road Tipper Truck	Road Tipper truck	Road Tipper Truck	Road Tipper truck	Road Tipper truck	Road Tipper truck	Road Tipper Truck
Application		On- and off road	On road	On- and off road	On- and off road	On- and off road	On road	On- and off road
Load capacity		17 ton	25 ton	17 ton	13 ton	15 ton	23 ton	15 ton
Availability		Yes	Yes		For EU to be checked	Yes, small series (2023)	Yes, small series (2023)	
Assessment		Possibility GVW limited for road use	No Mainly for road use (on site use limited)		Possibility GVW limited for road use If with EU compliance	Possibility GVW limited for road use	No Mainly for road use (on site use limited)	
Drivetrain								
Propulsion type		Diesel combustion	Diesel combustion	Diesel combustion	Li-Ion LFP	Li-Ion NMC ?	Li-Ion NMC ?	Li-Ion
Layout and configuration		8X4 (8X8)	4X2 (4X4)	8X4	8X4	8X4 (tridem)	4X2	8X4
Number of motors	[-]	1	1		2	2 / 3	2 / 3	
Location of motors		Front under cab	Front under cab		Axel	In frame	In frame	
Power per motor	[kW]	330	375		180	163	163	
Total power of drivetrain	[kW]	330	375	330	360	330 / 490	330-490	490
Number of forward gears	[-]	16	12		TBD	2	2	
Capacity diesel tank	[l]	290	390	300				
Capacity per battery pack	[kWh]				TBD	90	90	90
Number of battery packs					TBD	4 / 6	4 / 6	6
Energy density per litre	[kWh/l]	9,72	9,72	9,72				
Energy density per kg	[kWh/kg]				0.09 - 0.12	0.15 - 0.28	0.15 - 0.28	
Total energy of drivetrain	[kWh]	2819	3791	2916	435	450 / 540	450 / 540	540
Refuelling time	[min]	6	8	6				
Battery swapping time	[min]				No swapping possible	No swapping possible	No swapping possible	No swapping possible
Battery recharging time	[min]				120	150	150	150
Drivetrain efficiency	[%]	20% (estimate)	20% (estimate)	20%	80% (estimate)	80% (estimate)	80% (estimate)	80%
Range of utilisation (SoC)	[%]	5-100%	5-100%	5-100%	5-90%	5-90%	5-90%	5-90%
Total effective energy of drivetrain	[kWh]	536	720	554	296	306 / 367	306 / 367	367
Regenerative braking system		No, engine breaking	No, engine breaking	No, engine breaking	Yes, battery recharging	Yes, battery recharging	Yes, battery recharging	Yes, battery recharging
Vehicle characteristics								
Loading capacity	[ton]	17 (estimate)	25 (estimate)	17	13 8estimate)	15 (estimate)	23 (estimate)	15
Box volume (heaped)	[m3]	15 (estimate)	24 (estimate)		TBD	15,87	24 (estimate)	
Vehicle weight - empty	[ton]	10.5 + 4.5 (estimate)	8.5 + 6.5 (estimate)	15	18 (assumed incl. box)	12 + 5 (estimate)	10 + 6.5 (estimate)	17
Vehicle weight - loaded	[ton]	32 (GVW road limited)	40 (GVW road limited)	32	31	32 (GVW road limited)	40 (GVW road limited)	32
Max. inclination uphill (practical)	[%]	TBD	TBD		TBD	TBD	TBD	
Max. speed flat / downhill - empty	[km/h]							
Max. speed uphill 7% - empty	[km/h]	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Max. speed flat / downhill - loaded	[km/h]							
Max. speed uphill 7% - loaded	[km/h]							
Total vehicle length	[m]	8,51	6.2 + 9 (estimate)	8,50	9,17	10.5 - 11.5 (chassis variations)	6.2 + 9 (estimate)	10,00
Total vehicle width	[m]	2,50	2,50	2,50	2,55	2,50	2,50	2,50
Total vehicle height	[m]	3,62	3,62	3,60	3,11	2,99	3,35	3,00
Radius turning circle of vehicle	[m]	TBD	TBD		TBD	TBD	TBD	
Box height (load height)	[m]	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Box dump height (max. height opened)	[m]							
Loading time	[min]	2	3	2	2	2	3	2
Dumping time	[min]	1	1	1	1	1	1	1

TBD = to be determined

Sources	Mercedes Arocs 4145K	Mercedes Arocs 1851 LS	Diesel reference	BYD T10 ZT	Volvo FMX 84R TE	Volvo FH 42T E	Electric alternative
Sources	Mercedes Benz; Data sheet: Mercedes-Benz Arocs 5 4145 K 8X4 + Meiller rear-way tipper H436 20m3 EMPL; Product sheet: Gesteinsmulde mit hydraulisch abklappbarer Seitenwand	Mercedes Benz, roadstars; Die Müller Transport AG und Ihr Arocs 1851 LS 4X2; roadstars.mercedes-benz-trucks.com Meiller; Product brochure: Kippsattel		BYD; Product brochure: BYD battery electric truck series BYD; Presentation: BYD electric vehicle program for Europe	Volvo Trucks; Volvo FMX Electric; volvotrucks.com Volvo Trucks; Data sheet: FMX Battery Electric 8X4 Rigid Tag Tridem FMX 84R TE; 2023 Volvo Trucks; Product brochure: Volvo Trucks FH / FM / FMX electric (tractor); 2022	Volvo Trucks; Volvo FH Electric; volvotrucks.com Volvo Trucks; Data sheet: FH Batter Electric 4X2 Tractor - Full Air Suspension FH 42T E; 2023 Volvo Trucks; Product brochure: Volvo Trucks FH / FM / FMX electric (tractor); 2022	

Table II-1: Overview of vehicle database, vehicle class: Road Tipper truck (RTT)

Sovik Consulting, TU Graz & ILF Consulting Engineers

Project:	Risk with battery operated transport vehicles in tunnel excavation
Projectnr.:	15958
Client:	Statens vegvesen
Service:	Risk analysis of electric vehicles transporting excavated rock
Document:	Vehicle database - Articulated Dump Truck
1. Date:	14.06.2023
Revision:	-
Date:	-
Processed by:	BL, OH, PF

Vehicle Database		Diesel					Battery-electric		
		Articulated Dump Truck (ADT)					Articulated Dump Truck (ADT)		
						Diesel reference Articulated Dump Truck			Electric alternative Articulated Dump Truck
General									
Vehicle: brand & type		Volvo A30G	Volvo A40G	Epiroc MT42	Sandvik TH551i		Epiroc MT42 Battery	Sandvik TH550B	
Tipper: brand & type		-	-	-	-		-	-	
Drivetrain		ICEV	ICEV	ICEV	ICEV	ICEV	BEV	BEV	BEV
Vehicle class		Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck	Articulated Dump Truck
Application		Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road	Off-road
Load capacity		30 ton	40 ton	40 ton	50 ton	40 ton	40 ton	50 ton	40 ton
Availability		Yes	Yes	Yes	Yes		Yes	Yes	
Assessment		Yes Typical vehicle	Yes Typical vehicle	Possibility Not typical, intended for mining	Possibility Not typical, intended for mining Practicality to be checked		Possibility Not typical, intended for mining Adaptation to new vehicle type	Possibility Not typical, intended for mining Adaptation to new vehicle type Practicality to be checked	
Drivetrain									
Propulsion type		Diesel combustion	Diesel combustion	Diesel combustion	Diesel combustion	Diesel combustion	Li-Ion NMC	Li-Ion LFP	Li-Ion
Layout and configuration		6X6	6X6	4X4	4X4	4X4	4X4	4X4	4X4
Number of motors	[-]	1	1	1	1		2	4	
Location of motors		In front of cab	In front of cab	Besides cab	Besides cab		Axel	Wheel hub	
Power per motor	[kW]	265	350	399	515		200	180	
Total power of drivetrain	[kW]	265	350	399	515	400	400	720	400
Number of forward gears	[-]	6	9	8	8		1	1	
Capacity diesel tank	[l]	380	480	580	840	500			
Capacity per battery pack	[kWh]						90	177 / 241 (NEW)	90
Number of battery packs							5	2	5
Energy density per litre	[kWh/l]	9,72	9,72	9,72	9,72	9,72			
Energy density per kg	[kWh/kg]						0.15 - 0.28	0.09 - 0.12	
Total energy of drivetrain	[kWh]	3694	4666	5638	8165	4860	450	354 / 482 (NEW: 2023)	450
Refuelling time	[min]	8	10	12	17	10			
Battery swapping time	[min]						10 (estimate)	5 (estimate)	10
Battery recharging time	[min]						180 (0-90%)	180 (estimate)	180
Drivetrain efficiency	[%]	20% (estimate)	20% (estimate)	20% (estimate)	20% (estimate)	20%	80% (estimate)	80% (estimate)	80%
Range of utilisation (SoC)	[%]	5-100%	5-100%	5-100%	5-100%	5-100%	5-90%	5-90%	5-90%
Total effective energy of drivetrain	[kWh]	702	886	1071	1551	923	306	240 / 328 (NEW: 2023)	306
Regenerative braking system		No, engine breaking	No, engine breaking	No, engine breaking	No, engine breaking	No, engine breaking	Yes, battery recharging	Yes, battery recharging	Yes, battery recharging
Vehicle characteristics									
Loading capacity	[ton]	29	39	42	51	40	42	50	40
Box volume (heaped)	[m3]	18	24	19	28		19	28	
Vehicle weight - empty	[ton]	23,6	30,7	34,5	46,9	30	37,7	49,6	40
Vehicle weight - loaded	[ton]	52,6	69,7	76,5	97,9	70	79,7	99,6	80
Max. inclination uphill (practical)	[%]	20%	20%	20%	20%		20%	20%	
Max. speed flat / downhill - empty	[km/h]	50	53	42	34	40	20	39	20
Max. speed uphill 7% - empty	[km/h]	33	30	33	31	30	20	32	20
Max. speed flat / downhill - loaded	[km/h]	40	40	41	33	40	20	37	20
Max. speed uphill 7% - loaded	[km/h]	13	12	14	16	15	18	23	18
Total vehicle length	[m]	10,30	11,26	10,95	11,58	11,00	10,95	10,70	11,00
Total vehicle width	[m]	2,95	3,40	3,10	3,12	3,00	3,10	3,24	3,00
Total vehicle height	[m]	3,67	3,60	2,69	3,46	3,50	2,69	3,03	3,50
Radius turning circle of vehicle	[m]	8,11	8,96	8,97	9,35		8,97	9,34	
Box height (load height)	[m]	3,20	3,13	2,59	2,90	2,50	2,59	3,03	2,50
Box dump height (max. height opened)	[m]	6,56	7,27	5,63	7,00	5,75	5,63	6,66	5,75
Loading time	[min]	3	4	4	5	4	4	5	4
Dumping time	[min]	1,0	1	1	1	1	1	1	1
Sources		Volvo Construction Equipment; Product brochure: Volvo Articulated Haulers A25G, A30G; 2023	Volvo Construction Equipment; Product brochure: Volvo Articulated Haulers A35G, A40G; 2023	Epiroc; Product brochure: Epiroc minetruck MT42; 2022	Sandvik; Product brochure: Sandvik TH551i; 2022		Epiroc; Product brochure: Epiroc minetruck MT42 battery; 2022	Sandvik; Product brochure: Sandvik TH550B battery-electric truck; 2021	

TBD = to be determined

Table II-2: Overview of vehicle database, vehicle class: Articulated Dump Truck (ADT)

Sovik Consulting, TU Graz & ILF Consulting Engineers

Project:	Risk with battery operated transport vehicles in tunnel excavation
Projectnr.:	15958
Client:	Statens vegvesen
Service:	Risk analysis of electric vehicles transporting excavated rock
Document:	Vehicle database - Rigid Dump Truck
1. Date:	14.06.2023
Revision:	-
Date:	-
Processed by:	BL, OH, PF

Vehicle Database		Diesel	Battery-electric
		Rigid Dump Truck (RDT)	Rigid Dump Truck (RDT)
			
General			
Vehicle: brand & type		Komatsu HD605-7	Kuhn /eMining E-Dumper
Tipper: brand & type		-	Retrofitted Komatsu HD605-7
Drivetrain		ICEV	BEV
Vehicle class		Rigid Dump Truck	Rigid Dump Truck
Application		Off-road	Off-road
Load capacity		55 ton	55 ton
Availability		Yes	No
Assessment		No Not practical	No Prototype Not practical
Drivetrain			
Propulsion type		Diesel combustion	Li-Ion
Layout and configuration		4X4	4X4
Number of motors	[-]	1	
Location of motors		Besides/under cab	TBD
Power per motor	[kW]	575	
Total power of drivetrain	[kW]	575	590
Number of forward gears	[-]	7	TBD
Capacity diesel tank	[l]	780	
Capacity per battery pack	[kWh]		120
Number of battery packs			5
Energy density per litre	[kWh/l]	9,72	
Energy density per kg	[kWh/kg]		Li-Ion dependent
Total energy of drivetrain	[kWh]	7582	600
Refuelling time	[min]	16	
Battery swapping time	[min]		Probably not
Battery recharging time	[min]		Loaded-downhill regeneration
Drivetrain efficiency	[%]	20% (estimate)	80% (estimate)
Range of utilisation (SoC)	[%]	5-100%	5-90%
Total effective energy of drivetrain	[kWh]	1441	408
Regenerative braking system		No, engine breaking	Yes, battery recharging
Vehicle characteristics			
Loading capacity	[ton]	55	55
Box volume (heaped)	[m3]	34	34
Vehicle weight - empty	[ton]	46,5	50
Vehicle weight - loaded	[ton]	101,5	105
Max. inclination uphill (practical)	[%]	20%	20% (assumed)
Max. speed flat / downhill - empty	[km/h]	67	TBD
Max. speed uphill 7% - empty	[km/h]	34	
Max. speed flat / downhill - loaded	[km/h]	47	
Max. speed uphill 7% - loaded	[km/h]	14	
Total vehicle length	[m]	10,12	10,12
Total vehicle width	[m]	4,24	4,24
Total vehicle height	[m]	4,78	4,78
Radius turning circle of vehicle	[m]	8,50	8,50
Box height (load height)	[m]	3,60	3,60
Box dump height (max. height opened)	[m]	8,80	8,80
Loading time	[min]	5	5
Dumping time	[min]	1	1

TBD = to be determined

Sources	Diesel	Battery-electric
Sources	Komatsu; Product brochure: Komatsu HD465-7, HD605-7; 2017	Komatsu; Product brochure: Komatsu HD465-7, HD605-7; 2017 Kuhn; E-Dumper; kuhn-gruppe.ch eMining; Referenzprojekt: eDumper 65 Tonnen Nutzlast; emining.ch

Table II-3: Overview of vehicle database, vehicle class: Rigid Dump Truck (RDT)