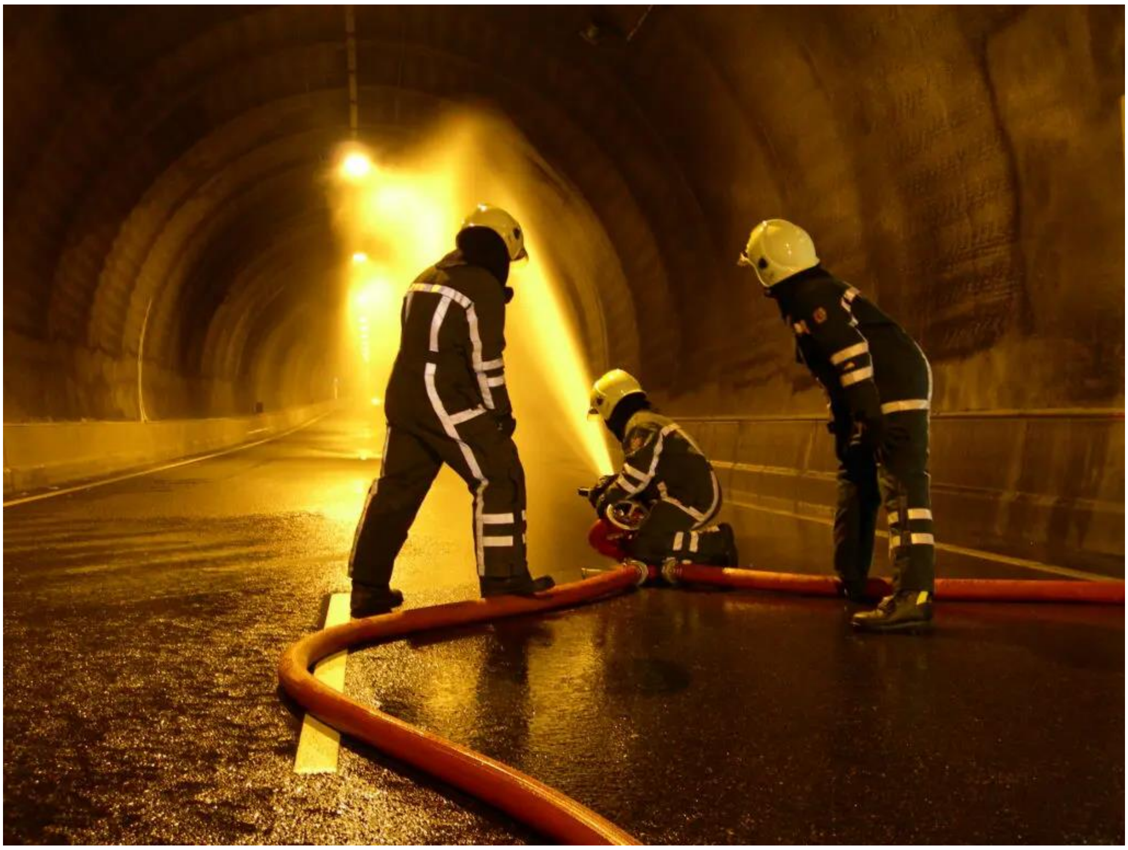
Availability of tunnels for new energy carriers



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i. Management Summary

The objective of this research paper is to determine whether the availability of Dutch tunnels is impacted by the vehicle transition. All events that are impacted by the vehicle transition and may cause unavailability have been identified in chapter 5. Three mayor events were expected to influence tunnel availability. These are; planned unavailability by cleaning, unavailability by vehicle fire and planned unavailability by replacement of the asphalt layer.

In chapter 6.1 has been concluded that the total emissions of Battery Electric Vehicles (BEV) and ICEV are approximately equal. This is explained by the fact that 90% of all vehicle emission is not-exhaust emission, mostly comprised of particulate matter emitted by tyres, brake and road surface wear. BEV and Plug-in Hybrid vehicles (PHEV) emit an increased amount of particulate matter when related to ICEV because of their increased weight. No change in unavailability is expected because pollution levels are similar. However, exhaust emission is composed of different chemicals than not-exhaust emission, this might impact the optimal cleaning interval. Further research is recommended to determine the effects of different chemicals on the “wear” rate of tunnel walls and tunnel technical installations. These wear rates can be related to the total vehicle distribution to estimate optimal cleaning interval.

Fire as a result of an incident does not have significant impact on the total availability of tunnel systems. It has been determined that the probability of ignition as a result of an incident is 3,17% for ICEV, 2,21% for PHEV and 2,00% for BEV’s. Mean Time to Recovery (MTTR) increases from 30 minutes for ICEV to 55,5 minutes for PHEV’s and 68 minutes for EV’s. Moreover, during towing of the vehicle the batteries can reignite, in this case extinguishing of the vehicle needs to be restarted. The expected probability of this happening during towing phase is 5%. The Landelijke Tunnel Standaard (LTS) budgets 90 hours of unavailability per year for incidents and emergencies, the unavailability as a result of this event decreases by less than 5 minutes the quantitative analysis and is therefore negligible. It is recommended that fire resistant materials will be tested to ensure safety in the case of an EV fire, which has a slightly higher peak Heat Release Rate (HRR). Based on current variables it has been calculated that BEV will exceed the share of ICEV by 2034 – 2037. It is advised that, before this time, the extinguishing medium in emergency posts will be replaced with a medium that has the best extinguishing properties for BEV.

It has been determined that heavier PHEV and BEV have a negative effect on the life expectancy of asphalt. An estimation of the increased wear rate once EV saturation reaches 100% is established at 12,9%. Moreover, it has been concluded that the expected replacement interval of DAB asphalt changes from 17 years in 2022 to 15,2 – 15,5 years in 2040. It is recommended that ZOAB and DAB asphalt degradation will be modelled using data gathered from real life testing. The expected decrease in life expectancy will be extremely costly for contractors, RWS and municipalities

It is not expected that FCEV will get a large enough share on Dutch infrastructure to have an impact on availability of Dutch tunnels. In the LTS the allowed unavailability of planned maintenance is 75 hours per year is. The total calculated unavailability increases from 4 hours and 25 minutes in the current situation to 4 hours and 52 minutes in the worst case scenario of 2040. This is an increase of 27 minutes on a yearly basis and does not substantially impact availability of tunnels. It has been concluded that the current levels of availability of Dutch tunnels can be maintained, even when all vehicle on Dutch infrastructure are PHEV or BEV.

ii. Preface

This research report was written for the course Master Maintenance & Asset Management. After successful conclusion the Msc grade will be acquired. I am happy with the results of this thesis and I hope that this master will provide foundation for the future, both for me personally as for future research. Whilst I had a lot of fun proving to myself that I am a competent researcher, I cannot wait to spend some more time with my friends and family. Somewhere during this research I realized that time is fleeting. Now is the time for balance.

I would like to sincerely thank Thijs van den Eerenbeemt for his guidance during my first few years as a reliability engineer. Your time and insight have been as helpful. Moreover, I would like to thank Bram ten Klei, you have provided fun and challenging projects and are always great to work with. Lastly, I would like to thank my employer, Innocy for the opportunity they provided.

I would like to thank my sister, parents and grandparents, even though I do not always show it, you mean the world to me.

Thank you, Renee, for supporting me during exhausting and difficult times, and listening to my incoherent stories.

Chris Vriens,

Eindhoven, Juli 27th, 2022

Post scriptum

Reliability or inability?

Information is at my fingertips, in a moment I slip and here I find myself, lost in this sticky web. Reliability engineers always try to guide designers in such a way that failure is unlikely, redundant so to say. Redundancy after redundancy is used so that the hinterlands of the Netherlands is virtually impervious to flooding. While the hinterland is protected, information floods the shores of the internet. I wonder, if all scientists had access to pristine shores instead, would they be able to solve humankind's latest dilemma? With all this access to information, how little do we actually know?

iii. Colophon

Revision log

Version	Status	Date	Description	Name
0.1	Pre-draft	16-02-2021	Creation of format	C. Vriens
0.2	Pre-draft	23-12-2021	Introduction and Plan of approach	C. Vriens
0.3	Draft	20-05-2022	Finished RQ 1 and 2	C. Vriens
0.3TEE	Draft	27-05-2022	Review	T. van den Eerenbeemt
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0.5	Draft	24-06-2022	Finished RQ 4, 5	C. Vriens
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0.6	Draft	18-07-2022	Finished RQ 6 conclusion & recommendation	C. Vriens
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iv. Table of content

v. List of abbreviations

Abbreviation	Definition
AADT	Annual Average Daily traffic
ACEA	The European Automobile Manufacturers' Association
ADAS	Advanced Driver Assistance System
ADS	Automated Driving Systems
ASB	Afsluitboominstallatie
ATS	Amsterdamse tunnelstandaard
BEV	Battery Electric Vehicle acronym for EV
BLEVE	boiling liquid expanding vapor explosion
CADO	Calamiteitendoorsteek
CBS	Centraal bureau voor de statistiek (Central office for statistics)
CCTV	Closed Circuit Television
CFM	Computational Fluid Mixing
CN	Carbon neutral
CNG	Compressed natural gas
CNV	Carbon Neutral Vehicles
COB	The Netherlands Knowledge Centre for Underground Space and Underground Construction
CPB	Centraal Planbureau (Central office for economic policy)
CROW	CROW is the name of a knowledge centre that is involved with centrum voor regulations, research in ground, water, road construction and traffic Engineering
DAB	Dicht asfalt beton
DBFM	A contract form, Design, Build, Finance and Maintain
DBM	A contract form, Design, Build and Maintain
DC	A contract form, Design and construct
EC	European credit
ECEA	The European Automobile Manufacturers' Association
ECM	Electromagnetic compatibility
EV	Electric vehicle
FCEV	Fuel Cell electric vehicle
FMECA	Failure Mode, Effects & Criticality Analysis
HEV	Hybrid vehicles
HF (chemical)	Hydrogen fluoride
HF (subsystem)	High frequency

HRR	Heat Release Rate
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
Km	kilometre
KPT	Kennisplatform Tunnelveiligheid (Knowledge Platform on Tunnel Safety)
LCC	Life Cycle Costs (analysis)
LTS	Landelijke Tunnelstandaard
MTM	Motorway Traffic Management
MTTR	Mean Time to Repair / Mean Time to Recovery
MW	Mega watts
NFPA	National Fire Protection Association
NTSB	National Transportation Safety Board
OTO	Opleiden, Trainen en Oefenen
PBL	Planbureau voor de Leefomgeving (Central office for the environment)
PHEV	Plug-in hybrids
PINFA	Phosphorous, inorganic and nitrogen flame retardants association
PwC	PricewaterhouseCoopers
RAMS	Reliability, Availability, Maintainability and Safety
rEV index	Readiness for electric vehicles
RPM	Revolutions per minute
RWS	Rijkswaterstaat
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek
TTI	Tunnel Technische Installaties
VEVA	Verrijdbare/ verplaatsbare vangrail
VRI	Verkeersregelinstallatie
WARVW	Wet aanvullende regels veiligheid wegtunnels
ZOAB	Zeer Open Asfalt Beton

vi. List of Tables and figures

Tables

Figures

1. Introduction

This research proposal is written for the Master of Engineering in Maintenance & Asset Management. This research proposal provides the framework for the completion of the master thesis. This thesis aims to quantify the impact of new energy carriers on the availability of Dutch road tunnels and determine if any countermeasures are required in upcoming constructions and renovations.

Road tunnels, henceforth named; tunnel(s), are mostly located in urban areas or as part of a highway, these roads are essential for a significant portion of the traffic movements in the Netherlands. The social and economic damage of a tunnel closure is enormous, even more so for unplanned tunnel closures. The CROW estimated that congestion of all traffic in the Netherlands would result in approximately € 4 billion in damages in 2021 (Voerknecht, 2021). Actual numbers have not yet been published, however the economic damage of 2021 is likely to be smaller due to Covid-19 measures.

In the Dutch socio-political landscape carbon neutral means of transportation are widely accepted as a method to address further damage by climate change. It is estimated that by 2024 electric vehicles will be cheaper than conventional internal combustion engine (ICE) vehicles (Berings & Kop, 2021). By 2030 only carbon neutral vehicles will be sold in the Netherlands (Rutte, et al., 2017, p 37). Moreover, increasingly higher demands are established regarding reliability, availability, maintainability and safety throughout the life cycle of Dutch tunnels.

The changing usage of roads and tunnels, specifically the extend in which carbon neutral vehicles like electric and hydrogen based vehicles and carbon neutral heavy transport have not been taken into the design of these civil structures. This major shift in road usage leads to the question; is the Dutch infrastructure prepared for such a significant shift in method of transportation?

2. Problem definition

Approximately half of the tunnels in the Netherlands that are in use today have been designed at least twenty years ago (2002) and have been taken into commission shortly afterwards (Wikipedia, 2022). The civil structure of Dutch tunnels can easily last 100 years since they are theoretically designed for approximately 200 years (Ir. Siemes, Dr. Polder, & Castenm, 1999). Tunnels are expensive assets of municipalities and Rijkswaterstaat (RWS). The design of these tunnels happened without designers considering the explosive rise of carbon neutral vehicles.

In the Dutch socio-political landscape carbon neutral means of transportation are widely accepted as a method to address further damage by climate change. This is emphasised by the governing agreement of 2017 (Regeerakkoord) that states that from 2030 onwards, only carbon neutral vehicles are allowed to be sold in the Netherlands (Rutte et al., 2017, p. 37). PwC states that enough Carbon neutral vehicles will be available and affordable by 2030 that this ambition is achievable (Berings & Kop, 2021). PwC also estimates that approximately 1.9 million electric passenger cars will be driving on Dutch roads in 2030. Moreover, from 2030 approximately 400,000 electric vehicles will be introduced to the road system each year.

The governing agreement of 2017 also states that infrastructure has to be designed, build and maintain for self-driving vehicles. Surprisingly enough the governing agreement does not include carbon neutral vehicles in this statement. Due to the long lead time of constructing and renovating tunnels it is vital to consider the effects of new energy carriers on the availability and wear patterns of the tunnel systems. As described in the introduction, congestion in the Netherlands amount to approximately € 4 billion. Availability of tunnels should remain excellent to prevent more congestion.

Some research has been conducted on the effects of electric vehicles on safety in tunnel. However little to no research has been conducted on effects of new energy carriers on *availability* of Dutch tunnels. This research paper aims to address this lack of research.

3. Research design

The chapter identifies the main research question and sub-research questions. The complete research proposal including project management and peripheral maters, like project planning can be found the research proposal which is attached as a separate document.

3.1. Research objective

The objective of this research is to address a void in literature on the effects of new energy carriers on the availability of Dutch tunnels. By quantifying risk to the availability of Dutch tunnels in future scenario's, this research project will contribute to the existing literature effective decision making of contractors and contract givers regarding tunnel construction and renovation projects. The research is successful when all research questions have been answered within the budgeted 420 hours.

3.2. Main research question

The main research question of this thesis is stated below:

> What is the effect of the increasing representation new energy carriers on the availability of Dutch tunnels and how does this change in availability affect design decisions for renovations and newly constructed tunnels?

3.3. Conceptual research model

To determine what variables influence the main research question a conceptual model has been created conform the theory of Piet Verschuren and Hans Doorewaard (2010). A conceptual model visualises the relationship between variables to assist in designing acceptable sub-questions. In the conceptual design the positive and negative effects are presented. Figure 1 shows the conceptual model of Dutch tunnel availability. In this conceptual model the letters refer to; R, direct relationship; C, controlling variable and I, direct feedback.

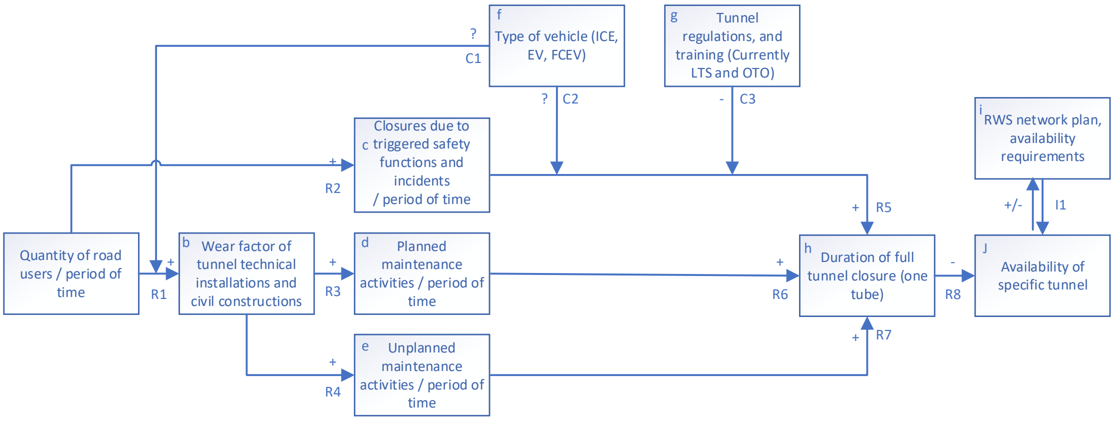

Figure 1 Conceptual model of Dutch tunnel availability

3.4. Sub-research questions

To answer the main research question, several sub-questions have been identified by considering the variables described in the conceptual model (see chapter 0) using the Heinze Oost model (Oost & Markenhof, 2002). This method describes the reason, desired answer, knowledge domain and method for answering each sub-question. This information can be found in Appendix A. The following sub-questions have been identified;

1. How severe is the increase in carbon neutral vehicles on Dutch road systems?
2. What is the influence of traffic intensity on the probability of an accident in a tunnel?
3. How do vehicle types contribute to unavailability of Dutch tunnels?
4. What is the difference in mean time to recovery of an incident with carbon neutral vehicles in relation to ICE vehicles?
5. What is the difference between conventional ICE cars and carbon neutral vehicles in relation to wear of tunnel installations in Dutch tunnels?
6. What are the most significant quantitative differences between the current situation and the future including CN vehicles?

3.5. Scope

In this paragraph the boundaries of the research project are described.

In scope

- Research will be focussed on Dutch tunnels. When reglementary documentation is required, the Dutch standard will be followed, the LTS (Landelijke Tunnelstandaard).
- Only road tunnels are in scope, no train, pedestrian or other tunnels.
- The research will focus on the most common, one tunnel tube per driving direction tunnel version, to calculate availability.
- As explained in the problem definition the life expectancy of tunnel constructions is not precisely known. Therefor improvements will be near impossible to define. The research will focus on technical installations and civil installations like physical road systems.
- Fully carbon neutral vehicles including; electric vehicles and hydrogen fuel cell electric vehicles and hybrid vehicles. These will be compared with combustion engine vehicles.

Out of scope

- Tunnels outside of the Netherlands will not be considered.
- Destructive testing to measure mean time to recovery in tunnels for any type of vehicle is not included in the research.
- The research project will identify the most prominent changes that CN vehicles present to tunnels and what actions may be taken to control these risks. Business cases will not be included. It is expected that insufficient time is available to make a satisfactory business case.

- Actual calculations for comparison of fire capacity (brandvermogens) and toxic gasses will not be conducted in this research, a previous paper from Arcadis does an excellent job describing these risks (Gideonse, et al., 2019).
- Regional tunnel standards like the Amsterdamse tunnelstandaard (ATS) are out of scope.
- In the quantitative part of the research, potential reduction in probability of incidents due to technological advances in self driving vehicles will not be considered since it is not possible to give an accurate estimation of incident reduction due to these systems.
- The individual probability of failure of the vehicles themselves will not be calculated. Research presumption is that most vehicles are highly reliable and there is no significant difference between EV/ FCEV and combustion vehicles.

3.6. Reading guide

This chapter aims to clarify the structure of the master thesis. To improve readability and logic the order of the research questions has been changed. See the change log in chapter 12.

In the research design a total of six sub-research questions have been created. Theoretically, answering all sub-research questions should result in a definitive answer to the main research question. In the research framework several overarching themes have been determined. The structure of this research paper is based on these overarching themes.

Sub-research question	**Original number**	**Theme**	**Chapter**
What are the physical differences between ICEV and CNV?	-	Vehicle type comparison	4
What events that contribute to un-availability of Dutch tunnels are impacted by the vehicle transition?	3	Unavailability in Dutch tunnel systems	5
What is the difference in mean time to recovery of an incident with carbon neutral vehicles in relation to ICE vehicles?	4	Probability and MTTR of unavailability phenomena	6
What is the difference between conventional ICE vehicles and carbon neutral vehicles in relation to wear of maintenance activities in Dutch tunnels?	5	Probability and MTTR of unavailability phenomena	6
How severe is the increase in carbon neutral vehicles on Dutch road systems?	1	Quantification of future road intensity	7
What is the influence of traffic intensity on the probability of an accident in a tunnel?	2	Quantification of future road intensity	8
What are the most significant quantitative differences between the current situation and the future including CN vehicles?	6	Expected unavailability of road tunnels	9

4. Vehicle type comparison

There are many similarities and differences between ICE vehicles and EV's. This chapter aims to clarify the main working mechanism of the different forms of propulsion and identify relevant differences between conventional ICE vehicles and carbon neutral vehicles (CNV). Carbon neutral vehicles are also known as new energy carriers. After the working mechanism is clarified, differences that could potentially influence availability in tunnels are analysed. In this research paper five main types of propulsions are discussed. These are internal combustion engines (ICE) or internal combustion engine vehicles (ICEV), Plug-in hybrids (PHEV), Hybrids (HEV), full electric vehicles (EV) and fuel cell electric vehicles (FCEV). Many papers have been written about the advantages and disadvantages of each form of propulsion for the consumer, however this is not relevant for this study and will not be analysed.

4.1. Internal combustion engine vehicles (ICEV)

The conventional ICE vehicle uses an on board fuel tank filled with high energy density fuel like gasoline or diesel. ICE engines come in all forms and sizes since they have been in production for over a century. In modern times all engines have the same working principle, a complex system of cylinders in which controlled explosion of the fuel-air mixture results in mechanical work. This drives the crankshaft which in turn makes the wheels of the vehicle turn. Figure 2 shows a more detailed flow scheme of torque creation by an internal combustion engine (Biček, et al., 2020).

Internal combustion engines generate peak torque and power in a narrow power band. The powerband of an engine is the range of operating speeds under which the engine or motor is able to output the most power that is, the maximum energy per unit of time. Internal combustion engines generate peak torque and power in a narrow power band. Specifically between 3000 and 4000 RPM. Therefor it is critical that a multistage gearbox is used so that RPM stays between this level on the full range of vehicle speeds.

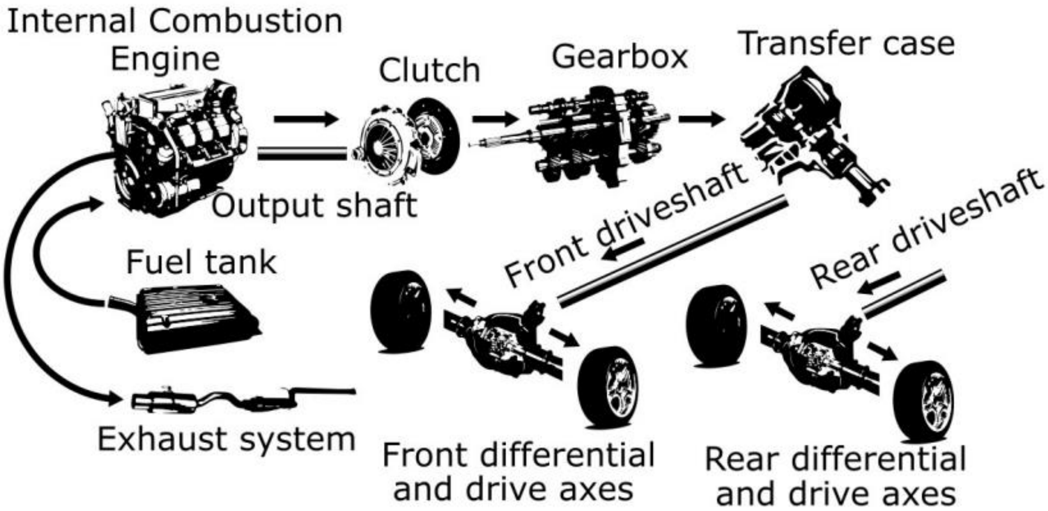

Figure 2 Working mechanism of ICEV

A problem that occus in ICEV and not in vehicles without an ICE engine is fuel leakage. Gasoline and diesel are petroleum products that absorbed by the asphalt, permanantly reducing its structural integrity if not cleaned properly. This often results in potholes and long strips of damaged asphalt at the location of the exhaust. Fuel leakage can significantly damage asphalt to the point that it requires emergency reparations. Additionally, oil reduces grip vehilces have on the road surface. Incidents can happen as a result of a slip cause by an oil spill. This also results in unavailability.

4.2. Full electric vehicles (EV or BEV)

The primary difference between EV's and ICEV is the form of propulsion. The drive train in an EV makes use of an electric motor to transform chemical energy into kinetic energy. The chemical energy is provided by a series of battery packs. The DC current provided by the battery packs is used to power the electric motor. An DC/DC converter is used to change 200-800V into lower voltage that power auxiliary systems. See Figure 3 for an example of a fully electric vehicle (U.S. Department of Energy's Vehicle Technologies Office, 2022).

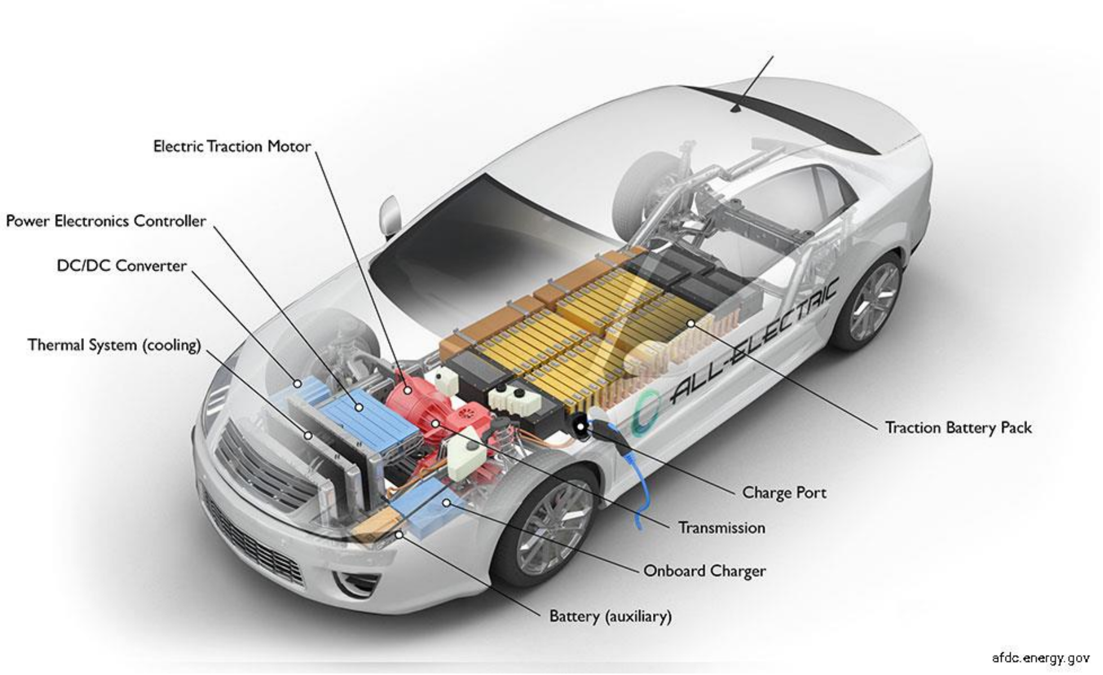

Figure 3 Components in an all-electric vehicle

From a reliability perspective electric vehicles allow for a much greater reliability. In an ICE vehicle there are approximately 2000 moving parts that are subject to wear and tear failure mechanisms (Raftery, 2018). Since the technology of the ICE engine is so well established in modern society many improvements have been made to increase reliability of these components. A drivetrain of an EV only contains around 20 moving parts. Should the failure rate of individual components be relatively on par with the moving parts of the ICE engine a huge increase in reliability is possible. Whereas many sensors and other electrical components are used in all modern forms of transportation, not only electric vehicles. Meaning it is to be expected that no significant difference in reliability is induced by sensors.
In the upcoming years many kilometres will be driven using EV transport, automobile manufacturers can use failure data to improve the working mechanisms in newer variations of the vehicles.

Gasoline and diesel are lightweight in relation to the heavy battery packs that are used by EV's. The energy density of gasoline is approximately 90 times larger than that of a lithium ion battery (The Geography of Transport, 2022). This means that producers of EV's have to introduce more efficient batteries or a larger quantity of batteries so that the consumer can travel the same distance on a single charge. As of the present, technology does not provide an economical option to reduce the weight to ICE levels and more battery packs are used. Resulting in heavier vehicles that in turn require stronger bodywork and suspension to account for the additional weight. This is the main reason that generally speaking EV's are 24% or 288,34 kg heavier than ICEV, see the end of appendix B (Liu, et al., 2021). Moreover, it is a known fact that electric vehicles have shorter ranges on a single charge than ICE vehicles on a single tank. Battery technology is improving and, in the future, a larger energy density may be acquired, so that vehicle weight may be reduced.

4.3. Hybrid vehicles (HEV) & Plug-in hybrid vehicles (PHEV)

Hybrid vehicles combine both forms of propulsion. The vehicle is usually primarily powered by the internal combustion engine, during regular operation the battery pack is charged, for example by recovering braking energy. Hybrid vehicles allow for great efficiency on the internal combustion engine. Similarly plug-in hybrids use both forms of propulsion. However the battery capacity of plug-in hybrids is much greater than regular hybrids and they can be charged form the energy grid like full electric vehicles. The plug-in hybrid is basically an electric vehicle that can switch to an ICE engine when the batteries are depleted. This naturally increases costs and increases the probability of a fire since both the ICE engine and the batteries can catch fire. Hybrid vehicles are approximately 24,5% heavier than regular ICEV or 345 kg (Martynyuk, 2022).

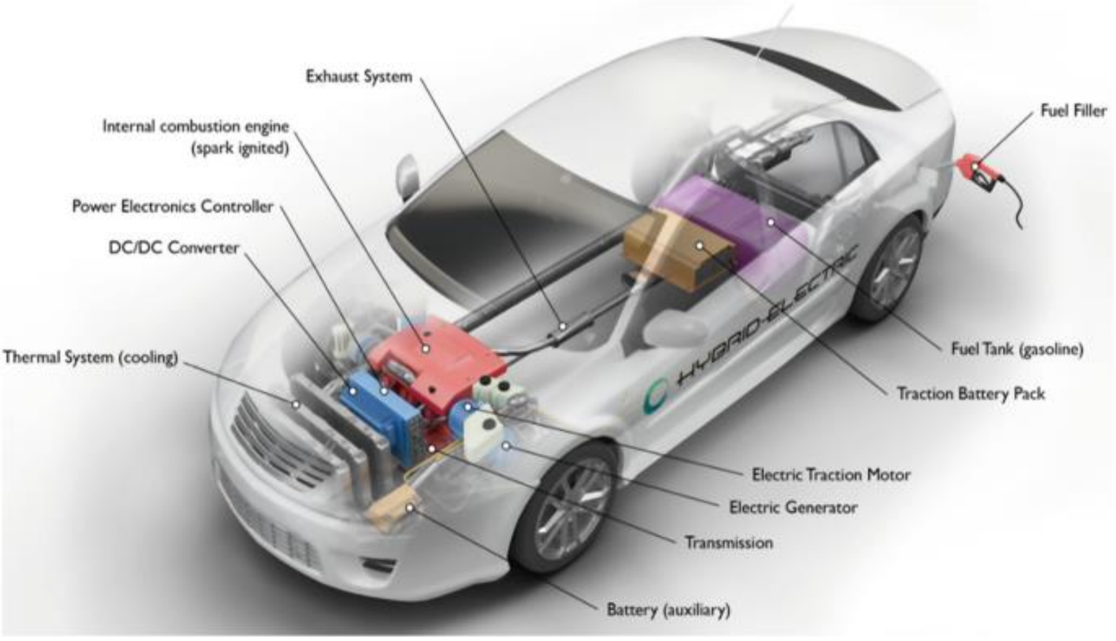

Figure 4 Components in a plug-in hybrid vehicle

4.4. Fuel-cell electric vehicles (FCEV)

Fuel cell electric vehicles are quite similar to full electric vehicles. Both use an electric traction motor that is powered by electricity. The electricity is produced on board. When the fuel cell produces more electricity than required at that moment the battery pack is charged. Whenever extra electricity is needed it is provided by the battery pack in the vehicle. A fuel cell uses hydrogen and oxygen to create water and electricity. Figure 5 shows the components of an FCEV (U.S. Department of Energy's Vehicle Technologies Office, 2022)

As visible in Figure 5 the hydrogen is stored onboard in the fuel tank. This is a pressurised vessel that can be fit for pressures of 350-700 bars. Pressurised fuel tanks contribute to all kinds of safety hazards. Including boiling liquid expanding vapor explosion (BLEVE), vapour clouds, jet flames and fireball explosions. A research paper requested by the Swedish Fire Research Board states that pressurised tank fires are of extremely short duration but the fires are much greater in size (Li, 2019). Moreover, hydrogen fuel tanks have a significantly larger fire size than conventional compressed natural gas (CNG) fuel tanks. The fireball length in a tunnel may be much greater than the fireball diameter in the open.

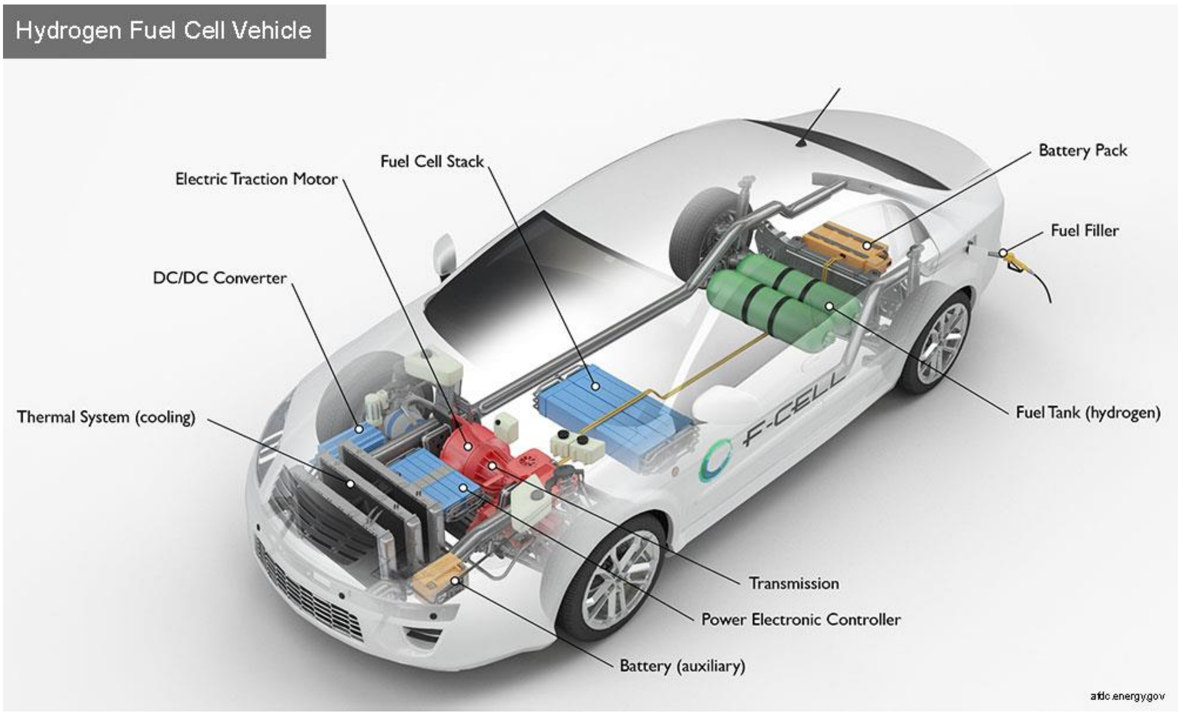

Figure 5 Components in a hydrogen fuel cell vehicle

4.5. Vehicle types and their components

The previous sections have described the primary differences in propulsion between conventional vehicles and EV's. The first step in determining the effects of EV's are on the availability of tunnels is to detect the differences in components, and distinguish possible scenarios that can lead to un-availability. The table with critical components is adapted from the Alternative Fuels Data Center (U.S. Department of Energy's Vehicle Technologies Office, 2022). If any type of vehicle has a certain component it is marked with a "x." Should the Alternative Fuels Data Center indicate that a component is not present but it is likely wrongfully excluded it is marked with an "-."

Component	ICEV	EV	HEV	PHEV	FCEV
Fuel filler	x		x	x	x
Fuel tank (gasoline)	x		x	x	
Fuel tank (hydrogen)					x
Fuel pump	x		-	-	-
Fuel line	x		-	-	-
Fuel injection system	x		-	-	
Internal combustion engine (spark-ignited)	x		x	x	
Electronic control module	x		-	-	
Exhaust system	x		x	x	
Exhaust system (FCEV)					-
Transmission	x	x	x	x	x
Auxiliary Battery	x	x	x	x	x
Traction battery pack		x	x	x	x
Charge port		x		x	
Onboard charger		x		x	
Thermal system (cooling)	-	x	x	x	x
DC/DC converter		x	x	x	x
Power electronics controller		x	x	x	x
Electric traction motor		x	x	x	x
Electric generator					x

Table 1 Vehicle types and their critical components/ systems

5. Unavailability in Dutch tunnel systems

The first step in the analysis is to determine whether (the individual components of) the different vehicle types or their risks influence the availability of a general tunnel system. As described in the scope of this research the reference tunnel is a standard two tunnel tube tunnel with two lanes per tunnel tube. To estimate the effects of the vehicle types on a general tunnel it is necessary to determine what events will result in tunnel or tunnel tube closure. Tunnels are required to close in a couple of instances;

1. The tunnel operator closes the tunnel or tunnel tube due to an incident.
2. The tunnel operator closes the tunnel or tunnel tube because operation is not possible due to technical failure.
3. The tunnel operator closes the tunnel or tunnel tube because safety systems do not function properly or vital installations are damaged.
4. The tunnel or a tunnel tube is closed to allow for maintenance of installations.
5. The tunnel is closed to allow OTO (Opleiden, Trainen en Oefenen) training for emergency personnel.
6. The tunnel is closed due to political decisions or external events.

To be able to systematically check all vehicle types for events that can lead to unavailability each of these closure requirements have been analysed. After analysing the closure requirements, it is possible to cross-reference the events that can cause unavailability with the components and aspects of the different vehicle types to determine risk factors.

The LTS requirement SO#1902 states that once every 4 years each tunnel needs to be closed for training purposes (OTO). The total minimal unavailability due to OTO is 1 night of approximately 8 hours. Since this planned unavailability has its duration documented in the LTS there is no increase or decrease in unavailability expected. It should be noted that different vehicle types will bring different risks that should be trained on to control, however this should be possible in the same time period since different risks will become loss common.

5.1. Tunnel closure due to an incident

Tunnel operators receive a long education to become a tunnel operator. A long part of the training focusses on incident procedure. This section will elaborate on what incidents can cause un-availability of the tunnel system

How to act in the case of an incident is always up to the knowledge and experience of the tunnel operator. The tunnel operator finds guidance in the tunnel specific incident procedure. Each tunnel has its own specific risks and thus own procedure. In appendix C a copy of the general incident procedure of south Netherlands is attached. When an incident occurs in a tunnel the operator choses a measure to take based on the situation. Then the operator follows all steps as described in appendix C. Table 2 shows when an operator closes a tunnel or tunnel tube based on what incidents can occur.

Measure level	Tunnel operator takes the following initial actions	In what situation
Measure I	Take all tunnel tubes out of commission and start emergency and evacuation procedure	1. Fire 2. Hazardous chemicals
Measure II	Take all tunnel tubes out of commission and start emergency procedure	1. Severe collision 2. Multiple vehicle collision 3. Water on the road
Measure III	Take incident tube out of commission	1. Animals on road 2. Terrorism threat
Measure IV	Take incident lane out of commission using MTM, then take incident tube out of commission using automatic barrier gate system	1. Vehicle collision with injury 2. Loss of consciousness 3. Pedestrian or cyclist in tunnel 4. Demonstration or vandalism 5. Ghost rider
Measure V	Take incident lane out of commission using MTM (if unsafe for road users the entire tube has to be taken out of commission)	1. Vehicle collision with damage 2. Vehicle stopped due to internal failure 3. Object within free driving space 4. Truck load fallen 5. Oil spill

Table 2 General incident procedure of South Netherlands

It is interesting to note that measure V only requires the incident lane to be taken out of commission, not a full tunnel tube. However when a situation occurs that is unsafe for any tunnel user, the tunnel operator can take the tunnel tube out of commission for safety concerns. External factors are not relevant for the research. Therefore the primary risks identified are;

1. Fire
2. hazardous chemicals
3. Collisions
4. Water on the road
5. Internal vehicle failure
6. Oil spills

Vehicle type impact analysis

In Table 1 of chapter 4.5 “Vehicle types and their components”, the primary differences between vehicle types that have been analysed are stated. This information has been cross referenced with the events that can cause un-availability in chapter 5.1 and 5.3 to determine whether the individual components have an influence on the availability of a generic Dutch tunnel. Table 1 shows that ICEV and EV’s have many similarities. The most apparent differences are the engines, exhaust systems and fuel transport systems. Whilst a form of transmission is present in all forms of propulsion the system has a distinctive design. The same holds true for the thermal cooling system. In Table 3 events have been listed that can cause unavailability of at least a single tunnel tube based on the components of different types of vehicles. The phenomena that can cause unavailability have been listen next to the components for readability.

Component	Impact on availability of tunnel system
Fuel tank (gasoline) Unavailability phenomena: 1. Fire risk 2. Asphalt damage	Leakage of a single vehicle can lead to tunnel closure. Fistly gasoline and diesel are highly flammable and can quickly result in a fire. An intact fuel tank can explode should the temperature of the fuel reach its ignition temperature of 232 °C. Additionally, Gasoline and diesel are petroleum products that absorbed by the asphalt, permanantly reducing its structural integrity of asphalt when it is not quickly removed. When not cleaned properly, this can result in potholes and long strips of damaged asphalt. Fuel leakage can be spontanous during an incident, or can be the result of a faulty fuel line, fuel tank, ICE engine. Usually faulty seals or hoses are the origin of failure. A partial tunnel closure is required to clean up fuel spills. Sometimes during an incident fuel can leak on both lanes and the entire tunnel will be unavailable during the cleanup. Tunnel closure may be required to repair damaged asphalt, especially if the fuel leak is undetected and a long line af gasoline has contaminated the road. These events can also happen in the following components, these will not be described individually; Fuel pump, Fuel line, Fuel injection system, ICE engine, ECM.
Fuel tank (hydrogen) Unavailability phenomena: 1. BLEVE’s 2. Vapour cloud explosion 3. fireball explosion	Should a fire occur, the tunnel has to be closed in immediately. Hydrogen gas is highly flammable and has a lower ignition energy than both gasoline and LPG. Conversely, the autoignition temperature is greater than that of gasoline at 580 °C. Hydrogen has a higher deflagration index and it requires less ignition energy (Crowl & Jo, 2007). This means that considering purely the chemical properties of the element the probability of ignition is greater than for gasoline and LPG. Crowl and Jo state that he consequence of is relatively similar. As stated in 4.4 pressurised fuel tanks come with all kinds of safety hazards. Fires are expected to be much greater in size and explosions are a plausible risk. Critical failure of a fuel tank will result in a longer MTTR (Mean Time to Recovery) than critical failure in an ICE vehicle fuel tank/ engine. This is mostly due to the lower ignition energy required of hydrogen. Moreover due to pressurised fuel tanks BLEVE’s or other instantaneous release of all pressurised gas can occur with will significantly damage the tunnel system. As of yet no research has been conducted on the effects of pure hydrogen on asphalt. Therefor it is not possible to provide a substantiated estimation of the effects of hydrogen on asphalt. However pure hydrogen leakage is not expected since rupture of the vessel will result in an instantaneous explosion. Under high temperatures the pressure relieve valve may kick in and expel gasses that are compressed in the tank. Due to the high temperatures this

	hydrogen will instantly ignite causing constant fire to be expelled, creating a jet flame. After this a BLEVE may occur.
Exhaust system Unavailability phenomena: 1. Pollution of technical installations	The exhaust system expels combusted gases into the open air. Exhaust fumes of gasoline and diesel vehicles contain pollutants. Many tunnel technical installations require preventive maintenance to remain functional in a heavily polluted environment. Pollution can cause some technical installations like tunnel ventilation to have an increased wear rate and thus a reduced timespan. Should ICEV be less prevalent in the future these preventive maintenance actions may be required less often or not at all.
Exhaust system (FCEV) Unavailability phenomena: 1. Water excretion	No pollutants created during generation of energy, no direct or undirect availability is expected FCEV are known to excrete water as a by-product. It is a little known fact that ICEV also excrete water in addition to carbon dioxide. The Office of Energy Efficiency & Renewable Energy calculated that both types of propulsion excrete approximately the same amount of water per kilometre. This means that no extra capacity is required for pump installations or rainwater drainage (Office of Energy Efficiency & Renewable Energy, 2022).
Transmission Unavailability phenomena: 1. Asphalt damage	ICEV and EV's use distinct types of transmission. Most ICE vehicle use 5 or 6 gear transmissions. Whilst EV's use a single gear transmission that accelerates faster at lower speeds. Vehicles travelling in tunnels travel at a near constant speed. Braking and quick accelerations can only be expected in heavy traffic conditions. In heavy traffic it can be expected that wear of the road surface slightly increases. In other conditions different forms of transmission is unlikely to influence wear of the road surface. Most ICEV gain their momentum by front-wheel drive, whilst EV's are mostly powered by rear-wheel drive. This does not matter for wear of the road surface, only grip and vehicle weight, in other words, friction is expected to make a difference.
Traction battery pack Unavailability phenomena: 1. Fire risk by puncture 2. Thermal runaway 3. Extinguishing difficulties	The traction battery pack is one of the largest differences between EV and ICEV. Battery packs are notorious for their fire hazards. Fires in tunnels are especially dangerous since road users can only flee in certain directions. Fleeing is also hampered by the formation of smoke and dangerous chemicals that can immobilise a person. Once lithium-ion batteries reach an internal temperature of approximately 130 °C thermal runaway will occur. When this happens an exothermic reaction occurs that generates heat this causes other cells of the battery to go into thermal runaway, exponentially increases heat generation. This can result in severe fires and in some cases in an explosion. Thermal runaway of a single cell in the battery

	pack can spread to different cells and can be introduced by external effects, like penetration of the battery pack. This can happen during a car crash. Chapter 6.1 aims to quantify the probability of such an event. Car batteries do not seem subject to degradation patterns that increase the failure rate over time (Wang, et al., 2019). When air or smoke of around 500°C is around the batteries, it will take a few minutes for thermal runaway to actually occur (Gideonse, Noordijk, Boschloo, & Duijvestijn, 2019). Once battery packs undergo thermal runway the fires are extremely difficult to contain and extinguish. Once the fire has been extinguished the battery pack may ignite on its own again due to lingering core temperatures of the battery pack. Literature suggest that this can happen anywhere from 24 hours to weeks after the initial incident (Christensen, et al., 2021)
Onboard charger Unavailability phenomena: 1. Internal fire	Failure can result in overcharging which can result in fire, however charging of EV's can only be done stationary. Therefore the onboard charger is excluded from the research.
Thermal system (cooling) Unavailability phenomena: 1. Internal fire	Failure of the thermal system may increase the chance of fire, however in chapter 6.1 specific fire risk is calculated using failure data of complete vehicles, not failure data of individual components.
Electric traction motor Unavailability phenomena: 1. Wear of asphalt due to acceleration	Electric traction motors have a much wider power band than ICE engines. Only a single gear is required to produce maximum torque at zero RPM. This allows for great acceleration when starting movement from a standstill. The higher torque at low speeds theoretically increases friction on the asphalt. "

Table 3 Events that can lead to un-availability of the tunnel system due to (failure of) specific component(s)

These components do not come into contact with any tunnel installations and cannot cause direct downtime;

- Fuel filler
- Auxiliary battery
- Charge port
- DC/DC converter
- Power electronics controller
- Electric generator

Some electrical components may ignite and cause a starting vehicle fire. However in chapter 8.2 specific fire risk is calculated using failure data of complete vehicles, not failure data of individual components. Estimation of potential increase in probability of internal fire due to faulty electrical components would be pure speculation without failure data form manufacturers.

5.1. Tunnel closure due to no operation

In accordance with the Warvw (Wet aanvullende regels veiligheid wegtunnels), the Tunnelbeheerder (TB) is responsible for the maintenance of a tunnel. This also includes normalizing the tunnel tubes after an incident or other closure. The tunnel operator will often take actual operational actions.

There are several instances when a tunnel operator is not able to perform incident control actions. In this case the tunnel has to be closed. Almost all of these instances can be directly related to components in the tunnel, these are analysed in the chapter 5.2. There is one exception, tunnel closure due to no available operators. This variable is not impacted by the type of vehicle that travels through a tunnel and will therefore not be analysed further in this research paper.

5.2. Tunnel closure due to failure or damage of subsystems

To be able to determine what subsystems can influence the availability of a tunnel the LTS (Landelijke tunnelstandaard) has been consulted (Ministerie van Infrastructuur en Waterstaat, 2021, pp. 628-629). In the LTS a table of subsystem is listed in combination with their failure category, this list is exhaustive for the technical installations (TTI). Failure categories state whether failure of the installation will lead to tunnel or tunnel tube closure. In other words, in what scenario does a tunnel(tube) need to close so that emergency repair can be conducted. Maintenance crews are only allowed to work in tunnels during a tunnel closure due to safety concerns. Civil constructions and asphalt including their respective failure category are added based on expert judgement. This complete list of 52 sub-systems is attached to this document in appendix D.

The failure categories are defined in Table 4 and are used to determine whether or not functional failure of the subsystem can lead to unavailability of the tunnel system. For unplanned maintenance the allowed unavailability is stated in the LTS, this value does **not** take into account unavailability caused by incidents and is therefore not used in the research, however these values are indicative in the relative importance of each failure category in relation to each other.

Failure category	Definition of failure category (unplanned downtime due to technical failure)	Reference allowed technical unavailability, source: LTS (h/year)	Reference allowed failure rate, source: LTS (with MTTR of 3 hour)
A	Unavailability of the entire tunnel.	4	1,14E-04
B	Partial unavailability of the tunnel (tube or lanes), where traffic can still move in both directions.	12	3,43E-04

C	Traffic is delayed due to speed restriction or heavy transport has to divert to a different route.	80	1,15E-03

Table 4 Failure categories

As visible in the table above tunnel or tunnel tube closure can occur for subsystems that have either failure category “a” or “b.” Since single tube failure may lead to unavailability category “b” requirements have been included in the analysis even though the LTS states that traffic can still travel in both directions. All subsystems that can cause unavailability are shown in Table 5.

Location	Sub-system	Category
Traffic tube	Height detector	b
Traffic tube	Tunnel Lighting	b
Traffic tube	Traffic management installation (VRI)	a1
Traffic tube	Automatic barrier gate system (ASB)	a1
Traffic tube	SOS	b
Traffic tube	MTM-Coupling	b
Traffic tube	Air quality installation	b
Traffic tube	Closed Circuit Television (CCTV)	b
Traffic tube	Row of escape doors	b
Traffic tube	Row of latchable escape doors	b
Tunnel	Operation control (besturing & bediening)	a2
Tunnel	Transmission	a
Tunnel	Emergency operation	b
Tunnel	Eventrecorder	b
Tunnel	CADO	b
Tunnel	VEVA	a1
Tunnel	Movable barrier	a1
Tunnel	Pump installation	a
Tunnel	Power supply	a
Tunnel	NoBreak	b
Tunnel	Emergency power supply	b
Safe space (veilige ruimte)	Broadcasting installation	b
Relevant Non-LFV installations	Asphalt	a

Relevant Non-LFV installations	Tunnel walls	a
Relevant Non-LFV installations	Civil tunnel foundation/ substructure	a

Table 5 Tunnel sub-systems that can cause unavailability

**a1 Category a applies for unintentional movement. Category b applies in the case of non-functioning.*
Systems that can cause downtime by functional failure may also cause downtime when preventive maintenance is conducted. Preventive maintenance is planned and can be conducted when little traffic travels through the tunnel during night-time. In most cases, when preventive maintenance is conducted the system is not functional since the sub-system has to be made voltage free to conduct safe maintenance. Preventive maintenance of subsystems with a failure category “a” or “b” will cause downtime in most cases. Additionally, should a tunnel system be located in the tunnel tube, then a tunnel- or tube closure is required to perform heavy maintenance or preventive maintenance. This is true for all subsystems even category “c” and uncategorised systems. The sub-systems shown in Table 6 are located in the tunnel tube and may cause downtime during maintenance activities, complete renovations or replacement activities.

Location	Sub-system	Category
Traffictube	Emergency post	-
Traffictube	Emergency services panel	-
Traffictube	Tunnel ventilation	c
Traffictube	Broadcasting installation	-
Traffictube	High frequency (HF)	-
Traffictube	Emergency phone	-
Traffictube	Escape door indication	-

Table 6 Subsystems located in tunnel tubes

Considering that ICEV and EV’s share many similarities, and travel in a near identical way, it can be expected that not many events will be found that impact unavailability, however these events *may* have significant impact. The relevant subsystems as displayed in Table 5 and Table 6 may influence the downtime of a tunnel.

To establish which relevant subsystems (Table 5 and Table 6) do in fact influence the availability of the total tunnel system a flow schema is used, see Figure 6. In this research qualitative judgment is used to determine whether each relevant subsystem is potentially impacted by the transition from ICEV to EV’s. This approach is similar to the qualitative approach of the industry standard “failure mode effect and criticality analysis” (FMECA) method. All types of vehicles have been compared with ICE as reference point. In the scenario’s, regular movement through the tunnel and Incidents.

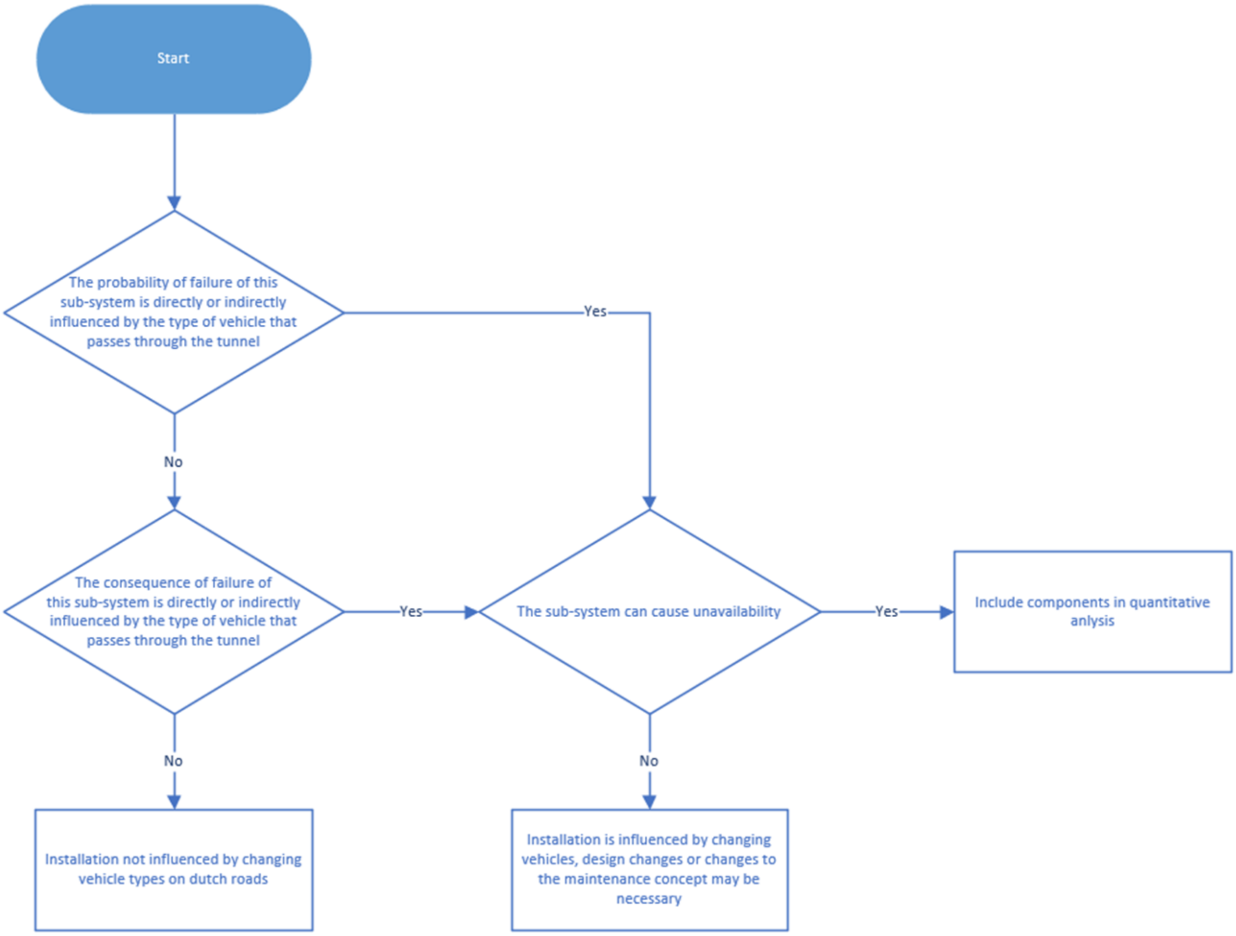

Figure 6 Flow scheme availability impact

The results of this qualitative analysis are quite concise. Of the total 52 subsystems analyses only 8 have been flagged as systems that can contribute to the unavailability **and** are impacted by the changing vehicle types, as visible in Table 7. The resulting risks are similar in all installations, they have been clustered in phenomena. Where possible these systems will be analysed using a quantitative analysis to estimate the total impact of vehicle transition on tunnel availability.

Another 5 can only cause downtime during maintenance since they are located in the tunnel tubes (Table 8). And lastly, 2 subsystems are impacted by the vehicle transition, however these do not contribute directly to un-availability (Table 9). For these sub-systems, a consideration should be made whether the maintenance concept or design change may be wanted based on a change in risk. A lower risk can allow for less maintenance actions that may reduce the Life Cycle Costs (LCC) of installations significantly. A higher risk may warrant more maintenance or a complete change in design to reduce the risk to acceptable levels.

Subsystem	Category	Probability of failure changes	Consequence of failure changes	Cluster phenomenon
Asphalt	a	Yes	No	1. Wear of asphalt due to acceleration 2. Wear on asphalt due to weight
Civil tunnel foundation/ substructure	a	No	Yes	1. Fire (consequence)
Tunnel walls	a	Yes	Yes	1. Pollution of tunnel installations (probability) 2. Fire (consequence)
Automatic barrier gate system (ASB)	a1	Yes	No	Specifically the Inductive Loop Detectors 1. Wear of asphalt due to acceleration 2. Wear on asphalt due to weight
Traffic management installation (VRI)	a1	Yes	No	Specifically the Inductive Loop Detectors 1. Wear of asphalt due to acceleration 2. Wear on asphalt due to weight
Closed Circuit Television (CCTV)	b	Yes	No	1. Pollution of tunnel installations
Row of escape doors	b	No	Yes	1. Fire intensity
Tunnel Lighting	b	Yes	No	1. Pollution of tunnel installations 2. Smoke composition impacts visibility

Table 7 Sub-systems that contribute to un-availability and are impacted by vehicle transition

Subsystem	Category	Consequence of failure changes	Probability of failure changes	Cluster phenomenon
Air quality installation	b	No	Yes	1. Pollution of tunnel installations
Tunnel ventilation	c	Yes	Yes	1. Pollution of tunnel installations 2. Smoke composition may impact life expectancy 3. Fire intensity
Broadcasting installation	-	No	Yes	1. Pollution of tunnel installations

Escape door indication	-	No	Yes	1. Pollution of tunnel installations 2. Smoke composition impacts visibility

Table 8 Sub-systems that contribute to un-availability during preventive maintenance

Subsystem	Category	Consequence of failure changes	Probability of failure changes	Cluster phenomenon
Emergency post	-	Yes	No	1. Type of extinguishing product
Fire retardant plating	-	Yes	No	1. Fire intensity
Fire resistant transits	-	Yes	No	1. Fire intensity

Table 9 Sub-systems that may be impacted in design

Tunnels are expected to be impacted by the vehicle transition in a couple of ways. Based on expected component risk increase and reduction as identified in chapter 5.1 and installation risk increase and reduction as identified chapter 5.3 sub-research question 3 can is answered; What events that contribute to un-availability of Dutch tunnels are impacted by the vehicle transition?

The following list has been created to summarise the expected differences in conventional ICEV and EV regarding availability.

Group	Event	Effect	Expected increase or decrease
Changed risks	Fire probability (vehicle internal)	Probability of tunnel closure	Reduction
Changed risks	Fire probability (incident)	Probability of tunnel closure	Reduction
Changed risks	Fire maximum size (MW)	Duration of tunnel closure	Equal
Changed risks	Fire growth (temperature)	Duration of tunnel closure	Equal
Changed risks	Total extinguishing time	Duration of tunnel closure	Increase
Introduction of new risks	Compressed gasses (BLEVE's, vapour clouds, fireball explosions)	Probability of tunnel closure Duration of tunnel closure	Increase

Maintenance effects	Damage to asphalt due to leakage	Probability of tunnel closure	Reduction
Maintenance effects	Wear of asphalt due to acceleration	Probability of tunnel closure	Increase
Maintenance effects	Wear on asphalt due to weight	Probability of tunnel closure	Increase
Maintenance effects	Pollution of technical installations	Probability of tunnel closure	Reduction
Maintenance effects	Toxins released during extinguishing (extinguishing water)	Duration of tunnel closure	Increase
Design	Toxins released during fire (smoke)	Design	Equal
Design	Extinguishing products in emergency post	Design	Potential change
Design	Visibility during fire	Design	Potential change
Design	Water excretion of vehicles fills pump cellar	Design	Equal

Table 10 Events that contribute to unavailability

6. Probability and mean time to recovery of unavailability phenomena

This section aims to quantify the differences between each vehicle type in relation to probability of occurrence and MTTR. These are the two variables that are required to make a thorough quantitative impact analysis. By finding the probability and MTTR influences two research questions will be answered;

4. What is the difference in mean time to recovery of an incident with carbon neutral vehicles in relation to ICE vehicles?
5. What is the difference between conventional ICE cars and carbon neutral vehicles in relation to wear of tunnel installations in Dutch tunnels?

6.1. Compressed gases

The risks of compressed gasses have been adequately explained in Table 3 under the component “Fuel tank (hydrogen)”. The risk for compressed gasses is only present in vehicles that contain their fuel in pressurised vessels, in this research only FCEV contain this risk. In chapter 7.2 will be concluded that the percentage of FCEV’s on Dutch roads in 2040 will be insignificant. Moreover, the consequence of a crash in a FCEV is unlikely to induce additional hazards compared to ICEV. The probability of no additional hazards is 98,1 - 99,9% according to Ehrhart et al (2019). This figure is specific for a tunnel environment. When additional hazards are present it will most likely (0,03 - 1.8%) be in the form of a jet flame from the pressure relieve valve. Since the increase in total quantity of vehicles, and thus probability of an incident with a FCEV, is inconsequential and the risks increase only marginally no (re)design or maintenance actions are required to make tunnels FCEV proof in the future.

Moreover, tests with new pressurised vessels show that a the BLEVE risk can be fully mitigated using melting coating that turns porous under high temperatures, allowing gradual release of the gas inside (Willstrand, 2021). Fire tests with these tanks show that there are no pressure waves, flames or fireballs are present in the event of failure. For these reasons FCEV’s will be exluded from further quantitative research. Should FCEV or CNG vehicles become more prevalent in the future, it should be considered to change legislation, so that pressurised vessels on the road should be equiped with this method of BLEVE prevention.

6.2. Fire risk

Multiple sources show that a vehicle fire in an ICEV and BEV are quite similar to each other (Gideonse, et al., 2019) (Willstrand, 2021). Appendix E shows 4 destructive tests conducted by the research institute of Sweden, in these tests 2 ICE and 2 EV’s have been ignited to test the thermal effects of vehicle fires (Bisschop, et al. 2019). The most important conclusion of this study is that the total HRR (heat release rate) seems to be marginally higher for ICE vehicle than EV’s. In the study it was noticed that the peak HRR was approximately 10MW higher for EV’s. This means that the battery fire can reach remarkably high temperatures for short durations. Some protective materials like rock wool lose most of the protective function once their maximum temperature is exceeded. This can lead to disintegration of the binding material at 1200°C in the case of rock wool. In tunnel environments calcium silicate plates are mostly used. Special attention is required to test the fire-resistant materials in tunnels with these increased temperatures.

It should be noted that this information is fully dependant on the materials used in batteries. This analysis is based on the currently used li-ion, but new battery innovations should be monitored to analyse new risks. These risks can range from fire intensity, fire probability, chemicals released during fire and ease of extinguishing.

The probability of a vehicle fire in a tunnel is influenced by three factors;

1. Internal vehicle fire
2. Fire by incident
3. Horizontal fire spread (brandoverslag)

For this research, the most important factor is the probability of the vehicle igniting as a result of an incident. To determine whether the fire probability of EV is influenced by an incident research of the NTSB (National Transportation Safety Board) has been consulted. The data of the NTSB is summarised in Table 11. As visible in the data, the sample size for fire rate in BEV's is simply too low to be statistically reliable. To increase reliability of the research fire rates per 100.000 sales have been added (AutoinsuranceEZ, 2022).

Vehicle type	Fatal collisions (NTSB)	Fire rate as a result of collision (NTSB)	Fire rate per 100.000 sales (AutoinsuranceEZ)
ICEV	20,315	3,17%	1,5%
PHEV	543	2,21%	3,4%
BEV	41	2,44%	0,03%

Table 11 Fire rate as a result of an incident

The data remains inconclusive. It seems incorrect that PHEV's which use two forms of propulsion have the lowest rate of fire in a collision. Again this is most likely due to the sample size of BEV's. There can be several explanations to the variance in the data. Firstly, all EV and PHEV designs are relatively new and have comply with higher industry standards then older ICEV. Furthermore, there are many older ICE vehicles on the road. Whereas most EV's are younger than 5 years. Logically an ICE vehicle that is 15 years old has a higher fire rate. Secondly, there are many more ICEV on the road giving a larger sample size which will be more accurate than the small sample size of the EV's and PHEV's.

Pinfa (Phosphorous, Inorganic and Nitrogen Flame Retardants Association) have determined that the probability of a fire is around 34,2 fires per billion kilometres travelled in ICEs compared to 3,1 fires per billion kilometres travelled for EVs (Sun & et al., 2020). The combination of all these sources prove that the probability of a fire in an EV is considerably lower than in an ICEV, however the fire probability should be monitored as the EV's age and enter the second-hand market.

It is known that the fire rate of an collision of a BEV should be lower than that of a PHEV, since the PHEV uses the same components but also has gasoline products and an combustion engine, this has been determined in chapter 5.1. To account for this fault in the inconclusive data, the fire rate as a result of collision of a BEV is adapted to 2% based the data from AutoinsuranceEZ and Pinfa.

The horizontal fire spread is dependent on the HRR. In the first paragraph of this chapter it has been determined that the HRR is virtually equal for all forms of propulsion. Therefore faster fire spread is not expected for EV's.

The LTS states (requirement SO#6320) that all tunnel technical installations should be fire resistant for 2 hours. Only tunnel ventilation is an exception, this installation should be fire resistant for 1 hour. The tunnel ventilation has a robust design to account for fires where smoke is released, so that travellers can bring themselves to safety. In the current fire scenario's, a normative fire of 50 to 200 MW is used in all design calculations. 200 MW is the equivalent of a tanker vehicle on fire. Considering that the expected HRR of a regular passenger vehicle decreases from ICE to EV, it is expected that larger transport vehicles also generate slightly less HRR. The tunnel installations and should not require significant design changes based on fire intensity. However it is advised to use a computational fluid mechanics (CFM) analysis to verify this conclusion.

6.3. Extinguishing fires

An important variable in the quantitative analysis is the MTTR. Taking two isolated tunnel fires, the tunnel that is safely released first has a higher availability. The MTTR is impacted by different vehicle types as determined by the National Fire Protection Association (NFPA) (2016). The MTTR of vehicle fires in tunnels is composed three parts as visible in Table 12. The time that it takes for emergency crews to douse the fire is greatly increased since reignition of the battery pack is common in vehicle fires. This greatly increases the MTTR for PHEV and BEV. Research from KPT shows that when water is able to penetrate into battery pack extinguishing time is reduced and reignition chance is greatly reduced. The probability of a battery reigniting is 10% according to Professor Paul Christensen (2022). It is assumed that the probability of the battery pack reigniting is the largest just after extinguishing. To be conservative it is assumed that 50% of the time this impacts the towing of the vehicle phase. Restarting the extinguishing phase, the extinguishing time is expected to be lower during extinguishing of reignited batteries, since all emergency services are already in the tunnel. For this research 50% of the original extinguishing time is used in quantitative analysis.

Vehicle type	**Time for emergency crews to travel to the vehicle fire**	**Total time to extinguishing**	**Cleaning of tube and Towing of affected vehicles**
ICE	10 min	10 min	10 min
PHEV	10 min	15 – 56 min Avg. 35,5 min	10 min + 5% chance of reignition
BEV	10 min	36 - 60 min Avg. 48 min	10 min + 5% chance of reignition
PHEV (Reignited battery pack)	-	17,75 min	10 min
BEV (Reignited battery pack)	-	24 min	10 min

Table 12 MTTR of vehicle fires

Egelhaaf et al. organised 6 fire tests on li-ion battery packs to determine what extinguishing method is viable in tunnel environments (2013). The batteries were extinguished using several methods, pure water, water with 1.8 % Firesorb® and water with 1 % F-500® in it. The Firesorb required about 3 time less water, and the F-500 used 4.5 less water. Techniques with gases such as aerosols, nitrogen, CO2 and the extinguishing agent Novec are all effective in preventing other cells in the battery pack from igniting (Willstrand, 2021). It is suggested that more tests will be conducted to find the most suitable extinguishing method. Once the best method has been established it is advised to change the extinguishing charge of all hand extinguishers located in the tunnel tube emergency posts. A perfect time to do this would be during the 10 yearly NEN 2559 replacement, when all hand extinguishers (or their payload) have to be replaced.

Water that is used to extinguish battery fires are approximately 70 times more contaminated than the Swiss threshold values for industrial wastewater (Klose, 2020). This water cannot be allowed to enter the general sewer system without proper decontamination. This generates extra workload for maintenance crews. No unavailability is expected when the pump cellars are availability without tunnel closure.

The soot that is left after a larger fire is abundant in heavy metals. Especially cobalt oxide, nickel oxide and manganese oxide (Klose, 2020). Regular maintenance crews cannot clean these chemicals. These chemicals are collected in the pump cellar. The pump cellar is then emptied using a vacuum truck and the contaminated water is transported to a specialistic environment where it is purified. These chemicals are harmful when exposed to unprotective skin. Protective equipment and training should be given to maintenance crews that respond to tunnel fires.

6.1. Smoke composition

Li-ion battery fires contain nickel and other heavy metals. For a long time it has been presumed that Li-ion batteries would expel many more toxic gasses than regular ICE fires. Research shows that the only notable difference in hazardous chemicals expelled are higher emissions of CO, HF and NOx (Gideonse, et al., 2019). These chemicals all stay within the bounds set by the LTS and will not hamper self-rescue of civilians. This is because other parameters like heat radiation are lethal before sufficient levels of these chemicals have been reached. Furthermore, the dangerous chemicals are ventilated before they can build up to dangerous concentrations by the tunnel ventilation.

Egelhaaf et al. (2013) have found that a much larger volume of smoke was released from the battery pack after extinguishing battery fires. It is possible that the volume of smoke increases the likelihood of damage to other subsystems that are located in the tunnel tube. There is a lack in research of the volume of smoke released during battery pack fire. Therefor this parameter will not be included in the quantitative analysis. Since the fire intensity is relatively equal it is not expected that this omission is statistically significant. It is worthwhile to analyse whether emergency and towing crews are hampered by this increased smoke production. This could increase the MTTR in the case of an incident and thus influence availability.

In normal situations when a fire starts in the tunnel, all road users that are located behind the vehicle fire can just drive on and escape. Road users located in front of the vehicle fire will need to flee to safety. Tunnel ventilation will push smoke in the opposite direction of the fleeing road users. It is expected that visibility of critical installations like escape door installations, does not decrease during this (self-saving) phase of a tunnel fire.

6.2. Pollution of technical installations

Functionality of several subsystems is hampered by pollution. For example, a camera needs to have at least 30% visibility of the letter M on a rotakin test target at 100 metres away conform the LTS failure requirements. Should the lenses of the camera's get too polluted and the promised performance cannot be met the contractor will have to clean the lenses immediately, this requires a lane closure. To prevent this from happening the lenses are cleaned periodically, during planned tunnel closures.

The party responsible for the maintenance of tunnels will execute maintenance during planned tunnel closures. These tunnel closures are in the middle of the night so than minimal traffic is hindered. These closures are mostly 4 - 8 hours long when a full tunnel tube needs to be taken out of commission. Availability in these low traffic hours is less important than availability during peak hours since less traffic is affected.

In chapter 5 it has been concluded that during the vehicle transition more vehicles will be on the Dutch road systems that do not expel exhaust fumes since they have no combustion engine. For EV's pollution in Dutch tunnels is mostly caused by particulate matter. Pollution of tunnel installation is not only caused by vehicles. Particular matter can enter the tunnel when vehicles enter or when it is blown in by the wind. Pollution of subsystems can also be caused by insects, fatigue of the concrete and particulate matter originating from the asphalt. Particulate matter is also expelled by the ICE engine, brakes and tires of each vehicle. These factors influence this study.

Interestingly enough based on thorough research conducted by Liu et al., it has been concluded that there is no significant decrease in total particulate matter generated by EV's compared to ICEV (2021). Actual data that support this conclusion is attached in appendix B.

The authors of this paper point out that 90% of total vehicle emissions are the direct result of non-exhaust emission. They explain that particulate matter generated for braking and tyres stress increase dramatically because of the weight of the vehicles. In most cases 100% regenerative braking is required for EV's to be at *equal* pollution levels as ICEV. This analysis includes all particle emissions generated by ICEV's the exhaust fumes, braking, road wear emission and tyre wear. The main reason that EV's are on the same pollution levels is because of the greater vehicle weight, that directly increases emission of tyres and the road surface. Concluding, the type of vehicle has no significant impact on the unavailability of road tunnels. This can be explained by due to cleaning activities since particulate matter also pollutes the tunnel and the reduction, and particulate matter is increased significantly. The chemical composition of the emission type, diesel, gasoline or particulate matter may influence the rate of pollution. Due to time and scope restraints these will not be analysed.

Interesting to this research is that the road wear emissions increase by 11,93% for small EV's when compared to representative ICEV. An increase in 15,1% for medium EV's and 15,24% for large EV's. The increase is slightly lower when diesel vehicles are used for comparison, however Dutch roads are mostly populated by the gasoline vehicles used in the comparison.

6.3. Asphalt replacement

All vehicles in a tunnel drive on the road surface, which is mostly composed of asphalt in the Netherlands. There are many diverse types of road surfaces, each with differing life expectancies. It is common practice to overlayer when the road surface is worn out. Meaning that the old road surface is not removed before the new asphalt layer is placed, this is of course cheaper than replacement with removal of the original road surface. In tunnels this is not possible. This is because there is limited vertical space in a tunnel and escape doors and emergency posts are dimensionally dependent on the height of the road surface. Replacing the road surface in a tunnel can therefore only be conducted once the older layer has been removed. This is one of the most expensive maintenance activities in a road tunnel and causes significant downtime.

Almost all Dutch roads are built using ZOAB (Zeer Open Asfalt Beton), however tunnels have different design parameters. Other forms of asphalt with more closed mixtures like DAB (Dicht Asfalt Beton) can have up to 17 years life expectancy (RWS, 2015). This makes DAB the obvious choice for tunnels, since the life expectancy of this material is longer and replacing the road surface is a costly affair. The wear factor of DAB is 1/17 per year. Wear of asphalt is not linear however for purposes of this study intermediate failures are not relevant, and only end of life is considered. End of life replacement of DAB requires complete tunnel closure. Unless the damage is dangerous, corrective maintenance of road damage is scheduled in a planned tunnel closure. In this case corrective maintenance does not contribute to the unplanned unavailability budget. It also does not contribute to planned unavailability since the downtime is already planned. In exceptional cases the damage is dangerous and will have to be repaired before a planned maintenance slot. It is not possible to determine what percentage of the time road surface damage is so severe that emergency tunnel closure is required. But it is expected that with proper maintenance management this percentage will be low. In later stages of the lifecycle of asphalt more emergency repairs are expected. Then the asset manager can decide to replace the entire road surface to reduce the probability of emergency failure. In principle this process remains the same after the vehicle transition and the same amount of emergency repairs can be expected before the asset manager decides that the road surface needs to be replaced. this is the total reduction of life expectancy.

The time it takes for an entire tunnel that consists of tube of two lanes to be resurfaced is one weekend or 72 hours. This information is based on the weekend closure of the Kiltunnel that took one weekend for 400 meters of tunnel tube to resurface.

The most common failure modes of road surface are ravelling, skid resistance, longitudinal unevenness, rutting and cracking of the asphalt. There is a strong relationship between traffic intensity, traffic load and axial load and the failure modes of road surfaces (van Steeg, 2020). The failure mechanism at work is general wear. To determine whether wear of the road surface is impacted by the transition for ICEV to alternative energy carriers further research on traffic intensity, traffic load and axial load has been conducted.

EV's accelerate faster and weight more than conventional ICEV. Acceleration, braking, and steering movements cause additional wear to the road surface." Says Sandra Erkens, who hold the Chair of Pavement Engineering Practice at Delft University of Technology (2019). Experts predict that this phenomenon can cause considerable damage to asphalt during a traffic jam with many starts and stops in a short period of time. Erkens also indicates that years of data is required before the effects on the degradation of asphalt can be adequately modelled. No sufficient research has been conducted to make a proper estimation on the effects of EV's on the wear. To be able to continue this research an estimation has been made based on the wear particles generated by the road surface as a result of increased weights of EV's as stated in the previous chapter. The general hypothesis here is; particular matter is expelled at an increased rate therefor failure modes of asphalt should be present in an earlier stadium.

It has been determined that the particulate matter generated by the road surface is in fact impacted by the vehicle transition. Particulate matter generated by driving on road surfaces is increased as shown in Table 13.

Passenger vehicle size	Relative percentage on Dutch roads	Particulate matter increase related to ICEV
Small	40%	11,93%
Medium	50%	15,10%
Large	10%	15,24%
Total	100%	13,85%

Table 13 Wear particles as a result of increased weight

From chapter 4.2 and 4.3 it is known that the total weight increase of EV's and PHEV's is 24% and 24,5% respectively. Since the weight increase is similar it is assumed that the PHEV and EV's have similar effects on the wear of roads.

Axle weight is another important variable that influences wear of asphalt. For passenger vehicles this increase in axle weight does not seem to have an extreme influence on the life expectancy of asphalt. The axle weight of an average passenger vehicle does not exceed 1-2 tonnes. Axle weight under 5 tonnes have almost no impact on life expectancy of roads (Salem, 2007). The axle weight of passenger vehicles easily falls within the tolerances of the asphalt even with an increase of 24% weight. This does not mean that the failure rate of the asphalt does not increase, it increases within the regular bounds, in this case linearly. Most failure modes, like rutting and fatigue, seem to increase exponentially from an axle weight of approximately 15 tonnes.

A DAF truck that has a carrying capacity of 12 tonnes has a gross vehicle weight of 11,6 tonnes. However the DAF LF Electric (BEV) that has a similar carrying capacity has a gross vehicle weight of 19 tonnes. A massive increase of 64%. Appendix F shows these two trucks modelled in truckscience.com to determine the increase in axle weight (2022). The increase is approximately 10%, from 12 tonnes to 13,2 tonnes. Salem determined that an axle weight of 5 tonnes the failure modes fatigue and rutting increase exponentially. Comparing these numbers with the failure models in Salem's research, the decrease in design pavement life is 10% - 20% depending on the elastic modulus of the asphalt, the elastic modulus is in turn dependant on the temperature of the asphalt. The temperature in a tunnel environment is very favourable, in summer it is shaded from the sun and in the winter it is warmer than asphalt out in the open. Taking an elastic modulus of 2760 MPa (Temperate climate), a reduction of 12% is expected following Salem's research. This corresponds to the wear increase estimated by the particulate matter technique. With a similar number of heavy vehicles that pass over the asphalt daily.

By taking the average of the particulate matter and axle load methods, it is suggested that with 100% EV the wear rate of asphalt increases by approximately 12,9%. Taking the life expectancy of ZOAB and DAB. The new life expectancy can be calculated by multiplying the old degeneration by the increased wear rate. This is depicted in Table 14. Since vehicle weight is a leading factor in according to most sources, and PHEV weight is near equal to that of EV's. This increased wear rate can also be used for PHEV's.

Type of asphalt	Life expectancy	Old degeneration model	New degeneration model	New life expectancy
ZOAB	12	1/12 or 0,083% per year	0,094	10,6 years
DAB	17	1/17 or 0,059% per year	0,066	15,0 years

Table 14 New life expectancy of asphalt types

6.4. Findings

Chapter 5 establishes 15 events that are impacted by the vehicle transition. After further research it has been determined that only two events that can cause downtime are significantly impacted by the vehicle transition. The first event is, fire as a result of an incidents, the MTTR increases from 30 minutes for ICEV to 55,5 minutes (185%) for PHEV's and 68 minutes (226%) for EV's. Moreover, during towing of the vehicle the batteries can reignite, in this case extinguishing of the vehicle needs to be restarted. The expected probability of this happening during towing phase is 5%.

It has been determined that the fire rate as a result of a collision is 3,17% for ICEV, 2,21% for PHEV and 2,00% for BEV's. The fire rate for BEV's has been adapted based on other data and expert judgement since the data is not statistically significant. The probability of internal fire is 3,42E-08 per kilometre for ICEV compared to 3,1E-09 per kilometre for EV's. The EV figure includes PHEV's.

The second event that is impacted by the transition is tunnel closure by replacing the asphalt layer in the tunnel. The replacement time will remain equal at 72 hours per 500m. But it is expected that the frequency increases by approximately 12,9% should all vehicle on the road be EV or PHEV. With current road usage the replacement of DAB asphalt interval is once every 17 years. When vehicle type is 100% EV it can be expected that one replacement is necessary every 15 years. Per year this amounts to 4 hours and 14 minutes to 4 hours and 48 minutes respectively, or a yearly increase in planned unavailability of 33,9 minutes. Dividing the unavailability per year by the hours in a year it is possible to determine the fixed unavailability per year. The fixed unavailability 4,83E-04 in the current situation and 5,48E-04 for 100% EV.

7. Quantification of future road intensity

The previous chapter gives clear quantitative evidence to show that tunnel availability is directly influenced by the wear factor of asphalt. Additionally, road closures due to triggered safety functions will also influence the availability of Dutch tunnels. These factors are both heavily dependent on the usage of the road system. There is a direct correlation between quantity of road users and degradation of the asphalt. This section of the research report aims to provide a clear estimate of the number of new energy carriers that will be present on Dutch infrastructure in the future. At the end of this section the predicted absolute number of vehicles and percentage of NEC vehicles in the Netherlands will be presented. Information has been gathered from multiple sources to increase the validity of the research.

This research reports determines the future road intensity in the Netherlands in three steps. Firstly the political factors that influence the road intensity are discussed. Afterwards the absolute number vehicles in the future will be quantified using predictive models by respected institutions.

7.1. Political influences on future road intensity

The importance of policy has already been described in the problem statement of this research report. The governing agreement of 2017 states that from 2030 onwards, only carbon neutral vehicles are allowed to be sold in the Netherlands (Rutte et al., 2017, p. 37). This does not include second-hand vehicles. From 2035 onwards the sale of hybrid vehicles will also be banned. These facts will likely result in an accelerated fadeout of conventional combustion vehicles after 2030. The CPB indicates that fuel prices heavily influence consumers to consider buying EV’s. The war in Ukraine has skyrocketed fuel prices. Should the war and world tension take on a more permanent stage the transition to EV’s will likely accelerate.

During the COVID-19 crisis working from home was the norm in the Netherlands. The Planbureau voor de Leefomgeving (PBL) analysed the long term effects of working from home on the road intensity in the Netherlands ('t Hoen & Nauta, 2020). The effects on commuting are irrefutable, working from home reduces the transport movements form employees to the office. However more recent papers conclude that the effects on the total driven kilometres per capita are uncertain, some papers even expect an increase in the total driven kilometres. Researchers ascribe this to indirect effects, such as more and longer business- and social journeys and more car use by other members of the household, due to the vehicle being more readily available.

The Netherlands and its population rank 5th on the rEV index (Economist Impact, 2021). The rEV index yearly British report on 9 developed nations and their readiness for electric vehicles. This analysis focusses on plugin hybrids and full EV’s. In total 21 factors, combined in 8 score groups, are used to determine each countries readiness for electric vehicles. The data collection was conducted in August 2021. Figure 7 shows the relative score of Netherlands in relation to the other countries. Appendix G shows a more in depth analysis of the rEV index. The data indicates that customer sentiment is relatively high, 56% of consumers would consider buying an EV. Moreover, purchasing incentives and regulations facilitate rapid EV growth in the Netherlands.

Charging of electric vehicles is also heavily facilitated. Only China surpasses the Netherlands in absolute number of public charging stations. As of 2021 it is estimated that one public charging station is available for every two kilometres of road. A significant percentage, over 98% of these charging stations are low voltage and have a slow charging speed. Moreover, the Netherlands scores relatively low on affordability of EV’s. These variables might hamper growth of EV’s relative to total passenger vehicle stock in the future. According to the ANWB there are a total of 83.000 charging stations in the Netherlands, of which only 3000 are fast charging (ANWB, 2022).

Netherlands
Country

Overall, category and sub-category scores
Score 0-100 where 100=highest EV readiness

OVERALL READINESS	**46,3**
1) REV INPUTS	**48,1**
1.1) Affordability	38,4
1.2) Purchase incentives	70,0
1.3) Consumer sentiment	61,3
1.4) Charging infrastructure	27,0
1.5) Energy infrastructure	53,6
1.6) Regulations	75,0
2) REV OUTPUTS	**39,0**
2.1) Uptake	26,8
2.2) Availability	51,3

Population	17.441	Thousands
Land Area	34.065	Square kilometres
Population density	512	People per square kilometre
GDP per capita	52.295	USD
EVs in use	196.649	Number of EVs

Figure 7 rEV index variables

7.2. Quantification of vehicles on Dutch infrastructure in future scenario’s

In 2021 the Planbureau voor de Leefomgeving (PBL) has published a research paper that describes the expected growth of vehicles on Dutch infrastructure (van Meerkerk, et al., 2021). The validity of this research is exceptional since the modelling instruments are created by the Centraal Planbureau (PBL) and RWS and are independently reviewed by the TNO. The research focusses on growth of vehicles in the Netherland and the portion of EV’s in future scenarios (until 2050). Appendix H shows 6 figures that have been used to determine the approximate vehicle park in Netherlands in 2030, 2035 and 2040. The figures that have been used are;

Figure number from PBL	Figure information
Figure 1	Population growth in the Netherlands
Figure 5	Share of Full electric and PHEV new car sales
Figure 6	Proportion of vehicle park
Figure 7	Distribution of total kilometres travelled by fuel type
Figure 9	Share of carbon neutral new vehicle sales for light-medium and heavy commercial vehicles
Figure 10	Proportion of light-medium and heavy commercial vehicles

Table 15 Figures TNO

Current road intensity:
To give a clear indication of the future road intensity an indicative baseline is shown in Table 16. The ACEA shows that a total just over 10 million vehicles are registered in the Netherlands in 2020, of which approximately 90% are passenger vehicles.

Description	Value	Relative to 100%	Year	Source
Total vehicles in use	10,248,388	100%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (Passenger vehicles)	9,049,959	88,31%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (light commercial vehicles)	1,031,010	10,06%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (Medium and heavy commercial vehicles)	157,638	1,54%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)

Table 16 Vehicles in use as of 2020 (ACEA)

Recent motorisation in the Netherlands:
Information from the ACEA also shows that the number of vehicles per 1000 inhabitants of the Netherlands has increased over the last couple of years, this is represented in Table 17. This data shows that trend where, on average, more vehicles are owned by the same number of inhabitants.

Year	Passenger cars per 1000 inhabitants	Change relative to previous year
2016	497	-
2017	503	1,21%
2018	511	1,59%
2019	517	1,17%
2020	520	0,58% (can be explained due to COVID-19)

Table 17 Passenger cars per 1000 inhabitants

Future road intensity

The research paper “Actualisatie invoer WLO autopark mobiliteitsmodellen 2020” gives a substantiated estimation of the volume of vehicles in the future. The starting point of the research is the WLO2015 Thema Mobiliteit (Snellen, Romijn, & Hilbers, 2015), this document describes the population growth in the Netherlands based on two reference scenarios. The scenarios are; high growth, which assumes a high economic growth of 2 percent per year and a relatively strong population growth. Resulting in a population of approximately 20 inhabitants in 2040. The low scenario takes moderate economic growth of 1 percent into account combined with limited demographic development. The PBL states that this scenario is more likely to occur should there be more world tension and conflict, with current developments concerning the Russia-Ukraine war this scenario is more likely to occur than before. This scenario estimates approximately 18 million inhabitants in the Netherlands in 2040.

Description	2022	2030	2035	2040	Source
Volume of passenger vehicles in the Netherlands (Scenario Low)	8.7M	9M	9.1M	9.2M	PBL (van Meerkerk, et al., 2021)
Volume of passenger vehicles in the Netherlands (Scenario High)	8.7M	10M	10.4M	10.9M	PBL (van Meerkerk, et al., 2021)

7.1. Quantification of vehicle kilometres on Dutch infrastructure in future scenario's

To determine the effects of vehicles on wear installations of tunnels it is critical to make an estimation of the total kilometres travelled through the tunnel by each vehicle type.

The CBS has posted actual driven kilometres per vehicle type (CBS, 2022). Over the last 15 years the total KM driven per passenger vehicle has been on a slight decline. From 13,7 thousand in 2003 to 12,9 thousand in 2019. During this time, the decline has been constant. In 2020, during the corona pandemic the average kilometres driven per vehicle was 10.5 thousand. This variable is an inconsistent outlier and will be excluded.

EV's and diesel vehicles make many more kilometres per year according to the CBS. This can be explained by two reasons. The amount of ICE vehicles in the Netherlands is approximately 50 times greater than the amount of EV's, so the kilometres driven by ICE vehicles is realistically near the actual average. The number of kilometres driven by EV's is artificially increased since most of these vehicles are leased by the employers, this means these vehicles are almost exclusively for people that work and travel for their work. The CBS also states that more KM per vehicle can be expected for business kilometres.

This paper assumes that when EV's are rolled reach the general public the passenger KM will not differ for ICEV and EV's. For any calculation purposes the average of 12,9 thousand km per vehicle will be used.

7.2. Distribution of vehicles per fuel type on Dutch infrastructure in future scenario's

To determine the distribution of vehicles per fuel type 2 approaches have been considered. Firstly in figure 7 of the PBL paper an estimation of the total percentage of travelled kilometres per fuel type is given. This would have been valuable information however the difference between the high and low scenarios are too far apart to provide insights in the future situation. Moreover, the accelerated transition due to legislation has not been taken into account.

Therefore, a calculation has been used to determine the distribution of the vehicles per fuel type in the future. All data that has been used is collected and displayed in Appendix I. A run on conventional ICEV just before the legislation period has also not been taken into account. The calculation consists of the following steps, which are repeated for the low and high scenario's;

1. The absolute number of passenger cars has been determined 2022, 2025, 2035 and 2040 based on PBL data. Growth in between these years is modelled linearly.
2. The relative sales of BEV's and PHEV's to total sales has been determined, from 2020 until 2040. The following sales information has been adapted from the to account for ban on ICE sales by 2030 and ban on PHEV by 2035. In current projections the total percentage of FCEV on Dutch roads in 2040 will account to <1%, even in the high scenario of the PBL. Therefor FCEV's have been excluded in further FTA calculations since the effects will be insignificant.
3. The phase-out rate of vehicles has been determined (what percentage of the total vehicle stock is being replaced each year). According to the European Automobile Manufacturers' Association the average passenger car is 11.2 years old as of 2020. Only 47% of the passenger vehicles that are registered in the Netherlands by the European Automobile Manufacturers' Association (ECEA) are older than 10 years (ACEA, 2022). This means that 53% of the vehicles are younger than 10 years, this indicates that approximately 5,3 percent of the vehicles are being replaced each year.
4. Vehicle sales for each year are determined by taking the difference in absolute passenger cars from one year to the next and adding the absolute number of vehicles that are phased out in that year. (The calculated sales numbers have been compared with actual sales numbers in 2018-2022 and seems highly accurate.)
5. For each year, the vehicle sales are multiplied by the relative sales of BEV's and PHEV's to determine the total vehicle park.

The results of the calculation for scenario low growth are shown on the next page in Table 18 & Figure 8. The volume of passenger cars and projected total numbers are in million vehicles. The results of the calculation for the high scenario are depicted in Table 19 & Figure 9. The results show that in both scenarios PHEV's are unlikely to become dominant on Dutch roads, never reaching more than 12% of the total vehicle park. There is a large variance in projected vehicles between the low scenario and the high scenario. For example, the relative amount of BEV's is 62,5% in the low scenario and 82,4% in the high scenario. Moreover, the total amount of vehicles in the Netherlands will only slightly increase in 20 years in the low scenario whilst it increases by 2,2 million vehicles in the high scenario.

Scenario Low	2022	2025	2030	2035	2040
Volume of passenger vehicles in the Netherlands	8,7	8,8	9,0	9,1	9,2
Projected BEV's total	0,3	0,6	1,3	3,2	5,7
Projected BEV's relative to total vehicle park	3,9%	6,7%	14,3%	35,5%	62,5%
Projected PHEV total	0,2	0,2	0,6	1,1	1,1
Projected PHEV relative to total vehicle park	1,8%	2,6%	6,2%	12,0%	11,9%
Projected ICEV total	8,2	8,0	7,2	4,8	2,4
Projected ICEV relative to total vehicle park	94,4%	90,7%	79,5%	52,4%	25,6%

Table 18 Calculated absolute and relative vehicles on Dutch infrastructure 2022-2040 (Scenario Low)

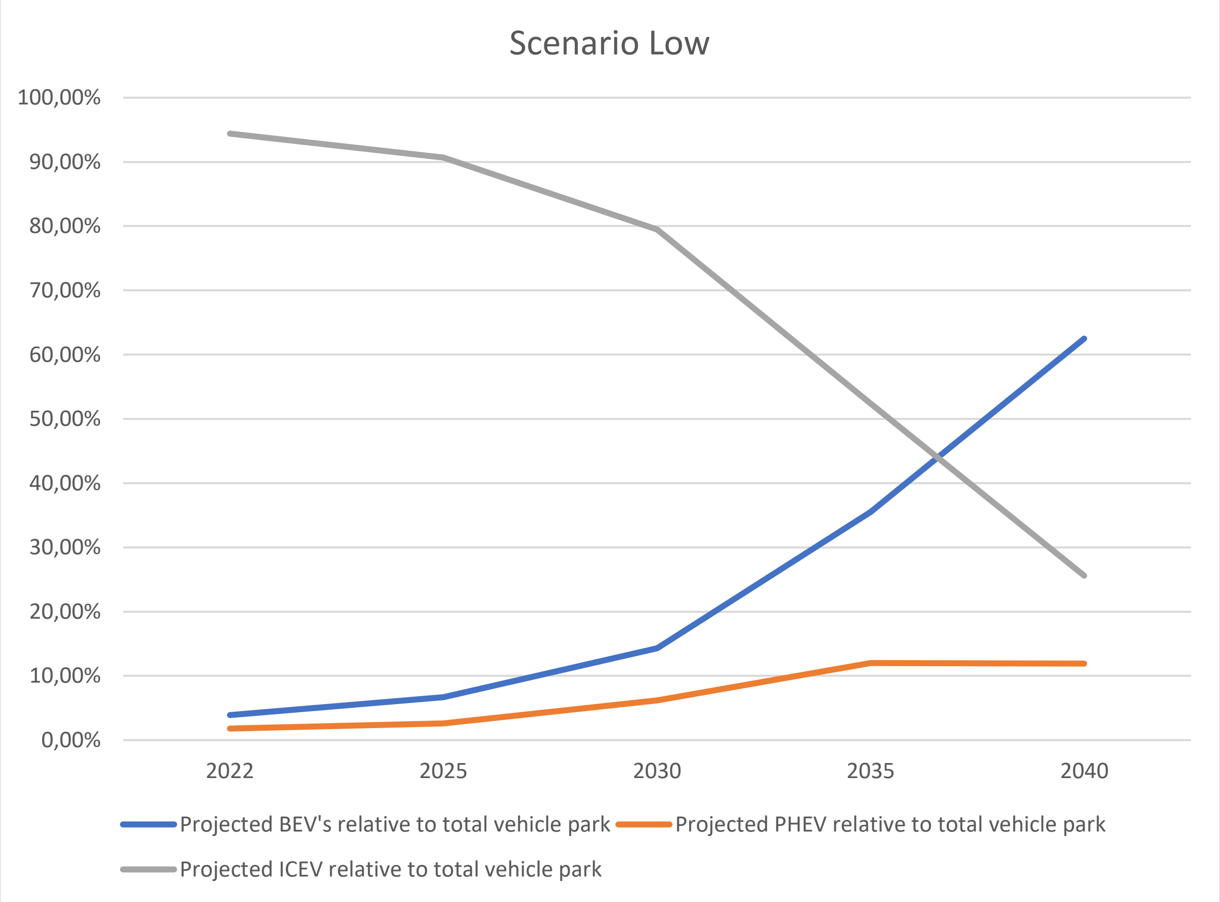

Figure 8 Calculated relative vehicles on Dutch infrastructure 2022-2040 (Scenario Low)

Scenario High	2022	2025	2030	2035	2040
Volume of passenger vehicles in the Netherlands	8,7	9,2	10,0	10,4	10,9
Projected BEV's total	0,4	1,0	2,6	5,7	9,0
Projected BEV's relative to total vehicle park	4,2%	10,4%	26,1%	54,4%	82,4%
Projected PHEV total	0,2	0,2	0,3	0,4	0,4
Projected PHEV relative to total vehicle park	1,8%	2,2%	3,2%	3,7%	3,5%
Projected ICEV total	8,2	8,0	7,1	4,4	1,5
Projected ICEV relative to total vehicle park	94,1%	87,4%	70,7%	41,9%	14,1%

Table 19 Calculated absolute and relative vehicles on Dutch infrastructure 2022-2040 (Scenario High)

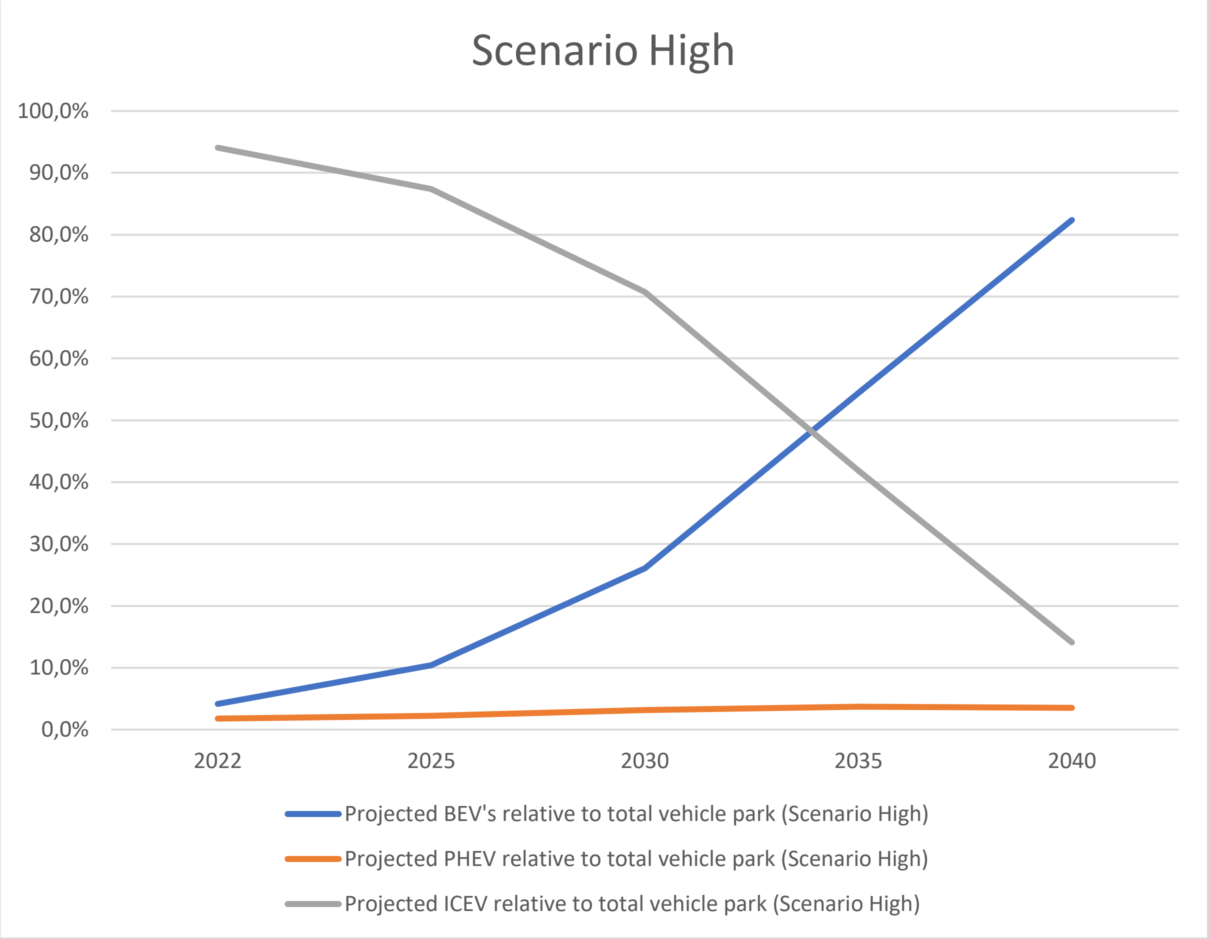

Figure 9 Calculated relative vehicles on Dutch infrastructure 2022-2040 (Scenario High)

8. What is the influence of traffic intensity on the probability of an accident in a tunnel?

Experts claim that an increase in road users is a major factor in determining the probability of an incident (Bergmeister & Francesconi, 2004). Road intensity is a dependent variable of the probability of an incident. As road intensity increases there are more vehicles on the road that each have an independent chance to have a technical failure that results in an incident or fire. Moreover, more vehicle saturation leads to me less space, which will require road users to brake or act within a shorter timespan to prevent an incident.

This section of the research reports will determine the effects of traffic intensity on the probability of a traffic accident. Should the probability of an incident increase or decrease in the future the total downtime of tunnel systems will be influenced. This information will be used in chapter 9 to model the expected availability of tunnel systems in the future.

8.1. Traffic intensity

Tunnels prove to induce dangerous conditions for traffic users. On Italian roadways from 1995-2003 a total of 4,60% of the total number of incidents happened in tunnels. Corresponding with the total distance of highways in Italy only 0,45% of the highway is confined in a tunnel (Bergmeister & Francesconi, 2004). This shows that, in this case, the probability of an accident in a tunnel is approximately tenfold greater than during regular traffic conditions. Moreover the impact of a tunnel incident is likely to be larger since civilians often underestimate the risks and there is a limited fleeing capacity.

A research paper containing statistical analysis of traffic accident in Chinese tunnels gives clear quantitative evidence that increasing traffic volume significantly increases the probability of an accident (Lu, et al., 2013). Lu reasons that during peak hours road users are more likely to adopt high risk driving behavior. Traffic theory and the previous quantitative study shows that the crash frequency will increase with greater traffic. However fewer serious crashes are to be expected once traffic is congested, this is due to the fact that traffic is travelling at lower speeds and less lane transitions are likely to occur (Marchesini & Weijermars, 2010). These being the main factors that influence crash frequency, it is to be expected that crash severity does not increase due during congestion. Nevertheless, at the end of the que serious crashes can be expected due to the difference in speed of the congested traffic and free flowing traffic. The general perception is that crash frequency will increase in the coming years and that crash severity will stay relatively equal considering solely the increase of traffic volume.

Crash frequency has been modeled in 2022 using machine learning to determine the factors that induce the highest risk to crash frequency (Wen, et al., 2022). The relative results are shown in Table 20. Factors that cannot be changed and are determined by tunnel design are indicted with “design parameter”. Clearly 3 parameters contribute the most to crash frequency; Segment length, AADT (Annual Average Daily traffic) per lane and the number of lanes. Of these 2 factors are a design parameter, after construction or renovation of a tunnel these factors cannot be changed. AADT is a variable that is fluctuating in time. It is interesting to note that in this study the percentage of trucks has a neglectable impact on crash frequency. Other studies indicate that the percentage of trucks does significantly increase the crash frequency (Lu, et al., 2013).

Caliendo, De Guglielmo & Russo confirm that these variables are statisticallaly significant using a correlated random-parameters approach (2019). They attribute the increase in expected accidents to diminishing driver concentration when the length of a tunnel increased. During regular tunnel operation, the frequency of lane changing and overtaking movements increase when the variables AADT or percentage of trucks increase, this attributes in a higher expected accident rate. Using this approach they state that the following variables are not statistically significant; the presence of sidewalk, the longitudinal slope, and the presence of mechanical ventilation.

Risk factor	Design parameter or changing variable	Relative to other variables
Segment length	Design parameter	0,550
AADT per lane	Variable	0,227
Number of lanes	Design parameter	0,157
Grade percentage	Design parameter	0,014
Curvature degree	Design parameter	0,014
Truck percentage	Variable	0,014
Posted speed limit	Variable	0,010
Lane width	Design parameter	0,010
Left shoulder width	Design parameter	0,003
Right shoulder width	Design parameter	0,001

Table 20 Risk factors that influence crash frequency

It is expected that these variables from Table 20 will influence total unavailability. However only the total AADT will be considered in this research. Adding too many variables will result in unreliability research. It is recommended that the variables truck percentage and posted speed limit will be analysed in further research and cross referenced with the effects of the vehicle transition on the availability of tunnels.

8.2. Influence of traffic intensity on fire risk

Theoretically a fire can result in a significant loss of availability in a tunnel due to the high MTTR. The probability of a large fire (where the ignition source is the vehicle) is influenced by the traffic intensity, probability of an accident and the type of vehicle. The later including the difference in MTTR between ICEV and EV is analysed in chapter 4.

Rijkswaterstaat has developed a method for quantifying the risk of an accident that results in death. The method is named “QRA-tunnels” and is used to determine internal risk in a tunnel in the Netherlands (RWS Steunpunt Tunnelveiligheid, 2012). An important parameter in the QRA tunnels is the probability of a fire in the tunnel. Based on the two large tunnel fires in the Netherlands, the TNO has conducted a Bayesian inference calculation to determine the probability of a fire with an intensity of over 25 MW per vehicle kilometre (Nelisse & Vrouwenvelder, 2016). The research has been conducted by the TNO and is valid since the data is based on actual fires in tunnels in Europe, tracked by RWS and the TNO.

Table 21 shows the probability of a large fire in the Netherlands per vehicle kilometre. A fire is considered large when the heat release rate (HRR) is greater than 25 MW. The research only considers vehicles as primary ignition source. Since this research is conducted in 2016 when only <2% of the vehicles on Dutch roads were EV's the data is mostly based on ICEV.

Fire size (MW)	Interval HRR (MW)	Probability per vehicle km
25	15-35	8,0E-11
50	35-75	7,2E-11
100	75-150	4,4E-11
200	150-300	1,8E-11
Total	-	1,1E-10

Table 21 Probability of a large fire (>25 MW) per vehicle km in Dutch tunnels

8.3. ADAS & ADS

Automobiles are becoming smart integrated systems with more electronical systems. This fact provides both risk and opportunity. To clarify, each electronical system has an independent probability of failure. However due to technological advancements these electronical systems are likely to improve in reliability. Failure of such systems will not lead to functional failure of het vehicle, there is always redundancy in the form of manual control. Moreover, these systems might provide a reduced risk of the automobile being involved in an incident. An example of such a technology is an ADAS (Advanced Driver Assistance System). At the end of the spectrum is ADS (Automated Driving Systems) level 5, which will provide full autonomous driving vehicles, where no human interaction is necessary. These vehicles have overwhelming safety requirements and laws. Because of these reasons they are not likely to be allowed on infrastructure in the near future (Berk, 2019).

Automatic vehicles can theoretically improve total road capacity and reduce the probability of an accident. A shorter headway, removal of human error, and reduced reaction time of autonomous vehicles explains the potential improvements (Caliendo, De Guglielmo, & Russo, 2019). For automated vehicles to have these positive effects a high percentage of all vehicles on the road need to be automated. The benefits will gradually become apparent at first. When around 40% of all vehicles on the Dutch road system are automatic, benefits will start to increase dramatically (Lu, et al, 2019). At 100% autonomous vehicles traffic flow will be improved by approximately 16-23%. This research will not include potential improvements to availability of tunnels due to ADS since the technology is not available yet, and it is likely that it will not be available in the considerable future. Any data on improvements will be pure speculation.

9. Expected unavailability of road tunnels

This chapter will combine all quantitative data that has been gathered during the research to answer sub question 6; What are the most significant quantitative differences between the current situation and the future including CN vehicles?

Firstly a frame of reference will be provided. The system specification of the LTS states that, given the very high availability package (which is mostly used for highway tunnels) a tunnel is expected to be available for 8147 hours per year. Table 22 shows how many hours per year a tunnel is allowed to be unavailable. Any event that closes a full tunnel tube is seen as “No availability of tunnel.”

Availability RWS Tunnel system		Frequency (# per year)	Duration (h)	Hours per year
Tunnel fully available	93%			8147
Tunnel fully available				
Limited availability of tunnel	5%			438
Recovery after incident		62	0,45	28
Unplanned maintenance		10	8	80
Unplanned maintenance		3	6	18
Planned maintenance		52	6	312
No availability of tunnel	2%			175
Incidents or emergencies		30	3	90
Unplanned maintenance		1	6	6
Planned maintenance		13	6	75
OTO		1/5	6	1,2

Table 22 Availability requirements for very high availability

9.1. Unavailability by vehicle fire

To determine the effects of the vehicle transition on the availability of tunnels, first the incident rate has to be determined. By consulting the current traffic accident figures posted by the CBS (2022). Only serious accidents are considered since slight damages will not result in ignition of the vehicle or battery pack. The CBS has determined that the sum of the number of serious road injuries and lethal road accident victims is 21635. From the previous chapter, it is known that the total amount of vehicles is 8,7 million. Moreover, the total km driven per vehicle is 12,9 thousand. The total vehicle kilometres per year is just over 112 billion or 1,1223E+11 km. By dividing the total incidents by the total kilometres it is possible to determine the incident rate per year per kilometre. This is important since the fire rate per incident differs for ICEV, PHEV and BEV. The incident rate per year per vehicle is 1,93E-07.

Bergmeister & Francesconi have determined that an incident is 10 times more likely to occur in a tunnel in Italy (2004). In the Netherlands, an incident is also more likely to occur in a tunnel, however in the Netherlands an incident is only 2 times more likely to occur in a tunnel (SWOV, 2011). To combat this inaccuracy the incident rate will be multiplied by 2. The adapted incident rate per year per kilometre is 3,86E-07.

Now that the incident rate is known, the next step is to determine the Annual Average Daily traffic (AADT) of Dutch tunnels. Several Dutch tunnels and their AADT have been compared and their average is taken. The AADT information has been gathered at wegenwiki.nl since this data is the most accurate and managed by tunnel operators (2022). Only tunnels with 2 tunnel tubes have been selected for the analysis.

Tunnel	Number of lanes	AADT	Length (m)	AADT per kilometre
Botlektunnel	3 lanes	118900	539	64087
Heinenoordtunnel	3 lanes	111000	614	68154
Noordtunnel	3 lanes	109100	540	58914
Zeeburgertunnel	3 lanes	132300	546	72235
Piet Heintunnel	2 lanes	30000	1490	44700
Velsertunnel	2 lanes	68600	768	52684
Vlaketunnel	2 lanes	56300	327	18410
Wijkertunnel	2 lanes	70300	685	48155
Average				53417

Table 23 AADT for Dutch tunnels

It is possible to predict the AADT for BEV, PHEV and ICEV by taking the percentage of projected vehicle per types as determined in chapter 7 and multiplying it with the average AADT per kilometre of tunnel. The AADT increases based on the total amount of vehicles projected in chapter 7. The AADT for each vehicle type has been multiplied by 365 to get the total kilometres per vehicle type, per year. The result for scenario low is shown in Table 24, the results for scenario high are shown in Table 25.

Scenario Low	2022	2025	2030	2035	2040
Adapted AADT per kilometre of tunnel	53.418	53.647	55.260	55.874	56.488
Kilometres ICEV per year (in thousand)	18396	17920	16040	10691	5284
Kilometres BEV per year (in thousand)	760	1320	2879	7250	12881
Kilometres PHEV per year (in thousand)	342	510	1251	2453	2453

Table 24 Kilometres per vehicle type, per year (scenario Low)

Scenario High	2022	2025	2030	2035	2040
Adapted AADT per kilometre of tunnel	53.418	56.411	61.400	63.856	66.926
Kilometres ICEV per year (in thousand)	18340	17992	15850	9760	3443
Kilometres BEV per year (in thousand)	810	2143	5849	12684	20121
Kilometres PHEV per year (in thousand)	348	455	712	864	864

Table 25 Kilometres per vehicle type, per year (scenario high)

The adapted incident rate per year per kilometre is 3,86E-07, by multiplying the incident rate with the kilometres per vehicle type the expected incidents per vehicle type per kilometre of tunnel can be determined. See figures Table 26 and Table 27 for both PBL scenarios.

Scenario Low	2022	2025	2030	2035	2040
Expected incidents ICEV per km of tunnel	7,09	6,91	6,18	4,12	2,04
Expected incidents BEV per km of tunnel	0,29	0,51	1,11	2,80	4,97
Expected incidents PHEV per km of tunnel	0,13	0,20	0,48	0,95	0,95

Table 26 Expected incidents per km per vehicle type (scenario Low)

Scenario High	2022	2025	2030	2035	2040
Expected incidents ICEV per km of tunnel	7,07	6,94	6,11	3,76	1,33
Expected incidents BEV per km of tunnel	0,31	0,83	2,26	4,89	7,76
Expected incidents PHEV per km of tunnel	0,13	0,18	0,27	0,33	0,33

Table 27 Expected incidents per km per vehicle type (scenario High)

In chapter 6.2 it has been determined that the fire rate as a result of a collision is 3,17% for ICEV, 2,21% for PHEV and 2,00% for BEV's. These probabilities have been multiplied with the expected incidents as shown above to determine the probability of fire as a result of an incident per vehicle type, afterwards they have been divided by the hours in a year to create for the failure rate per hour. These probabilities are shown in Table 28 and Table 29. These probabilities will be modelled in the fault tree analysis as separate events with the MTTR's as described in chapter 6.3.

Scenario Low	2022	2025	2030	2035	2040
Probability of fire as a result of incident ICEV	2,6E-05	2,5E-05	2,2E-05	1,5E-05	7,4E-06
Probability of fire as a result of incident BEV	6,7E-07	1,2E-06	2,5E-06	6,4E-06	1,1E-05
Probability of fire as a result of incident PHEV	3,3E-07	5,0E-07	1,2E-06	2,4E-06	2,4E-06

Table 28 Probability of fire due to collision per vehicle type per year (Scenario Low)

Scenario High	2022	2025	2030	2035	2040
Probability of fire as a result of incident ICEV	2,6E-05	2,5E-05	2,2E-05	1,4E-05	4,8E-06
Probability of fire as a result of incident BEV	7,1E-07	1,9E-06	5,1E-06	1,1E-05	1,8E-05
Probability of fire as a result of incident PHEV	3,4E-07	4,4E-07	6,9E-07	8,4E-07	8,4E-07

Table 29 Probability of fire due to collision per vehicle type per year (Scenario High)

The chance of reignition has been set at 5%, since reliability workbench does not allow for if statements (if a fire occurs then there is a 5% chance of reignition) this unavailability has to calculated and added to the MTTR. By taking the average amount of incidents per vehicle per year and multiplying it with the chance of reignition, it is possible to determine the average added MTTR per year. This number is added with the original MTTR of each vehicle type to determine the MTTR that includes the chance of reignition.

Total MTTR	2022	2025	2030	2035	2040
MTTR ICEV	30,0 min	30,0 min	30,0 min	30,0 min	30,0 min
MTTR BEV	68,5 min	69,4 min	71,8 min	76,3 min	81,2 min
MTTR PHEV	56,0 min	56,9 min	59,3 min	63,8 min	68,7 min

Table 30 MTTR per vehicle type per year

9.2. Asphalt replacement unavailability

In chapter 6.3 the wear rate of asphalt has been considered. The fixed unavailability of DAB asphalt with current vehicle distributions is 4,83E-04 in 2020 and 5,48E-04 for 100% EV. Using the predicted vehicle distributions from chapter 7 it is possible to determine the predicted fixed unavailability per year. The fixed unavailability is calculated for each year using the following formula.

$$Repl.\,interval = \left(\frac{4{,}83\mathrm{E}-04}{100}\right) * \mathrm{ICEV\%}) * 100) + \left(\frac{5{,}48\mathrm{E}-04}{100}\right) * (\mathrm{PHEV\%} + \mathrm{BEV\%})) * 100)$$

The resulting fixed unavailability is presented in Table 31 which will be used to model total unavailability in the FTA.

Total unavailability by wear	2022	2025	2030	2035	2040
Wear factor ICE, BEV and PHEV combined (Scenario Low)	4,87E-04	4,89E-04	4,96E-04	5,14E-04	5,31E-04
Wear factor ICE, BEV and PHEV combined (Scenario High)	4,87E-04	4,91E-04	5,02E-04	5,21E-04	5,39E-04

Table 31 Fixed unavailability of DAB asphalt

9.3. Fault tree analysis

To determine the RAMS effects of the vehicle transition a quantitative risk analysis has been conducted. In chapter 6, 7 and 8 all relevant variables have been gathered or estimated to conduct an substantiated fault tree analysis (FTA). The contribution to the total unavailability of a tunnel is calculated for the events, fire as a result of an incidents and replacing the asphalt layer. An FTA has been created for each PBL growth scenario using the same time intervals of 5 years from 2022 to 2040. The obtained unavailability budgets will be compared to the LTS very high availability budgets to determine the significancy of the vehicle transition on tunnel availability. The probability of failure has been calculated using Reliability Workbench version 13.0.2.0.

The undesired top event that is calculated in the FTA is “Tunnel or tunnel tube closed due to events that are impacted by the vehicle transition.” All 10 fault tree analyses are attached to this document in appendix J. Since most calculations have been conducted before input in the FTA, the FTA is relatively simple. An example is shown in Figure 10. Differences in the FTA are in the form of failure rate, MTTR and fixed unavailability in the case of DAB asphalt. The results of all FTA's are displayed in Table 32 and Table 33.

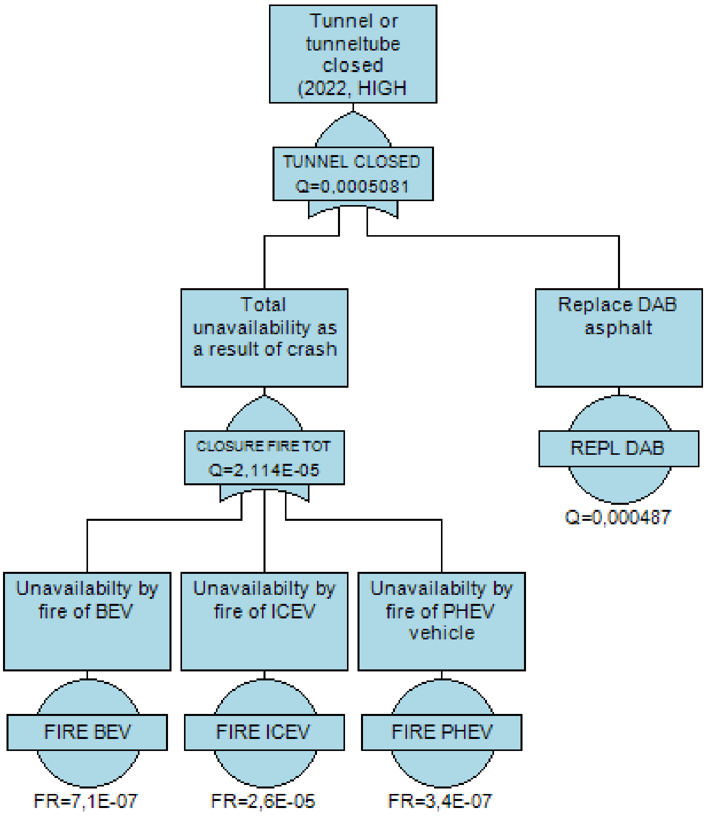

Figure 10 Example FTA 2022 Scenario High

Year	Total unavailability	Predicted total hours unavailable	Hours planned unavailable by asphalt replacement	Hours unplanned unavailable by fire
2022	5,04E-04	4,41	4,266	0,15
2025	5,05E-04	4,43	4,284	0,14
2030	5,12E-04	4,48	4,348	0,13
2035	5,28E-04	4,63	4,502	0,12
2040	5,42E-04	4,75	4,652	0,10

Table 32 Results FTA (Scenario low)

Year	Total unavailability	Predicted total hours unavailable	Hours planned unavailable by asphalt replacement	Hours unplanned unavailable by fire
2022	5,08E-04	4,45	4,266	0,19
2025	5,12E-04	4,49	4,301	0,19
2030	5,23E-04	4,58	4,398	0,19
2035	5,40E-04	4,73	4,564	0,17
2040	5,56E-04	4,87	4,722	0,15

Table 33 Results FTA (Scenario High)

From Table 22 Availability requirements for very high availability” it is known that, on a yearly basis, the unavailability budget is 90 hours for incidents or emergencies and 75 hours are budgeted for planned maintenance.

Based on the results of the fault tree analysis it is clear that the unavailability increases gradually from 2022 to 2040. From 4 hours and 25 minutes (2022 low) to 4 hours and 52 minutes in the worst case (2040 High). This is entirely the result of more *planned replacements* of the DAB asphalt. Taking the budgeted 75 hours of planned maintenance per year, it is clear that an increase of 27 minutes in the worst case is not significant based purely on unavailability. When it comes to unavailability of tunnels, planned unavailability is the more favourable than unplanned unavailability. The tunnel can be closed during a period in a year when there is little traffic, or during night time for shorter tunnel closures. This increase is likely to be important for contractors since replacement of asphalt is one of the costliest maintenance activities. Long term performance contracts (Prestatiecontracten) with contractors may prove to be significantly less profitable for the contractor.

Table 34 shows the calculated replacement interval of the DAB asphalt based on the FTA analysis. It is expected that he replacement interval of DAB asphalt is at least a year shorter by 2035. This is essential information for the maintenance department. Following condition based maintenance, the actual quality of the asphalt should be monitored. Replacement should be planned and the MJOP (Meerjaren Onderhoudsplan) should be altered when real life situations prove that degradation of DAB asphalt accelerates.

It is important to note that increased wear by vehicles quantity has not been taken into consideration since it could not be adequately modelled due to lack of data. It is likely that more vehicles will result in an even shorter life expectancy of the asphalt layer. Moreover, the overall quality of the asphalt will also be lower, this could result in more unplanned maintenance activities if the TB decides to try and prolong the life expectancy of the road surface. This again increases total cost of ownership.

Scenario	Year to replace DAB asphalt				
Scenario Low	16,9	16,8	16,6	16,0	15,5
Scenario High	16,9	16,7	16,4	15,8	15,2

Table 34 Replacement interval of DAB asphalt

The MTTR of extinguishing fire increases from 30 minutes for ICEV to 81 minutes for BEV in the worst case scenario. This increase in MTTR is completely balanced by the reduction in fire rate when an incident occurs. The MTTR is still relatively low together with the low probability of occurrence this event does not contribute significantly to the total unavailability of a tunnel system. In fact, the total unavailability decreases slightly. However this decrease is less than 5 minutes in all FTA calculations and therefore negligible since the total yearly budget is over 90 hours. These differences are the most apparent quantitative differences between the current situation and life during and after the vehicle transition, hereby the last sub question is answered.

10. Conclusions

This research was started to determine the quantitative effects of new energy carriers on the availability of Dutch tunnels. The composition of new energy carriers is relatively similar to conventional ICEV. The most relevant differences are in energy storage, vehicle weight and weight distribution.

FCEV’s impose no serious threat to tunnel availability. Current projections show that in the best case scenario less than 1% of all vehicles on Dutch roads will used this form of propulsion. When compared to ICEV additional hazards are only expected in 0,01 – 1,90% of the incidents. Even if FCEV’s would have a higher share in the total distribution, these incidents would not increase the MTTR substantially. And thus have no reasonable impact on the availability of tunnels. Moreover new fuel tank designs eliminate the risks of BLEVE’s, the only event that would increase MTTR and tunnel safety substantially. Further action is only necessary when political drivers or technological advancements encourage FCEV transport in the future.

After initial research three mayor events had been identified that were expected to influence tunnel availability. These are, planned unavailability by cleaning, unavailability by vehicle fire and planned unavailability by replacement of the asphalt layer.

Unavailability by cleaning

At first it was expected that ICEV and PHEV were significantly more polluting than BEV. Suggesting that BEV would require less maintenance. However after further research it has been concluded that the total emissions of BEV and ICEV are similar. 90% of all vehicle emission is not-exhaust emission, mostly comprised of tyre dust and road surface wear. BEV emit an increased amount of particulate matter when related to ICEV. The total vehicle emissions increase slightly in the future, however very insignificantly. It is expected that the tunnel walls and other technical installations can be cleaned using the same interval as is used currently. This research has not analysed the effects of different pollutants on the degradation pattern, different chemical compositions might increase or decrease clean the maintenance interval. This justifies further research.

Vehicle fire

During a vehicle fire the HRR of ICEV is marginally higher for ICE vehicle than it is for BEV and PHEV. The peak HRR was approximately 10MW higher for EV. This means that the battery fire can reach extremely high temperatures for short durations. In tunnel environments calcium silicate plates are mostly used as fire resistant plating. These should be tested to see if they can withstand this shorter high intensity burning of EV without losing their fire resistance.

Special attention has been given to tunnel ventilation because the system is inherently connected with fires in tunnels. The tunnel installations and should not require significant design changes because EV fires seem to fit in the standard RWS brandcurve (fire curve). However it is advised to use a computational fluid mechanics (CFM) analysis to verify this conclusion.

Fire as a result of an incident does not have significant impact on the total availability of tunnel systems. It has been determined that the probability of ignition as a result of an incident is 3,17% for ICEV, 2,21% for PHEV and 2,00% for BEV’s. MTTR increases from 30 minutes for ICEV to 55,5 minutes for PHEV’s and 68 minutes for EV’s. Moreover, during towing of the vehicle the batteries can reignite, in this case extinguishing of the vehicle needs to be restarted. The expected probability of this happening during towing phase is 5%.

Asphalt degeneration

It has been determined that heavier PHEV and BEV have a negative effect on the life expectancy of asphalt. Precise modelling is difficult because of the many variables involved. However wear particles released by the asphalt layer increase by 13,85% once EV saturation on Dutch roads increase to 100%. A similar conclusion is found when consulting increased wear rates by axle loads. Here an increased wear rate of 12% is expected. An estimation of the increased wear rate once EV saturation reaches 100% is established at 12,9%. To be specific, the life expectancy of ZOAB decreases from 12 years to 10,6 years, and the life expectancy of DAB decreases from 17 to 15 years.

Modelling of failure modes

By modelling the expected vehicle growth and expected vehicle distribution up until 2040 it has been determined that by 2034 – 2037 the share of BEV will exceed the share of ICEV on Dutch roads. This is dependent on the economic growth of the Netherlands in between this period of time. The largest vehicle sets are ICEV and BEV respectively. PHEV does not exceed 12% of the total vehicle park in its most advantageous scenario.

The respective share of all vehicle types has been combined with the probability of unavailability and the MTTR of the events asphalt degeneration and fire as a result of an incident. This unavailability data has been modelled from 2022 up until 2040. The allowed unavailability is 90 hours for incidents or emergencies, the unavailability as a result of this event decreases slightly. However this decrease is less than 5 minutes per year in all FTA calculations and therefore negligible. No further design changes are necessary to control this unavailability event. These conclusions are based on future projections that are limited by current information, for example EV weight may reduce in the future because of battery capacity improvements.

The total planned maintenance budget is 75 hours. The total calculated unavailability increases from 4 hours and 25 minutes in the current situation to 4 hours and 52 minutes in the worst case scenario of 2040. This is an increase of 27 minutes on a yearly basis and does not substantially impact availability of tunnels. This does not mean that this information is not urgent. It is expected that he replacement interval of DAB asphalt is at least a year shorter by 2035. The increased cost can be important for contractors that are bound by a performance contract, since replacement of asphalt is one of the costliest maintenance activities. Moreover, it has been concluded that the expected replacement interval of DAB asphalt is 15,2 – 15,5 years at 2040. Such a dramatic decrease in life expectancy will be extremely costly for contractors that are unprepared. And on a higher level, total maintenance budgets of infrastructure will increase dramatically for RWS and municipalities. It can be expected that ZOAB will be affected by a similar degradation pattern.

Based on this analysis it could be proven that contractors need to be prepared to replace the road surface more often. The maintenance plan should be altered when real life situations prove that degradation of DAB asphalt accelerates. RWS and municipalities may need to rethink accepting tenders of organisations that claim that they can extend the life expectancy of asphalt. However, unavailability is not significantly impacted by the vehicle transition and no design changes, changes to the LTS or changes to national policy *are required* to reduce unavailability to acceptable levels in the future.

11. Recommendations

Based on the conclusions in the previous chapter several design changes and further research is recommended.

Maintenance interval for cleaning of tunnel installations

The total planned unavailability of tunnels is heavily dependent on the times per year that cleaning of technical installations and tunnel walls is necessary. Reducing this interval can be beneficial for the planned unavailability of tunnels and could help offset the increase in planned unavailability that is expected as a result of more wear on the road surface. There has been little to no research on the effects of different pollutants on the cleaning interval. It has been concluded that there is a same level of pollution present in tunnels no matter the type of vehicle distribution. However these vehicles produce different types of chemicals that might impact the cleaning interval in different ways. Researching the “wear” rate of tunnel walls and CCTV specifically for different chemicals may be beneficial to decrease the maintenance interval, or preventing corrective maintenance.

Asphalt degradation models

It is highly recommended that ZOAB and DAB asphalt degradation will be modelled using data gathered from real life testing. These degradation models should be related to existing infrastructure to make an estimation of needed future budgets. Tests should include asphalt that is only used by ICEV and asphalt that is only used by EV and should be repeated for all asphalt types that are relevant in the Netherlands. Weight and axle loads should be carefully monitored.

The expected decrease in life expectancy will be extremely costly for contractors that are unprepared. And on a higher level, total maintenance budgets of infrastructure will increase dramatically for RWS and municipalities. This is especially important since material prices are extremely high in the current market, and contractors are at real risk with their low profit margins.

Legislation for FCEV

Based on current predictions, FCEV are not likely to obtain a large share of total vehicles on Dutch roads in the future. Predictions do not always come to fruition, and it is possible that FCEV play a larger role in the futures society. Therefore it recommended that legislation is changed for FCEV. New designs have shown that it is possible to completely nullify the risk of the feared BLEVE. By making this new fuel tank design mandatory both safety and availability are increased.

Testing of calcium silicate plates

The peak HRR is slightly larger for BEV than it is for ICEV. It is possible that fire resistant materials lose their fire resistant properties when exposed to temperatures outside their tolerances. The calcium silicate plates and fire resistant transits should be tested to verify that they are able to withstand the shorter high intensity burning of BEV without losing their fire resistance.

CFM modelling of tunnel ventilation

It has been concluded that tunnel ventilation will not require any design changes to endure the vehicle transition. This conclusion is based on the fire intensity of vehicle fires. There are other variables that are also involved in vehicle fires, like fire growth which have not been included in this conclusion. It is suggested that an CFM analysis will be conducted to verify that no additional design measures are necessary for tunnel ventilation.

Replacement of extinguishing medium in emergency posts

PHEV and BEV prove difficult to extinguish. Starting fires are the easiest to extinguish and tunnel users should be facilitated. It is advised to determine the best extinguishing medium to extinguish EV fires. Once the best method has been established it is advised to change the extinguishing charge of all hand extinguishers located in the tunnel tube emergency posts. A perfect time to do this would be during the 10 yearly NEN 2559 replacement, when all hand extinguishers (or their payload) have to be replaced. Based on preliminary research it seems that the F-500 has the greatest extinguishing capability. However cost and safety considerations have not yet been taken into account.

12. Report information

12.1. Verification and validation

This thesis is mostly a research report, for this reason verification and validation has played a significant role throughout the project. Several forms of verification and validation have been used.

Following standard research procedures, all forms of qualitative research have been peer reviewed. In the case of the important FMECA like analysis, as conducted in chapter 5, a peer review of 3 respected experts has been conducted. Using careful research techniques, these experts were consulted individually so that their judgement would not be clouded by their peers. To obtain their contact information for verification, feel free to contact the author of this master thesis. All calculations have been reviewed by two reliability engineer experts.

To ensure that the research is valid all data is either based on real life evidence in the form of data collected by renowned organisations. When possible governmental data has been used. All data that has been used is based on strong scientific evidence. All sources used are retraceable, and triangulation was used for important information.

Usually conclusions can be easily verified, theoretical frameworks or building specifications (think about the V-model) can be used to support researcher judgement. In the case of this research this is somewhat more difficult. Since new knowledge has been created where little existed in the past. Full theoretical validation is not possible, it is possible to *use this report* to verify future test results or other research in similar fields.

In certain parts of the research calculations have been verified using data from renowned sources like the CBS or real life data. See the underlying paragraph for a concrete example from chapter 7;

“Vehicle sales for each year are determined by taking the difference in absolute passenger cars from one year to the next and adding the absolute number of vehicles that are phased out in that year. (The calculated sales numbers have been compared with actual sales numbers in 2018-2022 and seems highly accurate.)”

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Appendix A Sub-research questions

Sub-research question 1:	How severe is the increase in carbon neutral vehicles on Dutch road systems?	Ask Yourself
Reason for the question	Both the severity of the increase in CN vehicles and the exposure of these vehicles need to be known to make an estimation of the effects on wear and incidents in Dutch tunnels.	Is the question relevant
Desired answer or outcome	Predicted absolute number of vehicles and percentage of CN vehicles on Dutch infrastructure in 2022 (present), 2030, 2035, 2040.	How precise should the question be answered?
Knowledge domains & Laws and regulation	Course: Research Methods & Techniques Course: Risk Assessment & Safety Course: Principles of Law Amsterdamse tunnelstandaard (ATS), Landelijke Tunnelstandaard (LTS)	In which knowledge domain in the question anchored?
Method or strategy	Literature study, Data analysis	Is my method or strategy functional?

Sub-research question 2:	What is the influence of traffic intensity on the probability of an accident in a tunnel?	Ask Yourself
Reason for the question	Together with the information of sub-question one the probability of an accident can be modelled in time.	Is the question relevant
Desired answer or outcome	Should the probability of an incident increase/ decrease in the future, the total unavailability of the tunnel might be different for ICE and CN vehicles.	How precise should the question be answered?
Knowledge domains & Laws and regulation	Course: Research Methods & Techniques Course: Risk Assessment & Safety Course: Principles of Law	In which knowledge domain in the question anchored?
Method or strategy	Literature study, Data analysis	Is my method or strategy functional?

Sub-research question 3:	What events that contribute to un-availability of Dutch tunnels are impacted by the vehicle transition?	Ask Yourself
Reason for the question	To determine when a tunnel operator must shut down a tunnel due to regulations. This way the differences in potential triggers for the safety functions can be examined and the delta can be used to find differences in availability between ICE and CN cars.	Is the question relevant
Desired answer or outcome	The different triggers for both ICE and CN vehicles to potentially trigger safety functions.	How precise should the question be answered?
Knowledge domains & Laws and regulation	Course: Research Methods & Techniques Course: Risk Assessment & Safety Course: Principles of Law Landelijke Tunnelstandaard (LTS), procedure K, Veiligheidskritische functies (VKF's), Leidraad SE	In which knowledge domain in the question anchored?
Method or strategy	Literature study Analysis of laws and regulations	Is my method or strategy functional?

Sub-research question 4:	What is the difference in mean time to recovery of an incident with carbon neutral vehicles in relation to ICE vehicles?	Ask Yourself
Reason for the question	To determine whether there is a difference in duration of tunnel closures when safety function are triggered by ICE and CN cars.	Is the question relevant
Desired answer or outcome	An indication of the MTTR of failure modes that potentially trigger safety functions in Dutch tunnels. Both ICE and CN vehicles. Additionally, the MTTR of (CN) large transport vehicles is desirable (eg. Trucks).	How precise should the question be answered?
Knowledge domains	Course: Research Methods & Techniques Course: Risk Assessment & Safety Course: Life Cycle Engineering	In which knowledge domain in the question anchored?

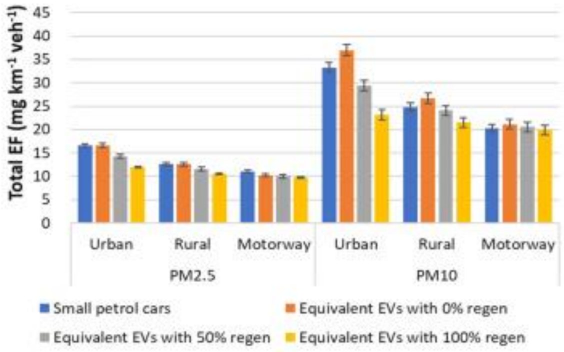
	Calamity procedures of Dutch tunnels	
Method or strategy	Literature study, Data analysis Potential semi-structured interviews with firefighters	Is my method or strategy functional?

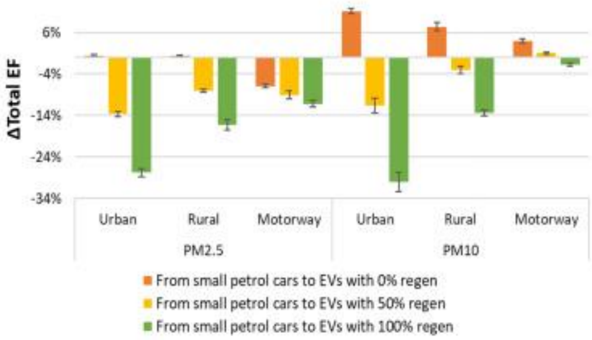
Sub-research question 5:	**What is the difference between conventional ICE cars and carbon neutral vehicles in relation to wear of tunnel installations in Dutch tunnels?**	**Ask Yourself**
Reason for the question	To determine if the interval for planned replacements needs to be decreased for the tunnel to perform at the applicable performance requirements.	Is the question relevant
Desired answer or outcome	For all maintenance activities that require a tunnel(tube) closure; An analysis whether the current interval is sufficient with the increase of different methods of transportation.	How precise should the question be answered?
Knowledge domains	Course: Research Methods & Techniques Course: Risk Assessment & Safety RAMS	In which knowledge domain in the question anchored?
Method or strategy	Literature study, Data analysis Regulatory documentation Potential semi-structured interviews with leading RAMS engineers in infrastructure	Is my method or strategy functional?

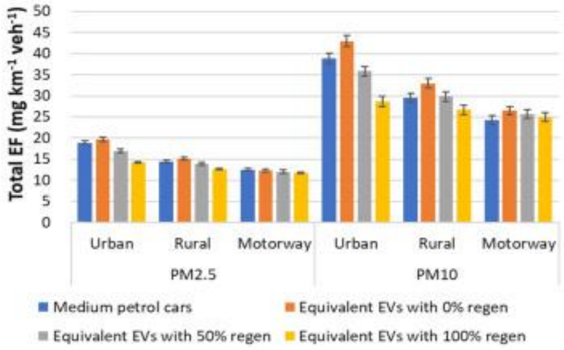
Sub-research question 6:	**What are the most significant quantitative differences between the current situation and the future including CN vehicles?**	**Ask Yourself**
Reason for the question	Partial answer to the main research question. Differences between current and future situation will determine whether action is required in tunnel renovation/ construction projects.	Is the question relevant
Desired answer or outcome	Fault tree analysis for current situation and expected future	How precise should the question be answered?

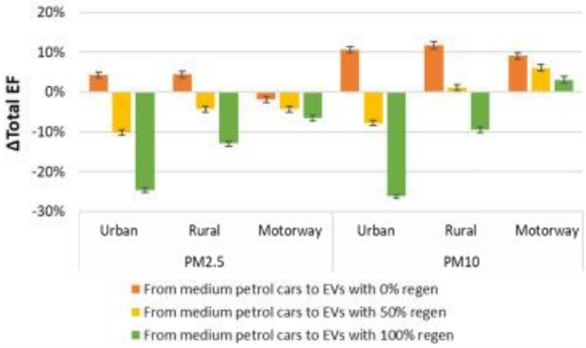
	situation. List with events that have the highest contribution to un-availability	
Knowledge domains	Course: Risk Assessment & Safety RAMS	In which knowledge domain in the question anchored?
Method or strategy	Fault tree analysis or Reliability block diagram Data analysis	Is my method or strategy functional?

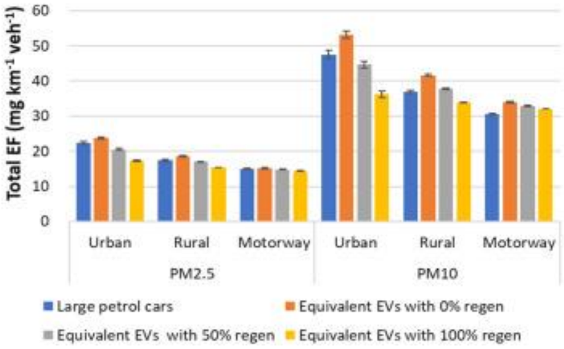
Appendix B rEV Analysis

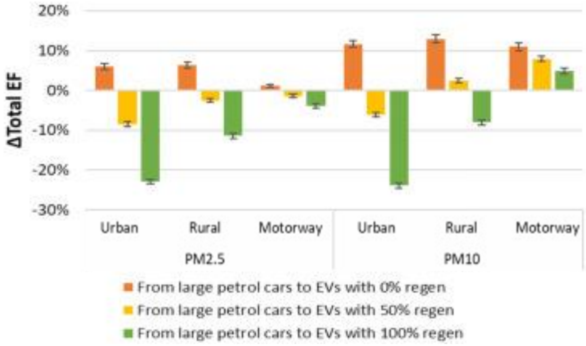


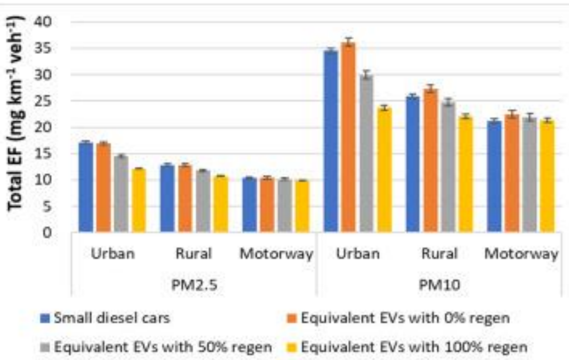


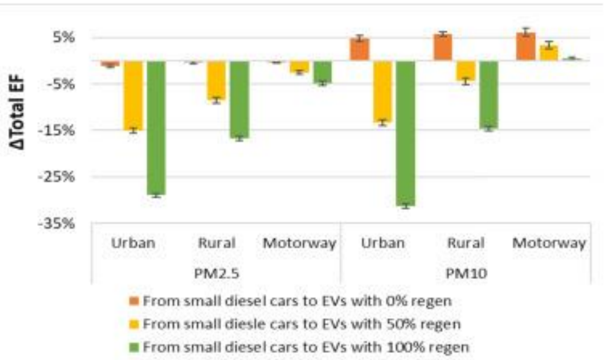


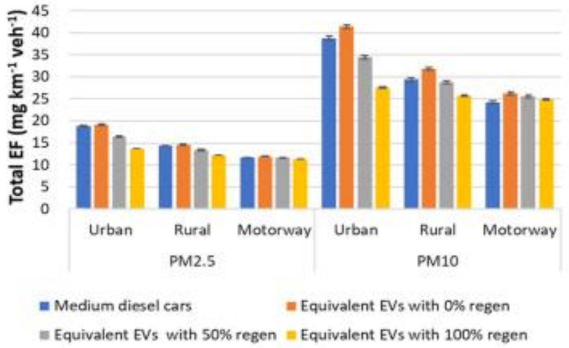


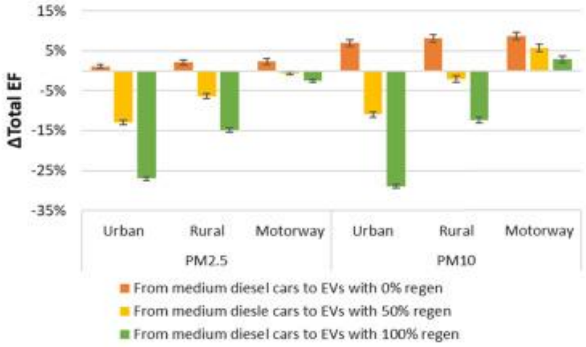


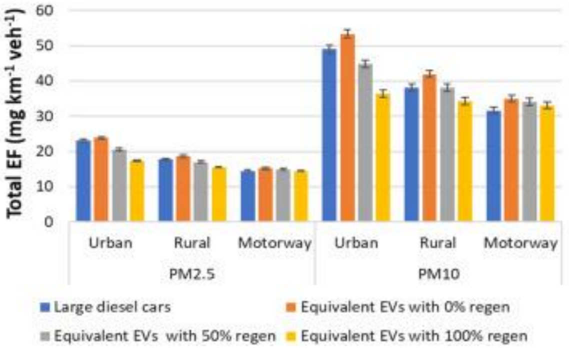


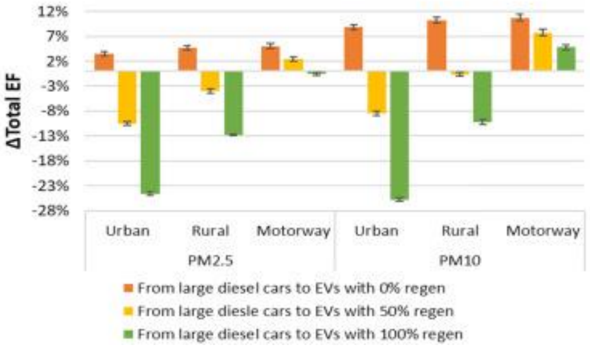

Total EF (mg km⁻¹ veh⁻¹)
40
35
30
25
20
15
10
5
0
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ Small diesel cars
■ Equivalent EVs with 0% regen
■ Equivalent EVs with 50% regen
■ Equivalent EVs with 100% regen

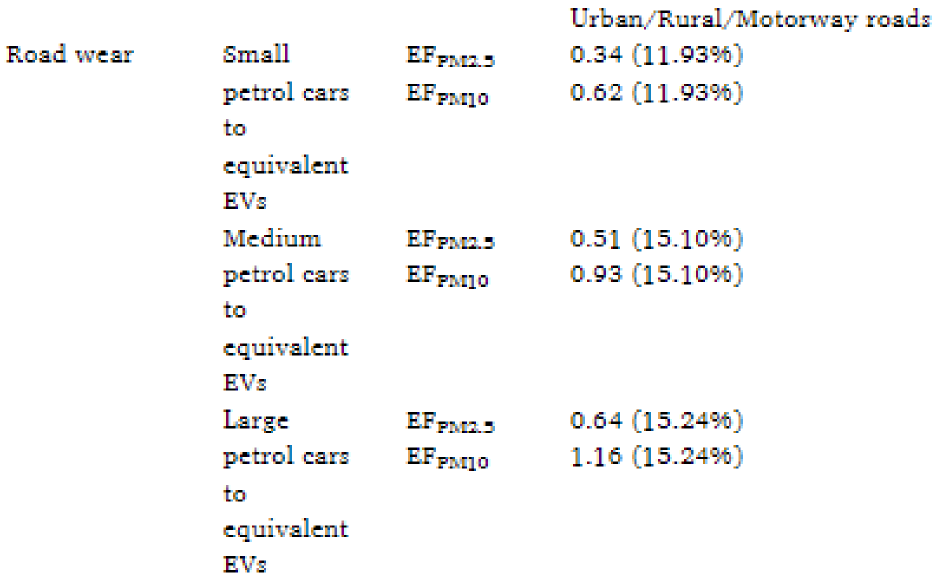

ΔTotal EF
5%
-5%
-15%
-25%
-35%
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ From small diesel cars to EVs with 0% regen
■ From small diesle cars to EVs with 50% regen
■ From small diesel cars to EVs with 100% regen


Total EF (mg km⁻¹ veh⁻¹)
45
40
35
30
25
20
15
10
5
0
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ Medium diesel cars
■ Equivalent EVs with 0% regen
■ Equivalent EVs with 50% regen
■ Equivalent EVs with 100% regen


ΔTotal EF
15%
5%
-5%
-15%
-25%
-35%
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ From medium diesel cars to EVs with 0% regen
■ From medium diesle cars to EVs with 50% regen
■ From medium diesel cars to EVs with 100% regen

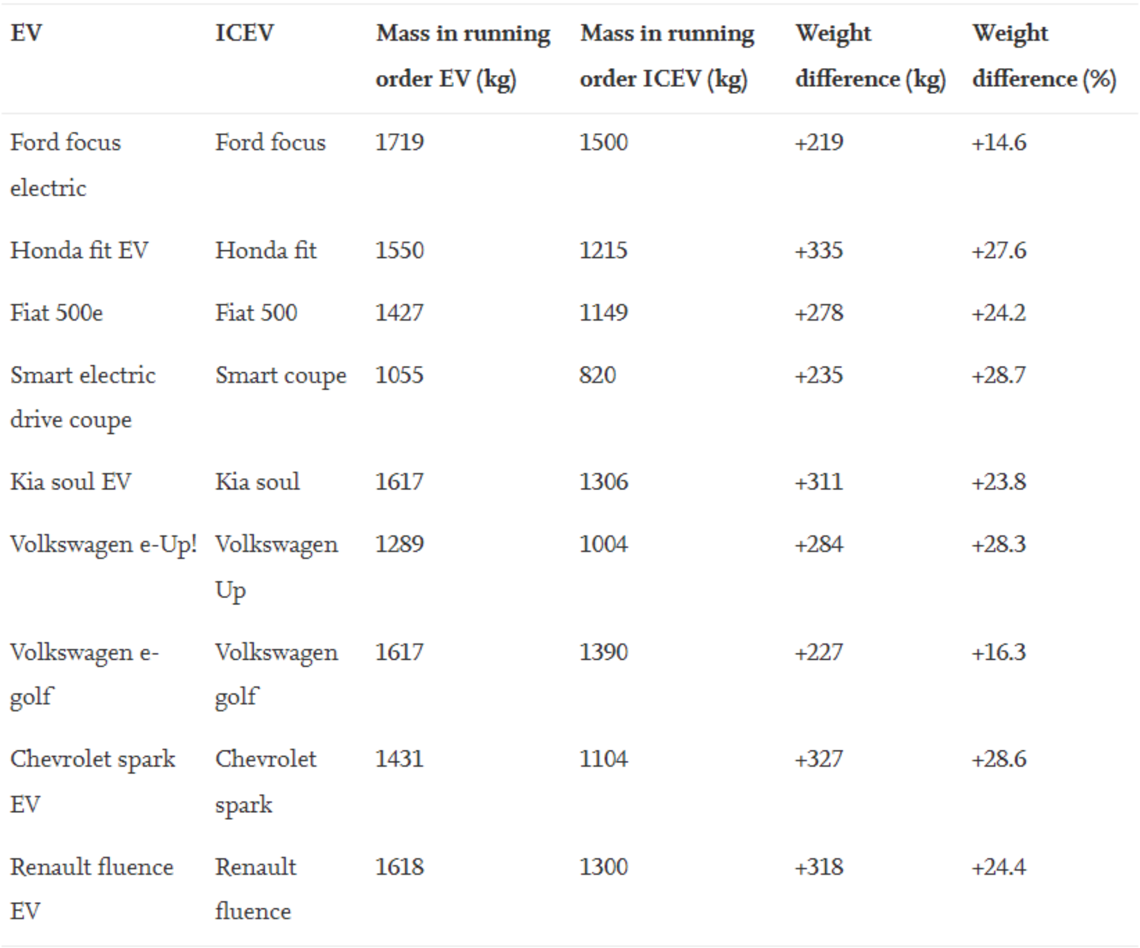

Total EF (mg km⁻¹ veh⁻¹)
60
50
40
30
20
10
0
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ Large diesel cars
■ Equivalent EVs with 0% regen
■ Equivalent EVs with 50% regen
■ Equivalent EVs with 100% regen


ΔTotal EF
12%
7%
2%
-3%
-8%
-13%
-18%
-23%
-28%
Urban
Rural
Motorway
Urban
Rural
Motorway
PM2.5
PM10
■ From large diesel cars to EVs with 0% regen
■ From large diesle cars to EVs with 50% regen
■ From large diesel cars to EVs with 100% regen



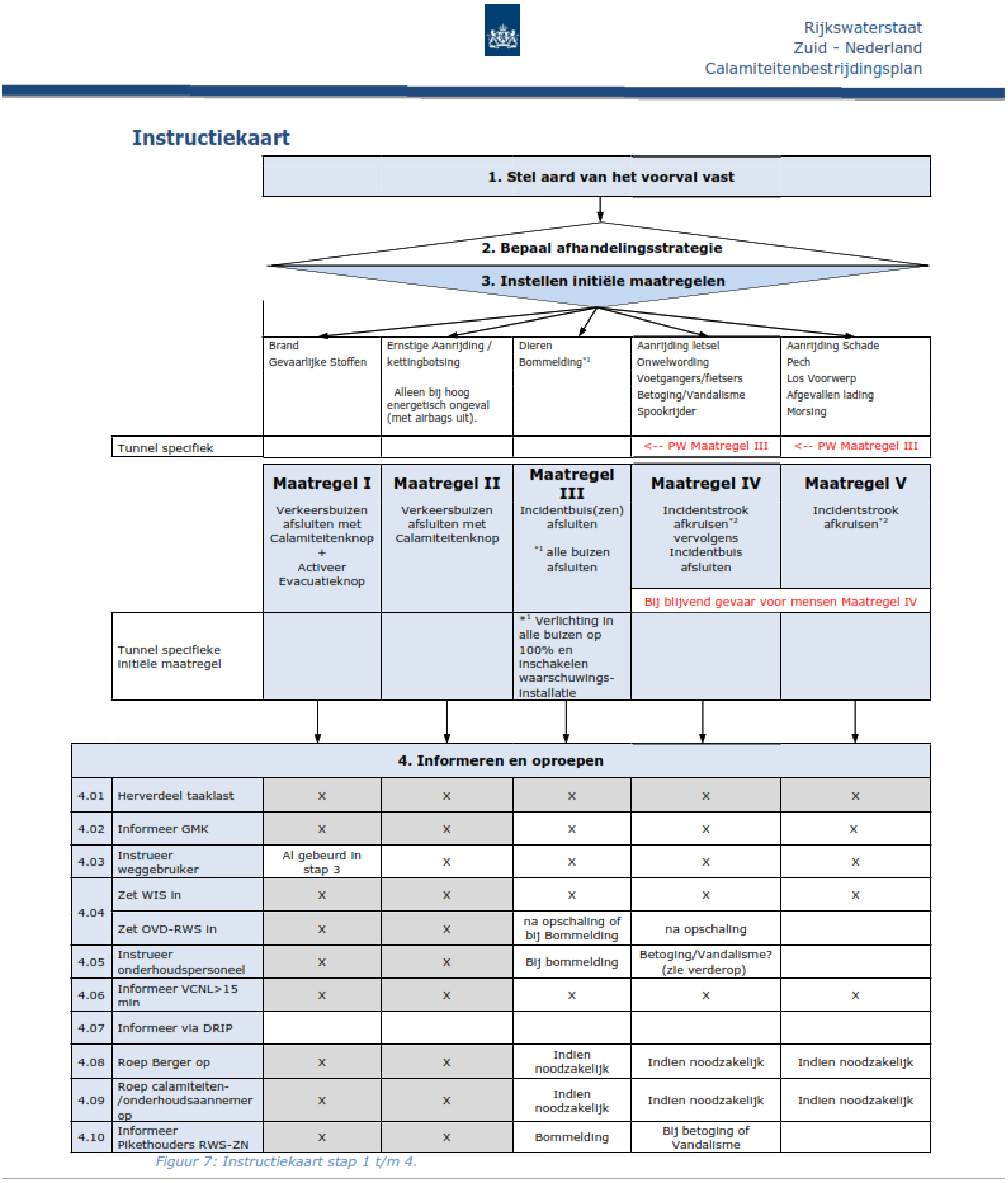
			Urban/Rural/Motorway roads
Road wear	Small petrol cars to equivalent EVs	$EF_{PM2.5}$ EF_{PM10}	0.34 (11.93%) 0.62 (11.93%)
	Medium petrol cars to equivalent EVs	$EF_{PM2.5}$ EF_{PM10}	0.51 (15.10%) 0.93 (15.10%)
	Large petrol cars to equivalent EVs	$EF_{PM2.5}$ EF_{PM10}	0.64 (15.24%) 1.16 (15.24%)

Weight difference



EV	ICEV	Mass in running order EV (kg)	Mass in running order ICEV (kg)	Weight difference (kg)	Weight difference (%)
Ford focus electric	Ford focus	1719	1500	+219	+14.6
Honda fit EV	Honda fit	1550	1215	+335	+27.6
Fiat 500e	Fiat 500	1427	1149	+278	+24.2
Smart electric drive coupe	Smart coupe	1055	820	+235	+28.7
Kia soul EV	Kia soul	1617	1306	+311	+23.8
Volkswagen e-Up!	Volkswagen Up	1289	1004	+284	+28.3
Volkswagen e-golf	Volkswagen golf	1617	1390	+227	+16.3
Chevrolet spark EV	Chevrolet spark	1431	1104	+327	+28.6
Renault fluence EV	Renault fluence	1618	1300	+318	+24.4

Appendix C Incident procedure RWS



Rijkswaterstaat
Zuid - Nederland
Calamiteitenbestrijdingsplan

Instructiekaart

1. Stel aard van het voorval vast

2. Bepaal afhandelingsstrategie

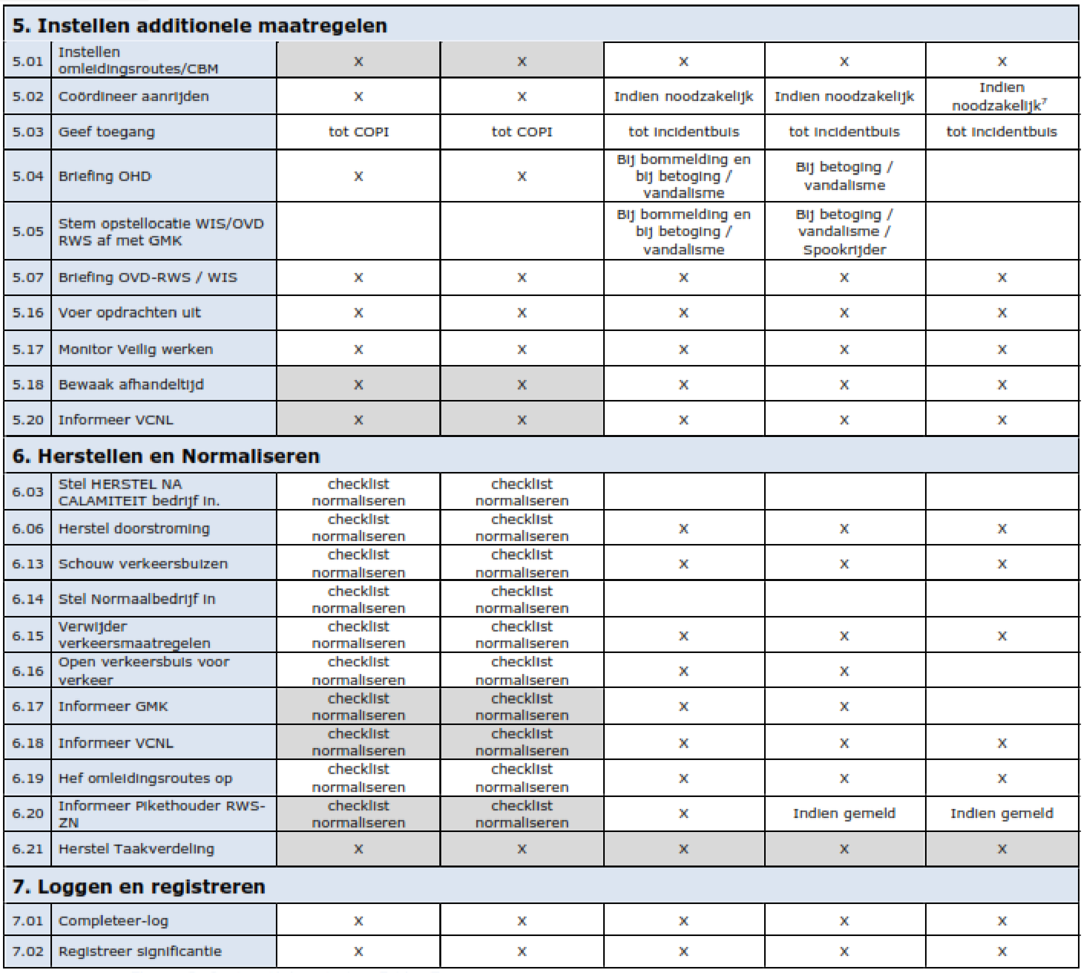
3. Instellen initiële maatregelen

	Brand Gevaarlijke Stoffen	Ernstige Aanrijding / kettingbotsing Alleen bij hoog energetisch ongeval (met airbags uit).	Dieren Bommelding^{*1}	Aanrijding letsel Onwelwording Voetgangers/fietsers Betoging/Vandalisme Spookrijder	Aanrijding Schade Pech Los Voorwerp Afgevallen lading Morsing
Tunnel specifiek				<-- PW Maatregel III	<-- PW Maatregel III
	Maatregel I Verkeersbuizen afsluiten met Calamiteitenknop + Activeer Evacuatieknop	**Maatregel II** Verkeersbuizen afsluiten met Calamiteitenknop	**Maatregel III** Incidentbuis(zen) afsluiten ^{*1} alle buizen afsluiten	**Maatregel IV** Incidentstrook afkruisen^{*2} vervolgens Incidentbuis afsluiten	**Maatregel V** Incidentstrook afkruisen^{*2}
				Bij blijvend gevaar voor mensen Maatregel IV	
Tunnel specifieke initiële maatregel			$*^{1}$ Verlichting in alle buizen op 100% en inschakelen waarschuwings-installatie		

4. Informeren en oproepen

4.01	Herverdeel taaklast	x	x	x	x	x
4.02	Informeer GMK	x	x	x	x	x
4.03	Instrueer weggebruiker	Al gebeurd in stap 3	x	x	x	x
4.04	Zet WIS in	x	x	x	x	x
	Zet OVD-RWS in	x	x	na opschaling of bij Bommelding	na opschaling	
4.05	Instrueer onderhoudspersoneel	x	x	Bij bommelding	Betoging/Vandalisme? (zie verderop)	
4.06	Informeer VCNL>15 min	x	x	x	x	x
4.07	Informeer via DRIP					
4.08	Roep Berger op	x	x	Indien noodzakelijk	Indien noodzakelijk	Indien noodzakelijk
4.09	Roep calamiteiten-/onderhoudsaannemer op	x	x	Indien noodzakelijk	Indien noodzakelijk	Indien noodzakelijk
4.10	Informeer Pikethouders RWS-ZN	x	x	Bommelding	Bij betoging of Vandalisme	

Figuur 7: Instructiekaart stap 1 t/m 4.



5. Instellen additionele maatregelen						
5.01	Instellen omleidingsroutes/CBM	x	x	x	x	x
5.02	Coördineer aanrijden	x	x	Indien noodzakelijk	Indien noodzakelijk	Indien noodzakelijk[7]
5.03	Geef toegang	tot COPI	tot COPI	tot incidentbuis	tot incidentbuis	tot incidentbuis
5.04	Briefing OHD	x	x	Bij bommelding en bij betoging / vandalisme	Bij betoging / vandalisme	
5.05	Stem opstellocatie WIS/OVD RWS af met GMK			Bij bommelding en bij betoging / vandalisme	Bij betoging / vandalisme / Spookrijder	
5.07	Briefing OVD-RWS / WIS	x	x	x	x	x
5.16	Voer opdrachten uit	x	x	x	x	x
5.17	Monitor Veilig werken	x	x	x	x	x
5.18	Bewaak afhandeltijd	x	x	x	x	x
5.20	Informeer VCNL	x	x	x	x	x
6. Herstellen en Normaliseren						
6.03	Stel HERSTEL NA CALAMITEIT bedrijf in.	checklist normaliseren	checklist normaliseren			
6.06	Herstel doorstroming	checklist normaliseren	checklist normaliseren	x	x	x
6.13	Schouw verkeersbuizen	checklist normaliseren	checklist normaliseren	x	x	x
6.14	Stel Normaalbedrijf in	checklist normaliseren	checklist normaliseren			
6.15	Verwijder verkeersmaatregelen	checklist normaliseren	checklist normaliseren	x	x	x
6.16	Open verkeersbuis voor verkeer	checklist normaliseren	checklist normaliseren	x	x	
6.17	Informeer GMK	checklist normaliseren	checklist normaliseren	x	x	
6.18	Informeer VCNL	checklist normaliseren	checklist normaliseren	x	x	x
6.19	Hef omleidingsroutes op	checklist normaliseren	checklist normaliseren	x	x	x
6.20	Informeer Pikethouder RWS-ZN	checklist normaliseren	checklist normaliseren	x	Indien gemeld	Indien gemeld
6.21	Herstel Taakverdeling	x	x	x	x	x
7. Loggen en registreren						
7.01	Completeer-log	x	x	x	x	x
7.02	Registreer significantie	x	x	x	x	x

Figuur 8: Instructiekaart stap 5 t/m 7.

Appendix D Failure effects of tunnel subsystems

The list of subsystem and failure categories is first represented in English, the next page includes the same table in Dutch.

Container	LFV	Category
Traffic tube	Height detector	b
Traffic tube	Emergency post	
Traffic tube	Tunnel Lighting	b
Traffic tube	Traffic management installation (VRI)	a[1]
Traffic tube	Automatic barrier gate system (ASB)	a[1]
Traffic tube	SOS	b
Traffic tube	Emergency services panel	
Traffic tube	MTM-Coupling	b
Traffic tube	Tunnel ventilation	c
Traffic tube	Air quality installation	b
Traffic tube	Closed Circuit Television (CCTV)	b
Traffic tube	Broadcasting installation	
Traffic tube	High frequency (HF)	
Traffic tube	Emergency phone	
Traffic tube	Row of escape doors	b
Traffic tube	Row of latchable escape doors	b
Traffic tube	Escape door indication	
Tunnel	Terrain lighting	
Tunnel	Operation control	a[2]
Tunnel	Emergency operation	b
Tunnel	Eventrecorder	b
Tunnel	Warning system (service room)	
Tunnel	Fire alarm and evacuation system (service room)	
Tunnel	Fire extinguishing installation	c
Tunnel	C2000	
Tunnel	Intercom	
Tunnel	Telephone	
Tunnel	CADO	b
Tunnel	VEVA	a[1]
Tunnel	Movable barrier	a[1]
Tunnel	CCTV emergency dispatch	
Tunnel	Pump installation	a
Tunnel	Overpressure provision of boundary space	c
Tunnel	Power supply	a
Tunnel	NoBreak	b
Tunnel	Emergency power supply	b
Service building	Access installation	
Service building	Extinguishing facility service building	

Service building	Air conditioning installation	
Service building	burglary alarm	
Service building	Lighting	
Safe space (veilige ruimte)	Head door middle tunnel channel	c
Safe space (veilige ruimte)	Dynamic escape route indication	
Safe space (veilige ruimte)	Lighting	
Safe space (veilige ruimte)	Overpressure provision of boundary space	
Safe space (veilige ruimte)	Broadcasting installation	b
Relevant Non-LFV installations[3]	Asphalt	b
Relevant Non-LFV installations[3]	Tunnel walls	a
Relevant Non-LFV installations[3]	Civil tunnel foundation/ substructure	a
Relevant Non-LFV installations[3]	traffic signalling (MTM)	c
Relevant Non-LFV installations[3]	Fire resistant transits	b
Relevant Non-LFV installations[3]	Fire retardant plating	b

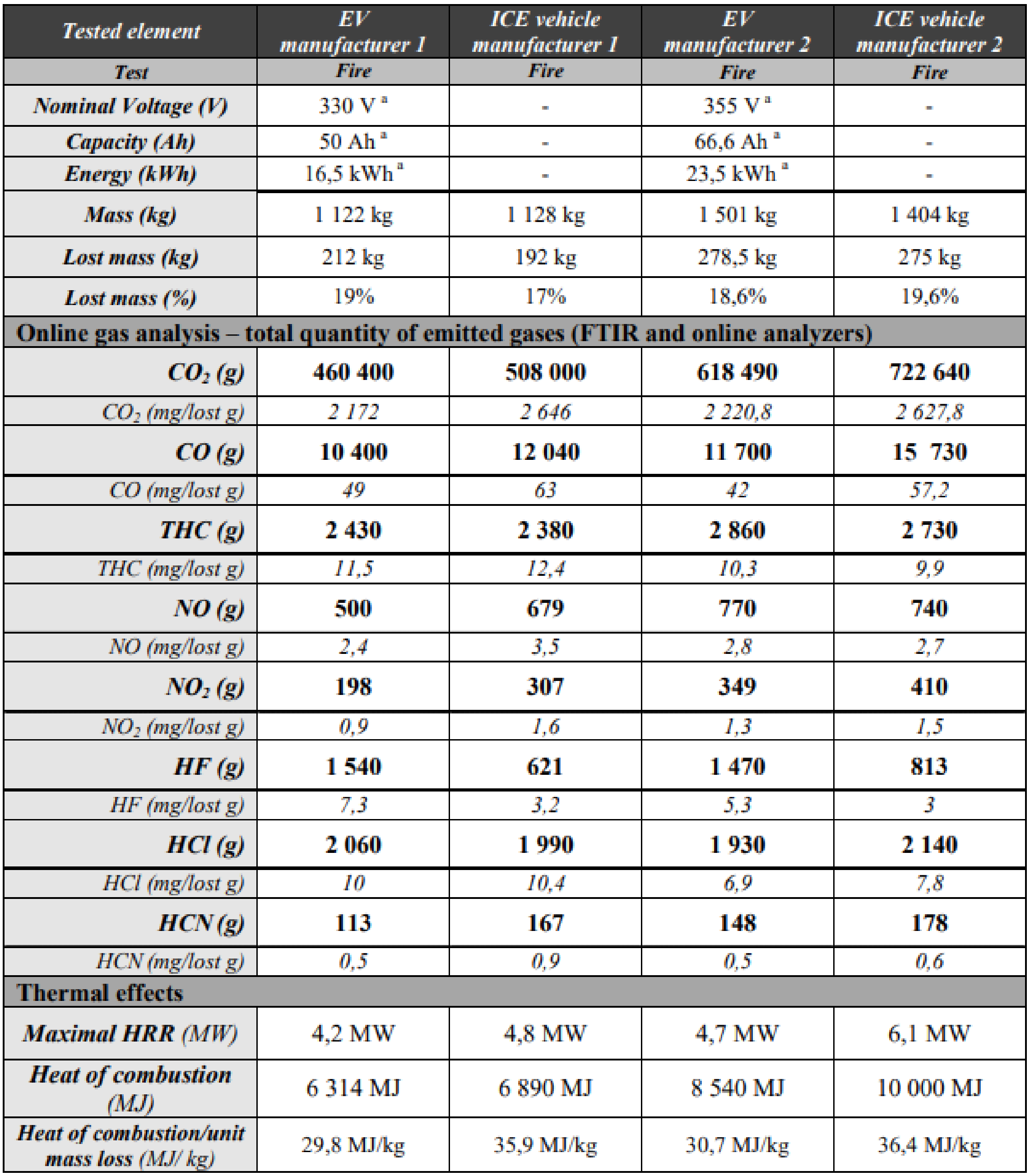
[1] Category a applies for unintentional movement. Category b applies in the case of non-functioning.
[2] Central
[3] Added since these subsystems are relevant to the research

Container	LFV	Categorie
Verkeersbuis	Hoogtedetector	b
Verkeersbuis	Hulppost	-
Verkeersbuis	Verlichting	b
Verkeersbuis	Verkeerslicht	a1
Verkeersbuis	Afsluitboom	a1
Verkeersbuis	SOS	b
Verkeersbuis	Hulpdienstpaneel	-
Verkeersbuis	MTM-Koppeling	b
Verkeersbuis	Ventilatie	c
Verkeersbuis	Luchtkwaliteitsmeter	b
Verkeersbuis	CCTV	b
Verkeersbuis	Omroep	-
Verkeersbuis	HF	-
Verkeersbuis	Noodtelefoon	-
Verkeersbuis	Rij van vluchtdeuren	b
Verkeersbuis	Rij van vergrendelbare vluchtdeuren	b
Verkeersbuis	Vluchtdeurindicatie	-
Tunnel	Terreinverlichting	-
Tunnel	Bediening	a2
Tunnel	Noodbediening	b
Tunnel	Eventrecorder	b
Tunnel	Waarschuwingsinstallatie dienstruimte	-
Tunnel	Brandmeld- en ontruimingsinstallatie dienstruimte	-
Tunnel	Blusvoorziening	c
Tunnel	C2000	-
Tunnel	Intercom	-
Tunnel	Telefoonvoorziening	-
Tunnel	CADO	b
Tunnel	VEVA	a1
Tunnel	Beweegbare barrier	a1
Tunnel	Beeldvoorziening meldkamer	-
Tunnel	Vloeistofpompoinstallatie	a
Tunnel	Overdrukvoorziening grensruimte	c
Tunnel	Energievoorziening	a
Tunnel	NoBreak	b
Tunnel	NSA	b
Dienstgebouw	Toegang	-

Dienstgebouw	Blusvoorziening dienstgebouw	-
Dienstgebouw	Klimaatregeling	-
Dienstgebouw	Inbraakalarm	-
Dienstgebouw	Verlichting	-
Veilige ruimte	Kopdeur middentunnelkanaal	c
Veilige ruimte	Dynamische vluchtroute indicatie	-
Veilige ruimte	Verlichting	-
Veilige ruimte	Overdrukvoorziening grensruimte	-
Veilige ruimte	Omroep	b
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Wegdek	b
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Tunnel wanden	a
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Civiele constructie	a
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Verkeerssignalering (MTM)	c
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Brandwerende doorvoeringen	b
Relevante deelsystemen welke niet vallen onder de noemer TTI[3]	Brandwerende beplating	b

[1] Categorie a geldt hier voor onbedoeld bewegen. Voor niet functioneren geldt categorie b.
[2] Centraal
[3] Deze deelsystemen zijn toegevoegd omdat ze relevant zijn voor het onderzoek

Appendix E Destructive test results

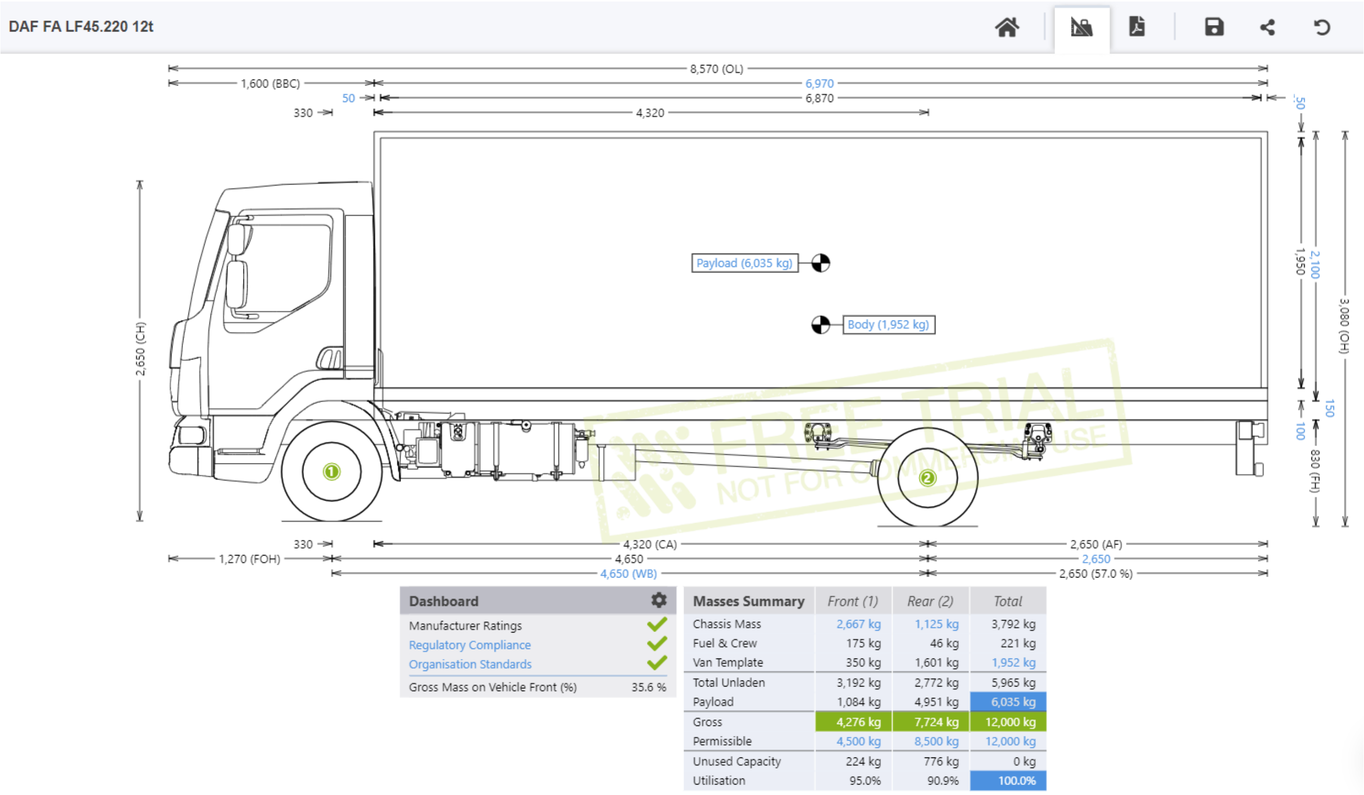


Tested element	EV manufacturer 1	ICE vehicle manufacturer 1	EV manufacturer 2	ICE vehicle manufacturer 2
Test	Fire	Fire	Fire	Fire
Nominal Voltage (V)	330 V [a]	-	355 V [a]	-
Capacity (Ah)	50 Ah [a]	-	66,6 Ah [a]	-
Energy (kWh)	16,5 kWh [a]	-	23,5 kWh [a]	-
Mass (kg)	1 122 kg	1 128 kg	1 501 kg	1 404 kg
Lost mass (kg)	212 kg	192 kg	278,5 kg	275 kg
Lost mass (%)	19%	17%	18,6%	19,6%
Online gas analysis – total quantity of emitted gases (FTIR and online analyzers)				
CO_2 (g)	**460 400**	**508 000**	**618 490**	**722 640**
CO_2 (mg/lost g)	2 172	2 646	2 220,8	2 627,8
CO (g)	**10 400**	**12 040**	**11 700**	**15 730**
CO (mg/lost g)	49	63	42	57,2
THC (g)	**2 430**	**2 380**	**2 860**	**2 730**
THC (mg/lost g)	11,5	12,4	10,3	9,9
NO (g)	**500**	**679**	**770**	**740**
NO (mg/lost g)	2,4	3,5	2,8	2,7
NO_2 (g)	**198**	**307**	**349**	**410**
NO_2 (mg/lost g)	0,9	1,6	1,3	1,5
HF (g)	**1 540**	**621**	**1 470**	**813**
HF (mg/lost g)	7,3	3,2	5,3	3
HCl (g)	**2 060**	**1 990**	**1 930**	**2 140**
HCl (mg/lost g)	10	10,4	6,9	7,8
HCN (g)	**113**	**167**	**148**	**178**
HCN (mg/lost g)	0,5	0,9	0,5	0,6
Thermal effects				
Maximal HRR (MW)	4,2 MW	4,8 MW	4,7 MW	6,1 MW
Heat of combustion (MJ)	6 314 MJ	6 890 MJ	8 540 MJ	10 000 MJ
Heat of combustion/unit mass loss (MJ/ kg)	29,8 MJ/kg	35,9 MJ/kg	30,7 MJ/kg	36,4 MJ/kg

[a] *Characteristics of the battery pack of the EV.*

Appendix F Axle load calculations

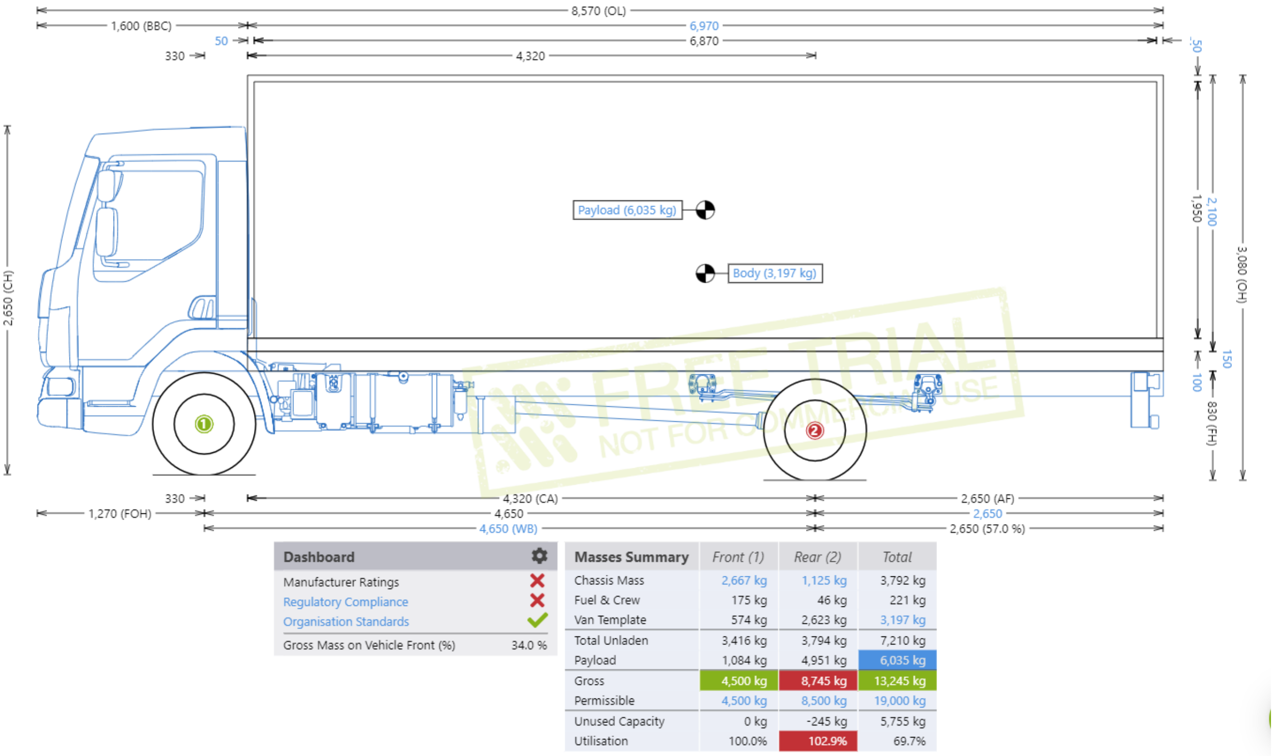
ICE Truck:



Dashboard	
Manufacturer Ratings	✓
Regulatory Compliance	✓
Organisation Standards	✓
Gross Mass on Vehicle Front (%)	35.6 %

Masses Summary	Front (1)	Rear (2)	Total
Chassis Mass	2,667 kg	1,125 kg	3,792 kg
Fuel & Crew	175 kg	46 kg	221 kg
Van Template	350 kg	1,601 kg	1,952 kg
Total Unladen	3,192 kg	2,772 kg	5,965 kg
Payload	1,084 kg	4,951 kg	6,035 kg
Gross	4,276 kg	7,724 kg	12,000 kg
Permissible	4,500 kg	8,500 kg	12,000 kg
Unused Capacity	224 kg	776 kg	0 kg
Utilisation	95.0%	90.9%	100.0%

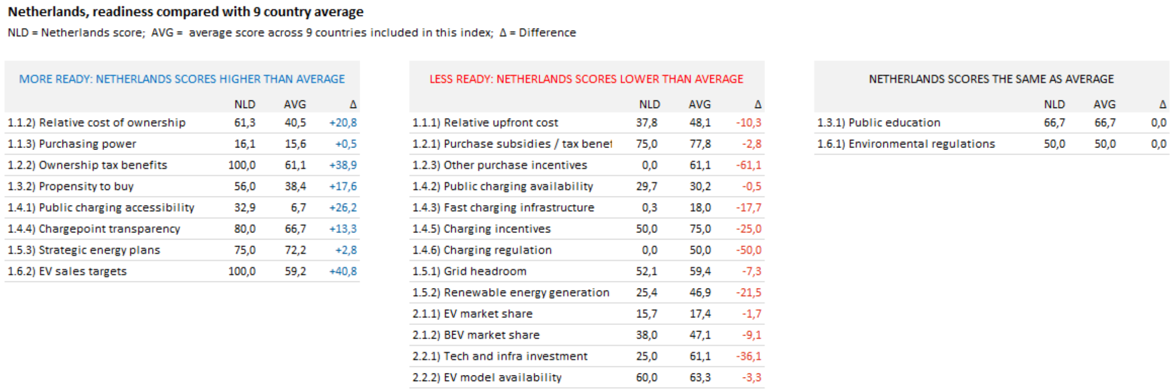
BEV truck:



Dashboard	
Manufacturer Ratings	✗
Regulatory Compliance	✗
Organisation Standards	✓
Gross Mass on Vehicle Front (%)	34.0 %

Masses Summary	Front (1)	Rear (2)	Total
Chassis Mass	2,667 kg	1,125 kg	3,792 kg
Fuel & Crew	175 kg	46 kg	221 kg
Van Template	574 kg	2,623 kg	3,197 kg
Total Unladen	3,416 kg	3,794 kg	7,210 kg
Payload	1,084 kg	4,951 kg	6,035 kg
Gross	4,500 kg	8,745 kg	13,245 kg
Permissible	4,500 kg	8,500 kg	19,000 kg
Unused Capacity	0 kg	-245 kg	5,755 kg
Utilisation	100.0%	102.9%	69.7%

Appendix G rEV index



Netherlands, readiness compared with 9 country average

NLD = Netherlands score; AVG = average score across 9 countries included in this index; Δ = Difference

MORE READY: NETHERLANDS SCORES HIGHER THAN AVERAGE

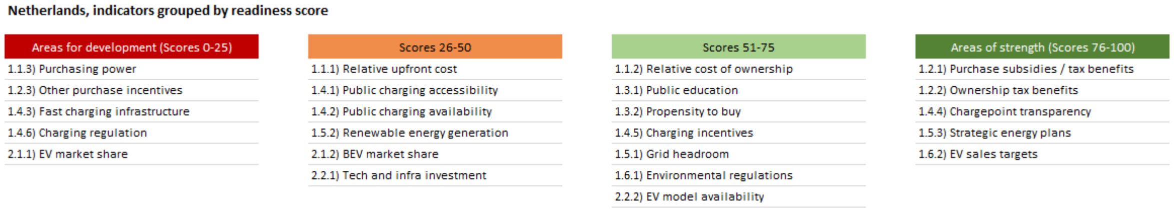
	NLD	AVG	Δ
1.1.2) Relative cost of ownership	61,3	40,5	+20,8
1.1.3) Purchasing power	16,1	15,6	+0,5
1.2.2) Ownership tax benefits	100,0	61,1	+38,9
1.3.2) Propensity to buy	56,0	38,4	+17,6
1.4.1) Public charging accessibility	32,9	6,7	+26,2
1.4.4) Chargepoint transparency	80,0	66,7	+13,3
1.5.3) Strategic energy plans	75,0	72,2	+2,8
1.6.2) EV sales targets	100,0	59,2	+40,8

LESS READY: NETHERLANDS SCORES LOWER THAN AVERAGE

	NLD	AVG	Δ
1.1.1) Relative upfront cost	37,8	48,1	-10,3
1.2.1) Purchase subsidies / tax benei	75,0	77,8	-2,8
1.2.3) Other purchase incentives	0,0	61,1	-61,1
1.4.2) Public charging availability	29,7	30,2	-0,5
1.4.3) Fast charging infrastructure	0,3	18,0	-17,7
1.4.5) Charging incentives	50,0	75,0	-25,0
1.4.6) Charging regulation	0,0	50,0	-50,0
1.5.1) Grid headroom	52,1	59,4	-7,3
1.5.2) Renewable energy generation	25,4	46,9	-21,5
2.1.1) EV market share	15,7	17,4	-1,7
2.1.2) BEV market share	38,0	47,1	-9,1
2.2.1) Tech and infra investment	25,0	61,1	-36,1
2.2.2) EV model availability	60,0	63,3	-3,3

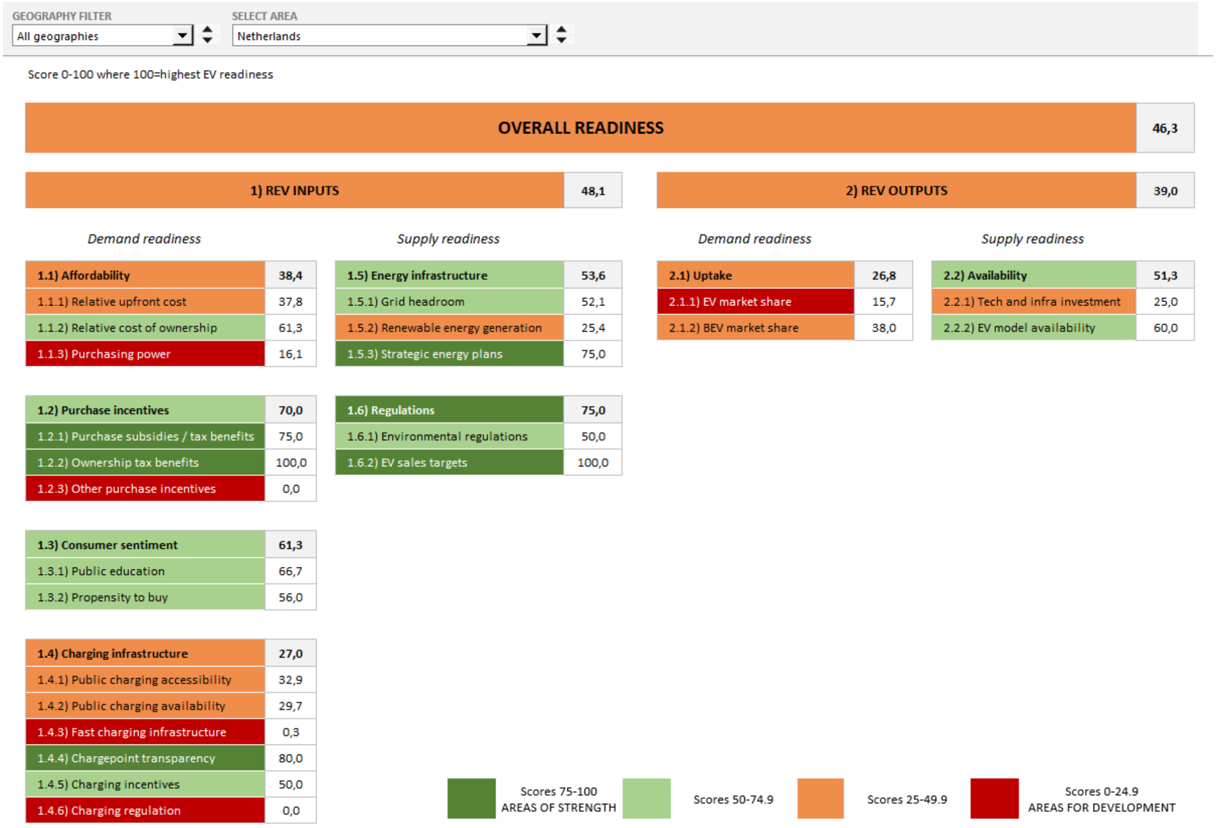
NETHERLANDS SCORES THE SAME AS AVERAGE

	NLD	AVG	Δ
1.3.1) Public education	66,7	66,7	0,0
1.6.1) Environmental regulations	50,0	50,0	0,0



Netherlands, indicators grouped by readiness score

Areas for development (Scores 0-25)	Scores 26-50	Scores 51-75	Areas of strength (Scores 76-100)
1.1.3) Purchasing power	1.1.1) Relative upfront cost	1.1.2) Relative cost of ownership	1.2.1) Purchase subsidies / tax benefits
1.2.3) Other purchase incentives	1.4.1) Public charging accessibility	1.3.1) Public education	1.2.2) Ownership tax benefits
1.4.3) Fast charging infrastructure	1.4.2) Public charging availability	1.3.2) Propensity to buy	1.4.4) Chargepoint transparency
1.4.6) Charging regulation	1.5.2) Renewable energy generation	1.4.5) Charging incentives	1.5.3) Strategic energy plans
2.1.1) EV market share	2.1.2) BEV market share	1.5.1) Grid headroom	1.6.2) EV sales targets
	2.2.1) Tech and infra investment	1.6.1) Environmental regulations	
		2.2.2) EV model availability	



GEOGRAPHY FILTER: All geographies
SELECT AREA: Netherlands

Score 0-100 where 100=highest EV readiness

OVERALL READINESS	46,3

1) REV INPUTS	48,1

2) REV OUTPUTS	39,0

Demand readiness

1.1) Affordability	38,4
1.1.1) Relative upfront cost	37,8
1.1.2) Relative cost of ownership	61,3
1.1.3) Purchasing power	16,1

1.2) Purchase incentives	70,0
1.2.1) Purchase subsidies / tax benefits	75,0
1.2.2) Ownership tax benefits	100,0
1.2.3) Other purchase incentives	0,0

1.3) Consumer sentiment	61,3
1.3.1) Public education	66,7
1.3.2) Propensity to buy	56,0

1.4) Charging infrastructure	27,0
1.4.1) Public charging accessibility	32,9
1.4.2) Public charging availability	29,7
1.4.3) Fast charging infrastructure	0,3
1.4.4) Chargepoint transparency	80,0
1.4.5) Charging incentives	50,0
1.4.6) Charging regulation	0,0

Supply readiness

1.5) Energy infrastructure	53,6
1.5.1) Grid headroom	52,1
1.5.2) Renewable energy generation	25,4
1.5.3) Strategic energy plans	75,0

1.6) Regulations	75,0
1.6.1) Environmental regulations	50,0
1.6.2) EV sales targets	100,0

Demand readiness

2.1) Uptake	26,8
2.1.1) EV market share	15,7
2.1.2) BEV market share	38,0

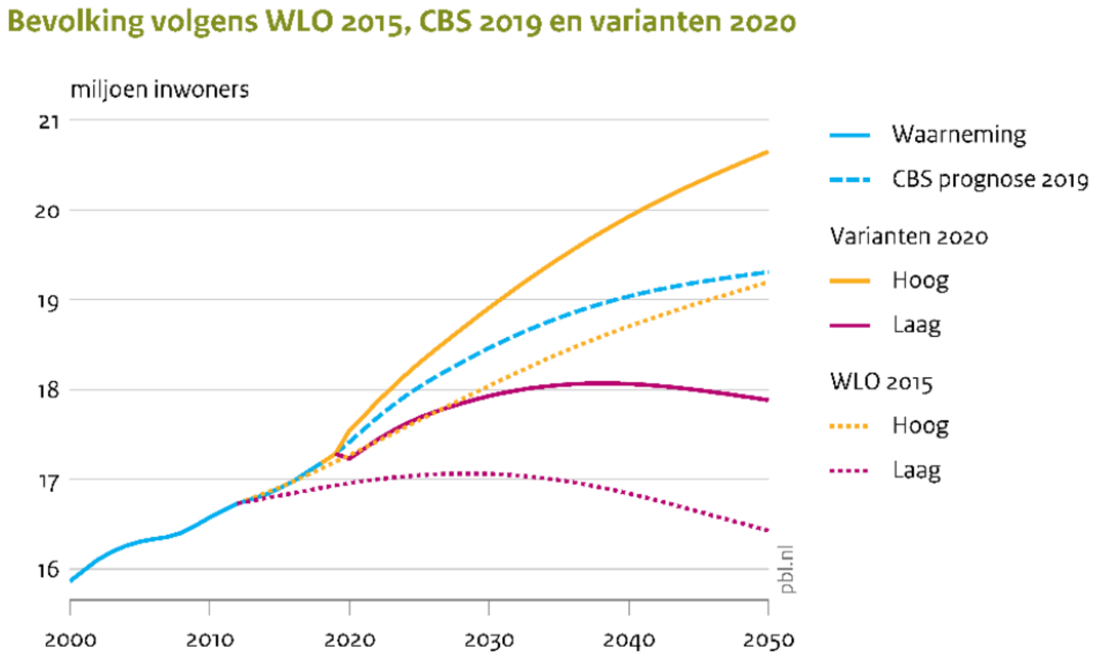
Supply readiness

2.2) Availability	51,3
2.2.1) Tech and infra investment	25,0
2.2.2) EV model availability	60,0

🟩	Scores 75-100 AREAS OF STRENGTH
🟩	Scores 50-74.9
🟧	Scores 25-49.9
🟥	Scores 0-24.9 AREAS FOR DEVELOPMENT

Appendix H Critical information from “actualisatie invoer WLO autopark mobiliteitsmodellen 2020”

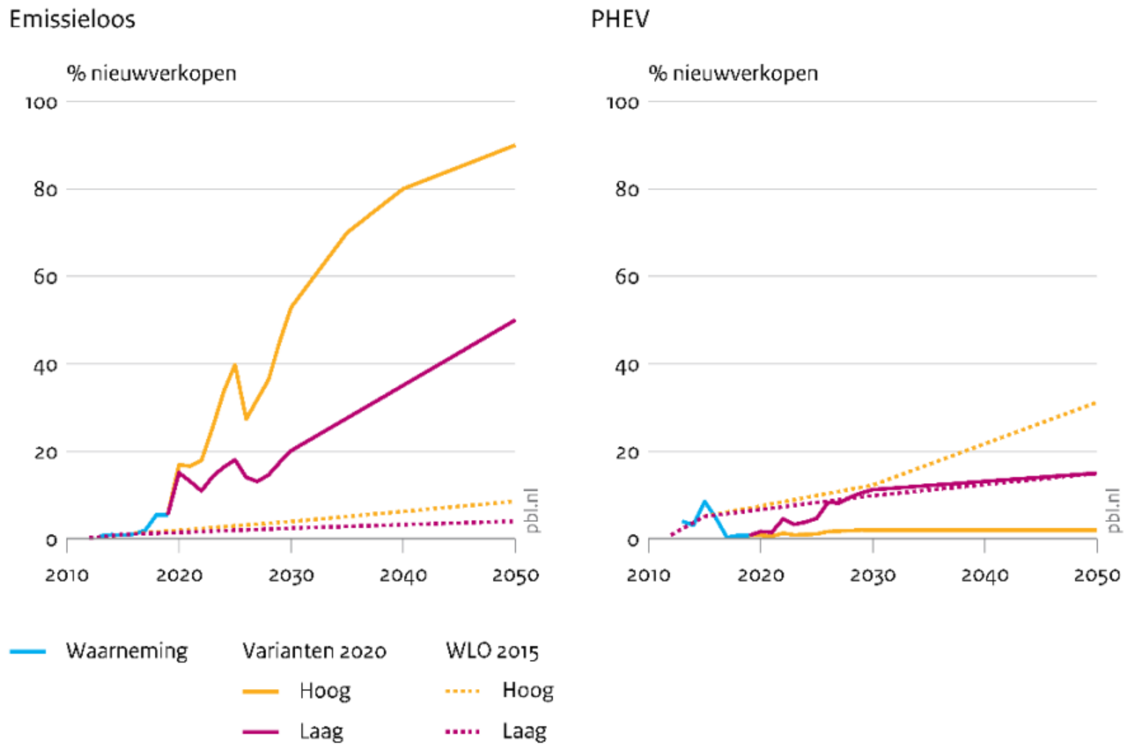
Figuur 1



Bron: CBS; WLO; bewerking PBL

Figuur 5

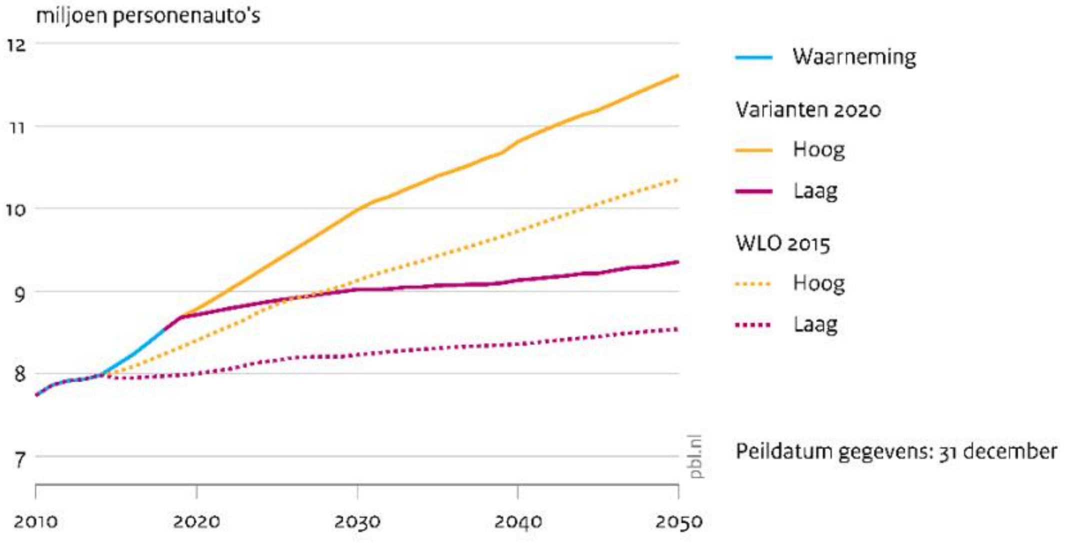
Aandeel nieuwverkopen personenauto's volgens WLO 2015 en varianten 2020



Bron: WLO; Revnext; bewerking PBL

Figuur 6

Omvang van het personenautopark volgens WLO 2015 en overige varianten

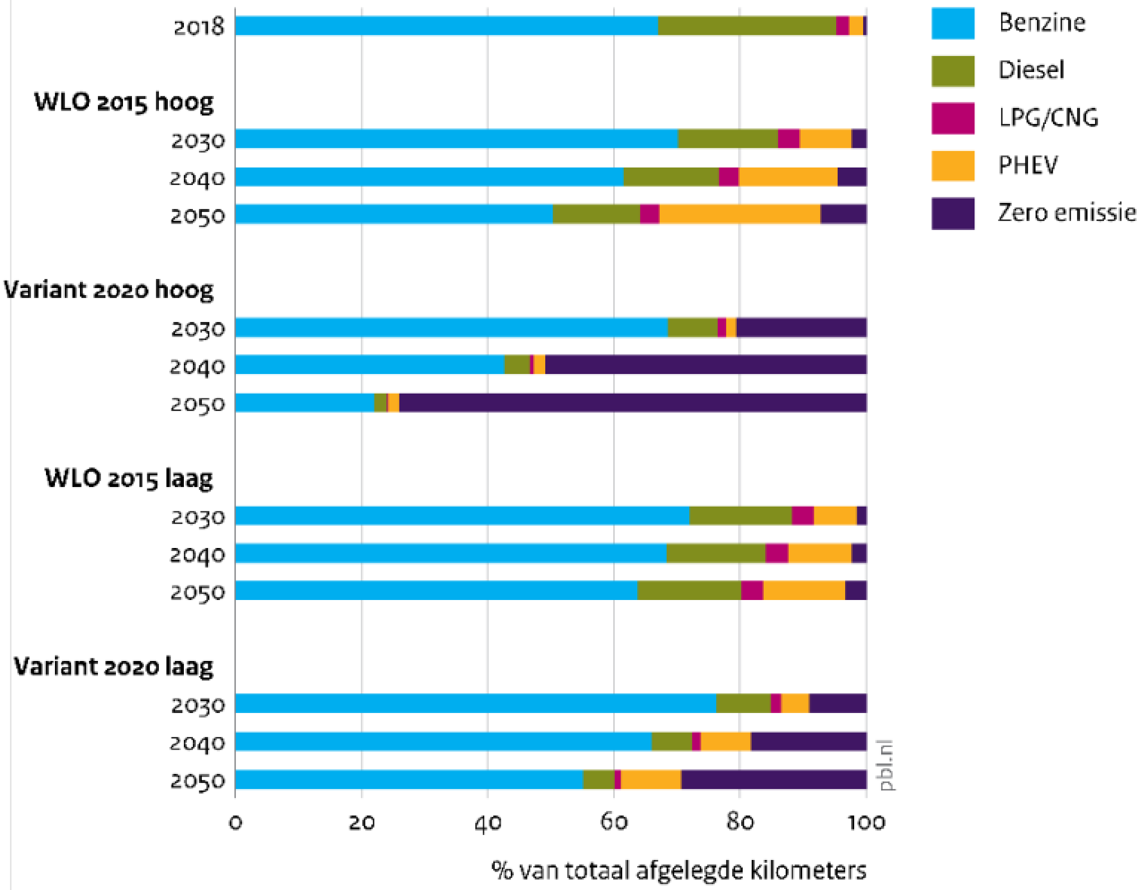


Peildatum gegevens: 31 december

Bron: CBS; WLO; bewerking PBL

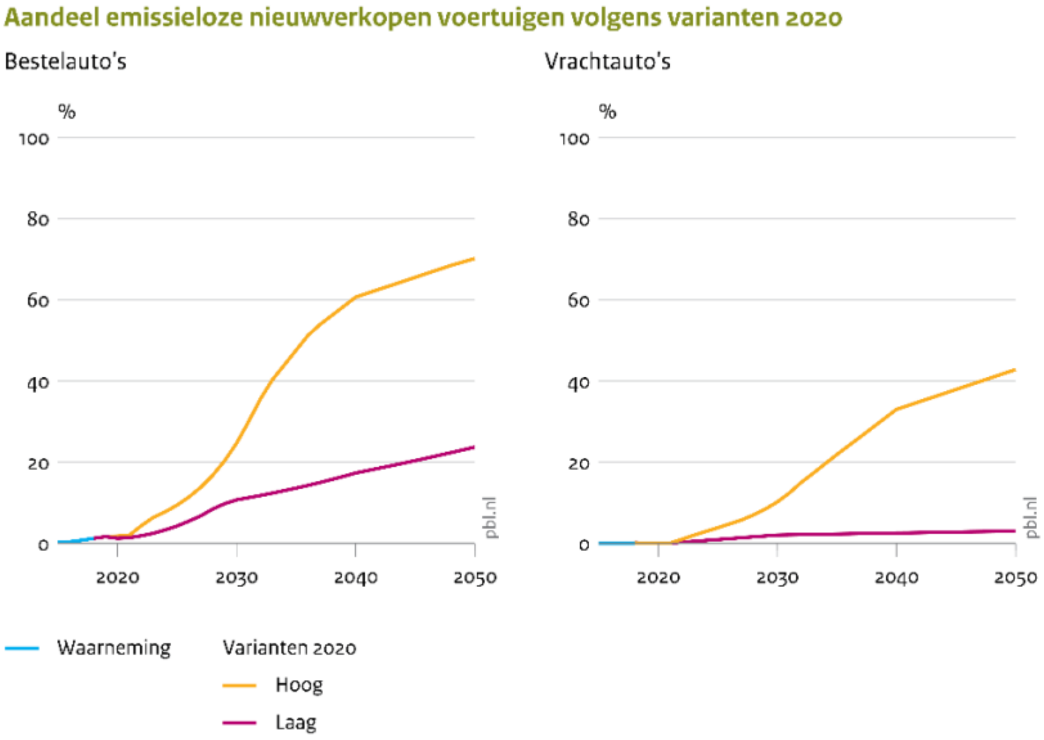
Figuur 7

Verdeling van de verkeersprestatie van personenauto's naar brandstofsoort volgens WLO 2015 en varianten 2020



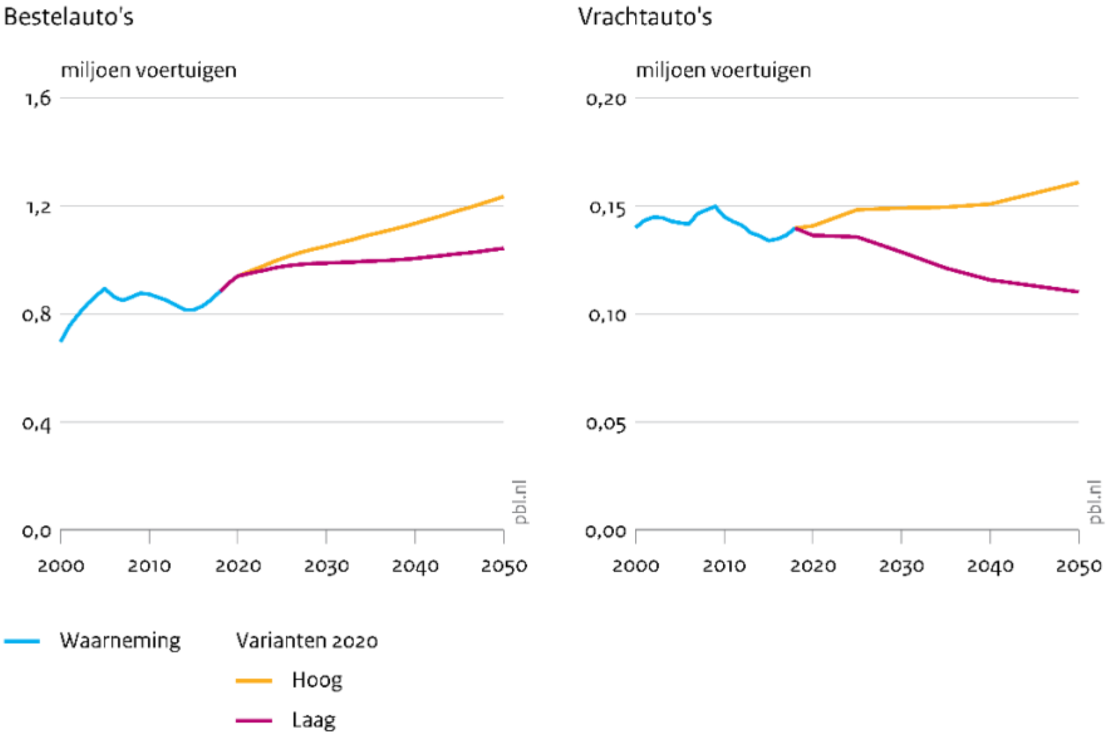
Bron: CBS; WLO; bewerking PBL

Figuur 9


Aandeel emissieloze nieuwverkopen voertuigen volgens varianten 2020
Bestelauto's
Vrachtauto's
%
100
80
60
40
20
0
2020
2030
2040
2050
pbl.nl
Waarneming
Varianten 2020
Hoog
Laag

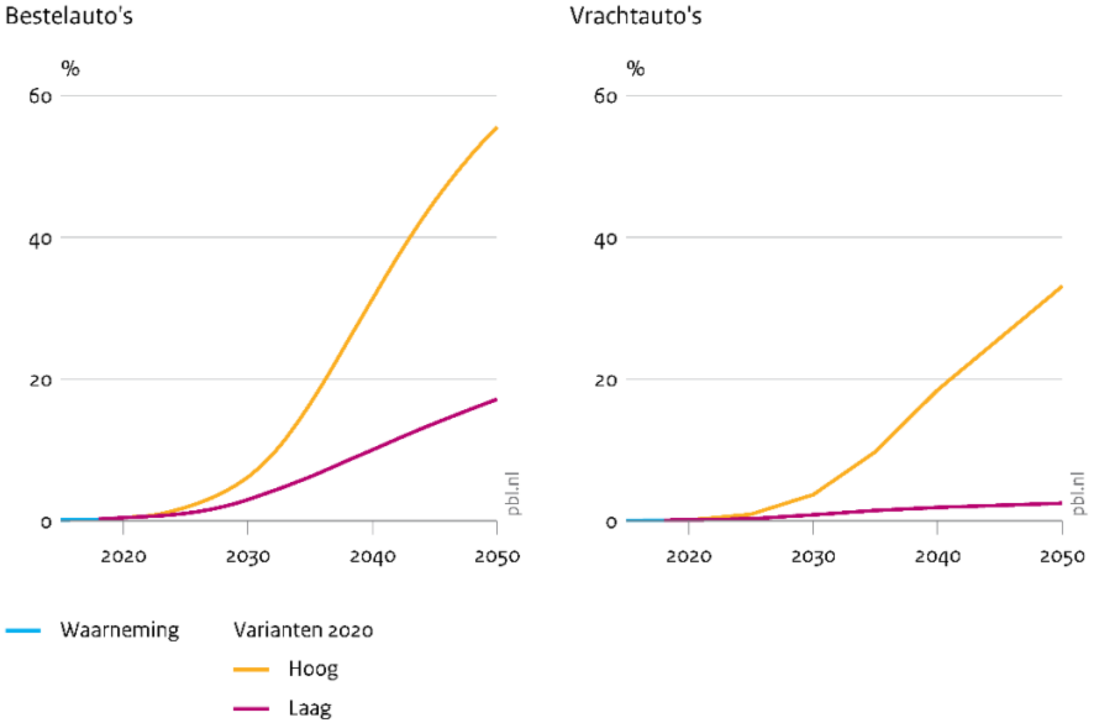
Figuur 10

Omvang bestel- en vrachtautopark volgens varianten 2020



Bron: CBS; PBL

Figuur 11



Aandeel emissieloze voertuigen in bestel- en vrachtautopark volgens varianten 2020

Bron: CBS; PBL

Appendix I Sources used for absolute and relative vehicle calculation

Figure	2022	2030	2035	2040	Source
Share of Full electric new car sales (Scenario Low)	18%	21%	25%	38%	PBL (van Meerkerk, et al., 2021)
Share of Full electric new car sales (Scenario High)	18%	55%	75%	80%	PBL (van Meerkerk, et al., 2021)
Share of PHEV electric new car sales (Scenario Low)	2%	10%	11%	11%	PBL (van Meerkerk, et al., 2021)
Share of PHEV electric new car sales (Scenario High)	2%	2%	2%	2%	PBL (van Meerkerk, et al., 2021)
Share of ICE new car sales (Scenario Low)	80%	69%	64%	51%	PBL (van Meerkerk, et al., 2021)
Share of ICE new car sales (Scenario High)	80%	43%	23%	18%	PBL (van Meerkerk, et al., 2021)

The following sales information has been adapted to account for ban on ICE sales by 2030 and ban on PHEV by 2035.

Figure	2022	2030	2035	2040	Source
Share of Full electric new car sales (Scenario Low)	18%	68%	100%	100%	Adapted from PBL (van Meerkerk, et al., 2021)
Share of Full electric new car sales (Scenario High)	18%	96%	100%	100%	Adapted from PBL (van Meerkerk, et al., 2021)
Share of PHEV electric new car sales (Scenario Low)	2%	32%	0%	0%	Adapted from PBL (van Meerkerk, et al., 2021)
Share of PHEV electric new car	2%	4%	0%	0%	Adapted from PBL

sales (Scenario High)					(van Meerkerk, et al., 2021)

Figure	Value	Year	Source
Total vehicles in use (Passenger vehicles)	9,049,959	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Passenger vehicles)	4,281,970	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (Passenger vehicles)	41,8%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (light commercial vehicles)	1,031,010	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Light commercial vehicles)	391,281	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (light commercial vehicles)	37,9%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Medium and heavy commercial vehicles)	49,261	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (Medium and heavy commercial vehicles)	31,2%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)

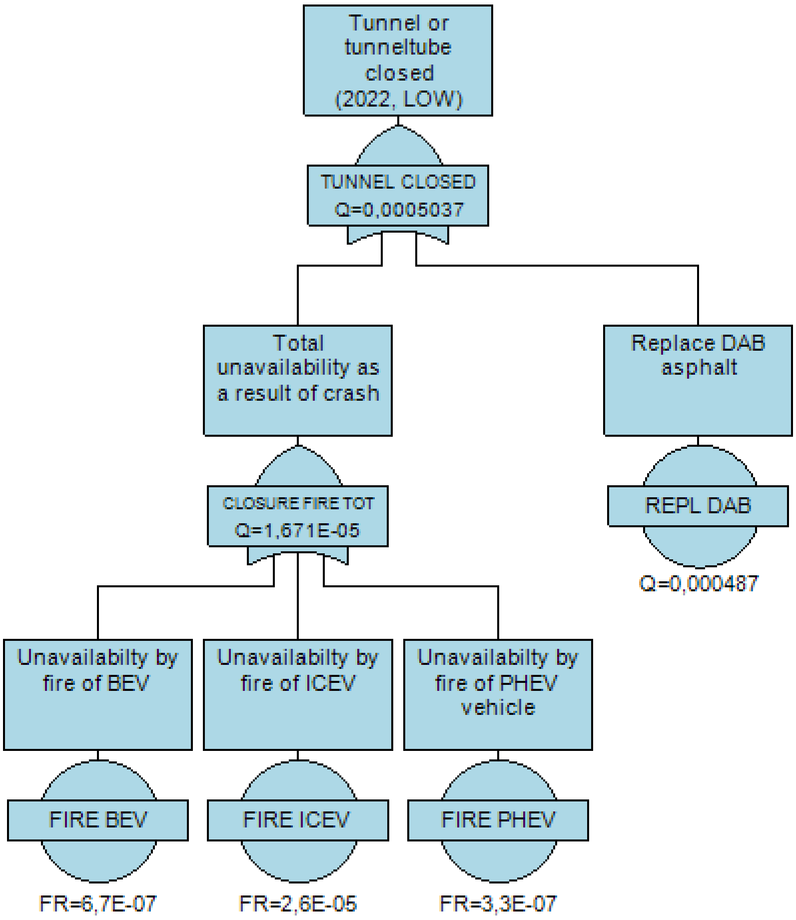
Figure	Value	Year	Source
Average EV cost relative to ICE	145%	2021	rEV index (Economist Impact, 2021)
Average EV ownership cost for 3 years relative to ICE	110%,	2021	rEV index (Economist Impact, 2021)

EVs relative to total passenger vehicle stock	2,20%	2021	rEV index (Economist Impact, 2021)
BEVs relative to total EV stock	54,5%	2021	rEV index (Economist Impact, 2021)
Total vehicles in use	10,248,388	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (Passenger vehicles)	9,049,959	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Passenger vehicles)	4,281,970	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (Passenger vehicles)	41,8%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (light commercial vehicles)	1,031,010	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Light commercial vehicles)	391,281	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (light commercial vehicles)	37,9%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Total vehicles in use (Medium and heavy commercial vehicles)	157,638	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Vehicles older than 10 years (Medium and heavy commercial vehicles)	49,261	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Relative vehicles older than 10 years (Medium and heavy commercial vehicles)	31,2%	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)

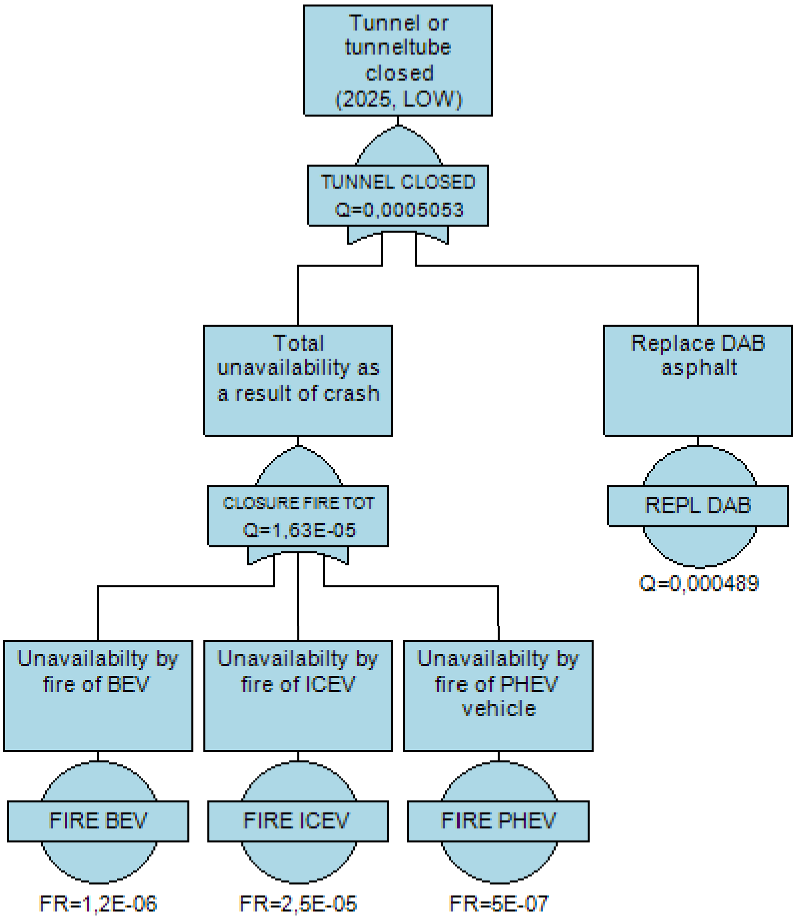
Average distance travelled by vehicle	10,454 km	2021	ACEA-report-vehicles-in-use-europe-2022 (ACEA, 2022)
Average kilometres travelled per person per day	17,5 km	Stable from 2000-2010	Planbureau voor de Leefomgeving (Planbureau voor de Leefomgeving , 2014)
Average kilometres travelled per person per day	28,05 km	2022	km travelled from ACEA-report, total vehicles from CBS

Appendix J Fault Tree Analyses

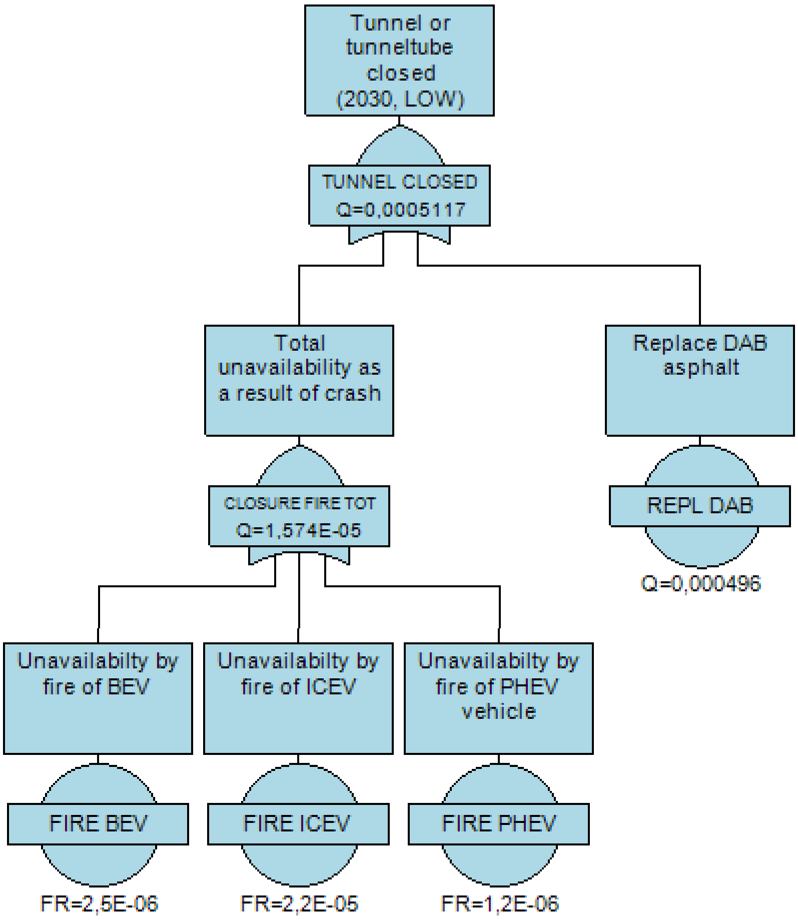
Unavailability FTA 2022 Low



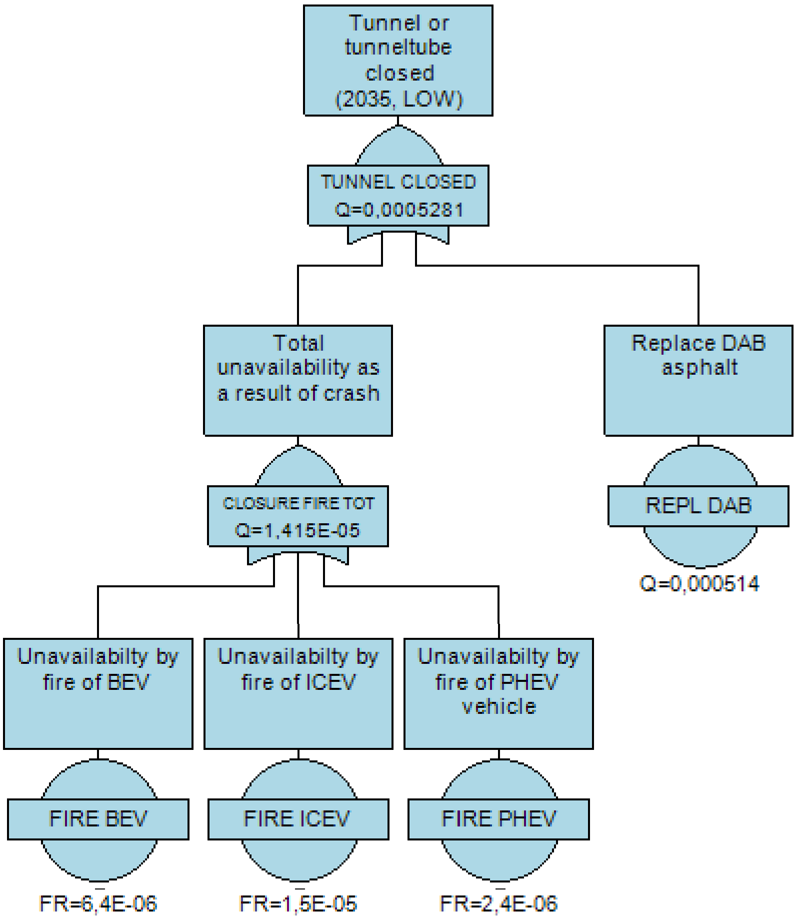
Unavailability FTA 2025 Low



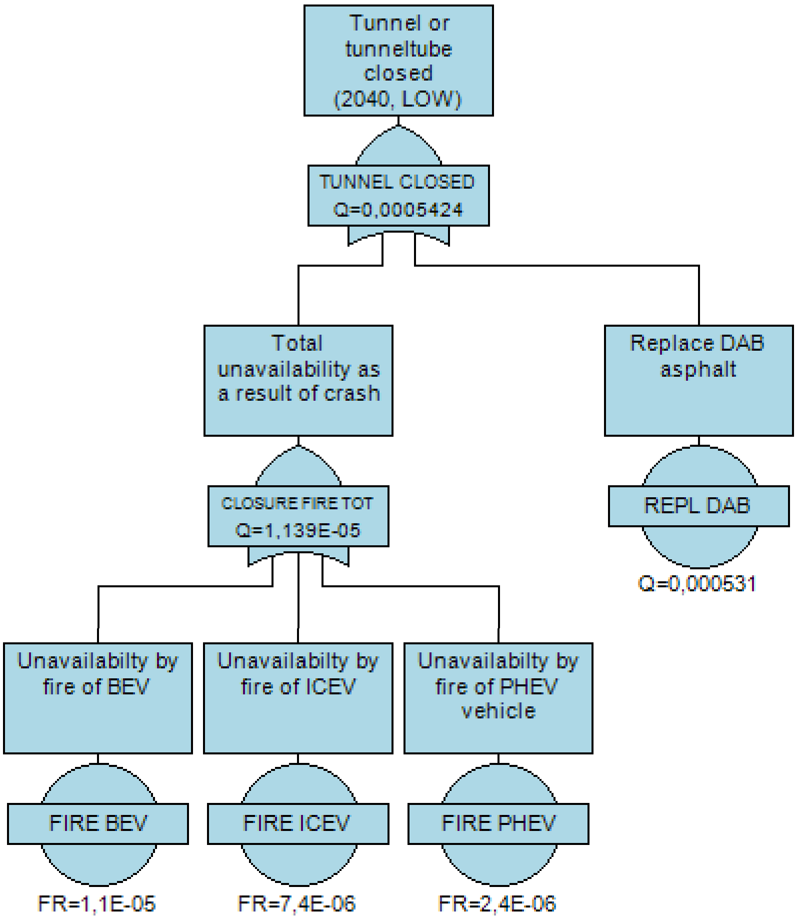
Unavailability FTA 2030 Low



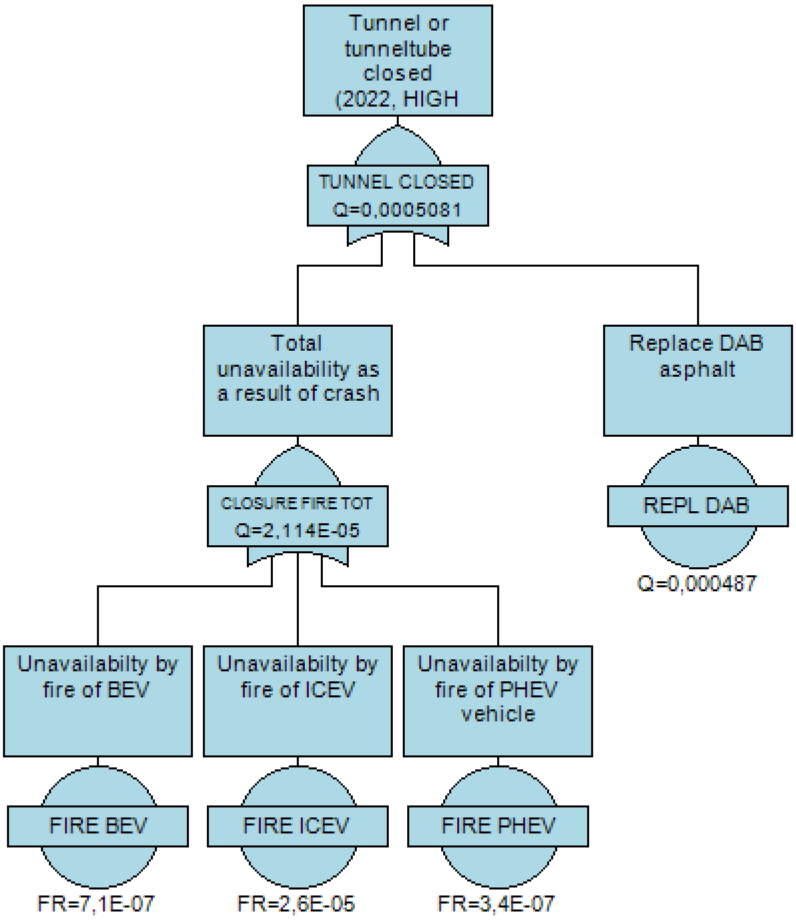
2035 Low


Tunnel or tunneltube closed (2035, LOW)
TUNNEL CLOSED
Q=0,0005281
Total unavailability as a result of crash
Replace DAB asphalt
CLOSURE FIRE TOT
Q=1,415E-05
REPL DAB
Q=0,000514
Unavailabilty by fire of BEV
Unavailabilty by fire of ICEV
Unavailabilty by fire of PHEV vehicle
FIRE BEV
FIRE ICEV
FIRE PHEV
FR=6,4E-06
FR=1,5E-05
FR=2,4E-06

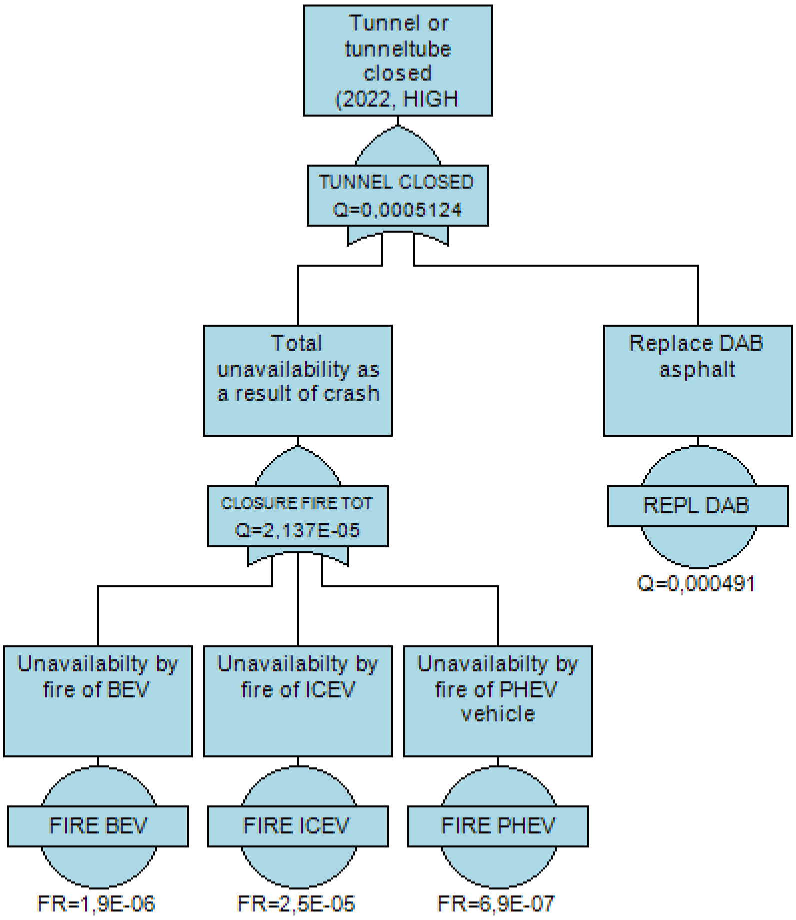
Unavailability FTA 2040 low



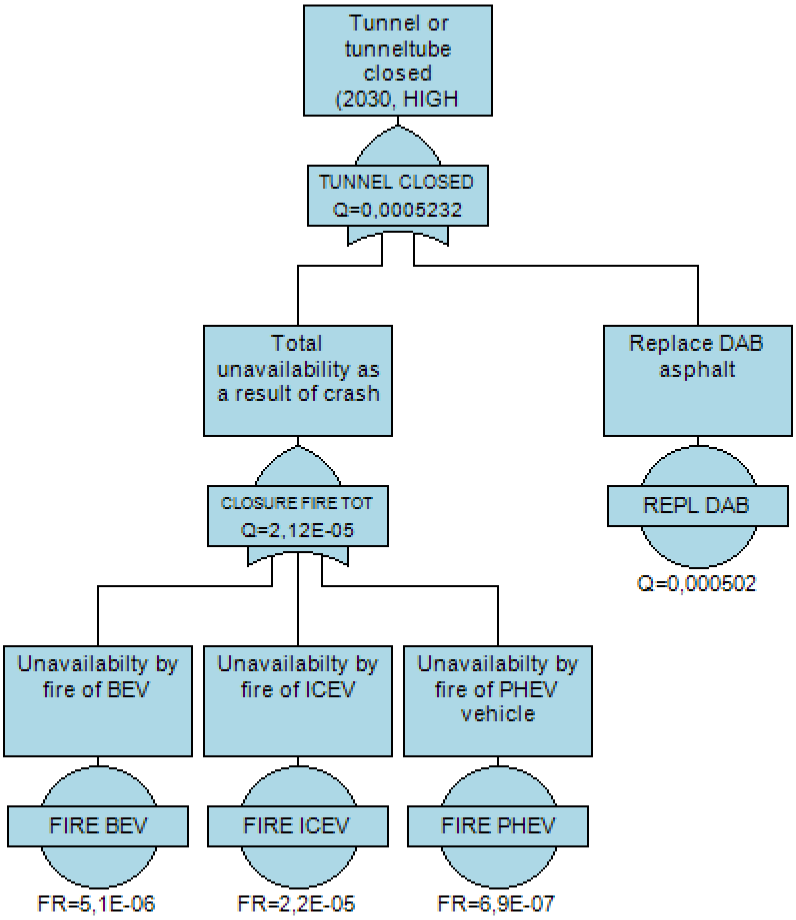
Unavailability FTA 2022 HIGH



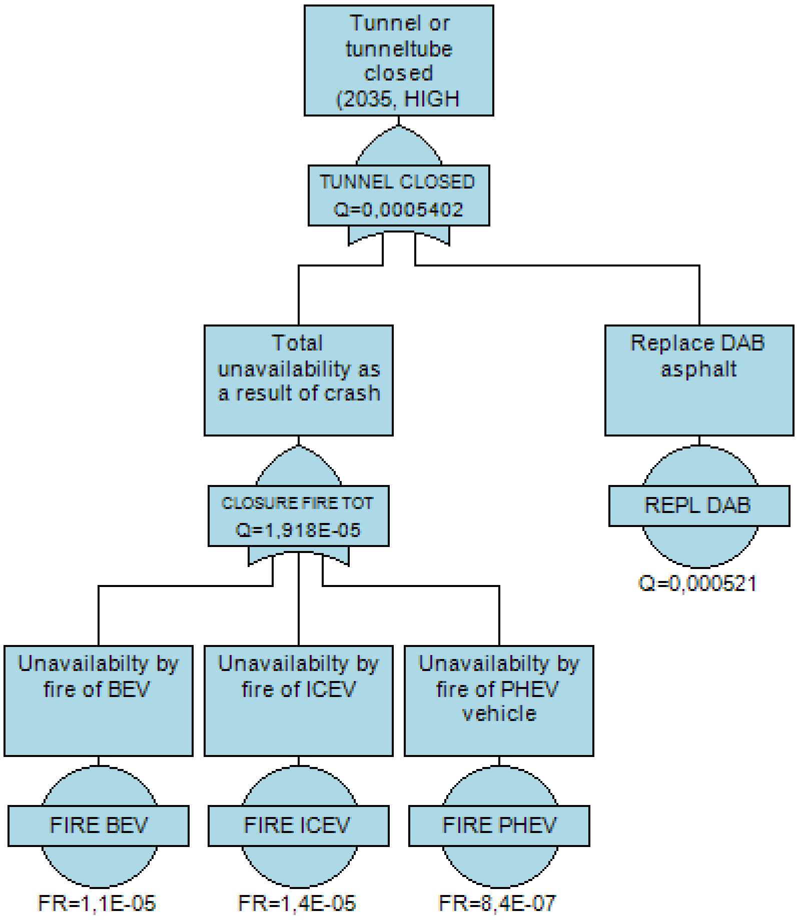
Unavailability FTA 2025 HIGH



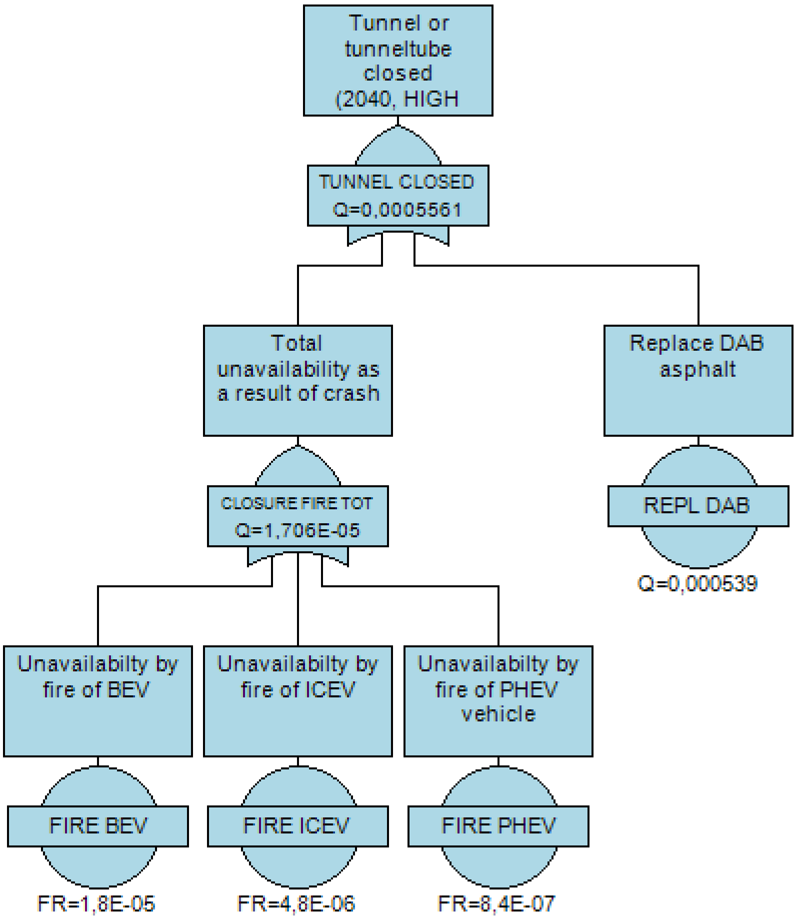
Unavailability FTA 2030 HIGH



Unavailability FTA 2035 High



Unavailability FTA 2040 High



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