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Master's Thesis

Technology competition for the low-carbon transport transition in Switzerland

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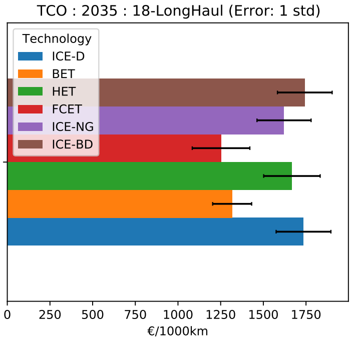

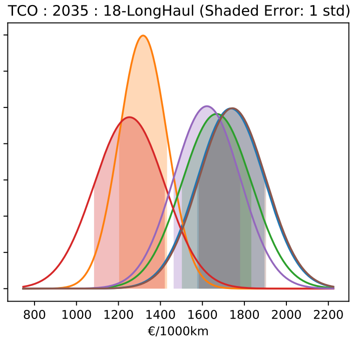

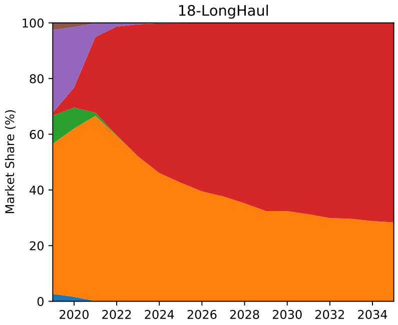

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Abstract

The transition to low-carbon pathways to reach the goals of the Paris Agreement is an often discussed topic. However, it is still unclear how economically feasible low-carbon drive-technologies are as a solution to decarbonizing the road-freight sector. Policy-makers strive to intervene in such a transition at minimal financial cost.

This work specifically aims to identify and understand the drivers behind market share competition between commercial vehicle drive-technologies in Switzerland. These objectives are addressed by projecting the road-freight transport transition in Switzerland based on an accurate representation of the road-freight landscape. To this end, a modeling framework is presented that builds on an existing dynamics model and enriches it with very detailed transport data, additional parameters and customized Swiss-specific input parameters. To gain a better understanding of the Swiss transport sector and its country-specific patterns, a detailed analysis of national transport performance is performed. The model is further validated with industry feedback obtained by expert interviews.

Overall, we find a strong dominance of battery electric trucks (BETs) in Switzerland's road-freight future. Fuel cell electric trucks (FCETs) are only able to gain a cost advantage if the costs of hydrogen decrease significantly over the next years. For the case of light-duty 3.5 tonne vehicles, drive-technology cost reductions of zero-emission vehicles (ZEVs) alone are unlikely to result in a thorough decarbonization of the segment. A sensitivity analysis of the model input parameters confirms detailed insights gained from a literature review and expert interviews. Lastly, a proposed policy-mix lays a foundation for discussion and indicates areas in which political intervention is imperative in achieving the agreed-upon climate targets for the Swiss transport sector.

Zusammenfassung

Der Übergang zu einner kohlenstoffarmen Gesellschaft zur Erreichhung der Ziele des Pariser Abkommens ist ein oft diskutiertes Thema. Es ist jedoch noch unklar, wie wirtschaftlich kohlenstoffarme Antriebstechnologien als Lösung zur Dekarbonisierung des Strassengüterverkehrs sind. Politische Entscheidungsträger sind bestrebt, finanzielle Kosten von Eingriffen auf ein Minimum zu begrenzen.

Diese Arbeit zielt speziell darauf ab, die Treiber hinter dem Marktwettbewerb zwischen Antriebstechnologien für Nutzfahrzeug in der Schweiz zu identifizieren und sie zu verstehen. Diese Ziele werden durch die Projektion des Wandels des Strassengütertransports in der Schweiz auf der Grundlage einer genauen Darstellung der Strassengüterverkehrslandschaft erreicht. Zu diesem Zweck wird ein Modellierungsrahmen vorgestellt, der auf einem bestehenden dynamischen System aufbaut und dieses mit sehr detaillierten Transportdaten, zusätzlichen Parametern und angepassten Schweiz-spezifischen Eingabeparametern anreichert. Um ein besseres Verständnis des Schweizer Transportsektors und seiner länderspezifischen Muster zu erhalten, wird eine detaillierte Analyse der nationalen Transportleistung durchgeführt. Das Modell wird darüber hinaus mit den durch Experteninterviews gewonnenen Erkenntnisse verifiziert.

Insgesamt finden wir eine starke Dominanz von batterie-elektrischen Nutzfahrzeuge in der Zukunft des Schweizer Strassengüterverkehrs vor. Brennstoffzellen-elektrische Nutzfahrzeuge sind nur dann in der Lage einen Wettbewerbsvorteil zu erlangen, wenn die Kosten für Wasserstoff in den nächsten Jahren deutlich sinken. Für den Fall der leichten 3.5-Tonnen Lieferwagen ist es unwahrscheinlich, dass die Kostensenkungen der Antriebstechnologien von emissionsfreien Fahrzeugen allein zu einer vollständigen Dekarbonisierung der Fahrzeugkategorie führen. Eine Sensitivitätsanalyse der Eingabeparameter bestätigt die detaillierten Erkenntnisse aus der Literaturrecherche und den Expertenbefragungen. Zum Schluss bildet eine Kombination vorgeschlagener politischer Massnahmen eine Diskussionsgrundlage und zeigt Bereiche auf, in denen politische Interventionen zwingend notwendig sind, um die vereinbarten Klimaziele für den Schweizer Verkehrssektor zu erreichen.

Acknowledgments

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I was able to benefit from the knowledge at EPG and ETH Zurich. In particular, my thanks are addressed to my supervisors Prof. Dr. Tobias S. Schmidt and Prof. Dr. Bjarne Steffen for their valuable feedback. I would also like to thank all the researchers, doctoral and master's students of EPG who have always motivated me to critically examine my arguments and who provided me with valuable feedback.

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A special thank you to all those who took the time to read through my work and motivated me with their suggestions for improvement to be able to present you, the reader, with an interesting and hopefully comprehensible report.

Last but not least, I thank my beloved wife for her support and for being appreciative of my increased absence. Merci.

Andreas Eckmann, Zurich, April 2021

Contents

List of Figures

List of Tables

Abbreviation

AKT	annual kilometers travelled
ARE	Federal Office for Spatial Development *(Bundesamt für Raumentwicklung)*
BET	battery electric truck
CAPEX	capital expenditure
CO_2	carbon dioxide
DETEC	Federal Department of the Environment, Transport, Energy and Communications *(Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation)*
EU	European Union
FCA	Federal Customs Administration *(Eidgenössische Zollverwaltung)*
FCET	fuel cell electric truck
FOT	Federal Office of Transport *(Bundesamt für Verkehr)*
FSO	Federal Statistical Office *(Bundesamt für Statistik)*
GHG	greenhouse gas
GTW	gross train weight
HDT	heavy-duty truck
HET	hybrid electric truck
ICE	internal combustion engine
ICE-D	internal combustion engine - diesel truck
ICE-BD	internal combustion engine - biodiesel truck
ICE-NG	internal combustion engine - liquefied natural gas truck
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
LDT	light-duty truck
LSVA	Leistungsabhängige Schwerverkehrsabgabe (performance-related heavy vehicle charge)
MDT	medium-duty truck
MPW	maximum permissible weight
OPEX	operational expenditure
SFOE	Swiss Federal Office of Energy *(Bundesamt für Energie)*
TCO	total cost of ownership
ZEV	zero-emission vehicle

1 Introduction

This chapter introduces the reader to the subject of Swiss road-freight transport. The first section includes background knowledge on the historical development of greenhouse gas (GHG) emissions and introduces a selection of known market actors. The second section deals with the existing scientific literature and the current transport and climate policy in Switzerland. From these insights, we draw the research motivation and derive two research questions. Lastly, the objectives of this work are presented.

1.1 Background

In Switzerland, the energy sector has been the main contributor to the total national GHG emissions. About three quarters of Switzerland's total GHG emissions without land use, land-use change and forestry have emerged from the energy sector. This share has been stable over the past thirty years (Fig. 1.1). In 2018, it made up 76% of the total GHG emissions. Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities and contributes 80% to Switzerland's GHG emissions.

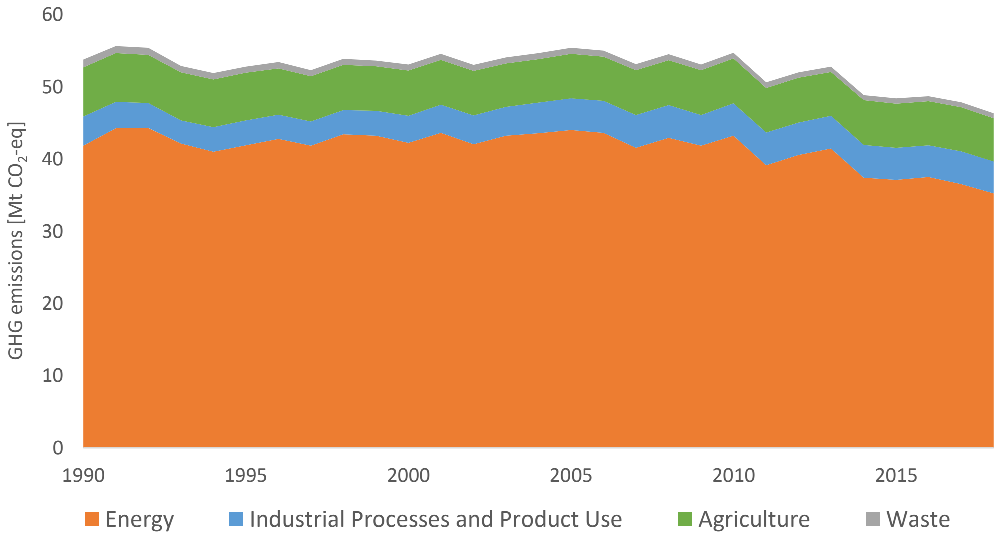


Figure 1.1: GHG emissions in Switzerland by sector in Mt CO_2 equivalent (1990–2018).

All subsectors of the energy sector except the energy industry decreased their GHG emissions from 1990 to 2018, but emissions from the transport sector are nearly the same as in 1990 (Fig. 1.2, blue curve). While the total Swiss CO_2 emissions decreased by 16% between 1990 and 2018, CO_2 emissions from transport increased by 2.6% over the same period [1].

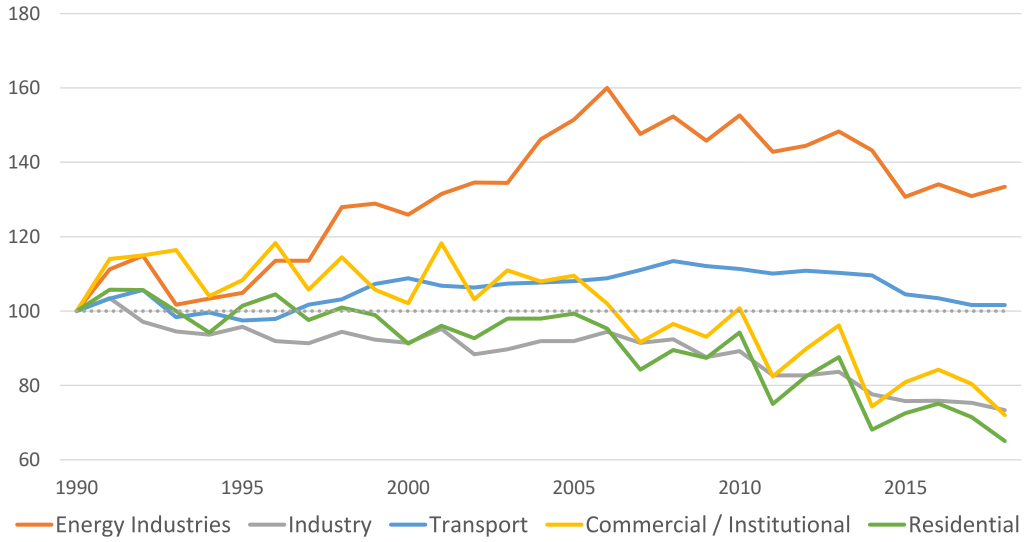


Figure 1.2: Evolution of GHG emissions from energy combustion (1AA) (1990–2018: 1990=100%).

In 2018, the transport sector emitted nearly 15 Mt CO_2, which represents 42% of Switzerland's CO_2 emissions from energy combustion. This is a significantly higher proportion than Germany (23%), the European Union (EU) (29%), or even the US (33%). When excluding non-domestic GHG emissions from civil aviation, road transportation is responsible for almost all GHG emissions (98%) in the transport sector. While private passenger vehicles account for three quarters of these emissions, light and heavy duty trucks as well as buses contribute considerably to these pollution with a combined share of 23% (Fig. 1.3). Overall, commercial vehicles in Switzerland were responsible for 9% of the national CO_2 emissions and 7.2% of the national GHG emissions in 2018 [1].

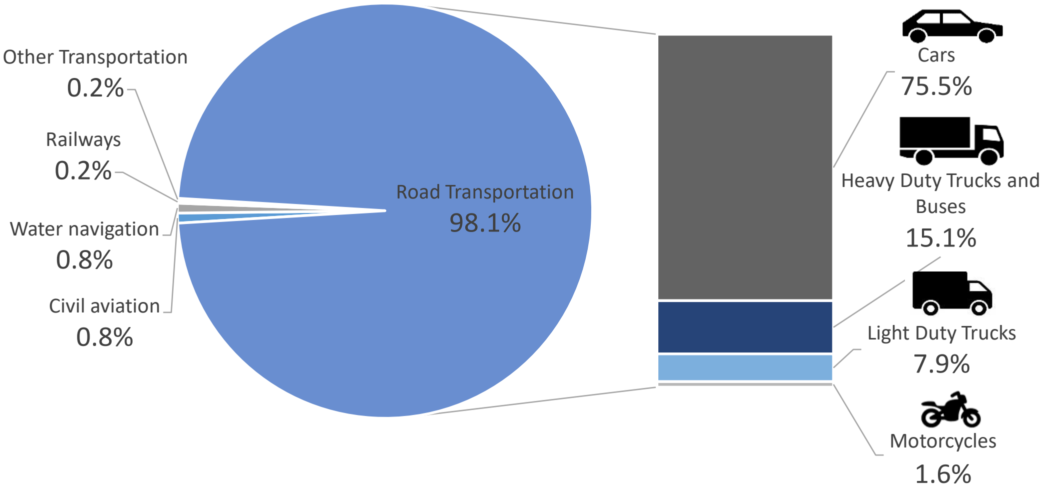


Figure 1.3: GHG emissions breakdown by transport mode in Switzerland (2018).

This begs the question, what has caused the lack of decrease in GHG emissions from Swiss road transportation over the last 30 years? On the one hand, this is due to the high average purchasing power of Swiss households and the country's topography, as Alberini et al. [2] describe. Newly registered passenger cars in Switzerland have one of the highest CO_2 emissions in Europe. In

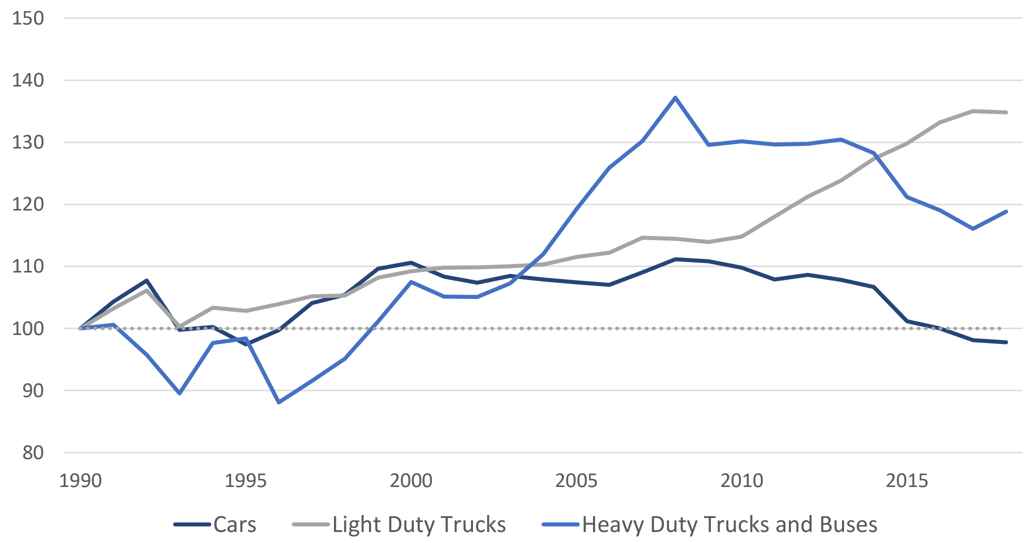


Figure 1.4: Evolution of GHG emissions in Switzerland from road transportation (1A3b, without Motorcycles) (1990-2018; 1990=100%)

2019, they emitted on average 135 g of CO_2 per kilometer, compared to the EU average of 122 g [3]. Not only do vehicles tend to be larger, an above-average number of all-wheel-drive vehicles are also purchased. More than one in two new (51%) vehicles purchased in Switzerland in 2019 had all-wheel drive [3]. Although this may describe consumer behavior of citizens, where factors such as brand loyalty play a role [4], the matter is different for freight transport vehicles. Here, it is not private individuals who make the purchasing decision—status symbols are less important. Nevertheless, emissions caused by road vehicles transporting goods have increased sharply over the last 15 years (Fig. 1.4). The road freight sector seems to struggle with reducing its emission, despite rapid technological process and decreasing cost of alternative drive-technologies.

Because the high purchasing power of Swiss households is also reflected in the quantities of goods to be transported, Thalmann and Vielle [5] see the main reason for the sharp increase in emissions in the strong demographic and economic growth. Between 1990 and 2019, the population grew by 28% and GDP per capita by 55%, and this trend is not expected to change in the near future (all data from FSO database). The Federal Office for Spatial Development *(Bundesamt für Raumentwicklung)* (ARE) projects a growth in freight transport of 37% by 2040, compared to 2010 (Fig. 1.5). This generates a transport performance of 36.6 billion tonne-kilometers on Swiss roads. Furthermore, ARE identifies three important logistics trends in their *Transport Outlook 2040* report [6]:

- increasing importance of reliability
- decreasing shipment sizes (while the total volume remains the same)
- increasing expectations of the quality of transport

They conclude that this will increase shuttle traffic in hub and spoke systems and that the trend towards a progressive increase in the transport of packaged goods, will continue to set the pace for logistics processes in the future. This trend is triggered by a further decrease in the depth of value added and the individualized on-demand manufacture of products [6]. In 2019, road

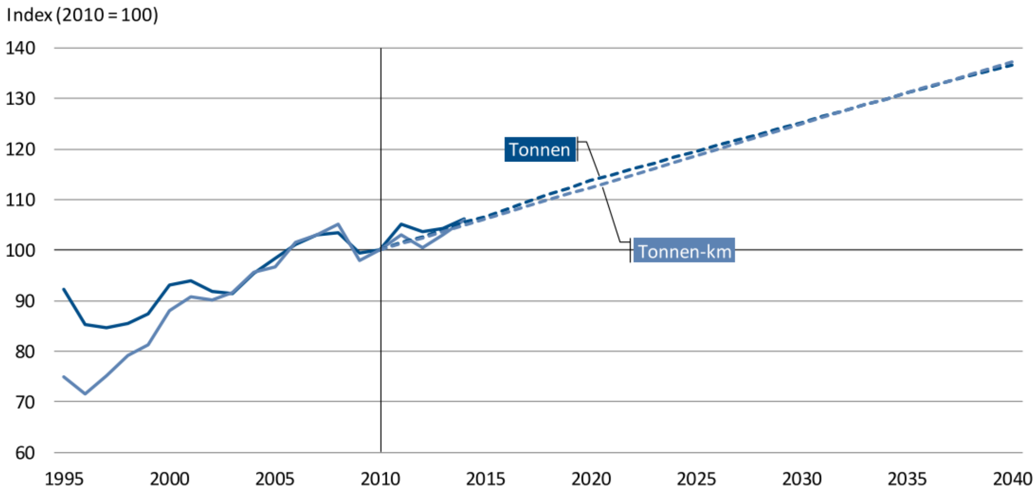


Figure 1.5: Historical and projected freight traffic volume (Tonnen) and performance (Tonnen-km) from 1990 to 2040. (2010=100%) [6]

freight constituted 63% of the total freight activity [7]. The problem is, 92% of all transport in Switzerland runs on fossil fuels (2018) [8]. This share is expected to be even higher when it comes to road-freight only, since the number of freight vehicles running on biofuels or electricity is still very low.

News about clean and sustainable propulsion solutions for road-freight transport seem to have been pouring in over the last few months. Press releases of electric vehicle prototypes, the formation of joint ventures between major original equipment manufacturers and logistics companies, or large order intakes have been announced seemingly every week. Probably one of the best-known figures when it comes to announcing new developments in the vehicle sector is Elon Musk—CEO of Tesla, Inc. While Tesla models have already shaken up the passenger car market and put great pressure on traditional car manufacturers, Musk is planning something similar in the commercial vehicle sector with the Tesla semi-truck. At the time of writing, however, the vehicle can only be reserved and has not reached state of production yet [9].

The picture is similar for a competitor in the field of commercial vehicles with alternative drive-systems. Nikola Corporation, also an American group, is working exclusively on battery electric and fuel-cell electric trucks. For their latest heavy-duty truck model Nikola Tre, they partnered up with the Italian vehicle manufacturer Iveco S.p.A. and announced plans to produce a battery electric version in 2021 and a fuel cell electric version in 2023 [10], [11]. General Motors Company (GM) has announced that it will sell exclusively zero-emission vehicles by 2035 [12]. Although this statement refers to passenger cars, it puts additional pressure on vehicle manufacturers around the world. There have been similar developments in Europe. Two of the biggest players when it comes to commercial vehicles, Daimler Truck AG and Volvo Group AB, have founded the joint venture cellcentric GmbH & Co. KG. The Daimler Group brings many years of experience in the fuel cell sector. According to their website, their ambition is to make cellcentric a leading global manufacturer of fuel cells, and thus help the world take a major step towards climate-neutral and sustainable transportation by 2050 [13]. Swedish truck and bus manufacturer Scania AB is testing the use of hydrogen in a combustion engine. To this end, the company of the Volkswagen Group has launched a joint research project with Westport Fuel Systems, Inc., a Canadian company specializing in natural gas [14]. Two German heavy-duty vehicle manufacturer MAN and Mercedes-Benz (brand of Daimler Truck AG) have launched a version of an all-electric battery truck [15], [16]. Vehicle manufacturer Traton SE, the parent company of MAN and Scania, sees only a niche existence for trucks powered by hydrogen, while Daimler and Iveco clearly see the future of long-haul trucking in hydrogen and are pushing ahead with their work on corresponding vehicles [17].

This current situation lends to the conclusion that a transition to low-carbon freight transport is not possible yet, because the market of such vehicles is non-existent. Despite existing investment potential and efforts by fleet operators to increase sustainability, there are currently hardly any vehicles available that fully accommodate the variety of use-cases in the freight sector.

One could now hastily conclude that the situation in Switzerland hardly presents a different picture and that it is more or less dependent on developments abroad due to its small market. This is, however, not the case. For example, H_2 Energy AG has created a new business model together with the joint venture Hyundai Hydrogen Mobility AG, which was founded by them and Hyundai Motor Company, the Swiss company HydroSpider AG, which produces sustainable hydrogen (green hydrogen), and filling station operators. Truck operators can rent a vehicle designed specifically for Swiss applications on a pay-per-use basis through the vehicle manufacturer. The vehicles obtain the hydrogen exclusively from the participating filling stations, which guarantees a certain minimum sales volume for them and ensures the quality standards of the green hydrogen. At the time of writing, there are 27 such fuel cell trucks on Swiss roads and six filling stations in operation. This is a unique model which is increasingly garnering attention. It offers an approach to solve the well-known chicken-and-egg problem of vehicle fleet size and refueling station infrastructure [18].

There are also three companies in Switzerland that convert trucks with conventional drive systems to battery electric vehicles. At the end of 2013, E-Force One AG tested a purely electric truck for the traditional Swiss brewery Feldschlösschen. The EFORCE E18 was the world's first series-produced all-battery-powered 18 t truck [19]. Ceekon AG is also converting diesel trucks into battery-electric trucks in collaboration with the Dutch company emoss. With a 44 t MAN semitrailer tractor, they have tapped the maximum weight limit in the Swiss road transport sector for the first time with an electric truck [20]. Designwerk Products AG produces electric commercial vehicles under the Futuricum brand. They offer a variety of electric trucks for recycling, construction, distribution, and agricultural and forestry logistics. Just a few months before this study was completed, three all-electric concrete mixers were delivered to Holcim Ltd., a global building materials producer headquartered in Switzerland [21].

1.2 Overview of the field

This section presents an overview of the field of research. At first, the reader is introduced to published literature investigating non-freight as well as freight transport. Second, a summary of past and current Swiss policy is presented. The understanding of such is crucial to allow for a constructive discussion of possible policy interventions.

1.2.1 Literature review

There are many studies that analyze scenarios for decarbonizing the transportation sector investigating long-term options for zero tailpipe emissions technologies. A frequently chosen method is a total cost of ownership (TCO) assessment. Such an evaluation allows for cost comparison of different options over the whole lifetime of a vehicle, rather than comparing upfront costs only. While electric vehicles may perform better than those with an internal combustion engine (ICE), consumers perceive them to be more expensive due to higher capital expenditures (CAPEXs) [22]. This is different when it comes to commercial vehicles. The freight sector is concertedly more attuned to the total cost of the vehicle over its full operational lifetime. Such vehicles have a higher daily utilization rate and span longer lifetimes [23]. The TCO and payback period are main purchase criteria of fleet operators regarding the acquisition of new commercial vehicles [24].

Within the studies reviewed, TCO analyses are much more common in the passenger vehicle sector than they are in the commercial vehicle sector. But TCO comparison studies for commercial vehicles are increasingly gaining notice. Among these, the earliest and most frequently referenced is an EU-commissioned study on zero-emission trucks, which evaluates TCO for BETs and FCETs over three selected years in Europe [25]. Subsequent studies have followed from research groups as well as international agencies and consultancies. Although a considerable number of such studies have meanwhile been published, they all differ in scope, modeling methods, focus of analysis, boundary conditions and input parameters. Palmer et al. [4] provide a more extensive TCO assessment of conventional, hybrid, plug-in hybrid and battery electric vehicles in the UK, USA, and Japan. Wu et al. [22] performed a probabilistic analysis for electric vehicles capturing most of the national market in Germany. Both studies focus on passenger vehicles exclusively.

In the freight sector, there is a variety of studies that present possible approaches to decarbonization. The International Energy Agency (IEA) has dedicated an entire report to the future of trucks [26]. In their Modern Truck Scenario, they introduce targeted efforts to modernize road freight transport such as reducing oil demand from road freight vehicles. They also review the status and prospects of alternative fuels, including natural gas, biofuels, electricity, and hydrogen. Mulholland et al. [27] used the IEA's techno-economic simulation model “Mobility Model" (MoMo) to calculate future energy demand and emissions of road freight activity. The maximum potential of reduction in GHG emissions between 2015 and 2050 was found to be 60%. The limitations of such models is their tendency to focus on the measures needed to reduce emissions and evaluating the reduction potential from these options. Their main objective of achieving sustainability targets of different scenarios leads them to avoid a thorough consideration of the economic feasibility of the chosen solution. While the IEA concluded that the global transport sector could reduce its CO_2 emissions worldwide by 40% in 2050 relative to 2005 with measures costing not more than USD 200/t, costs may vary greatly between the different measures [28].

Case studies for Switzerland have also been published. A group of researchers at ETH Zurich have published two separate studies. One focuses on battery electric propulsion and its potential to power actual heavy-duty operations [29] and another one on fuel cell electric vehicles [30]. They introduce a data-driven, bottom-up approach to explore the technical limits of electrification. According to their results, a full electrification of the entire truck fleet by batteries increases Swiss electricity demand by about 5% (3 TWh per year), avoiding about 1 Mt of CO_2 per year, and by fuel cells with hydrogen produced exclusively by electrolysis an increase in electricity demand by 13% (8 TWh per year), leading to virtually no overall emission reduction with the current Swiss consumer mix. They conclude that hydrogen is technically a very attractive decarbonization option, but only if hydrogen production is truly renewable and vehicles have adequate access to additional energy during the day (fueling infrastructure). This has also been proven by expert interviews conducted within this study to be the main issue. Liimatainen et. al [31] show that national and sectoral differences in freight transport operations affect the viability of electric trucks. They further conclude that the degree of electrification is highly depending on the type of commodity transported. In their study, they estimate that 71% of road freight transport in tonne-kilometers may be electrified in Switzerland, whereas in Finland this potential is limited to 35% due to the use of long and heavy truck-trailer combinations. They also point out the fact that electric trucks have a large impact on the local grid near charging stations which needs to be considered when electrifying a fleet. Thalmann and Vielle [5] focus on the deep decarbonization pathways for Switzerland demanding a strong contribution from the transport sector. In their study, they simulate a CO_2 levy on thermal and transport fuels on different Swiss carbon budgets. Their main findings include the raised welfare cost of decarbonization through the preferential treatment of transportation fuels, compared to thermal fuels.

We find a few key gaps in the literature as a result of this literature review. To begin with, there is a lack of a comprehensive understanding of how drive-technology competition for road-freight vehicles differs by country and application. Cost estimates, statistical methods, considered time-periods, and regional scope are heterogeneous throughout studies and reports, which makes it difficult to compare results.

Furthermore, with dramatic cost reductions for rapidly maturing technologies in recent years, BETs and FCETs that were previously unavailable in the freight vehicle sector now appear to be completely viable. However, we find that it is still unclear how economically feasible low-carbon drive-technologies are as a solution to the road-freight sector. Finally, we find few comparative policy analyses of the industry, making it difficult to determine how and where policy intervention is most relevant. While the need for a transition to low-carbon pathways is rarely discussed, the debate over the choice of pathway is more relevant than ever. By setting ambitious CO_2 emission performance standards, politics strives for such a transition without endangering the economy. Reducing the fuel consumption of vehicles focuses mainly on incremental developments.

1.2.2 Current Swiss policy

Like many other countries, Switzerland has several transport-related policies that aim to reduce GHG emissions. This chapter provides an overview of some of the most important measures relating to road freight transport taken.

The Swiss toll **LSVA** is a performance-related heavy vehicle charge introduced in 2001. It must be paid by all vehicles and trailers that:

- have a gross vehicle weight of more than 3.5 t,
- are used for the carriage of goods and
- are registered in Switzerland or abroad and drive on Swiss public roads

Vehicles with electrical drive-technologies, agricultural and emergency service vehicles, among others, are exempted from the LSVA toll [32]. This data situation, as a result of this toll, is highly unique as Switzerland is one of only three countries world-wide to tax the usage of *any* of its roads, not just motorways, collecting such detailed data from freight vehicles [29]. This allows us to know every kilometer driven by all commercial vehicles >3.5 t with only a few exceptions. The recording is done by devices which are installed in the vehicles. The devices are equipped with GPS and thus record the distance traveled. The maximum permissible weight (MPW) of the vehicle and the MPW of the trailer, if attached, must be declared by the driver. However, the device detects via the electrical connections whether there is a trailer or semitrailer on the towing vehicle and prompts the driver to make the declaration. In addition, radio beacons on the highway serve as a check. These detect the declared combination via the LED lights on the windshield and validate via cameras whether a trailer or semitrailer has been coupled. The weight of the combination can be verified by means of a mobile traffic control. The transport companies receive a monthly invoice to settle the toll. This toll is calculated based on three parameters:

- Kilometers driven
- Relevant weight
- Rate according to emission

A simple example demonstrates the calculation of the toll:

Parameter	Value
Vehicle MPW	18 t
Trailer MPW	18 t
Gross train weight	32 t
Emission rate	2.28 Rp./km
Distance	1,000 km

Figure 1.6 & Table 1.1: LSVA calculation example for a rigid truck with trailer.

$$LSVA\ toll = 32\,t \times 2.28\ ct./km \times 1000\,km = 729.60\,CHF$$

Note: The relevant weight in this case is 32 t, since the vehicle MPW + trailer MPW is higher than the gross train weight (GTW). The tractor-trailer combination of the example is not allowed to be heavier than 32 t, although the two components separately can be 18 t each.

According to the federal law on performance-related heavy vehicle fees, the purpose of the performance-related heavy vehicle charge is to cover the infrastructure costs and costs attributable to heavy vehicles at the expense of the general public in the long term, insofar as they are not already covered by other services or charges. Furthermore, the charge also helps to ensure that the general conditions for rail in the transport market are improved and goods are increasingly transported by rail (modal shift) [33]. Thus, the toll serves not only to cover the costs directly incurred such as road wear, but also to internalize negative externalities. Currently, ZEVs are exempted from LSVA. Since they contribute equally to the wear of the road as ICE vehicles and also produce some sort of emissions and other negative externalities like particulates and traffic jam, they will sooner or later fall under the LSVA obligation in some way. The CO_2 savings induced by this policy measure were estimated at 3 million tons for the period 2001-2030 [34]. At the time of writing, the Federal Customs Administration *(Eidgenössische Zollverwaltung)* (FCA) is in the midst of a digital transformation, gradually evolving into the Federal Customs and Border Security. The key element of this comprehensive transformation is the DaziT program, which was officially launched on January 1^{st}, 2018 and will last until the end of 2026. With the connection of Switzerland to the European toll system EETS, essential preparatory work was carried out for the planned renewal of the LSVA collection system for domestic fleet owners in 2024. While this project is mainly concerned with digitization and the collection method, it also includes possible changes to how the toll is calculated. One proposal under discussion considers levying the charge based on the number of axles instead of the gross weight. This plan has been met with some criticism from national transport companies. Fleet operators that have voluntarily reduced the decisive weight of their vehicles in recent years and thus entered a lower gross weight value in the vehicle registration document see the resulting cost savings in jeopardy if the number of axles is defined as the decisive vehicle parameter [35].

Since 2008, Switzerland raises a **CO_2 levy** on fossil fuels. It's an incentive fee that supplements voluntary and other CO_2-related measures. Its purpose is to reduce the use of fossil fuels and thus lower CO_2 emissions [36]. The parliament decided in 1999 to split the 10% emissions reduction targets for the period 2008-2012 compared to 1990 committed under the Kyoto Protocol into two separate targets for heating and process fuels (thermal fuels, target: 15% reduction) and motor fuels (transport fuels, target: 8% reduction). This was to avoid other sectors being forced to compensate emissions in transportation [37]. This split is still clearly evident in the case of the CO_2 levy. The levy has been raised gradually to 96 CHF/t CO_2 (in force since January 1^{st}, 2018) for fossil fuels such as heating oil, natural gas, coal, petroleum coke and other fossil combustibles that are used to generate heat, produce electricity in thermal plants or operate combined heat and power plants, but still exempts transport fuels. A voluntary contribution by industry members of the transport fuel sector of 1.5 Swiss cents per liter gasoline and diesel (*Klimarappen*) into a fund managed by a foundation created by this same sector, the Climate Cent Foundation, was introduced as an alternative to the introduction of a CO_2 levy. Between October 2005 and August 2012, it levied the surcharge and used the revenue to finance measures to reduce GHG emissions in Switzerland and abroad. According to the Federal Department of the Environment, Transport, Energy and Communications *(Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation)* (DETEC), the foundation has fulfilled its agreement with the Swiss

Confederation. For the period 2013 to 2020, the Climate Protection and CO_2 Compensation Foundation (KliK) is the industry-wide CO_2 compensation community of the current CO_2 Act. Instead of the mineral oil companies, it fulfills their legal compensation obligation for this period. The new foundation is financed by the same levy on all gasoline and diesel oil imports in the amount of currently 1.5 Swiss cents per liter (the legal maximum is a compensation surcharge in the amount of 5 centimes per liter of fuel). These financial resources are used domestically for the financing, support, planning and implementation of compensation measures (offsetting) that are eligible under the provisions of the CO_2 Act [38].

At the time of publication of this thesis, a **revised CO_2 law** has been subject to an optional referendum and will be voted on by Swiss citizens on June 13th, 2021. The CO_2 law approved by Parliament in the 2020 fall session is a key prerequisite for achieving the long-term climate targets (see paragraph below) and is scheduled to come into force in 2022. With the revised CO_2 law, which is based on a combination of financial incentives, investments and new technologies, the Federal Council and Parliament have adopted various measures to this end. Important measures relating to the freight transport sector are summarized here. As in the current law, there is no CO_2 levy on transport fuels. Instead, the new law will adjust the previously mentioned cap to 10 centimes and, from 2025, to a maximum of 12 centimes per liter. This is to ensure that fuel importers do not pass on the costs of their offset projects excessively to motorists. If fuel importers exhaust this maximum, the fuel costs of an average household could increase by around CHF 4.50 per month by the end of the 2020's, according to the Federal Office for the Environment [39]. Offsetting means that the emissions generated in Switzerland must be offset with climate protection projects in Switzerland (as before) and now also abroad: in transport, buildings, industry or agriculture. A fixed proportion of the fuel offset projects must be implemented within Switzerland. In 2020, this share will be at least 10% of the emissions reduction. By 2024, the share is to be at least 15%, and thereafter at least 20%. Today, a CO_2 emission performance standard with a target value of 95 g_{CO_2}/km applies to new passenger cars and a target value of 147 g_{CO_2}/km for vans. From 2025, these target values will be reduced by 15% and from 2030 by 37.5% for new passenger cars and 31% for vans. From 2025, there will also be target values for new trucks. As with the emission performance standard for passenger cars and vans, these will also be in line with the EU regulation. Their emissions must then be reduced by 15% and by 30% in 2030. In addition to the aforementioned changes, the new law includes an increase in the CO_2 tax on fuels such as heating oil, natural gas and coal from 120 CHF/t_{CO_2} to a maximum of 210 CHF/t_{CO_2}. However, this only applies if CO_2 emissions do not fall sufficiently. Two-thirds of the money will be redistributed to the population and the economy. One third flows into the climate fund. The revised law also provides for an airline ticket levy, which can range from 30 to 120 CHF depending on the route. More than half of the money will be distributed back to the population and the economy. The rest flows into the climate fund. Under the new law, no heating systems based on fossil fuels would be allowed to be installed in buildings, which is hardly the case any more anyway. Existing buildings may continue to emit CO_2. They will only change if a heating system is replaced [40], [41], [42].

The long-term **climate strategy** of Switzerland ties in with the revised CO_2 Act. The law is said to put Switzerland back on track to mitigate climate change. Five years after the Paris Agreement, the Swiss government has revised its climate targets. By 2030, it wants to reduce its emissions by at least 50% compared to 1990. Furthermore, by 2050, Switzerland aims to have net-zero GHG emissions. This means Switzerland should not emit more GHGs than can be absorbed naturally or by technical means. On January 27th, 2021, the Federal Council adopted the corresponding "Long-Term Climate Strategy for Switzerland" [42]. The strategy is based in large part on the *Energy Perspectives 2050+* report published by the Swiss Federal Office of Energy *(Bundesamt für Energie)* (SFOE) in the fall of 2020 [43]. As an Alpine country, Switzerland is particularly affected by climate change, as temperatures here are rising twice as quickly as the global average. The Long-Term Climate Strategy formulates ten basic strategic principles that will shape Swiss climate policy in the coming years. It presents possible developments up to 2050 for the building, industry, transport, agricultural, and food sectors, financial markets, aviation, and the waste industry. It sets strategic targets for each of these sectors. The Long-Term Climate Strategy shows that Switzerland can reduce its GHG in transport, buildings and industry by almost 90% by 2050. The remaining GHG emissions from industry, waste management and agriculture will amount to around 12 million tonnes of CO_2 equivalents. These can be offset by Carbon Capture and Storage (CCS) and Negative Emissions Technologies (NET). As an innovative and financially secure country with near CO_2-free domestic power production, Switzerland is positioned well to achieve their net-zero target by 2050. An essential point made in the strategy is that the social and economic costs of unchecked climate change far exceed the costs of climate protection measures. The net-zero target is therefore also very much in Switzerland's economic interests. By moving away from fossil fuels such as oil, gas, petrol and diesel, Switzerland is also reducing its dependence on foreign countries [44].

One final policy that deserves special attention is the **modal shift policy** of Switzerland. Swiss transport policy aims to shift transalpine freight transport from road to rail. This policy is broadly supported and has been confirmed by Swiss citizens on several occasions: in 1992 with the approval of the New Rail Link through the Alps (*NEAT*), in 1994 with the acceptance of the Alpine Protection Article and in 1998 with the approval of the previously mentioned LSVA. The financing of large-scale railroad projects (*FinöV*) was even realized by increasing the value-added tax in 2001 [45]. The Alpine Protection Article requires that transalpine freight traffic must be handled by rail from border to border. At the same time, road-freight capacity in the Alpine region must not be increased. The Swiss Parliament has specified the requirements in the Freight Traffic Transfer Act and defined a maximum of 650,000 trucks that may cross the Swiss Alps by two years after the opening of the Gotthard Base Tunnel in 2018. However, this target was missed, as 941,000 trucks crossed the Alps in 2018 [46]. This shows once again that there is an urgent need for action in the area of road-freight transportation in Switzerland.

1.3 Motivation

It is worth focusing on road freight transport, not only because it accounts for a large share of Switzerland's GHG emissions, but also because history shows that it seems to be a major political challenge to reduce emissions from this sector. Thalmann and Vielle [5] model different policy scenarios and find, that deep decarbonization is not possible without involving the transport sector. This fact is also taken into account in Switzerland's current climate policy. When it comes to transportation, the *Energy Perspectives 2050+* report states [43]:
The transport sector currently emits the most greenhouse gases, so reducing GHG emissions in this sector plays a central role in achieving GHG targets.

- *The shares of (battery) electric vehicles must grow rapidly in all vehicle categories. In 2050, the stock of battery electric passenger cars will be around 3.6 million vehicles.*
- *In the long term, hydrogen, which is partly produced domestically, will play an important role in heavy-duty transport alongside battery-powered vehicles. The import of hydrogen requires a connection to the European network infrastructure.*
- *By 2050, it will be of great importance for the integration of renewable energies in the power system that a significant proportion of the charging processes of electric vehicles can be flexibly adapted to the supply of renewable energies.*
- *Furthermore, in addition to hydrogen, liquid electricity-based fuels (based on hydrocarbons) will be needed in the long term to reduce greenhouse gas emissions to zero in 2050.*

From the literature review, the current Swiss policies in place, and the federal climate goals, we draw the following research motivations:

1. To reach the goals of the Paris Agreement, we need to shift to low-carbon technologies in the transport sector.
2. To do so, we need to gain a better understanding of this transition to low-emission and zero-emission vehicles. The objectives must not only be sustainable, but also economically feasible.
3. With a better understanding, efficient ways must be found to use this knowledge to inform policy makers.
4. Finally, it is necessary to discuss, how such an examination of the Swiss case can inform the larger transition, i.e. the transport transition in other geographies.

From these motivations, two research questions are derived:

Research Question 1: What drives the market share competition between commercial vehicle drive-technologies in Switzerland?

Research Question 2: How do different policy scenarios affect the outcome of the drive-technology competition?

1.4 Objectives

The aim of this study is to provide answers to the presented research questions and show possible options for policy makers by looking at long-term solutions in the road-freight transport sector for zero tailpipe emissions technologies.

The first research question is addressed by projecting the road-freight transport transition for the Switzerland based on an accurate representation of the industry. This is done by building on an existing dynamics model and enriching it with very detailed Switzerland-specific transport data, additional parameters and carefully customized settings.

The model takes in a variety of current cost data and various projections of such. This allows to take uncertainty of future development and capacity uptake of the different drive-technologies into account. The special features and driving patterns of the Swiss transport sector are considered by means of representative weight categories and real-world range distributions. After a comprehensive segmentation of freight vehicles, the TCO for different drive-technologies is calculated. This is done by analyzing the specific components that contribute to the TCO. Addressing the freight transport sector, competitive technologies such as natural gas and biofuels are also considered. The model output, yearly market shares of newly registered freight vehicle's drive technologies, allows to assess the impact of the different input parameters on each application segment individually.

To gain a better understanding of the Swiss transport sector and its country-specific patterns, a detailed analysis of national transport performance is performed. Such accurate data on use cases is obtained by a comprehensive analysis, facilitated by the unique data situation owed to the collection system of LSVA. Since ZEVs are often range-restricted relative to their conventional counterparts and refueling infrastructure is still limited, the actual energy and power required to successfully complete a transport task is key. These data on use cases are complemented by expert interviews among different stakeholder groups which allow for a holistic perspective of the Swiss road-freight industry. Their feedback is considered in the model inputs as well as in the discussion of the results.

To address the second research question, several possible policy intervention are modeled using reasonable scenarios. A first such policy intervention aims at different LSVA tariff structures as well as an expansion of the current obligation by including 3.5 t vehicles. A second policy scenarios aims at eliminating the weight penalty of BETs based on payload losses due to heavy batteries. The approach that is being modeled allows BETs to have a higher MPW, compared to other drive-technologies. To display the full breadth of outcomes, the two extreme cases of scenario trajectories are modeled. For the technology and fuel cost components, a base case with reference scenarios is included.

1.5 Report structure

This thesis is structured as follows. Chapter 2 describes the methodology applied to answer the research questions, introduces the model framework and and provides a thorough elaboration of each model dimension and model inputs. Results of the model scenarios and the sensitivity analysis are presented in Chapter 3, followed by a discussion and policy implications of these results in Chapter 4. Chapter 5 emphasizes the most relevant points and summarizes the contribution of this thesis.

2 Methodology

In order to allow for comparable analyses of different vehicle concepts, the specification of the use case is crucial, as pointed out by Kleiner and Friedrich [24]. They outline the importance of the transport task, vehicle size and drive-technology. In order to provide a comparative cost analysis of specific modeled drive-technologies in specific applications, we use the TCO framework and modeling approach from Noll et al. [23] with some adjustments to the input parameters and segmentation of use cases.

The framework, which is laid out in three dimensions, is briefly introduced in Section 2.1. Thereafter, thorough elaboration of each of the model dimensions is presented in Section 2.2. The last Section 2.3 of this chapter shows how these intermediate results are obtained and how they are used as inputs to the model.

2.1 Overview and model description

The model is structured around defined use cases characterizing the region's road-freight pattern. It takes in cost data for a variety of parameters, such as battery and diesel costs, for example. Technology and fuel scenarios allow for different projections of technology and fuel component costs which are mainly depending on technological development and future deployment. Similarly, different policy scenarios alter some of the cost components or affect the composition of the cost calculation. For example, this can take place in form of subsidies or increasing emission performance standards. Based on this cost calculations, the model projects yearly market shares of specific drive-technologies (output). Figure 2.1 illustrates this in a highly simplified manner.

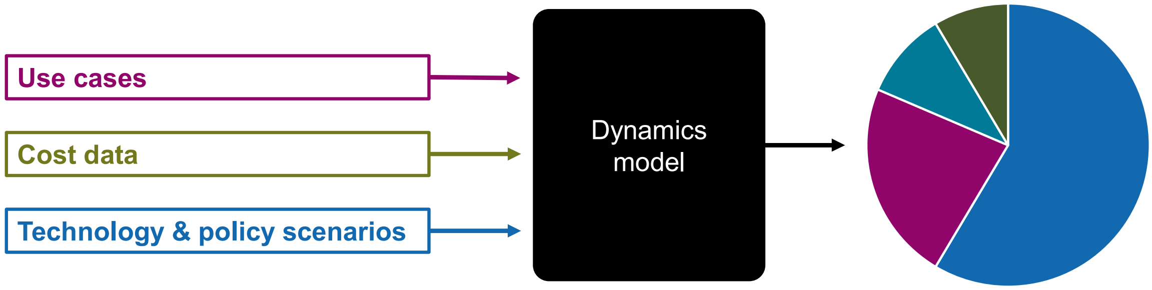


Figure 2.1: Overview of the dynamics model with different inputs and resulting output of yearly projected market shares of specific drive-technologies.

To account for the complexity of the road-freight transport system and its variety of use cases, a framework capable of characterizing the manner in which goods are transported is required. When assessing suitable drive-technology options, preferences are different for heavy-duty long-haul freight traffic compared to regional distribution networks or urban parcel delivery. The model used by Noll et al. [23] provides such a consolidated framework in which three dimensions—application, drive-technology, and geography—characterize and differentiate the road-freight transport landscape.

Application space

Within the application dimension, the framework is further segmented into a weight, range, and vocational dimension, as illustrated in Figure 2.2. In terms of vehicle size, the literature distinguishes between three broadly-defined categories of road-freight vehicles: light, medium, and heavy-duty trucks. For the range dimension, urban, regional, and long-haul traffic are common designations even though the associated distances may be different. Thus, the first two dimensions structure the physical landscape of road freight vehicles into a matrix of nine representative segments. The third dimension allows to further distinguish a vehicle's vocation to account for different payload, drive, and charge profiles.

The application matrix therefore provides a structural framework to categorize and segment the manner in which specified masses of goods are transported over representative distances with characteristic operational profiles.

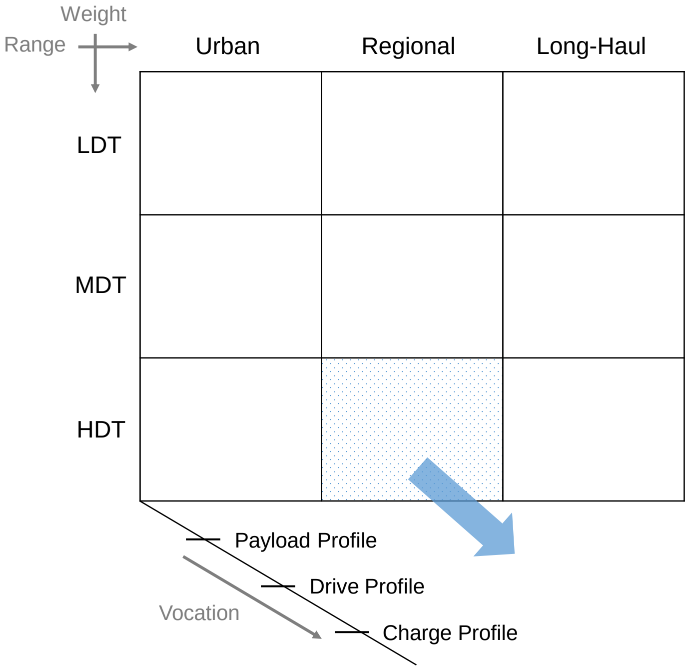


Figure 2.2: The application matrix characterizes the road freight landscape along the weight, range and vocation dimensions. Light (LDT), medium (MDT), and heavy (HDT) duty trucks travel in the urban, regional and long-haul ranges. Each matrix segment is then further characterized by the vocational dimension for which the payload, drive and charge profiles are defined [23].

Drive-technologies

In each application segment, selected drive-technologies are competing for market shares. The drive-technology is defined by the vehicle's primary propulsion method and the paired fuel type. For example, vehicles with an ICE may be fueled by diesel, biodiesel, or natural gas. All these fuel options are treated as separate drive-technology. The different technologies are considered as near-perfect substitutes. For a defined application, each technology can create the same value, though at varying costs.

The model runs iteratively in each of the application segments and projects the market shares of the specific drive-technologies for each segment of every year modeled. Therefore, the framework enables a comparative cost analysis of specific drive-technologies in specific applications and provides policy-makers an organized structure to discuss where, when, how, and in what manner to potentially place policy measures.

Geography

While the model used by Noll et al. analyses the competitiveness of low-carbon drive-technologies across multiple countries in Europe, this work focuses entirely on the case of Switzerland. As explained in Section 1.2.2, the data availability is highly unique. While this certainly contributed to the choice, the fact that ETH is located in Switzerland and the close contacts with industry were just as decisive for the choice of region.

2.2 Model framework

This section provides a thorough discussion of the model functionality and of the contributions and adjustments to the existing dynamics model. Since the geographic dimension is reduced to one country, it does not require any further elaboration.

2.2.1 Application segments

For this study, the weight dimension of the application matrix is segmented into seven vehicle weight categories which represent typical freight vehicle classes in Switzerland.

The light-duty truck (LDT) segment contains vans like the ones used by postal service providers to deliver packages. It includes all freight vehicle up to 3.5 t MPW. LDTs describes the lowest weight class and at the same time contains by far the highest number vehicles. In 2020, 28,592 vans up to 3.5 t were registered, while for all higher weight classes together there were 3,837 vehicles. This share matches with the current stock. With around 400,000 vehicles currently registered, approximately 88% of the domestic freight vehicles originate from the 3.5 t weight segment [47]. Moreover, it is the only category that can be driven with the conventional passenger car license. They are also completely exempt from the LSVA, regardless of the drive-technology, and pay only 40 CHF for the freeway vignette in addition to the conventional road traffic tax. This very low toll, which is also raised independently of transport performance, makes this weight segment an interesting subject for possible policy measures.

The medium-duty truck (MDT) segment consists of two typical weight categories. First, 7.5 t vehicles are larger vans, often equipped with dual wheel tires on the rear axle. They require a secondary driving license (subcategory of truck license) and cannot be driven with the Swiss passenger car license. Second, 12 t vehicles which mark the weight limit requiring the full truck driving license.

The heavy-duty truck (HDT) segment includes trucks with MPW of 18 t upwards. Within this segment, there is no further legal differentiation based on driving license or vehicle size. The characteristic vehicle weights are strongly oriented to the number of axles. The smallest weight category in the heavy-duty segment typically includes two-axle trucks with a wide range of use cases. Such trucks are often used for heavy freight transport in cities or regional distribution networks, and for the latter, they are also likely used in combination with a trailer. Since most tractor-trailers, which are often found on the highway with a semitrailer in long-haul traffic, correspond to two-axle vehicles of this weight class, this segment clearly contains the most vehicles with a weight $>$3.5 t. Where a two-axle truck can be up to 18 t, this number increases to 26 t with three axles, 32 t with four axles, and 40 t with five axles, which describes the highest weight class of road transport vehicles registered in Switzerland. This number of axles can be from both, the motor vehicle itself or combined with a trailer. However, if the latter is the case, the vehicle itself is registered with a lower MPW. For example, a typical two-axle tractor unit with a three-axle semitrailer may weigh 40 t in total. The motor vehicle itself, however, is registered with up to 18 t MPW. This differentiation becomes important when switching from transport performance data to new vehicle registration data.

For the range application, the common segmentation into urban, regional, and long-haul traffic is adopted. We consider daily trips between 50 and 100 km/day as urban freight traffic. Regional traffic includes distances from 100 to 250 km/day and long-haul traffic covers everything beyond 250 km/day. This segmentation is derived in Section 2.3.1.

The first two dimensions give us a matrix of 21 representative application segments, illustrated in Figure 2.3. The weight and distance dimension classifications reflect typical vehicle use cases of the Swiss road transport sector and are a result of the comprehensive LSVA data analysis, which is described in more detail in Section 2.3.1. These application segments may be categorized differently for other regions. The model runs iteratively in each of the application segments. The third dimension covers payload, drive, and charge profiles, which can depend on the application segment and the drive-technology. Within this study, a constant payload capacity is used for every weight segment (Table 2.1). The payload values are collected from online research on market models. The percentage of total payload capacity are in line with Noll et al. [23].

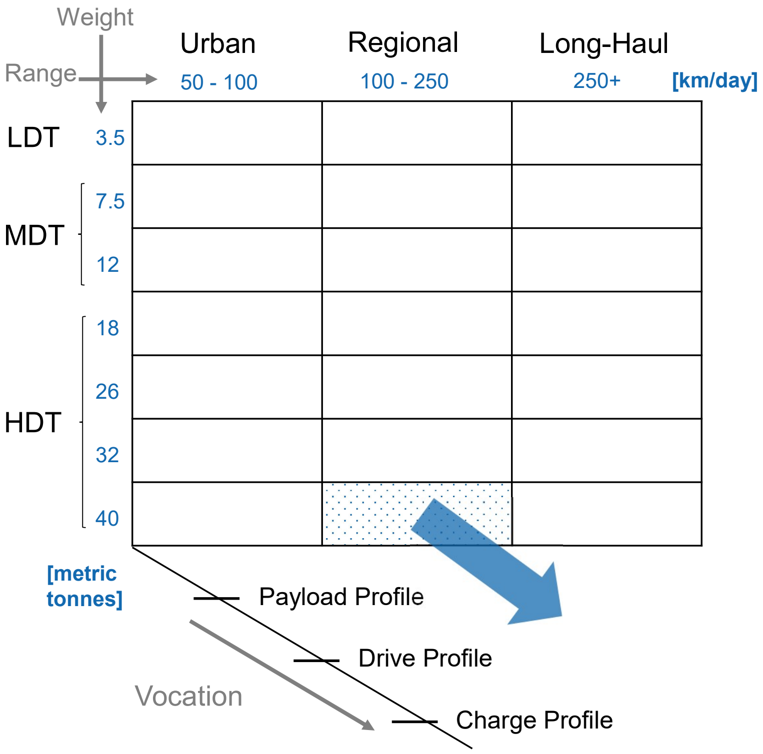


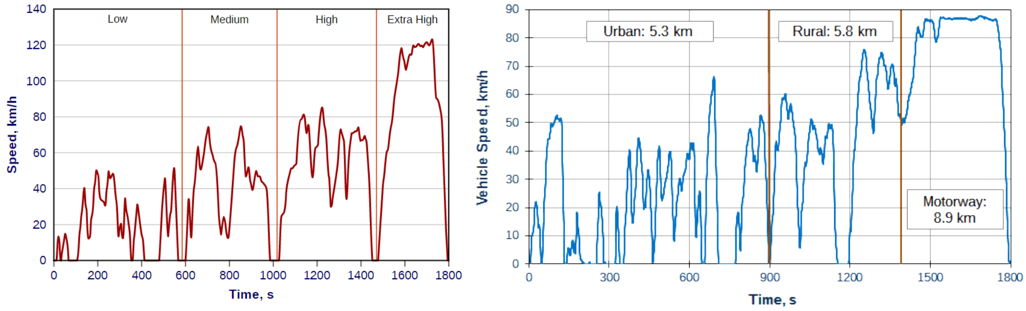
Figure 2.3: Swiss-specific application matrix for the model framework.

Table 2.1: Payload values and payload capacity used.

Application	Weight segment [t]	Payload [kg]	Payload Capacity
LDT	3.5	1,000	0.50
MDT	7.5	3,000	0.75
	12	5,000	0.75
HDT	18	8,000	0.75
	26	14,000	0.75
	32	18,000	0.75
	40	25,000	0.75

For the drive profiles, a first attempt was to use real-world drive profiles from fleet management software. Although such data were generously provided by fleet operators, the temporal resolution of the transmitted velocity values was unfortunately not sufficient for the calculation of realistic values. Instead, the World Harmonized Light-duty Test Cycle (WLTC) class 2 is used for the LDT and MDT segments and the World Harmonized Vehicle Cycle (WHVC) for the HDT segment (see Fig. 2.4). Both of these drive cycles are considered suitable approximations for their respective real-world applications [23].

The refueling process—in this sense referring to both the filling of liquid or gaseous fuels as well as the charging of a battery—describes an important component in a fleet operator's planning. Particularly time-intensive refueling procedures can make a drive-technology less competitive. In order to reduce such time-intensive refueling for BETs, there are two frequently discussed approaches: in-motion charging by means of overhead catenary systems or battery-swapping. Since neither of these technologies are likely to have the required infrastructure set up in Switzerland in the near future, only overnight charging of BETs is assumed.



(a) World Harmonized Light-duty Test Cycle (WLTC) for Class 2 vehicles

(b) World Harmonized Vehicle Cycle (WHVC)

Figure 2.4: Drive profiles from world harmonized vehicle drive cycles with defined velocity profiles [48].

2.2.2 Technologies considered

Despite the fact that ICEs dominate the existing road-freight vehicle market, a number of alternative drive-technologies are emerging as viable conversion options. The following drive-technologies are included in the calculations: within the group of internal combustion engine vehicles (ICEVs), we distinguish between conventional internal combustion engine - diesel trucks (ICE-Ds), the drop-in alternative internal combustion engine - biodiesel trucks (ICE-BDs), internal combustion engine - liquefied natural gas trucks (ICE-NGs) and hybrid electric trucks (HETs), equipped with a diesel engine and a battery module. Following the argumentation of Noll et al. [23], we choose ICE-Ds, ICE-NGs, and HETs due to their technical maturity. At the same time, biodiesel is seen by certain stakeholders in Switzerland as an option for rapid decarbonization. Based on such feedback from expert interviews, this study also includes this drive-technology. We acknowledge that HET, ICE-BD, and ICE-NG vehicles will not enable a zero-emission future, but they are still essential bridge technologies to achieve this target. BETs and FCETs are viewed as ZEVs and considered by policy-makers as options to lower GHG emissions from road-freight. Strictly speaking, of course, these are not zero-emission drive-technologies, since they are responsible for vehicle and fuel production-related emissions. Table 2.2 provides an overview of the different vehicle components considered in the CAPEX calculations of each drive-technology.

Table 2.2: Overview of drive-technologies CAPEX components.

CAPEX components	Drive-technology					
	ICE-D	**ICE-BD**	**ICE-NG**	**HET**	**BET**	**FCET**
Energy storage	Diesel tank	Biodiesel tank	LNG tank	Diesel tank Battery	Battery	Hydrogen tank Battery
Engine/ motor	ICE	ICE	ICE	ICE E-motor	E-motor	Fuel cell system E-motor
Additional systems	Exhaust system	Exhaust system	Exhaust system	Power electronics Generator Exhaust system	Power electronics Plug-in charger	Power electronics
Rest of truck	Glider and transmission	Glider and transmission	Glider and transmission	Glider and transmission	Glider	Glider

2.2.3 Total cost of ownership decomposition

The TCO is a crucial parameter in the freight business. Unlike the passenger vehicle industry, the commercial vehicle industry is focused on the overall cost of the vehicle over its entire operating life. The intense competitive pressure does not allow fleet owners to face a higher TCO for the same transport service provided [49]. While the CAPEX may be higher for vehicles with an alternative-drive, the operational expenditures (OPEXs) may enable lower long-term costs. This can be achieved by increased operating efficiency of the technology's core functionality, as well as by decreased fuel and maintenance costs of the new technology. Combining the CAPEX and OPEXs allows for a comparison of the cost effectiveness of alternative-drive vehicles over their complete lifetime [23]. Therefore, we base our cost comparison on calculated TCO values for specific drive-technologies on the in Section 2.2.1 specified application segments. The TCO equation from Wu et al. [22] is used and adjusted to parameter labels and addition or reconfiguration of select parameters.

$$TCO_{a,t} = \frac{(CAPEX_{a,t} \; - SUB_{a,t} \; - \; SV_{a,t} \cdot P\ V\ F) \cdot C\ R\ F + \frac{1}{N_a} \sum_{n=1}^{N} \frac{OPEX_{a,t}}{(1+i_r)^n}}{AKT_a}, \tag{2.2.1}$$

where TCO is the total cost of ownership per kilometer (EUR/km), $CAPEX$ is the capital expenditure or initial purchase cost of the vehicle (EUR), SUB is the subsidy on the initial vehicle purchase, SV is the scrappage value, $OPEX$ is the operating expenditure or annual operating cost (EUR), N is the lifetime of the vehicle (years), and AKT is the annual kilometers travelled (km). For the discounting terms, PVF is the present value factor $= 1/(1+i)^N$, CRF is the capital recovery factor $= (i(1+i)^N)/((1+i)^N - 1)$, and i is the discount rate. Subscripts a and t refer to the application, and drive-technology dimensions, respectively.

Within this study, five main contributions and modifications are made to the TCO calculation. First, different LSVA tariffs are modeled. The scenarios are explained in Section 2.3.3. Second, ICE-BD is introduced as an additional drive-technology in Section 2.2.2. This is done after receiving feedback from industry seeing biodiesel as a feasible option to reduce GHG emissions in the near future at low costs. Third, the insurance fees are adjusted for Switzerland. Cost data of insurance fees were obtained from fleet owners and insurance companies. The insurance fee is set to 3% of the vehicle's CAPEX for all weight categories. Fourth, a penalty is introduced for BETs if the required battery weight results in payload losses. A policy to eliminate such penalty is presented in Section 2.3.4 and its effects on market shares discussed in Section 3.5.4. Fifth, the assigned range a vehicle has to be able to cover without refueling or recharging is reflected by actual Swiss drive patterns, which results from the LSVA data analysis explained in Section 2.3.1. The annual kilometers travelled (AKT) are a function of the vehicle's daily range multiplied by the number of working days per year and are thus also affected.

Figure 2.5 provides an overview of all cost components considered. Framed components listed appear in the TCO equation of every drive-technology, where unframed components depend on the technology assessed and may not be included. Contributions and modifications made are denoted by superscripts.

We calculate the TCO for the years 2019 to 2035, where 2019 serves as the base year. This time period allows realistic assumptions on cost developments and price scenarios. It ends in 2035 to mark the halfway point to the net-zero emissions targets by 2050. It also includes the important year 2030, which defines interim targets for the Long-Term Climate Strategy for Switzerland (Section 1.2.2).

All cost data has been previously collected and updated where required. For values and sources, please refer to the supplementary documentation submitted with this thesis. For a more detailed elaboration on the other TCO components, please refer to Noll et al. [23].

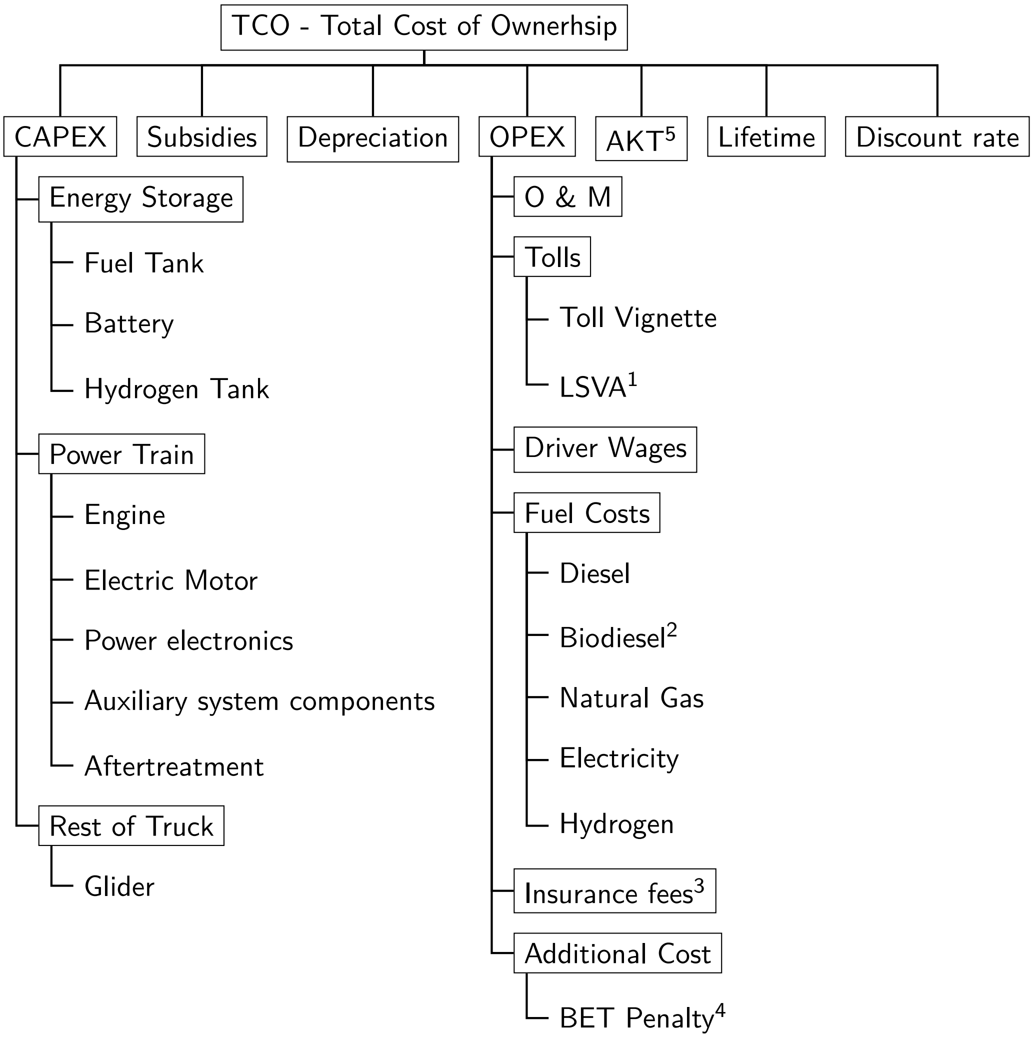


Figure 2.5: TCO decomposition tree. [1]For different LSVA scenarios, see Section2.3.3.[2]Introducing biodiesel as an additional fuel option, see Section 2.2.2.[3]Insurance fees updated.[4]Penalty for BETs introduced if payload losses occur, see Section 2.3.4.[5]Daily ranges according to Swiss drive patterns and thus adjusted AKT.

2.2.4 Power and energy ratings

The power and energy a vehicle requires to perform its transport task is depending on the application segment. As described in Section 2.2.1, this specifies the vehicle's weight and range, as well as payload, drive, and charge profile. This thesis employs the power and energy calculation methodology from Noll et al. [23] but modifications are made to the weight and range distribution to more accurately reflect the Swiss road-freight transport landscape.

Using drive profiles from world harmonized vehicle drive cycles allows for use case specific power and energy demands of the vehicle, which provides the performance specifications for a bottom-up vehicle cost formulation. It is assumed that every vehicle must be equipped with enough power to perform the assigned drive cycle fully laden. Equation 2.2.2 shows the propulsion power calculation as a function of time (time point in the drive cycle). The formula for vehicle propulsion power from the standard dynamic vehicle model is used [50]:

$$P_{prop}\left(t\right) = [\frac{1}{2} \cdot \rho_{air} \cdot \ c_D \cdot \ A_f \cdot \ v^2\left(t\right) + m \cdot \ g \cdot \ c_r + m \cdot \frac{dv\left(t\right)}{dt}] \cdot v\left(t\right) \ , \tag{2.2.2}$$

where ρ_{air} is the air density, c_D is the coefficient of drag, A_f is the frontal area, m is the total mass of the vehicle (maximum payload included), g is the gravitational constant, c_r is the coefficient of tire rolling resistance, and $v(t)$ is the velocity as a function of time. The gravitational constant and air density are ambient properties which marginally vary with the location of the vehicle. All other parameters are vehicle specific and thus depend on the application segment. Note that the road slope term is ignored in the propulsive power formulation (Equ. 2.2.2) as it has been found, that the type of mission, i.e. urban, rural or highway has a much higher impact on energy demand than topography [51]. This assumption is also in alignment with the work of Cabokoglu et al. [29].

A vehicle's required power is defined by adding the maximum propulsion power value to the vehicle's auxiliary power:

$$P_{vehicle} = max(P_{prop}(t)) + P_{aux} \ , \tag{2.2.3}$$

where P_{aux} is the total auxiliary mechanical power demand of the various non-propulsive subsystems of the vehicle, such as air conditioning or steering. The auxiliary power is a constant term that depends on both the application segment and the drive-technology.

It is also assumed that every vehicle must be equipped with enough energy to complete the required daily range without refueling or recharging. Integration of the total power over the specific drive cycle velocity profile yields the total energy demand for the trip:

$$E_{total} = \int\limits_{Drive\ Cycle} \frac{P_{total}\left(t\right)}{v(t)} \ dt; \quad where \ P_{total} = H\left(P_{prop}\right) \cdot \ P_{prop} + P_{aux} \ , \tag{2.2.4}$$

where H is the Heaviside step function, the value of which is zero for negative arguments and one for positive arguments. Thus, purely dissipative breaking is assumed. Equation 2.2.4 yields energy per unit distance (kWh/km) and is then multiplied by the range to determine the energy demand of a vehicle (kWh).

Instead of using constant range values, the detailed LSVA data allows for a more accurate approach. Since the drive pattern of every vehicle is known, we can derive range distributions for each of the previously defined use cases urban, regional, and long-haul, for each weight class. To do so, we use the Gaussian kernel density estimation to estimate the probability distribution of our range variable (Fig. 2.6a). This allows for a smooth density function representing the actual daily range values distribution from the LSVA data.

To be able to draw random range values while following this density distribution, we form the cumulative sum of the density values according to Equation 2.2.5 and normalize it (Fig. 2.6b).

$$\tilde{y}_k = \frac{y_k}{\sum_{i=1}^{m} y_i}; \qquad where\ y_k = \sum_{i=1}^{k} y_i\,, \tag{2.2.5}$$

where y_i is the probability of a value in the range density distribution and results from the Gaussian kernel density estimation, y_k is the cumulative probability of a value in the range density distribution, m the number of possible outcome range values, and $\tilde{y}_k$ is the normalized cumulative probability of a value in the range density distribution. These resulting cumulative distribution values allows us to look up n randomly drawn values between 0 and 1 following a normal distribution, where n is the number of investors simulated, and returns the corresponding range value. In other words, any number between 0 and 1 on the y-axis of Figure 2.6c yields a range value on the x-axis to a certain probability. This allows us to replicate real-world range distributions from Switzerland for every application segment and every investor. The described steps are summarized and illustrated in Figure 2.6 using the 40-Regional segment as an example. The results of this procedure for all application segment is described in Section 2.3.1 and illustrated in Figure 2.12.

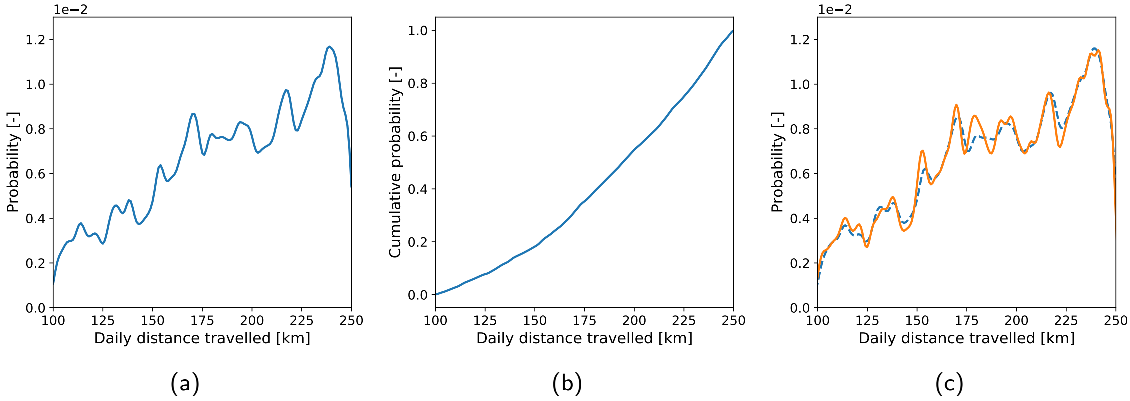


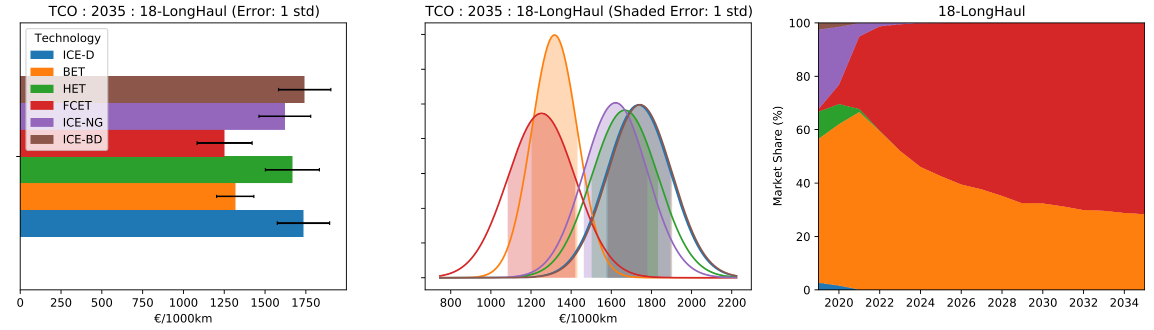
Figure 2.6: Range distribution example of the 40-Regional application segment. (a) Probability kernel density estimation from LSV data. (b) Cumulative probability of range values. (c) Resulting range distribution from draws (colored line) and actual range distribution from LSVA data (dashed line).

2.2.5 Probabilistic model

The uncertainty of input parameters is taken into account for the initial values in the base year 2019 as well as the projection of these values until 2035. Cost uncertainty of CAPEX and OPEX parameters is modeled with a probabilistic Monte Carlo simulation, based on the work of Noll et al. [23].

The relative impact of the parameter on the sensitivity of the TCO and thus the effects, as well as the relative uncertainty of the parameter itself, are used to evaluate the stochastic nature of a TCO parameter. Thus, parameters with relatively definite or even constant cost data, as well as parameters that have a minor impact on the TCO are not stochastically modeled. An assessment of the impact of all parameters is presented by a sensitivity analysis in Section 3.3.

First, the model calculates the TCO for each technology in each application segment of every year modelled. The decomposition of the TCO is described in Section 2.2.3. Second, a Monte Carlo simulated investor selection method is used to simulate outputs using the probabilistic inputs with specified stochastic distributions. We run 10,000 simulations for each dive-technology in each application segment from the base year 2019 to the last year modeled 2035. This simulated investor makes the decision for one drive-technology based on the TCO results. This means, an investor always picks the drive-technology with the lowest TCO. However, each investors sees a different cost for the same technology in the same application segment and the same year, due to the stochastic nature of the TCO parameters. Following this approach, we account for the uncertainty of cost components. Figure 2.7 contains plots of the three steps described.



(a) TCO values (b) TCO distributions (c) Market shares

Figure 2.7: After calculating TCO values for each technology in each application segment (a), an investor decides on a technology based on the TCO distributions (b). Repeating these steps yields market shares from 2019 to 2035 (c).

2.3 Model inputs

Out of the model parameters that were introduced in the previous sections, four main contribution to the dynamics model made within this study deserve further explanation. This section provides further insights of how the contributions were achieved. First, the range distribution and weight segmentation explained in Section 2.2.1 are results from a thorough and extensive data analysis that accounted for a considerable part of this work. The data analysis itself and the results, which function as model inputs to some extent, are presented in the next section. Second, to inform, understand, and validate the model introduced in Section 2.2, a number of expert interviews were conducted. The structure of the interviews, a list of interviewees and the main takeaways are summarized. Third, the scenarios used for different model cases are explained and discussed. Fourth, the BET penalty as an additional TCO component, which was introduced in Section 2.2.3, is further elaborated.

2.3.1 LSVA data analysis

In order to obtain a detailed understanding of the driving patterns of Swiss commercial vehicles, a comprehensive analysis of LSVA data covering five years of transport performance was performed. The data received from FCA consists of log entries for each commercial vehicle in Switzerland which is subject to LSVA and equipped with a LSVA monitoring device. Recall that such a device is mandatory for commercial vehicles registered in Switzerland and MPW >3.5 t. It is not mandatory for foreign vehicles, yet obtainable. Alternatively, foreign vehicles are recorded by manually entering the mileage when entering and leaving Switzerland. However, this does not allow any conclusions to be drawn about the daily mileage if the vehicle stays in Switzerland for multiple days. Since this study only examines vehicles registered in Switzerland and transport services on Swiss roads, foreign vehicles and kilometers driven abroad by vehicles registered in Switzerland are not included. The following events trigger a log entry:

- Ignition ON (only first ignition on per calendar day is logged)
- Calibration (alignment of vehicle odometer reading to tachograph by garage)
- Exit (vehicle leaving Switzerland)
- Entry (vehicle entering Switzerland)
- Trailer ON (attaching a trailer to a rigid truck)
- Trailer OFF (detaching a trailer from a rigid truck)
- Semitrailer ON (attaching a semitrailer to a tractor unit)
- Semitrailer OFF (detaching a trailer from a tractor unit)

Covering 68’412 vehicles and a period of five years from 2015 to 2019, the data set consists of more than 110 million log entries. Since the log entries only cover events where a LSVA relevant variable changes (except from ignition ON), extensive data processing is required to extract the distance travelled with the corresponding vehicle combination weight. For example, the log entries contain the current mileage reading. Thus, the distance needs to be calculated as a difference between two entries.

In addition, it has to be determined whether the vehicle had a trailer or semitrailer attached between two such entries, how heavy it was, and whether the vehicle had been in Switzerland at all. Such a determination is not trivial. Only when a trailer is coupled, for example, a log entry is produced and the declared weight recorded. In all following days this does not happen again. To determine the current combination and the applicable total weight for any given day, previous or subsequent entries are therefore required. To illustrate the data set, a subset of entries of one vehicle are presented in Table 2.3. The first six columns contain raw data as received from FCA and the right four columns contain additionally determined variables. Note that for simplicity, not all columns of the data set are shown.

Table 2.3: LSVA raw data as received from FCA and additionally determined variables (mock-up example).

Initial variables of LSVA raw data set					Additionally determined variables			
Date	**Event**	**Mileage [km]**	**Vehicle MPW [kg]**	**Trailer MPW [kg]**	**Trailer [bool]**	**Trailer MPW 2 [kg]**	**Abroad [bool]**	**Distance [km]**
29.04.2019	Stauts	570,803.0	17,900	0	1	NA	1	11.2
29.04.2019	Entry	570,814.2	17,900	0	1	NA	0	135.0
29.04.2019	Trailer off	570,949.2	17,900	0	0	NA	0	26.9
29.04.2019	Trailer on	570,976.1	17,900	14,400	1	14,400	0	116.7
29.04.2019	Exit	571,092.8	17,900	0	1	14,400	1	26
30.04.2019	Status	571,118.8	17,900	0	1	14,400	1	0
30.04.2019	Trailer off	571,118.8	17,900	0	0	0	1	11.2
30.04.2019	Entry	571,130.0	17,900	0	0	0	0	58.8
30.04.2019	Trailer on	571,188.8	17,900	18,000	1	18,000	0	NA

A second file from FCA contained more vehicle-specific data connected to the same anonymous vehicle-id as the transport performance file. Before merging the two data sets together, all non-freight vehicle categories were dropped. The selection was based on the vehicle type and the body type. Vehicle codes removed were categories with special vehicles such as fire trucks, ambulances, heavy motor vehicles, or other exceptional vehicles. Also removed were body codes including vehicles such as garbage trucks, concrete mixers, and construction cranes, among others. The analysis includes only vehicles used for freight transport. For a detailed list of ignored categories, see Appendix A.1.

This trip-based data was aggregated first to daily and in a second step to monthly, yearly, and five-year transport performance. Aggregated data includes the kilometers traveled, the average daily distance and the maximum daily distance traveled. For every aggregated entry, the corresponding averaged vehicle or vehicle-trailer-combination weight was calculated. Finally, data from all five years was used to obtain a representative picture of the transportation sector. This compensates for fluctuations in transport performance. The results of this analysis are presented in the following paragraphs. If not stated otherwise, the results cover the time period from 2015 to 2019. Thus, one actual vehicle may be represented by up to ten data points. Up to five for the full period, if the vehicle was registered before 2016 and has conducted transport performance in each year. Up to two per year, if it is a rigid truck and has conducted transport performance with and without a trailer.

Weight segments

Figure 2.8 illustrates the average vehicle weight distribution of the Swiss medium and heavy-duty fleet. Note that vehicles up to 3.5 t are not subject to LSVA, thus are not reflected in these illustrations. While the colored lines allow for differentiation between three broad types of trucks, the histogram shows the overall weight distribution in 1-ton bandwidths. The distinct peaks represent typical weight limits based on the number of axles, as explained in Section 2.2.1. Where a two-axle truck can be up to 18 t, this number increases to 26 t (three axles), 32 t (four axles), and 40 t (five axles).

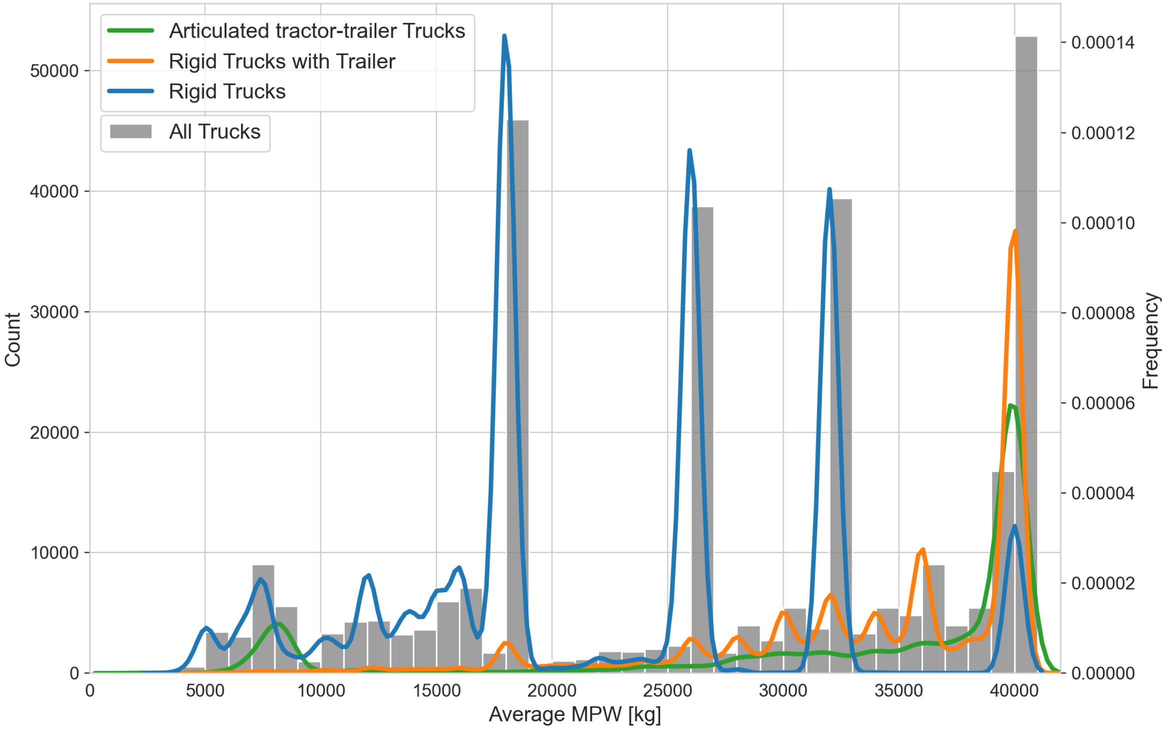
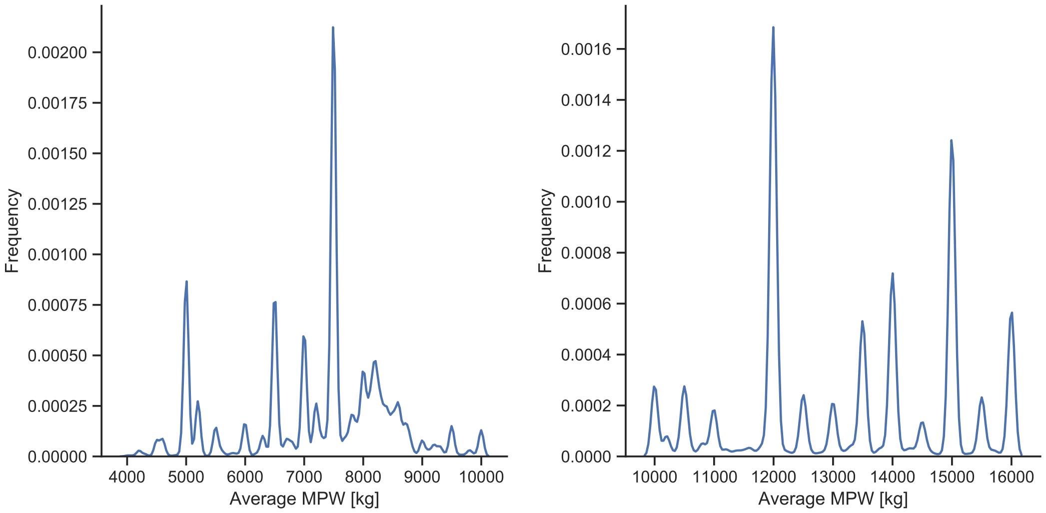


Figure 2.8: Distribution of averaged vehicle MPW by truck type (colored lines) and in total (histogram) based on LSVA data from 2015-2019.

A zoom-in on the MDT segments <18 t allows for further differentiation. Whereas the lowest freight vehicle class (3.5 t) is not included in the LSVA data, two additional peaks can be identified in Figure 2.9. A first one at 7.5 t (Figure 2.9a), which represents another typical weight limit in Switzerland. A second peak is found at 12 t (Figure 2.9b), which marks the weight limit requiring the full truck driving license. These results are consistent with the weight segments introduced in Section 2.2.1. Note that the y-values of different graphs are not directly comparable, as the distributions shown only contain data of the MPW range on the x-axis.

Although these two vehicle classes represent a relatively small share of the Swiss road freight fleet, we concluded that they deserve a separate evaluation by specific applications segments. Based on the results and evaluation presented in this paragraph, the vehicle classes are categorized as shown in Table 2.4.



(a) (b)

Figure 2.9: Distribution of averaged vehicle MPW between 4 and 10 tons (a) and between 10 and 17 tons (b) based on LSVA data from 2015-2019. Frequency values are not directly comparable between graphs.

Table 2.4: Min and max values used for segmentation of newly registered vehicles.

Application	Weight segment [t]	Min weight [t]	Max weight [t]
LDT	3.5	0	3.5
MDT	7.5	7	7.5
	12	11	13
HDT	18	11	19
	26	25	27
	32	31	33
	40	39	41

Range distribution

Figure 2.10 illustrates the average daily distance travelled of the Swiss medium and heavy-duty fleet. While the colored lines allow for differentiation between three broad types of truck, the black dashed line shows the overall range distribution. As additionally informed by expert interviews, this allows for a broad differentiation of use cases by vehicle type. Rigid trucks show a distinct peak at a range <100 km/day, therefore these vehicles are mainly used for urban and regional applications. Attaching a full trailer allows maximum payload with good maneuverability in tight urban conditions. Especially in traffic circles and narrow curves, this variant shows advantages over tractor units with semitrailers. Such combinations, on the other hand, are mostly seen on highways. While in long-haul traffic a single loading area allows faster loading and unloading, the maneuverability of the vehicle plays only a subordinate role. The average daily distance of rigid trucks is around 130 km, where articulated tractor-trailer trucks cover around 230 km, on average.

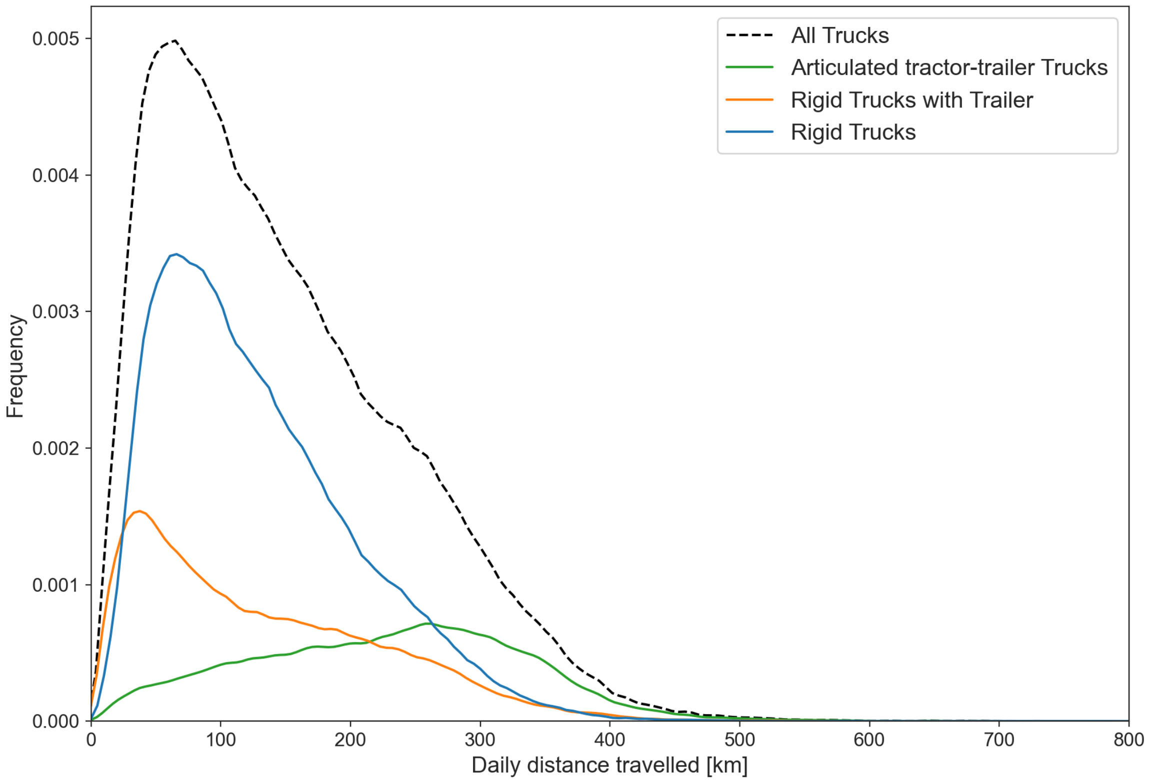


Figure 2.10: Distribution of averaged daily distance traveled by truck type (colored lines) and in total (black dashed line) based on LSVA data from 2015-2019.

Based on the results and evaluation presented in this paragraph, the ranges are categorized as introduced in Section 2.2.1: urban traffic is considered 50 to 100 km/day, regional traffic includes ranges from 100 to 250 km/day, and long-haul traffic covers everything beyond 250 km/day.

New vehicle registration data

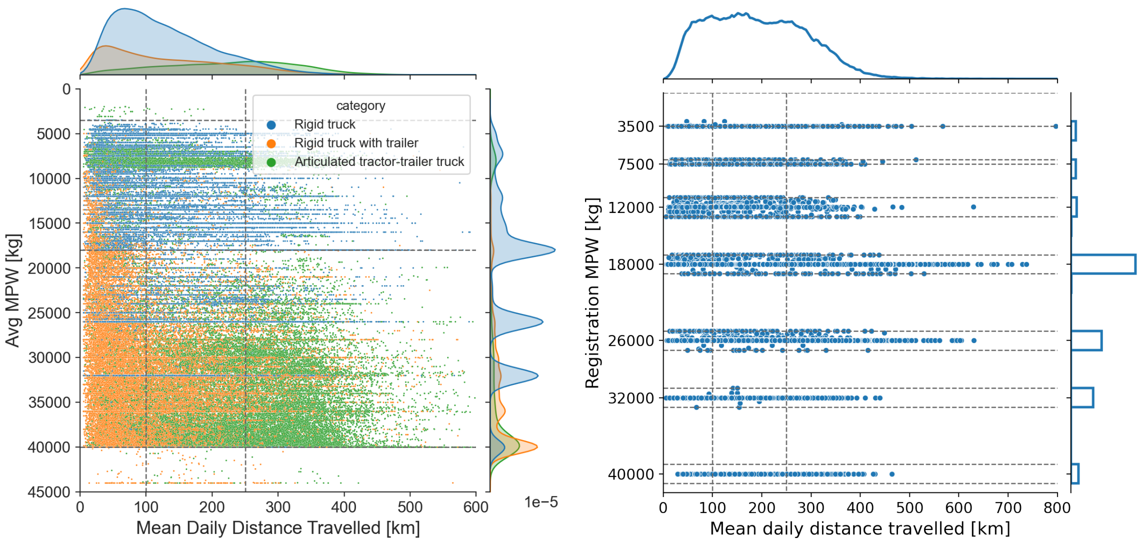
After identifying vehicle classes and use cases in the Swiss road-freight sector, a subset out of the received LSVA data is created, based on the condition, that its MPW is within one of the weight categories previously mentioned (Table 2.4).

With the registration date of every vehicle, historical data of newly registered vehicles is created for every application segment. The available data allows for a much more detailed segmentation. Not only are the actual vehicle weights available, rather than a broadly defined weight segment categorization, the vehicle weight can also be assigned to a specific range segment, which would otherwise not be possible to differentiate with the data collected from road traffic licensing departments. Based on this historical data between 2005 and 2018, trends for new vehicle registration for the years 2019 to 2035 are projected. For the 3.5 t vehicles, data on new vehicles registration from the Federal Statistical Office *(Bundesamt für Statistik)* (FSO) was used. The split into the three range dimensions is made analogously. Since there are 3.5 t tractor units which are subject to LSVA when carrying a semi-trailer, range data is also available for the LDT segment. Application segments showing a negative trend, or in other words, a decreasing number of new vehicle registration, are set to zero. This means that that the number of newly registered vehicles equals the amount of vehicle which are being decommissioned or exported. In this case, the number of vehicles in the segment stays constant from 2018 on. While the model projects market share of each drive-technology, these numbers are used to estimate an amount of potential ZEVs in each application segment. For the model calculations, however, the absolute values are not decisive.

Figure 2.12 shows the empirical range distributions of the raw data (blue dotted lines) and the resulting range distributions drawn from the cumulative distribution function (colored drawn lines). Note that we set the minimum range an investor in the urban segment can draw to 50 km to avoid unrealistically low energy ratings (see Section 2.2.4). This leads to a slightly higher probability for drawn ranges between 50 and 100 km, which is reflected by the small gap between the dashed line and the drawn line. However, the trend of the distribution remains the same.

Summary of LSVA data analysis and model input

This paragraph serves as a summary of the data cleaning and processing steps explained in this section. First, raw LSVA data from FCA is cleaned and multiple years are merged. Since the LSVA monitoring device logs mileage readings, the distance travelled for each trip is calculated. Additional variables such as trailer and abroad Booleans are determined. Second, the data is merged with a different data set containing vehicle attributes such as the registration date. All non-freight vehicle categories are dropped. The determining vehicle or vehicle-trailer-combination weight is defined. Third, this trip-based data is aggregated over different time periods of interest. The descriptive statistic (Fig. 2.11a) is used to categorize Swiss road-freight vehicles into weight and range segments. Finally, a subset based on vehicle registration weight is created (Fig. 2.11b). This data is used to inform the model in two aspects: to project new vehicle registration and to determine the range distribution for each application segment.



(a) (b)

Figure 2.11: (a) Intermediate results from LSVA data analysis. (b) Subset used to determine new vehicle registration (histogram on y axis) and range distribution (distribution on x axis).

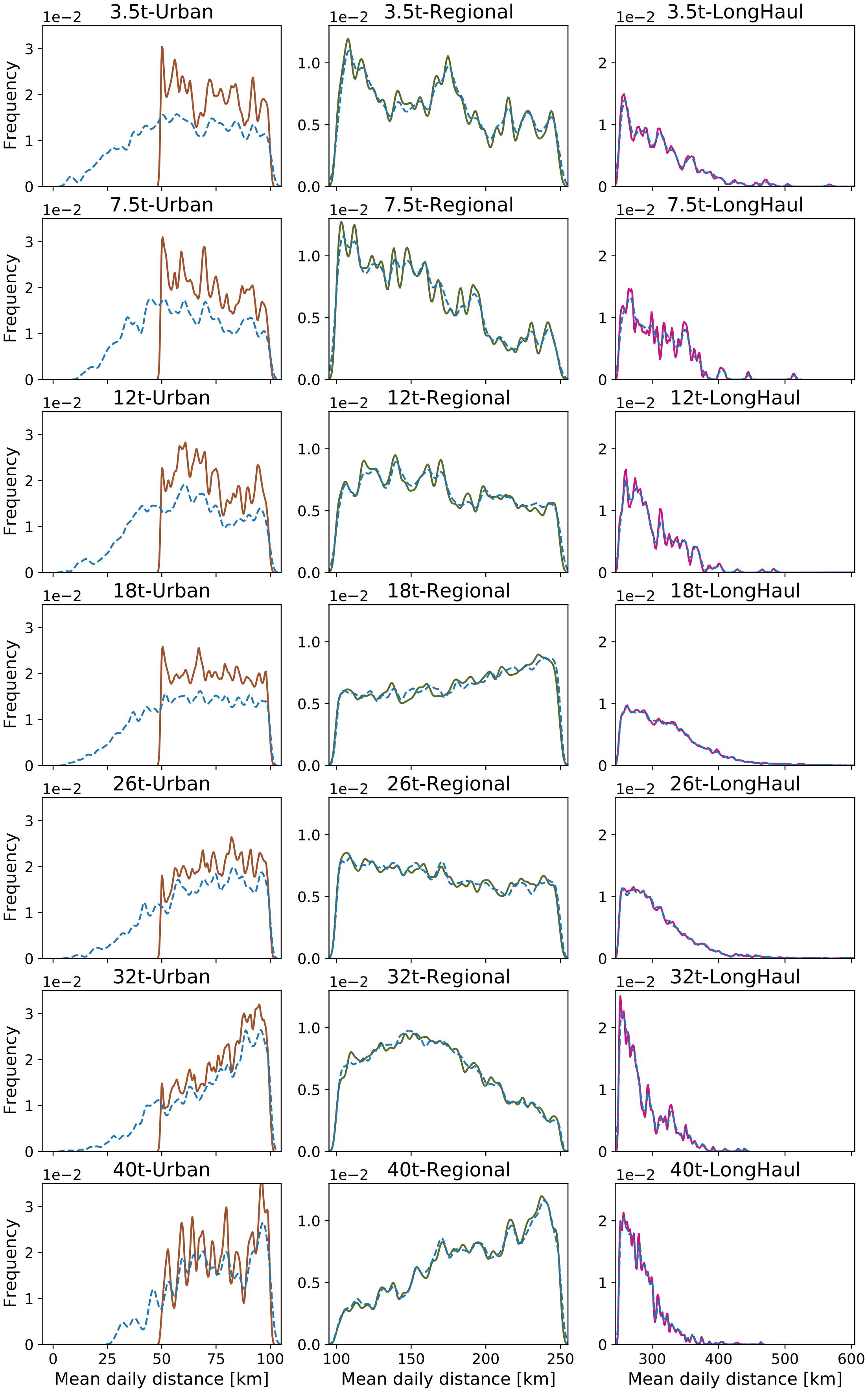


Figure 2.12: Range distribution of averaged daily distance traveled for all application segments from raw data (blue dashed lines) and from draws of the cumulative distribution function (colored lines).

The relatively small share of vehicles in the 40 t weight segment in the used subset to determine new vehicle registration (Fig. 2.11b) can be explained by the exclusion of construction trucks. Where trucks used to transport goods normally have a lower MPW and only reach the weight limit in combination with a trailer or semitrailer, there are many five-axle tippers and other construction site vehicles in Switzerland that reach the national weight limit with the truck alone. However, since we only consider freight transport and look at the motor vehicle alone in the cost evaluation (the assumption behind this is that trailer and semitrailer costs are independent of the drive-technology), the projected number of new vehicles in this segment is comparatively low. Since the model calculates a market share regardless of capacity additions of new vehicles, the absolute number behind it plays only a secondary role.

The Figures 2.13 to 2.16 give a glimpse into the wealth of available information. They show different visualizations of the daily and monthly driving distance of the Swiss medium and heavy-duty fleet in 2019.

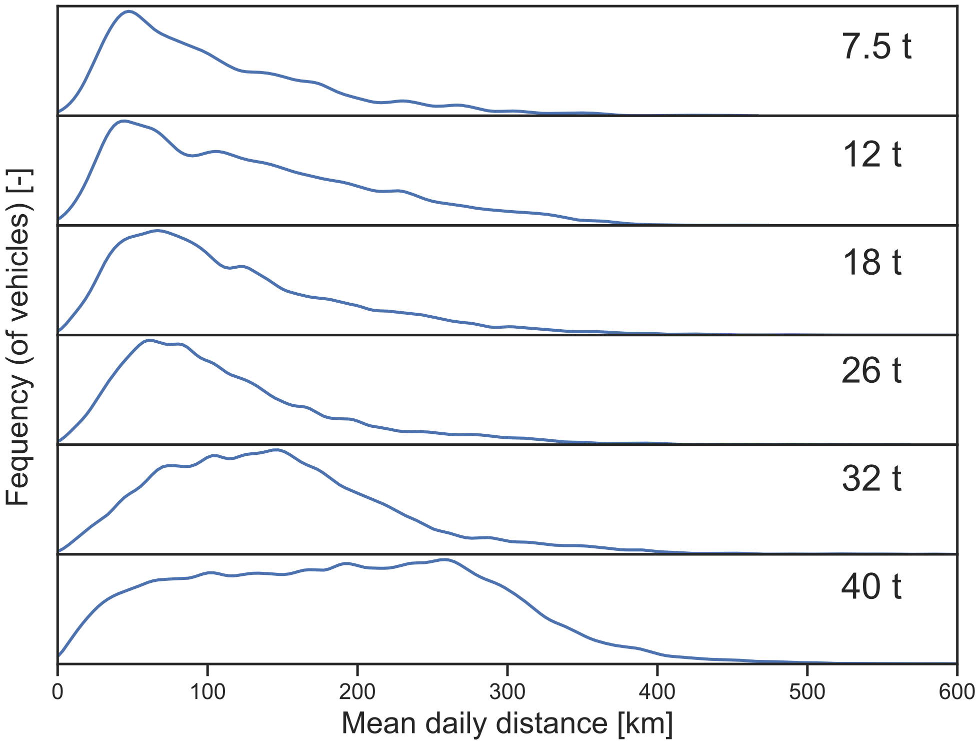


Figure 2.13: Distribution of averaged daily distance traveled by weight segment.

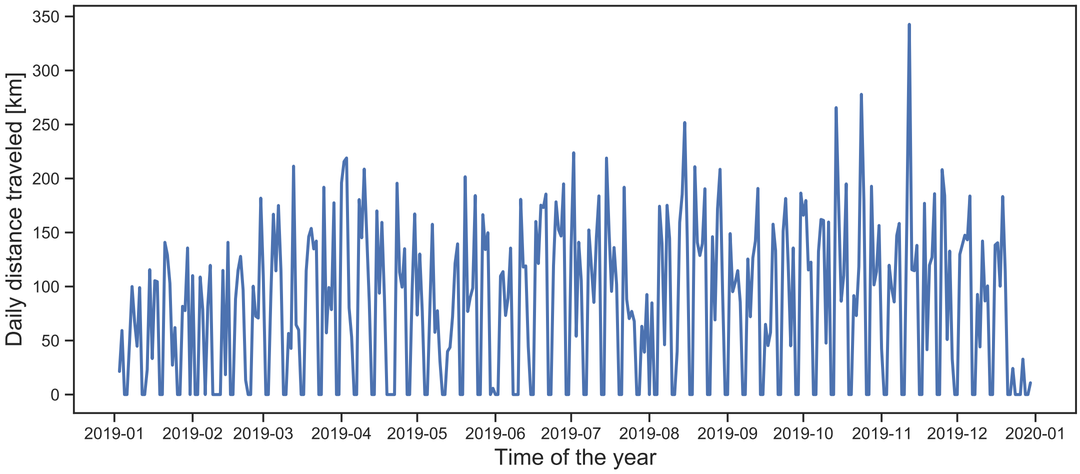


Figure 2.14: Daily distance traveled of a random truck over one year.

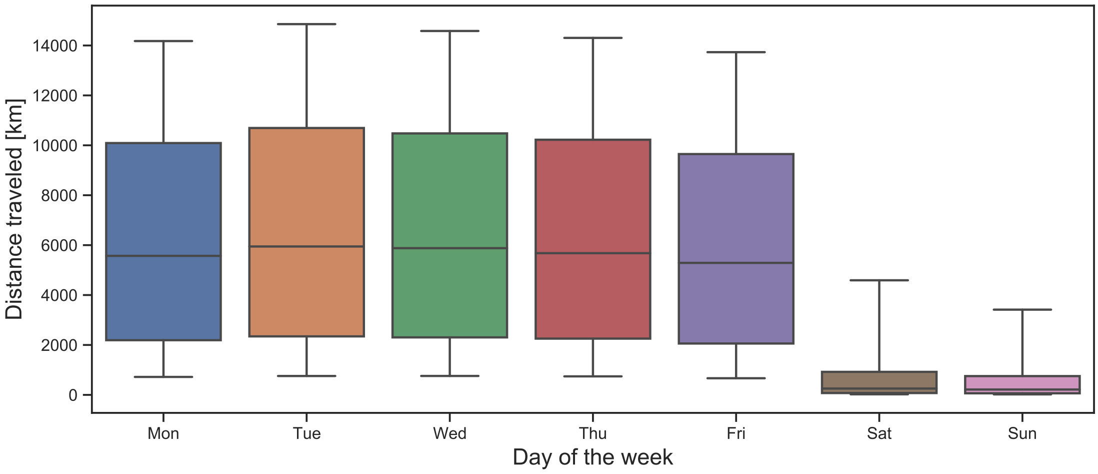


Figure 2.15: Box-plot of the distance driven per weekday (the box represents the first and third quartiles, the error-bars the 10 and 90 percentiles.

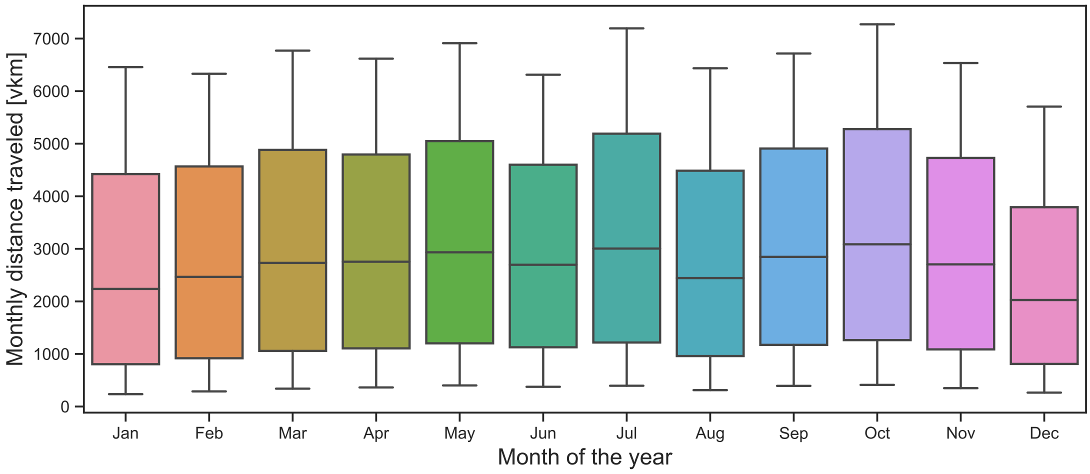


Figure 2.16: Box-plot of the distance driven per month (the box represents the first and third quartiles, the error-bars the 10 and 90 percentiles.

2.3.2 Expert interviews

To complete the picture on the Swiss freight transport landscape acquired through publically available literature, research studies and data analysis, 14 expert interviews were conducted throughout the course of this work. All interviews were hold under the "Chatham House Rule" [52] and hence no references to interviewees or their affiliations are made. The feedback received from these interviews helps to inform, understand, and validate the model. Table 2.5 provides an overview of the stakeholders consulted, listing them in an anonymized manner.

Table 2.5: Overview of the interviewees.

	Organization	**Expertise**	**Interviewee's role(s)**
1	Private company	Fleet operation	CEO
2	Private company	Fleet operation	Project manager
3	Private company	Fleet operation	CEO
4	Cooperative	Logistics	Senior project manager sustainability Project manager supply chain & logistics
5	Cooperative	Logistics	Head of logistics
6	Public company	Fleet operation	Head of transports
7	Private company	Logistics	Head of last mile delivery & services Global sustainability manager
8	Private company	Fueling infrastructure	Member of the Board of Directors
9	Private agency	Charging infrastructure	Business area manager, member of the management
10	Private company	Hydrogen solutions	Project manager
11	Association	Hydrogen solutions	President
12	Private company	Hydrogen solutions	Senior technical advisor
13	Private company	Insurance	Head of fleet and warranty insurance, member of the management
14	Public agency	Freight traffic	Project manager

The interviewees were sent two documents in advance. First, a study overview of this work and the model. Second, a questionnaire consisting of 19 questions. These were again divided into two parts. The first part was mainly about costs and other data on road-freight vehicles, such as lifetime and payload utilization. The second part was about trends in freight transport, mainly in regard of BETs and FCET. While most fleet operators received identical questions, other stakeholders had their questions adapted according to their area of expertise. At this point, it is worth mentioning that we received almost exclusively positive feedback on the interview requests. The participants were very motivated and generously supported this work. An interesting experience from the interviews was also that questions were often asked by the interviewed person. This shows that there is great interest from industry in this research and its results, and confirms the assertion that the competition between drive-technologies in the freight transport sector has not been decided. Below are the main takeaways from the interviews summarized.

The most important investment decision criteria when procuring new freight vehicles are the payload available, the operating costs (mainly fuel price and tolls), and the location of the next brand dealership. These criteria are independent of the drive-technology and are weighted higher than the CAPEX of the vehicle itself. In the case of ZEVs, the refueling options become one of the most decisive factors. This was also evident on the two ride-alongs that took place as part of this work. To get a hands-on feeling of the zero-emission drive-technologies for freight vehicles, I had the pleasure to hitch a ride with a BET and a FCET. In both cases, for the BET as well as the FCET, the limiting factor for the vehicle's operation turned out to be the charging and fueling procedure, rather than the drive-technology itself. Flexibility is a fleet operator's major factor of success and lower costs alone are not sufficient to shift towards low-carbon drive-technologies.

Insurance costs are difficult to quantify per vehicle. Most fleet owners have a frame contract with an insurance company, which includes a premium for a certain number of vehicles. This premium may differ significantly due to various individual factors. The fuel (electric, hydrogen) can have an impact of 10% to 25% on the premium (discount) depending on the constellation and coverage. The individual claims experience, on the other side, can increase or decrease the price by up to 50%. However, this cost component turns out to have a minor impact on the TCO of a vehicle, as the results of the sensitivity analysis will later show (Section 3.3).

When it comes to alternative fuels, opinions differ widely. While some see biodiesel or natural gas as viable options for a rapid decarbonization of the road-freight sector, others claim they have no place in any vehicle at all. It became apparent that this depends, among other things, on the view of whether we are aiming for complete decarbonization or merely a strong reduction in emissions. For a complete decarbonization to net-zero emissions, the amount of biofuels producible should be used for industrial high temperature processes, where an electrification is hardly feasible. The production of fertilizers and pesticides used for the production of biofuels also results in GHG emissions that are often not considered in their footprint assessment. Whether the use of agricultural land for the production of motor fuels is justifiable at all against the backdrop of of shrinking arable land for food worldwide is another question. Given these and other uncertainties and difficulties with biofuels, it is highly uncertain if the fuel efficiency improvements with the use of ICEs itself can result in the GHG emission reductions required from road-freight over the coming decades to reach the climate targets [25].

A similar disagreement can be seen in the question of the necessity of catenary systems to charge the batteries of BETs while driving (in-motion charging) and thus counteract one of the main disadvantages, the long charging time of large batteries. While some see this as a suitable solution for transit traffic on the north-south axis through Switzerland, others argue that this approach contradicts the Swiss modal shift policy. In particular, the interviewed expert from a public agency with expertise in freight traffic sees catenary systems, as incidentally also the use of hydrogen in the transport sector, as competing with rail-freight transport.

When asked why there is not an increased modal shift to rail, the answers again coincided. In addition to the fact that, from an economic perspective, it is often cheaper to choose the road as a transport route, it is primarily the bureaucratic effort and the higher safety requirements that prevent transport companies from transporting goods by rail. In any case, this is true during the day, when trucks are allowed to travel without restrictions and can be used relatively flexibly. With rail, the route must be reserved in advance. A train path (similar to a "slot" in aviation) is the authorization to use a specific section of the rail network at fixed times with a specific train (length, weight, profile, speed). Ordering such a train path seems to be an bureaucratic obstacle, according to fleet operators. In addition, the safety requirements are unjustifiably high and even differ according to route, which does not seem very plausible when comparing the accident risk of road-transport with that of rail. Also, the logistical handling is not where it should be. Wagons often have to be re-hauled and shunted, which takes time. For transports at night, when trucks are not allowed to drive, then rail transports can bring decisive advantages. With cleverly coordinated routes, a shipment can be loaded in Basel in the evening and reach its recipient in Valais as early as the next morning. Rail can be used to take advantage of the so-called night jump. This offers time savings.

2.3.3 Scenarios

Each model case is determined by a specific combination of scenarios regarding ZEV technology costs, fuel prices, and policy measures.

Technology Scenarios

For the battery pack costs, we consider three scenarios. The low scenario is based on Elon Musk's (CEO Tesla) projections to reach battery pack cost at round 57 USD/kWh (48 EUR/kWh) by 2030. The reference scenario is based on data from Bloomberg which estimates battery pack costs at around 77 USD/kWh (64 EUR/kWh) by the same year. The high scenario reflects a less optimistic cost projections with battery pack costs at around 100 USD/kWh (84 EUR/kWh) by 2030. Figure 2.17 illustrates the described scenarios.

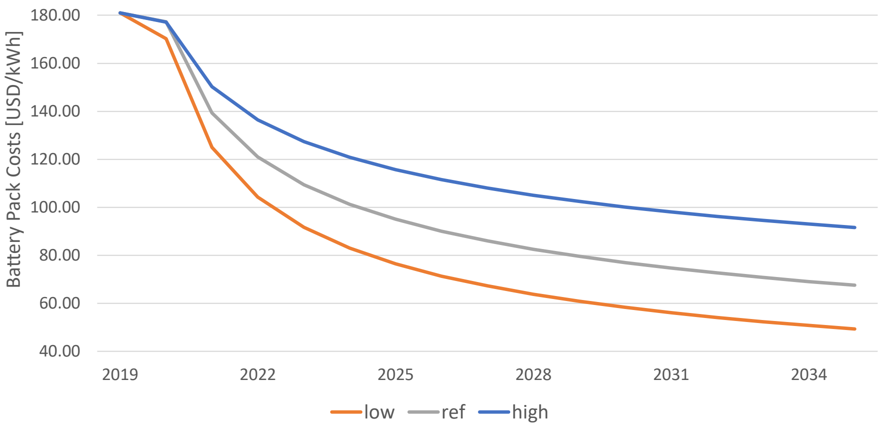


Figure 2.17: Cost projections used for battery packs.

For the fuel cell stack, we consider three scenarios based on cost projections from vehicle manufacturers. The high scenario projects cost developments if the technology remains a niche product, resulting in costs above 200 EUR/kW by 2030. The reference scenario assumes the technology reaches a rather niche market share by 2025 at stack costs around 165 EUR/kW. The optimistic scenario shows possible cost development if the technology reaches a rather mass production share by 2025 at costs around 106 EUR/kW. The drive-technology is not expected to be mass-produced before 2035. Figure 2.18 illustrates the described scenarios.

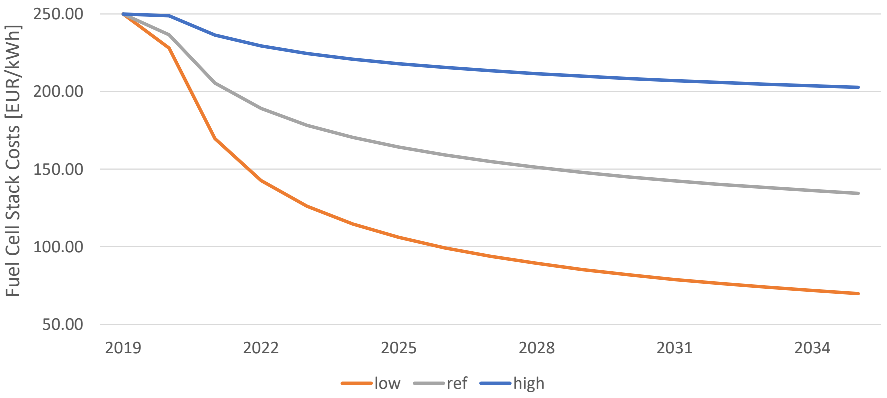


Figure 2.18: Cost projections used for fuel cell stacks.

For the hydrogen tanks, which contribute to the CAPEX of a FCET to a significant share, we consider three similar scenarios as for the fuel cell stack. A high scenario if the technology remains a niche product, a reference scenario if it reaches rather niche by 2027, and a low one if it reaches mass production by 2030. Note that the hydrogen tank cost development may be correlated with the fuel cell stack production size, but not directly linked. The two components can have different experience rates.

For the diesel and natural gas engine, we consider one scenario which assumes an annual cost increase of 1% due to higher emission standards which require more advanced engine and aftertreatment components.

For the electric motor, we consider one scenario which assumes an annual cost decrease of 1% due to economy of scales.

Fuel Scenarios

Fuel data is projected eight years beyond the last modeled year to appropriately reflect investor decisions as the model assumes a maximum 8-year lifetime for TCO calculations. For the fossil fuel costs, diesel, biodiesel, and natural gas, as well as for electricity costs, we consider three scenarios. The reference scenario assumes no change in fuel prices, whereas the high and low scenario assume an annual price increase and decrease of 1%, respectively.

For the hydrogen price, we also consider three different scenarios. The high scenario takes into account that economies of scale for electrolyzers is limited due to modularity and that electricity may not become cheaper. It projects no price decrease for hydrogen, keeping the price at the pump above 10 EUR/kg. The reference scenario is based on Craig Knight's projection (CEO Hyzon Motors), that an attractive FCET TCO comparison with diesel is expected once green hydrogen prices are between 5 to 6 EUR/kg around 2025 [53]. The low scenario is based on several claims ([54], [55]) that green hydrogen can be produced at costs below 1.50 EUR/kg by 2025. Figure 2.19 illustrates the described scenarios.

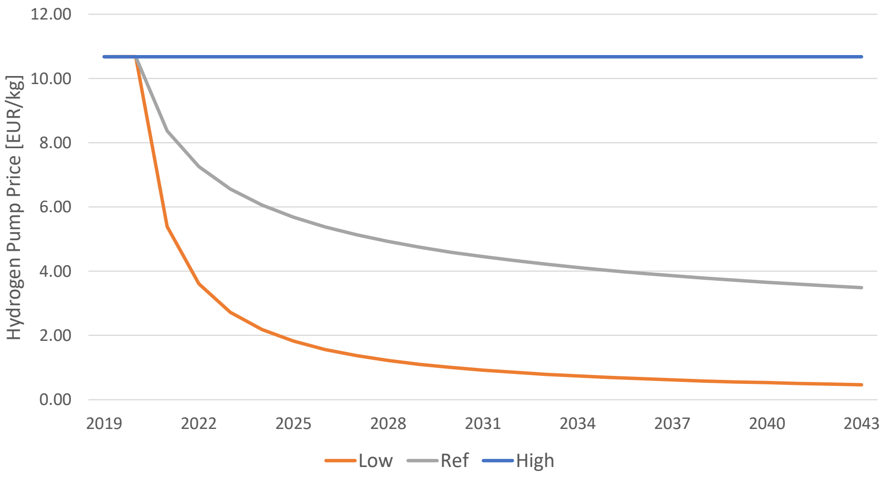


Figure 2.19: Cost projections used for hydrogen.

Policy Scenarios

For the LSVA tariff structure, we consider two extreme options in a first step. ZEVs are either fully exempted from the LSVA toll, or ZEVs pay the full tariff according to the Euro 6 tariff category of ICE trucks. In a second step, a progressive tariff structure for ZEVs starting in 2026 is assumed. Third, a scenario where the 3.5 t vehicles are placed under the obligation to pay LSVA is analyzed.

Under the current Swiss road traffic act, BET are subject to the same weight limits as conventional vehicles. This may result in lower payload capacity due to heavy batteries for energy storage, which results in a major competitive disadvantage in the freight transport sector. To address this, we consider a policy scenario which allows BET to exceed the current vehicle weight limits to reach the same payload capacity as their diesel counterparts. Modeling this policy measure requires a more in-depth discussion of the subject. Therefore, this particular measure will be dissected separately in the next section.

In addition, we analyze a policy-mix of different possible measures with the introduction of LSVA obligation for 3.5 t vehicles, a progressive LSVA tariff for ZEVs, an increase of LSVA tariff for Euro 6 ICEV, the elimination of preferential treatment of transportation fuels, removing the weight penalty by allowing BETs to be heavier, and a subsidy for green hydrogen.

2.3.4 Battery penalty

If a BET turns out to be heavier than its diesel counterpart, the loss in payload is a strong competitive disadvantage. In the survey of fleet operators and other experts from the Swiss transport industry on investment decisions in vehicle procurement, payload availability was among the most frequently mentioned criteria. Less payload means fewer goods transported, thus less revenue. So far in this analysis, such a payload loss is penalized by adding an CAPEX component to the BET TCO, based on the TCO results from its diesel counterpart. Policy-makers could, for example, allow BETs to be heavier by increasing their legal MPW.

If the payload difference turns out to be negative, in other words the battery option results in a lighter vehicle, which can carry more payload, it is rewarded by reducing the BET TCO, based on the TCO results from its diesel counterpart. Although this is more of a methodological question, rather than an actual policy tool, the effects of excluding it from the calculations are also analyzed.

The presented policy option requires some profound discussion from a modelling perspective. So far, we have investigated the cases where a penalty applies, or where a policy measure removes this penalty by allowing BETs to be heavier. But the implementation might not be so straight forward. Should BETs also be rewarded, if the turn out to be lighter than the corresponding ICE-D drive-technology? Table 2.6 serves as an overview of the possible penalty-reward-combinations.

Table 2.6: BET penalty-reward-combination matrix

		Penalty	
		True	False
Reward	True	*Base case:* current policy	*No BET penalty:* new policy
	False	*BET penalty only:* fairness argument	*No BET penalty and no BET reward:* ignoring payload difference

One can argue that BET should be rewarded in the model, because if a vehicle can carry more payload for the same trip (same distance and same MPW), this brings a competitive advantage to the owner. However, if it is only applied to BETs, other technologies that turn out to be lighter than their diesel counterparts do not get rewarded (fairness argument). This is very unlikely for any other technology than fuel cells to take place, since ICE-BD, ICE-NG, and HET all carry an ICE and a fuel tank. Within this study, it was not possible to collect reliable data on fuel cell drive-technology components to include FCETs in the reward system. Alternatively, one can assume that any investor would “fill up” the weight difference with additional battery capacity until the same payload, as the corresponding ICE-D has, is reached. Again, this would be a competitive advantage which deserves to be rewarded in some way. A third option is to ignore the payload difference completely by not comparing the weights of the drive-technology components. Although this option may not best reflect the real world, it treats all technologies equally. The effects of such a penalty on BET drive-technology market shares are presented in the results Section 3.5.4.

3 Results

In the following section, we will examine first the results of the base case vehicle cost for each drive-technology in each application segment, and second, the results of the TCO calculations for all drive-technologies in each application segment and region.

The following sections present the results of the market share projections of the scenarios from Section 2.3.3. First, we will examine the results of the base case. Second, the results of the sensitivity analysis illustrate the relative impact of the model input parameters on the sensitivity of the TCO as discussed in Section 2.2.5. Third, we investigate the best and worst case for ZEVs in terms of technology and fuel cost developments. Fourth, we analyze the effects of the different policy measures on the outcome of the market shares of the different drive-technologies. A possible combination of such policy measures is then presented in the discussion of policy implications in Chapter 4.

A brief refresher on how the results are obtained should remind the reader of the methodology used. First, the model calculates the TCO for each technology in each application segment and for every year modeled. Second, a Monte Carlo simulated investor selection makes the decision for one drive-technology based on the TCO results. Finally, this yields the market share for each application segment over the time period 2019 to 2035. The investor decides independently of the market availability of drive-technologies and vehicle models. The results presented should therefore be interpreted as "theoretical" market shares. For a more detailed description see Section 2.2.5.

3.1 Representation of results

In order to present the results in a digestible manner, not all 21 application segments are presented. Instead, the results of the three weight segments classified as most important are shown (see Section 2.2.1). These are ideally suited to be considered as a proxy for the entire Swiss road freight sector. The individual market share charts showing the results for all 21 application segments can be found in the appendix A.2.

Table 3.1 provides an overview of all scenario configurations for the cases modeled.

Table 3.1: Overview of the modeled cases with the scenarios applied.

Model cases	Technology scenarios			Fuel scenarios			Policy scenarios	
	Battery pack	**Fuel cell stack**	**Hydrogen tank**	**Diesel BD/NG**	**Electricity**	**Hydrogen**	**LSVA tariff**	**BET Penalty**
Base case	Ref	Ref	Ref	Ref	Ref	Ref	ZEVs exempted	Penalty applies
Best case	Low	Low	Low	High	Low	Low		
Worst case	High	High	High	Low	High	High		
Full LSVA		Ref			Ref		ZEVs full	Penalty applies
Progressive LSVA		Ref			Ref		ZEVs progressive	Penalty applies
Full LSVA for LDTs		Ref			Ref		ICEs 3.5 t full	Penalty applies
No BET penalty		Ref			Ref		ZEVs exempted	No penalty

3.2 Results of base case scenario

The base case serves as a benchmark. The reference scenario is assumed for all cost components. The political scenarios are based of the status quo. The subsequent cases are compared with this base case, unless otherwise mentioned.

3.2.1 Base case

The projected drive-technology market shares are shown in Figure 3.1. Overall, BETs are likely to outcompete alternative drive-technologies in most application segments.

Only in the LDT segment is the outcome more open. While a large proportion of vehicles in urban traffic could still be battery electric (approx. 40%), this proportion is vanishingly small in long-haul traffic. This can be explained primarily by the low payload and the resulting financial penalty for BETs. As an example, our model calculated an average payload loss of 485 kg for a van in the 3.5-LongHaul segment. This coincides very well with actual values. While a Mercedes Sprinter with ICE-D has a payload of 1100 kg, the battery vehicle of the same model has a payload of only 600 kg. The LDT segment is also the only segment where the exemption of ZEVs from the LSVA has no effect, since this weight segment does not fall under the LSVA obligation at all.

Here, the main financial advantage of ZEVs is not present. Thus, ICEVs are more cost competitive than ZEVs and share the market among themselves which is evident by the rainbow-like plots. This result begs the question whether or not this weight category should not also fall under the toll regulation. This possible approach is explained and analyzed in greater depth later in Section 3.5.3.

In the MDT and HDT segments, BETs become the drive-technology with the lowest TCO within a few years only and are able to maintain this market domination for almost the entire

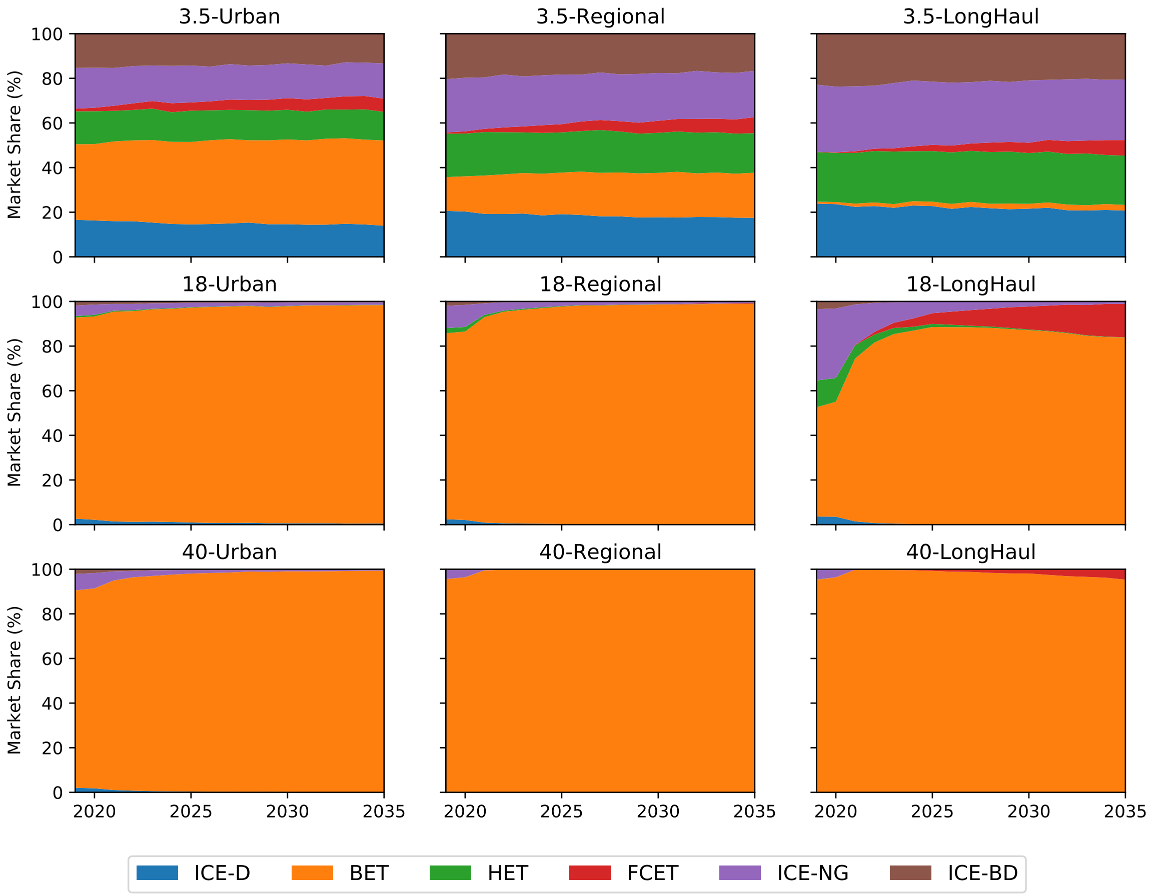


Figure 3.1: "Base case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

period. This fact can only be counteracted by a falling hydrogen price, which can be observed in increasing market share of FCETs towards the end of the modeled period. This already shows impressively that the market success of the fuel cell drive-technology depends to a large extent on the price of hydrogen.

3.3 Sensitivity analysis

The Monte Carlo simulation enables a statistical sensitivity analysis. This allows for taking into account the uncertainty of input parameters, as described in Section 2.2.5. The inclusion of a sensitivity analysis is therefore important to validate the parameters brought into focus from theory or expert interviews also from a modeling perspective. This is done by a variation of the input parameters of ±20% and ordering by importance the impact of the inputs in determining the variation in the output. This is done for each of the 21 application segments. Figure 3.2 illustrates the outcome of the sensitivity analysis in the 40-LongHaul segment, where the impact of the input parameters are best visible in form of a tornado graph. All other tornado graphs can be found in the Appendix A.3. Note that wages are excluded from this sensitivity analysis since we focus on one region only. When comparing multiple countries or regions, this parameter has to be included in the sensitivity analysis.

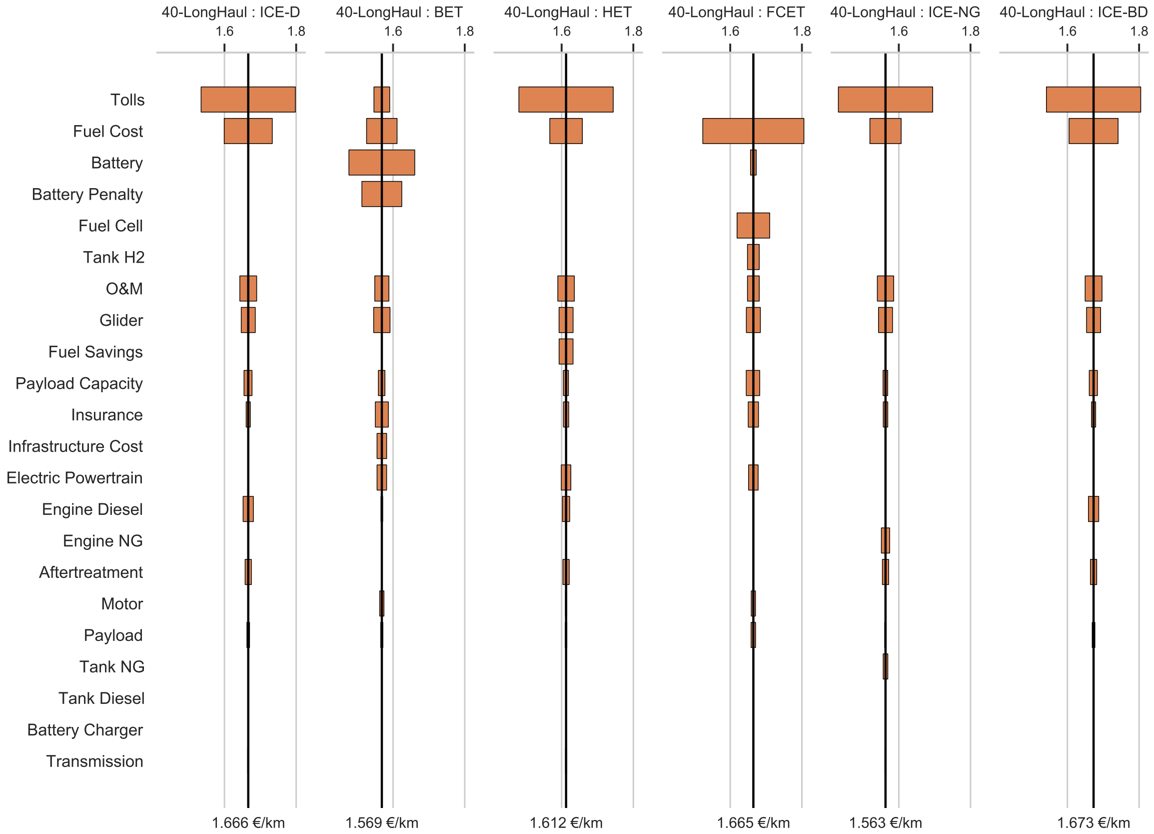


Figure 3.2: Results of the sensitivity analysis for the 40-LongHaul segment.

We can identify six input parameters with high impact on the TCO and categorize them by scenario type. The battery, fuel cell, and hydrogen tank can be grouped as technology cost components. The fuel cost is the most important cost component of the OPEXs from a technological perspective. Lastly, the battery penalty and toll are crucial decisive cost components from a policy perspective. These findings are consistent with our assumptions and experiences from the expert interviews. Thus, the presented scenarios in Section 2.3.3 capture the most important TCO input parameters. The following sections examine these influences in more detail.

3.4 Results of technology and fuel scenarios

To display the full breadth of outcomes, the two most dissimilar cases are compared to the previously presented base case. A best case, in which all technology and fuel scenarios are in favor of ZEVs and a worst case, in which each scenario disfavors ZEVs. To keep the degree of diversity within a manageable range, the policy scenarios are not varied in the same turn and are set to business-as-usual. Thus, ZEVs continue to be exempt from LSVA and BETs are penalized for payload losses. Note that the best and worst case for ZEVs represent extremes to show the entire spectrum of outcomes.

3.4.1 Best case

The "best case" assumes low technology and fuel prices for ZEVs, while technology and fuel prices for ICEs are set at the upper bound. If all the points are set in favor of ZEVs, the picture will change significantly. While fuel cells compete with the batteries in urban traffic only in the LDT segment, they are gaining strong market share in all weight categories in regional and long-haul traffic (see Fig. 3.3).

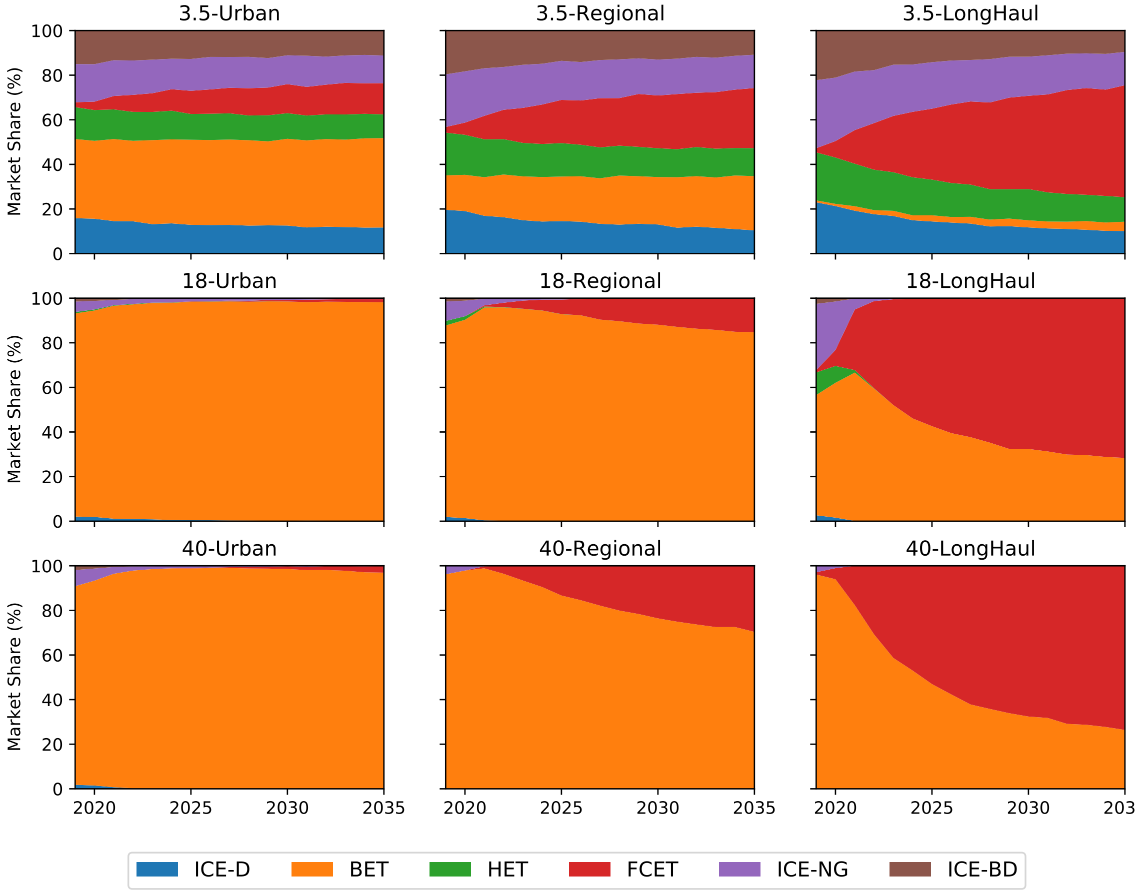


Figure 3.3: "Best case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

As the results of the sensitivity analysis have shown (Section 3.3), the reason for this shift is primarily found in fuel costs. The hydrogen price is decisive for the profitability of the FCET. This was also confirmed by the expert interviews. While the relative costs of the energy storage increases strongly with the required range in the case of BETs, a FCET simply requires more or larger hydrogen tanks for higher ranges. These make up a relatively low cost share of the TCO, compared to the rest of the system. The fuel cell itself does not need to be modified for higher range. This relative cost increase of the energy storage system of BETs can be observed in Figure 3.4. While the CAPEX of BETs increasing with higher range from urban to long-haul due to a more expensive energy storage system (green), the CAPEX values of the other drive-technologies stay about constant. Thus, when high ranges are requested, FCETs bring a clear advantage. However, as the LSVA data analysis from Section 2.3.1 has shown, the average daily distances of commercial vehicles in Switzerland are rather low. Most transport routes have an average daily distance of less than 300 km, which can usually also be accomplished with BETs.

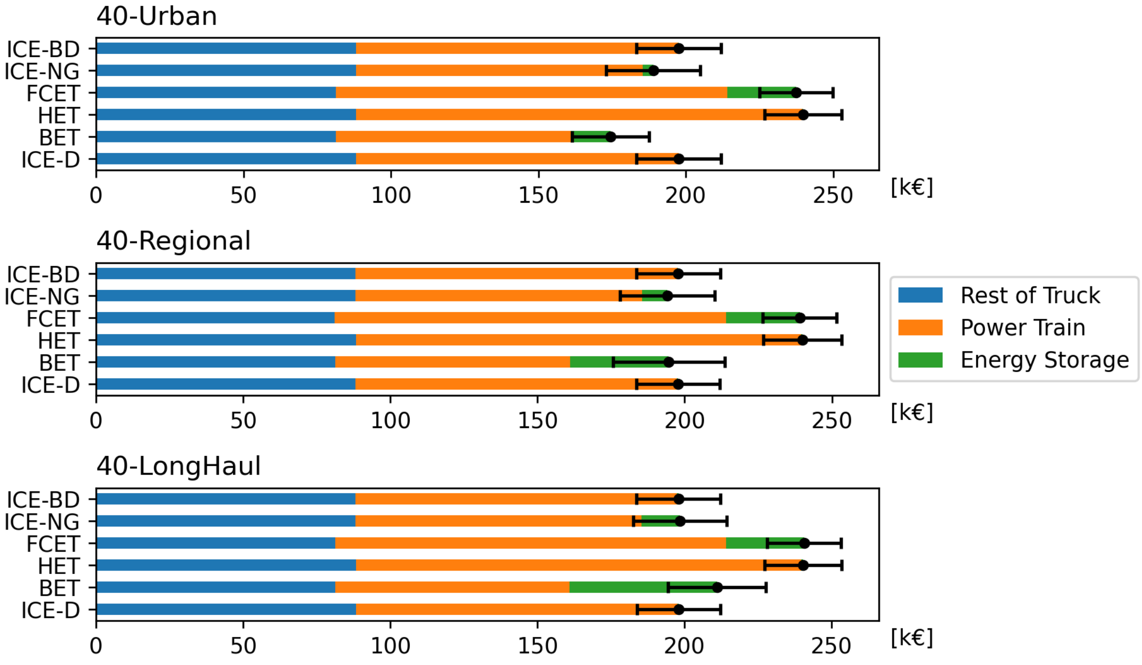


Figure 3.4: "Best case" segmented CAPEX values of 40 t vehicles for the year 2019.

From 18 t upwards, BETs remain the dominating technology in the urban (>90% market share) and the regional segments (>60% market share in 2035). It is interesting to note that the market shares of BETs in the LDT segments hardly change compared to the base case. This suggests that low technology and fuel costs alone are unlikely to be able to decarbonize this vehicle sector.

3.4.2 Worst case

The “worst case” assumes high technology and fuel prices for ZEVs, while they are set at the lower bound for ICEs. Even if we put all technical developments against ZEVs, BETs are unlikely to be outcompeted in the Swiss road freight transport. Battery propulsion remains the dominant drive-technology in most application segments (Fig. 3.5) even with lower than expected cost developments, while fuel cells are hardly the chosen option anymore. Only in the 3.5-Urban segment do FCETs maintain a, albeit very small, niche share.

The conclusion from the scenarios considered in this section are as follows: Although both extreme scenarios should be regarded as very unlikely outcomes, they impressively demonstrate the cost superiority of the battery technology. While the future of the fuel cell is much more uncertain, BETs show themselves to be truly attainable alternatives to conventional propulsion technologies from an economic perspective. The market shares of the other drive-technologies represent attractive options in the short and medium term. However, combustion engines of any kind should have no place in a long-term climate strategy. As previously explained, exempting

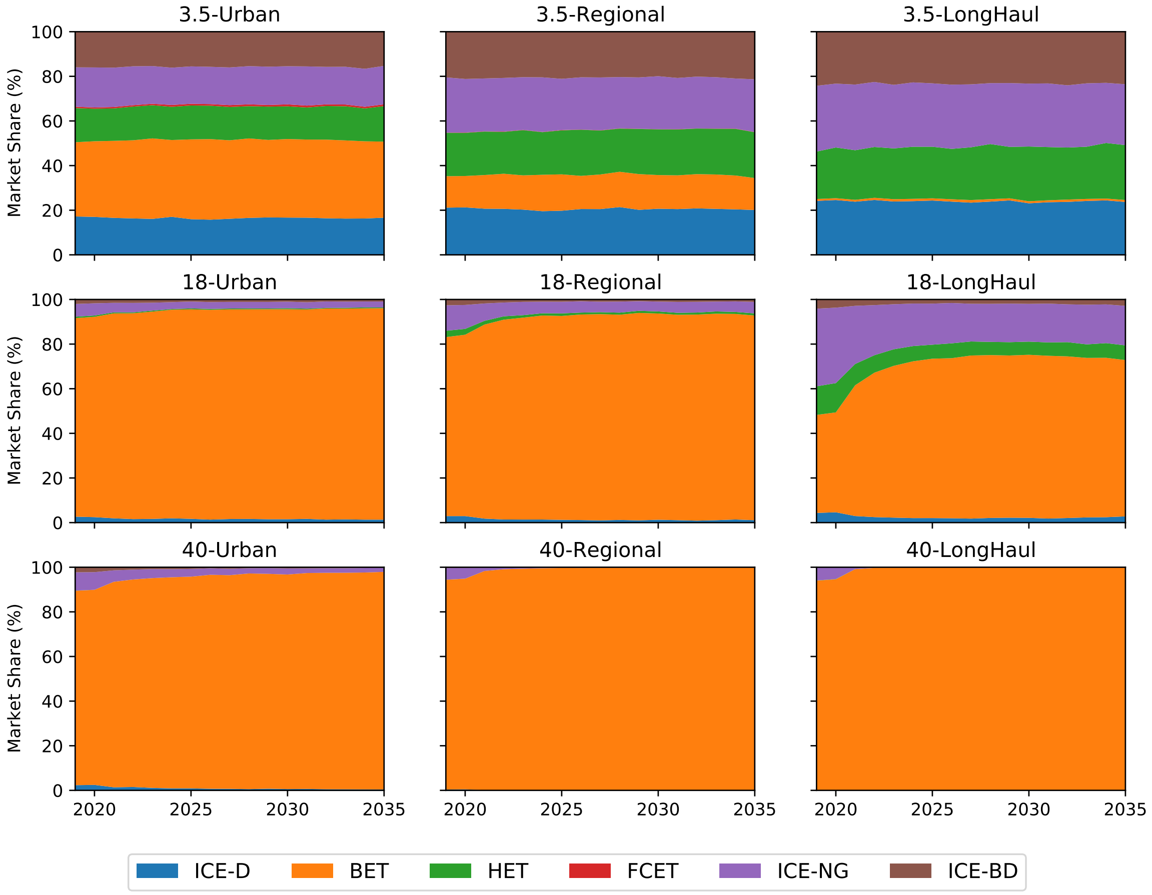


Figure 3.5: "Worst case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

ZEVs from LSVA in the mid- to long-term is not a realistically viable option (Section 1.2.2). We thus evaluate this policy question in the next section.

3.5 Results of policy scenarios

For the policy scenarios, the measures presented are first considered individually. In the case of the LSVA, the other extreme case of a full tariff for ZEVs is modeled first before a progressive tariff introduction is analyzed afterwards. Third, the case of a LSVA for LDT is also discussed. Finally, we examine the impact of a repeal of the weight penalty for BETs. A possible policy-mix of the individual measures will then be discussed in the next chapter in Section 4.2.

3.5.1 Full LSVA

To display the full breadth of outcomes, the most dissimilar case compared to the previously presented base case is selected. While ZEVs have been fully exempted from LSVA so far, the next scenario results presented use the same LSVA tariff for all ZEVs as it applies to ICEVs. The rate is kept constant for the period modelled and payload losses for BETs with heavy batteries are continued to be penalized.

A majority agrees that sooner or later the exemption from the toll will be removed, since ZEVs are also accountable for negative externalities others than tailpipe emissions, like road wear and traffic jam. But, it would not be appropriate to put them in the same tariff category as ICEVs. Thus, this extreme case should not be considered as reasonable options. Rather, it serves the purpose of better illustrating the extremity of results. From the results shown in Figure 3.6 we can see how impactful the LSVA toll is in Switzerland. Where before most of the market shares were held by BETs, now they are dominant only in the urban MDT and HDT and regional MDT segments. Since the LSVA tariff is calculated based on the distance traveled, the effects of this measure are strongest in long-haul traffic. While electrification is likely to progress quickly in this sector due to possible entry bans for diesel truck in cities and increasing request for sustainable transport logistics, it offers the lowest saving potential when it comes to LSVA. A 40-ton truck on the highway quickly pays several hundred Swiss francs in LSVA per day, a bill which every fleet owner is happy to avoid.

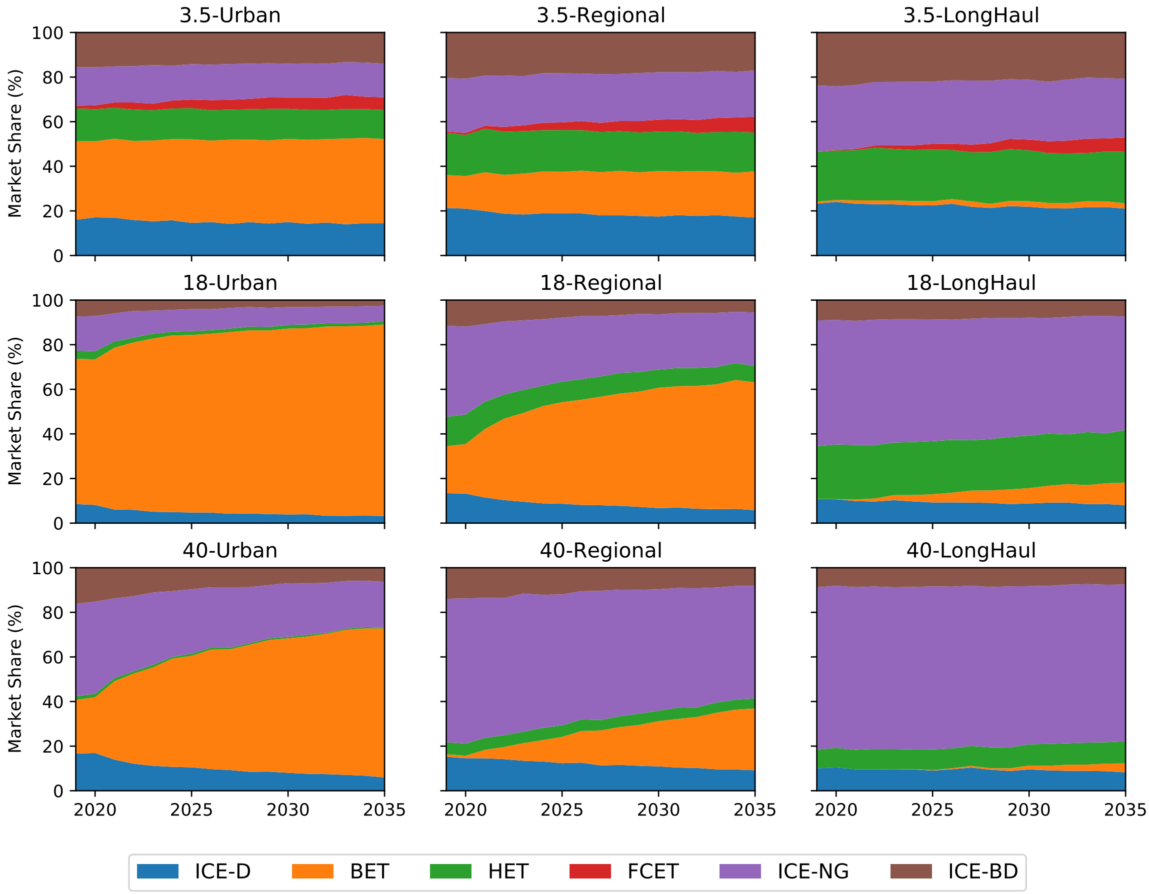


Figure 3.6: "Full LSVA case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

While full taxation of ZEVs analogous to ICEs is hardly seen as a realistic option, these results clearly display the power of the LSVA toll as a policy instrument. If used too early or calibrated improperly (i.e. set too high), it can inadvertently act as an innovation killer, slowing or even preventing a rapid diffusion of ZEVs.

3.5.2 Progressive LSVA

A more realistic way to tax ZEVs offers a later introduction and gradual increase of the tariff. The amount and timing of the increases must be aligned with the learning curves of the technologies to prevent a slowdown in diffusion or over-subsidization [56]. The result of such a sequential approach of a LSVA introduction for medium- and heavy-duty ZEVs as illustrated in Figure 3.7 is presented in this section and shown in Figure 3.8.

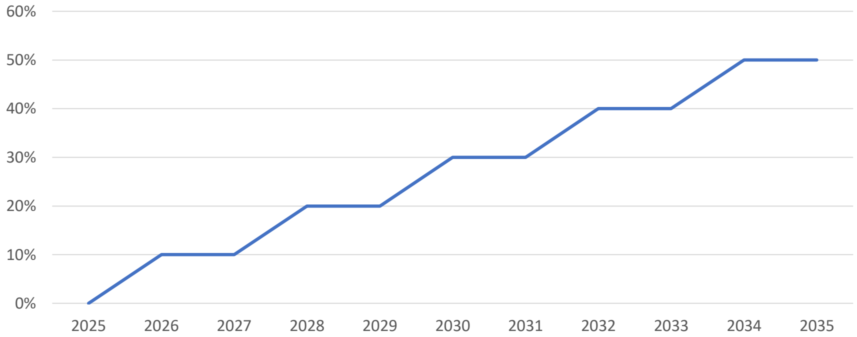


Figure 3.7: Applied LSVA tariff structure for ZEVs in percentage of the tariff for ICEVs in the "Progressive LSVA case".

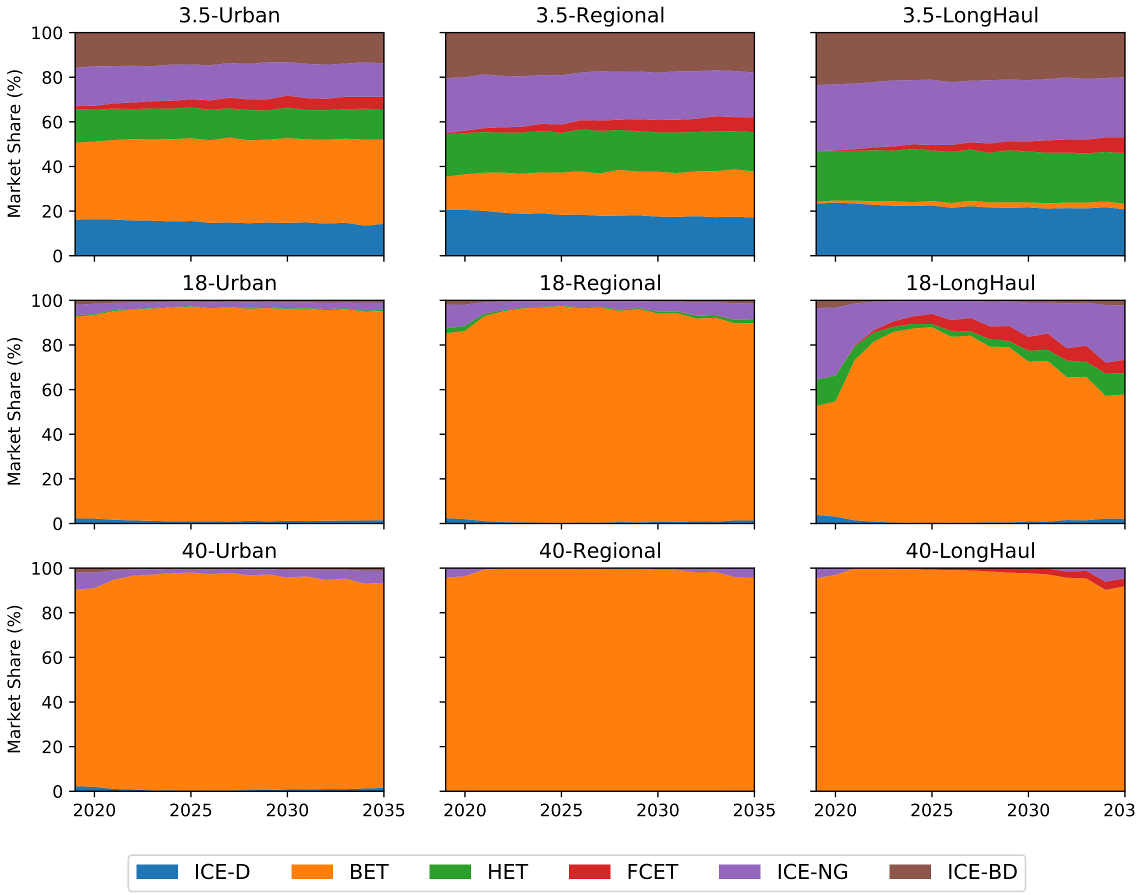
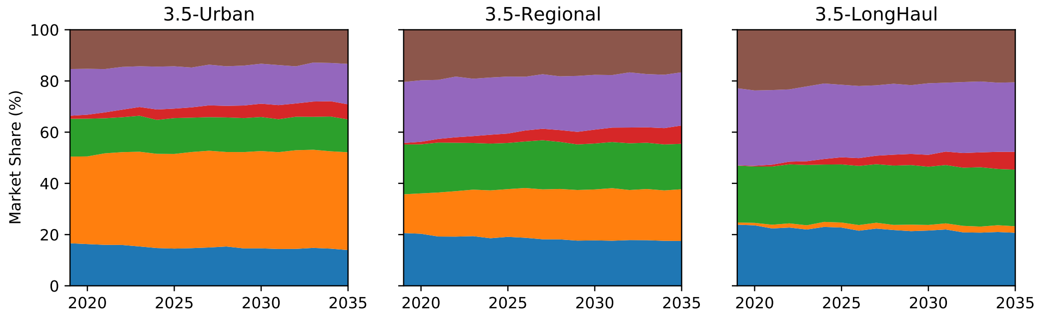


Figure 3.8: "Progressive LSVA case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

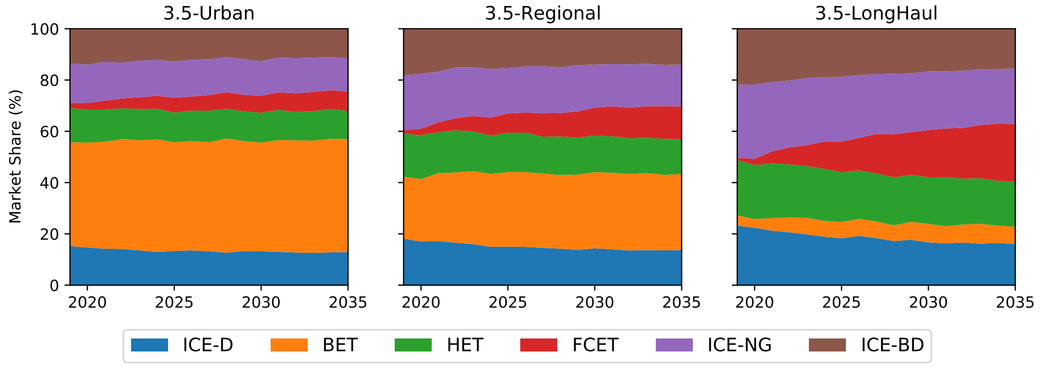
As expected, the effects of a gradual introduction of the LSVA for ZEVs are strongest in the long-haul segments. In the 18-LongHaul, the staircase-like increase of the tariff is clearly visible, but in a mirrored form, since the TCO for ZEVs increases and the difference to the tariff for ICEs decreases. The 3.5 t weight class is currently not subject to LSVA regulation, no changes can be seen in these application segments. However, the impact on the market share of drive-technologies through such a policy measure is presented in the next section.

3.5.3 Full LSVA for LDTs

Now the same LSVA tariff applies for the 3.5 t vehicles, as it is charged for the higher weight segments. ZEVs remain exempt from the toll. In this case, it is sufficient to look at the LDT segments (Fig. 3.9). Both technologies, FCET and BET, can increase their market share as a result of the new measure. However, since the vehicle weights are comparatively low, these effects are limited. In the long-haul segment, ZEVs will reach a market share of about 30% in 2035.



(a) "Base case"



(b) "Full LSVA for LDTs case"

Figure 3.9: (a) "Base case" drive-technology market shares of annual, additional freight vehicles (newly registered) for the LDT segments from 2019-2035.
(b) "Full LSVA for LDTs case" drive-technology market shares of annual, additional freight vehicles (newly registered) for the LDT segments from 2019-2035.

This implies that, from an emissions reduction point of view, the same tariff structure for the LDT segments may not be sufficient to yield the desired outcome. However, the introduction of the tariff also represents an interesting option for financing the energy transition.

3.5.4 No BET penalty

The effects on the deployment of drive-technology market shares of the policy described in Section 2.3.4 are presented in this Section.

Removing the BET penalty from the TCO equation by allowing BETs to be heavier helps the BET deployment in the upper right corner, namely the following application segments: 3.5-Regional, 3.5-Urban, and 18-LongHaul (see Fig. 3.10). In the 3.5-Regional segment, BETs manage to nearly double their market share by 2035, compared to the base case. The 3.5-LongHaul segment experiences the strongest influence of the policy. From a technology with niche market shares when the penalty applies, BETs become the dominant drive-technology once the penalty is removed. In the 18-LongHaul segment, BETs become the almost exclusive technology even faster than in the base case, supplanting FCETs completely. This does not come as a surprise, as the main competitive advantage of FCETs was discussed to be its small weight increase when demanding longer ranges. While such an abolition of the penalty clearly supports the diffusion of battery propulsion vehicles, its dominance can pose risks associated with technological lock-in.

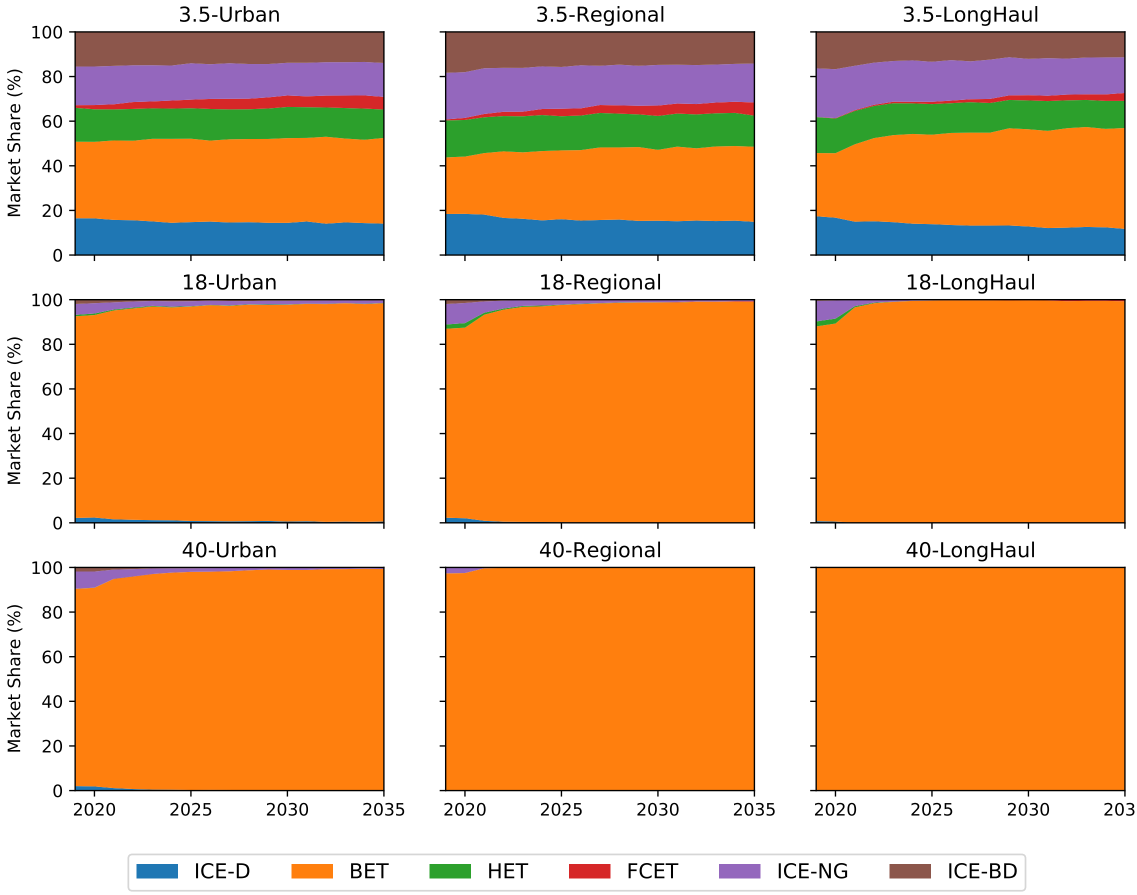


Figure 3.10: "No BET penalty case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

All possible combinations from Table 2.6 are modelled and the resulting market share plots can be found in appendix A.2. The "base case" (Fig. 3.7) and "No BET penalty" (Fig. 3.10) have already been discussed previously. "No BET penalty and no BET reward" yields lower BETs market share in the urban segments, but higher shares in the long-haul segments, compared to the base case. Thus, we can conclude that the reward has the greatest effect in the LDT and MDT urban segments and the consequences of the penalty appear mainly in the LDT and MDT long-haul segments. "BET penalty only" yields a superposition of "base case" and "No BET penalty and no BET reward" when looking at negative consequences for BETs. It results in lower BET market shares in the urban segments due to the absence of rewards and lower market shares in the long-haul segments to the penalty in place.

4 Discussion

This chapter allows for a discussion of the previously presented results and their implication. The first section provides a brief summary of the results and the key findings derived from them. The second section puts these findings into a policy perspective and proposes a policy-mix combining several scenario cases. Finally, limitations and implications for future research are discussed.

4.1 Summary of results

We find an overall strong dominance of BETs. The drive-technology persists its market share leadership even if all technological developments are set against ZEVs. The sensitivity analysis confirms the insights gained from literature review and expert interviews that the fuel costs represent a deciding factor for the success of FCETs. Only if the cost of hydrogen production decreases strongly will the drive-technology become competitive. However, if things develop to the disadvantage of ZEVs, fuel cells do not appear in any of the application segments.

The LSVA represents a powerful tool as a policy instrument in Switzerland. It can play a key role in decarbonizing the Swiss road-freight sector. While the taxation of ZEVs is indispensable, the progressive introduction of a LSVA tariff for ZEVs is shown to be a feasible policy option. While expanding the LSVA obligation to 3.5 t vehicles from the LDT segment offers an appropriate opportunity to co-finance the energy transition, a tariff analogous to the current one for MDTs and HDT will likely not be sufficient to drive the transition to ZEVs in the next decades.

Finally, a policy allowing BETs to increase their MPW to compensate for potential payload losses yields the strongest effects in the 3.5-LongHaul segment, while BETs experience a reward due to payload gains mainly in the MDT urban segments.

4.2 Proposed policy-mix scenario

The presented results contain important key findings. This section combines the individually investigated policy options and presents a possible policy-mix. The results serves to stimulate the subsequent discussion on policy implications. This policy-mix was also presented to the Federal Office of Transport *(Bundesamt für Verkehr)* (FOT) and reviewed for its feasibility. The policy-mix tries to address multiple challenges at the same time:

- Provide acceleration of CO_2 reduction efforts
- Create incentives to shift towards low-carbon trajectories within the transport sector
- Introduce levies to finance the energy transition
- Support a portfolio of energy carriers
- Mitigate the risk associated with technological lock-in

As Bach et al. argue [57], a massive acceleration of CO_2 reduction efforts must be initiated and maintained over the next decades to comply with the climate targets under the Paris Agreement. While technology-push policies stimulate R&D, demand-pull policies target consumers by creating financial incentives. To fund such incentives and other policies, a levy offers a feasible solution. With any instrument type, the earmarking of policy revenues is crucial to successfully overcome the political hurdles. While a tax creates a revenue stream into the government's budget, the revenues from a CO_2 levy are to be redistributed to the population. This makes it an interesting option to finance the energy transition. Governments picking winners is said to be a bad way to manage the energy transition. Thus, it should support a portfolio of technologies to avoid the dominance of a single technology. Such a technological lock-in can result in long-term inefficiencies due to locked-out technologies which are potentially more efficient in the long-term. In addition to that, the lock-out of a technology lowers diversity, resulting in lower resilience to external shocks [58], [59], [60].

From this motivation, the following policy measures were identified:

1. Introduction of LSVA obligation for 3.5 t vehicles
2. Progressive LSVA introduction for medium- and heavy-duty ZEVs
3. Downgrading Euro 6 ICEVs to lower LSVA category (equals increase of tariff)
4. Eliminate preferential treatment of transportation fuels by introducing a CO_2 levy on gasoline & diesel
5. Allow BET to increase current vehicle MPW
6. Subsidy of hydrogen if necessary

(1) Light-duty vehicles (vans) are introduced to LSVA from 2026. The same tariff applies as for medium and heavy-duty vehicles. The additional revenue allows for financial support of the energy transition and compensates revenue losses from increasing market shares of ZEVs.

(2) ZEVs are progressively introduced to LSVA from 2026. The tariff for BETs starts at 5% of the current Euro 6 category and is increased every few years. FCETs experience a 25% tariff reduction due to lower life-cycle emissions. This tariff structure needs to be monitored and adjusted if necessary to avoid decelerating diffusion or over-subsidization of ZEVs.

(3) All Euro 6 ICE vehicles are downgraded to the lower LSVA toll category with a higher tariff from 2026 (for more details on toll categories, see [32]). This creates additional incentives for fleet operators to shift towards low-carbon trajectories. Points (1), (2), and (3) are illustrated in Figure 4.1.

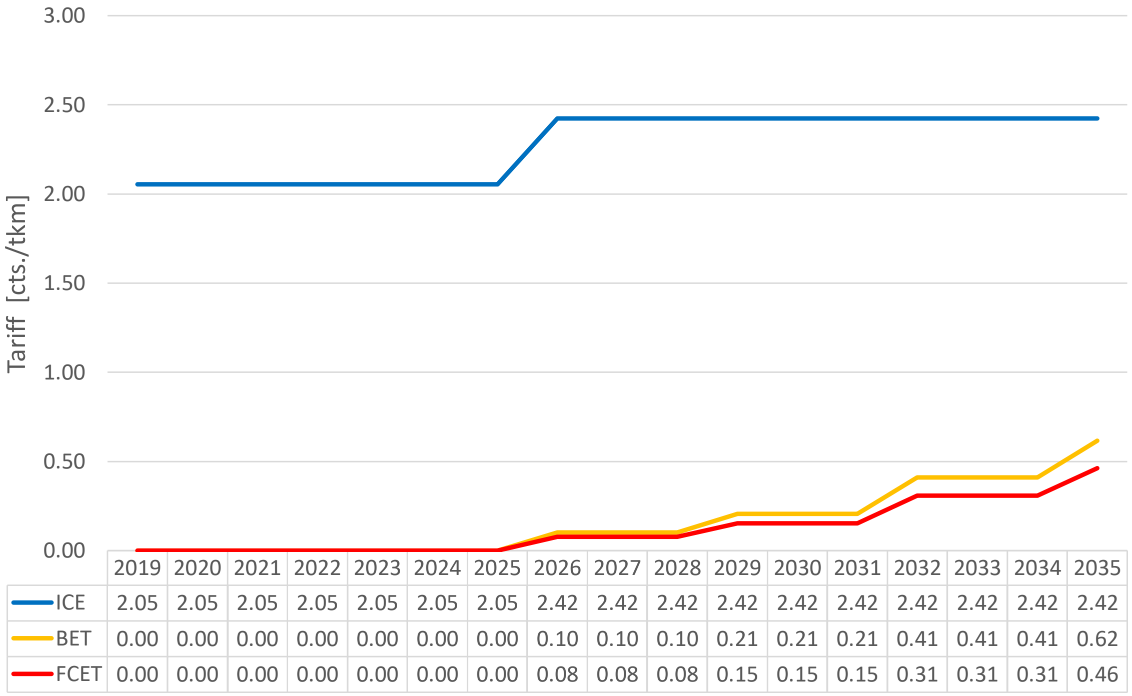
(4) A CO_2 levy applies on diesel and gasoline to eliminate the preferential treatment of transportation fuels. Derived from Thalmann and Vielle's [5] results, this maximum levy would amount

to about 1.50 CHF per litre of gasoline. This means it would double its current price by 2050. For such a trajectory, an annual diesel price increase of 2.25% is assumed in the policy-mix model. This provides an acceleration of CO_2 reduction beyond the road freight transport sector.

(5) To increase the competitiveness of BETs, a policy allows such vehicles to increase their MPW to compensate payload losses. The penalty is removed.

(6) Hydrogen is subsidized if necessary, for example by excluding domestic electrolyzers for green hydrogen production from grid fees. A broader approach is to subsidize hydrogen directly at the pump to increase demand. This would also include imported hydrogen. Such a policy measure supports a portfolio of energy carriers and mitigate risks associated with technological lock-in. It requires close monitoring and adjustment if necessary. To model this, the low hydrogen fuel cost scenario is assumed.

The presented policy-mix was also discussed with an expert from the FOT and reviewed for its feasibility. All proposed policy options were assessed as reasonable. In some cases, such or similar proposals are already under political discussion.



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
ICE	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42
BET	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10	0.21	0.21	0.21	0.41	0.41	0.41	0.62
FCET	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.08	0.08	0.15	0.15	0.15	0.31	0.31	0.31	0.46

Figure 4.1: Applied LSVA tariff structure for ICEs and ZEVs in the "Policy-mix case".

The resulting drive-technology market shares are illustrated in Fig. 4.2. We can recognize multiple of the previously discussed deployment patterns. Overall, BETs continue past trends and achieve the highest market share across all application segments. If batteries follow the expected cost trajectory and the electricity price stays within expected fluctuation, they are likely to become the dominant technology. Two segment dimensions, however, deserve a closer look. First, within the LDT segments (first row), both BETs and FCETs diffuse much faster compared to the base case. This is a direct consequence of the introduction of LSVA for this weight class. The results illustrate nicely, that such a policy kills two birds with one stone: it reduces emissions from this vehicle-intensive segment and at the same time contributes to the financing of the energy transition. It is worth noting that the other drive-technologies do not disappear in the near and medium term. Rather, they remain a feasible option for the next decades to come. This suggests that a transition to net-zero emission road freight requires stronger policy interventions than financial incentives alone. Second, the long-haul segments (right column) turns out to be supplied by two drive-technologies: batteries and fuel cells. Although BETs appear to be dominant in these segments as well, one should remember that the ranges used from the Swiss LSVA data for the energy storage calculation (Chapters 2.3.1 and 2.2.4) are rather low compared to other region's driving patterns. The data used also excludes transport performance provided by Swiss vehicles abroad. Vehicles are not designed for the Swiss market specifically. It can be assumed that long-distance vehicles will have to be able to cover a significantly longer range without refueling. Thus, the share of FCETs should rather be considered as a low value.

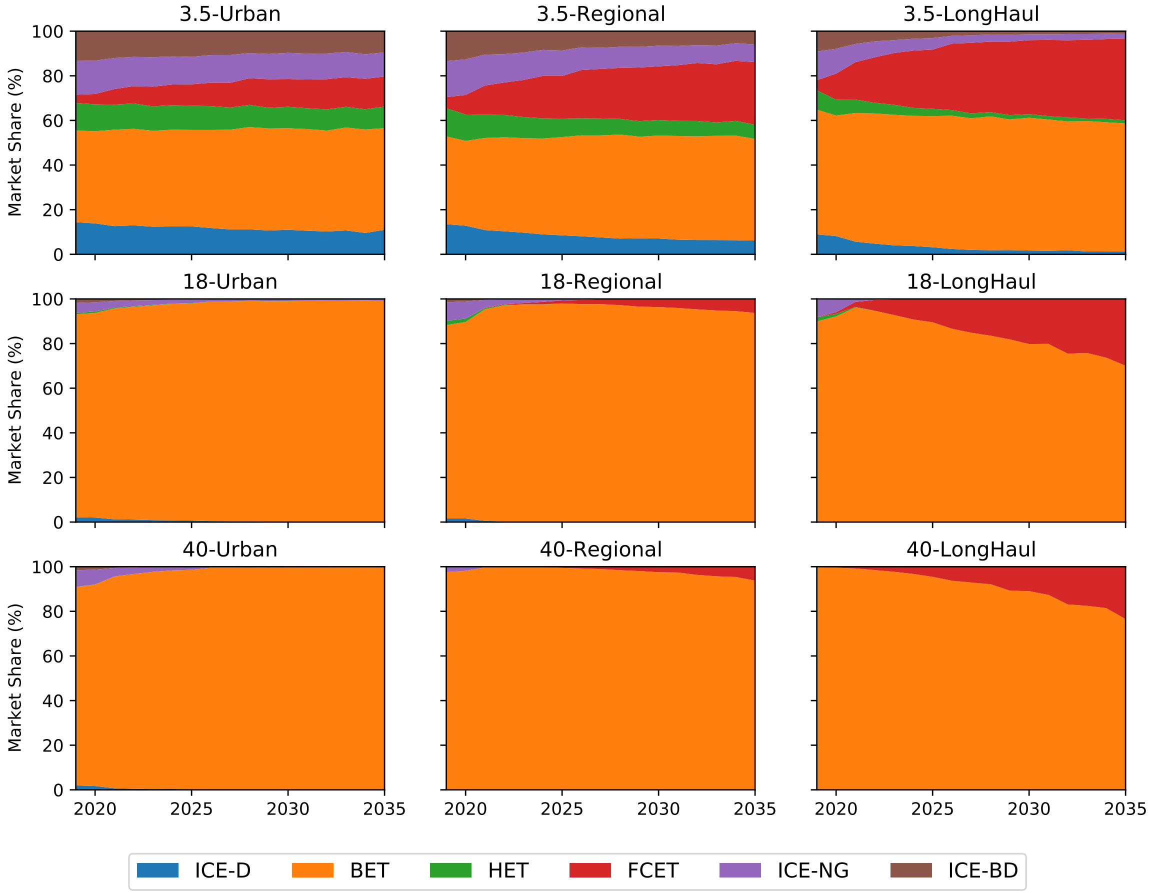


Figure 4.2: "Policy-mix case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 9 application segments from 2019-2035.

4.3 Policy implications

Unlike passenger cars, where we can observe a clear trend toward battery-electric vehicles, the drive-technology competition for commercial vehicles has not yet been decided. The need for a transition to low-carbon transport in Switzerland is uncontested. What is highly contested, however, is what the policy interventions setting the tracks for such a transition should include.

(1) Introduction of LSVA obligation for 3.5 t vehicles.
Introducing LDTs (vans) to LSVA turns out to have a strong impact on the diffusion of ZEVs in this weight segment. Drive-technology cost reductions of BETs and FCET alone are unlikely to be able to decarbonize this segment. This observation enhances the debate about the design of the LSVA tariff — a highly topical subject in Swiss politics at the moment. In progress in December 2020, a motion was submitted to the Swiss parliament, instructing the Federal Council to ensure equal contributions from trucks (>3.5 t) and vans (<3.5 t) in covering road wear in Switzerland [61]. At the time of writing, the Council of States has adopted this motion and it is now on the agenda of the National Council. It can be assumed that the motion will also receive strong support in the second chamber. However, the tariff structure would likely become more complicated. Vans transporting materials or equipment for professional use, for example, the delivery truck of a construction business, shall be exempt from the toll. Only postal service providers and other similar services would be subject to the new toll structure. The reach of the amended LSVA tariff would therefore increase considerably as it currently only covers MDTs and HDTs. There are presently about 50'000 such freight vehicles, which cover around 67% of the total mileage from road-freight transport in 2018, but only around 5% of the national transport performance in tonne-kilometers (numbers from [61]). For a detailed description of the different LSVA cost components and share of uncovered costs from freight transport, the reader is referred to the study of the ARE [62].

(2) Progressive LSVA introduction for medium- and heavy-duty ZEVs.
The introduction of tolls for medium and heavy-duty ZEVs is rarely debated. The tariff structure introduced in Figure 4.1 offers a first draft for further discussion. In the EU, first discussions have arisen regarding the introduction of a higher emission performance standards for ICEVs—the Euro 7 class. With a vehicle life of seven to eight years, an introduction of the tariff for ZEVs by 2026 is not unrealistic, but rather early. When recalling the purpose of the LSVA from Section 1.2.2, the toll is intended to cover the infrastructure costs and costs attributable to heavy vehicles at the expense of the general public in the long term, insofar as they are not already covered by other services or charges. Furthermore, the charge also helps to ensure that the general conditions for rail in the transport market are improved and goods are increasingly transported by rail (modal shift). From this perspective, the presented LSVA tariff for ZEVs should be regarded as rather low. Since ZEVs contribute to the road infrastructure costs to the same extent as freight vehicles with an ICE, they should also be tolled proportionally. Moreover, they do not help to ensure that the general conditions for rail-freight intermodal transport are improved, which is the second aim of the LSVA policy. Differentiated toll categories that consider life-cycle emissions of ZEVs should be discussed as a possible option.

The question of the tariff structure could become obsolete if the LSVA is considered in isolation from vehicle-related GHG emissions, by focusing the aim of modal shift policy. One possible approach to motivate the purchase of a ZEV is to subsidize the CAPEX, not the OPEXs, by having the government compensate the cost gap to the conventional diesel truck. This allows the LSVA to be seen simply as a toll for the use of the road. Accordingly, all road-freight vehicles—independent of the drive-technology—would pay the same tariff. This tariff would still be based on transport performance, or in other words, vehicle weight and distance covered.

(3) Downgrading Euro 6 ICEVs to lower LSVA category.
A policy intervention which downgrades Euro 6 ICEVs to the lower LSVA category II (instead of category III as now) represents a relatively straight-forward implementation option, provided that the weighted average of the toll for a 40 t vehicle over a distance of 300 km (reference route Basel-Ciasso) may not exceed 325 CHF, according to the Land Transport Agreement between Switzerland and the EU [63]. If calculated for a single 40 t truck driving the reference route of 300 km under the new tariff of 2.69 Rp./km (category II) this yields 323 CHF. For toll categories and their corresponding tariff see [32]. A similar measure has already been applied to Euro 4 and Euro 5 vehicles, which will by downgraded from the current category II to the same category I as Euro classes 0 to 3, by July 1st, 2021.

(4) Eliminate preferential treatment of transportation fuels.
The need for a CO_2 levy remains controversial in Switzerland. While many researchers demand the introduction of such a levy, the Swiss revised CO_2 law, which will be voted on in the summer of 2021, does not consider a levy on transport fuels. Higher fuel prices would not only increase the cost of operating an ICE truck, but also that of a passenger car. Therefore, special care must be taken to ensure that the policy does not have regressive effects, which occur if a policy reduces the available spending budget of households after covering basic demand like food, housing, and education. Just as we pay a fee to dispose of our household waste, policy-makers must also find ways to declare GHG emissions as a waste product to be disposed of, for which there is some cost due.

(5) Allow BETs to increase current vehicle MPW.
Such a political measure must be analyzed with great caution. It is true that tests of ZEVs with excess length or excess weight are already underway on Swiss roads. However, such a permission should at most be seen as a short-term market diffusion support mechanism, designed to improve market shares of ZEVs. Enabling higher MPW for BETs may reduce efforts in battery energy density R& D, as the policy does not necessarily drive innovation, but rather adjusts to the state-of-the-art. In addition, as the results from Section 3.5.4 show, this policy measure increases the risk of technological lock-in, which is contrary to the motivation presented earlier. Policy-makers would be wise to refrain from using this measure. Instead, politics should support technologies individually and concentrate their support on fast learning technologies. If it turns out that a state-of-the-art support mechanism is still necessary, such a policy should then only be implemented for a limited time.

(6) Subsidy of hydrogen if necessary.
Subsidizing hydrogen introduces perverse incentives similar to the removal of the weight penalty

for BETs. A policy measure is perverse if the total balance of intended and non-intended effects appears negative. While this policy clearly supports the diffusion of FCETs and offers reduced risk of technological lock-in, it operates in contrast to Switzerland's modal shift policy (as introduced in Section 1.2.2). Especially in the long-haul segments, where FCETs show a distinct advantage compared to BETs due to lower relative costs of energy storage, the best low-carbon transport solution may rather be to load freight onto a train and use road-freight vehicles only for the last mile delivery.

Excluding domestic electrolyzers for green hydrogen production from grid fees is a policy measure which is difficult to justify. There is no well-founded argumentation for such an exclusion of grid fees, since the grid is used in the same manner in all applications. Targeted interventions here should be more concerned with ensuring domestic hydrogen production takes place directly at the power plant. This way, the grid fees would be eliminated by necessity. Subsidizing hydrogen at the pump directly offers a more holistic approach, since it includes imported hydrogen as well. As with the proposed policy that allows BETs to increase their current vehicle MPW, a hydrogen consumption subsidy policy should only apply for a limited time to support the market diffusion of fuel cell electric vehicles.

4.4 Limitations and future research

The modelling framework used within this study projects market shares for selected drive-technologies for the years 2019-2035. These projected values should be seen as "theoretical" market shares, since the availability of drive-technologies and vehicle models is not considered in the model implementation.

The work described in this thesis started in fall 2020. To ensure that complete and reliable data on cost components and vehicle data were available, the base year 2019 was chosen. The results presented include strong market increases of ZEVs in the coming years or even already in the base year. Such an abrupt change cannot be expected, of course. Rather, the results illustrate possible developments but do not provide definitive conclusions of drive-technology market shares.

During the validation of the proposed policy measures, it became apparent that Switzerland has many national transport policies that are Swiss-specific, which limits the practical extrapolation of the results to other countries or geographies.

The model uses exogenous cost data, since the added capacity on Swiss roads has little impact on the global cost development due to the small market volume. If the model is extended to multiple geographies, then endogenous parameters would more accurately reflect the actual cost developments due to additional capacity additions using different experience curves for the specific drive-technologies and other cost components. For example, the decreasing costs of hydrogen-related infrastructure could be modeled endogenously.

As discussed in Section 4.3, subsidies that target CAPEX parameters may enable similar results while avoiding critical political interventions. Future research should also focus on modelling such policy scenarios.

5 Conclusion

This study set out to answer two research questions: what drives the market share competition between commercial vehicle drive-technologies in Switzerland and how do different policy scenarios affect the outcome of this competition.

First of all, we conclude that uncertainty about the economic feasibility of low-carbon drive-technologies as viable solutions for a low-carbon road-freight sector future persists not only within the existing scientific literature, but also among vehicle manufacturers, fleet owners, logistic companies, charging and fueling station operators, and policy-makers. There is great interest from road-freight industry and politics in this research and its results. The competition between drive-technologies in the freight transport sector has not been decided.

The TCO analysis shows that the main drivers behind drive-technology competition in road-freight vehicles are not largely CAPEX related, but are primarily reflected in the OPEX over the lifetime of the vehicle.

We find that BETs are likely to outcompete alternative drive-technologies by 2035 across most application segments which are under LSVA obligation and largely independent of selected drive-technology or fuel scenarios. Only if the costs of hydrogen decrease significantly over the next years will FCETs gain a cost advantage in long-haul transport ultimately leading to a potential market cornering. This dominance can pose risks associated with technological lock-in.

The described pattern is found to not be applicable in the LDT segments, consisting of 3.5 t vehicles which do not fall under the LSVA obligation. It turns out that lower technology costs alone will not allow BETs to become the drive-technology with the lowest TCO. FCETs appear to be the most feasible economic option, but once again, only if hydrogen costs drop steeply.

We find the role of politics to be imperative in achieving the agreed-upon climate targets for the Swiss transport sector. LSVA is shown to be the most impactful policy tool in Switzerland for decarbonizing the road-freight sector. While this offers opportunities to create incentives on the demand side, it also holds the potential to act as an innovation killer if calibrated improperly. Policy-makers must be aware of this fact when designing appropriate toll measures.

One can debate if electrification by way of battery or fuel cell is more suitable for the HDT long-haul segments. In Switzerland, this question becomes obsolete if we strictly follow the modal shift policy and put all goods from long-haul traffic on the train. Although rail is not within the scope of this study, it is in some contexts seen as the best option for decarbonizing the long-haul freight sector. Like in the historical energy transition from carriage to rail, horses were used over a century to transport people and goods to the railway station. Similarly, we will need freight vehicles in distribution networks and last mile deliveries. These vehicles must shift to alternative-drive, preferably zero-emission, technologies regardless.

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A Appendix: additional information

A.1 List of body codes

Table A.1: Vehicle body codes (ignored=x are excluded from data analysis)

Body code	Description German	Description English	Ignored
0	Fahzeugkategorie 38 Sattelschlepper	Vehicle category 38 articulated tractor unit	
1	—	—	
100	Abschleppwagen	Tow truck	x
102	Wechselabrollaufbau Kette	Swap body with roller (by chain)	
103	Asphaltkocher	Bitumen stove	x
104	Asphaltmischer	Bitumen mixer	x
106	Ausstellungsfahrzeug	Exhibition vehicle	x
108	Brücke	Loading bridge	
109	Betonmischer	Concrete mixer	x
116	Tank für Lebensmittel	Tank for food	
117	Containertransport	Container transport	
119	Silo für Lebensmittel	Silo for food	
122	Gasflaschentransport	Gas bottle transport	
123	Elementtransport	Element transport	
126	Fahrmischer	Concrete mixer	x
127	Fahrzeugtransport	Vehicle transport	
130	Flaschentransport	Bottle transport	
136	Gelenksteiger	Articulating boom lifts	x
138	Glasscheibentransport	Glass pane transport	
139	Kühlkasten mit Hebebühne	Cooling box with lifting platform	
144	Klimatisierter Kasten mit Hebebühne	Air conditioned box with lifting platform	
145	Kabeltransport	Cable transport	
147	Kasten	Box truck	
148	Kasten gepanzert	Box truck armored	x
150	Kehrichtabfuhr	Gargabe truck	x
151	Kippbrücke	Dump truck	
152	Kippmulde	Dump body	
153	Kippkasten	Tilting box	
156	Kran	Crane	x
157	Kühlkasten	Cooling box	
159	Langholz	Logging truck	
160	Langmaterial	Long material truck	
161	Stationswagen	Station wagon	x
167	Messwagen	Measuring vehicle	x
171	Motorspritze	Motorized fire engine	x

Table A.1: Vehicle body codes *continued* (ignored=x are excluded from data analysis)

Body code	Description German	Description English	Ignored
174	Kippbrücke mit Ladekran	Dump truck with loading crane	
177	Pferdetransport	Horse transport	
181	Reportagefahrzeug	Reporting truck	x
182	Saug- und Druckfass	Suction and pressure drum	x
187	Schlammsauger	Mud vacuum cleaner	x
189	Kippbrücke mit Seilwinde	Dump truck with cable winch	
190	Schneeräumung	Snow removal	x
191	Langholz mit Ladekran	Logging truck with loading crane	
196	Langmaterial mit Ladekran	Long material truck with loading crane	
200	Silo für Schüttgut	Silo for bulk freight	
201	Silo für Zement	Silo for cement	
207	Schwemmwagen	Cleaning truck	x
208	Streuer / Sprenger	Salt spreader vehicle	x
211	Tank für Getränke	Tank for beverage	
212	Tank für Milch	Tank for milk	
213	Tank für Teer/Bitumen	Tank for tar/bitumen	
214	Tank für Treibstoffe	Tank for fuels	
215	Tank für Wasser	Tank for water	
220	Transporter / Wechselaufbauten	Transporter / Swap body	
221	Verkaufsfahrzeug	Sales vehicle	x
223	Langmaterial mit Seilwinde	Long material truck with cable winch	
224	Abschleppwagen mit Seilwinde	Tow truck with cable winch	x
225	Abschleppwagen mit Ladekran	Tow truck with loading crane	x
226	Wechselaufbau	Swap body	
228	Viehtransport	Livestock transport	
231	Wechselladekipper Welaki	Swap body tipper	
232	Werkstatt	Workshop	x
234	Wohnwagen	Caravan	x
235	Zahnklinik	Dental clinic	x
238	Brücke mit Ladekran	Loading bridge with loading crane	
240	Brücke mit Hebebühne	Loading bridge with lifting platform	
241	Brücke mit Seilwinde	Loading bridge with cable winch	

Table A.1: Vehicle body codes *continued* (ignored=x are excluded from data analysis)

Body code	Description German	Description English	Ignored
242	Tank für Chemikalien	Tank for chemicals	
243	Tank für Speiseöl	Tank for edible oil	
244	Brücke mit Verdeck und Ladekran	Loading bridge with folding top and loading crane	
246	Brücke mit Verdeck und Hebebühne	Loading bridge with folding top and lifting platform	
247	Brücke / Verdeck / Seilwinde	Bridge / Folding top / Cable winch	
249	Kasten mit Hebebühne	Box truck with lifting platform	
252	Kasten mit Ladekran	Box truck with loading crane	
253	Kasten mit Seilwinde	Box truck with cable winch	
254	Wechselabrollaufbau (Kabel)	Swap body with roller (by cable)	
255	Wechselabrollaufbau (Haken)	Swap body with roller (by hook)	
258	Wechselabrollaufbau (Haken+Kette)	Swap body with roller (by hook+chain)	
261	Behälter für Beton	Concrete container	x
265	Einsatzfahrzeug	Emergency Unit	x
267	Fahrmischer mit Förderband	Concrete mixer with conveyor belt	x
274	Hubbrücke	Lifting bridge	x
275	Kanalreiniger	Sewer cleaner	x
287	Fahrzeugtransport mit Ladekran	Vehicle transport with loading crane	
291	Containertransport mit Hebebühne	Container transport with lifting platform	
292	Containertransport mit Seitenladevorrichtung	Container transport with side loader	
293	Büro	Office	x
294	Arbeitsbühne	Work platform	x
296	Tank für Gas	Tank for gas	
299	Kippbrücke mit Verdeck	Dump truck with folding top	
301	Brücke mit Verdeck	Loading bridge with folding top	
310	Kippsilo für Tierfutter	Tilting silo for animal food	
311	Kranwagen	Crane truck	x
312	Labor	Labor	x
319	Kasten abdeckbar	Box truck coverable	

Table A.1: Vehicle body codes *continued* (ignored=x are excluded from data analysis)

Body code	Description German	Description English	Ignored
321	Sämaschine	Seeder	x
328	Klimatisierter Kasten	Air conditioned box	
338	Silo für Tierfutter	Silo for animal food	
341	Offener Kasten	Open box truck	
342	Offener Kippkasten	Open tilting box truck	
343	Silotransport- und Silostellfahrzeug	Silo transport and silo set up vehicle	
347	Fahrmischer mit Betonpumpe	Concrete mixer with concrete pump	x
352	Werbeaufbau	Advertising structure	x
355	Kehrichtabfuhr mit Ladekran	Garbage truck with loading crane	x
360	—	—	x
361	—	—	x
363	—	—	x
699	Übrige gemäss Angaben des Verkehrsexperten	Other according to transportation expert	
999	Default für ausländische Fahrzeuge	Default for foreign vehicles	x

A.2 Market shares drive-technologies

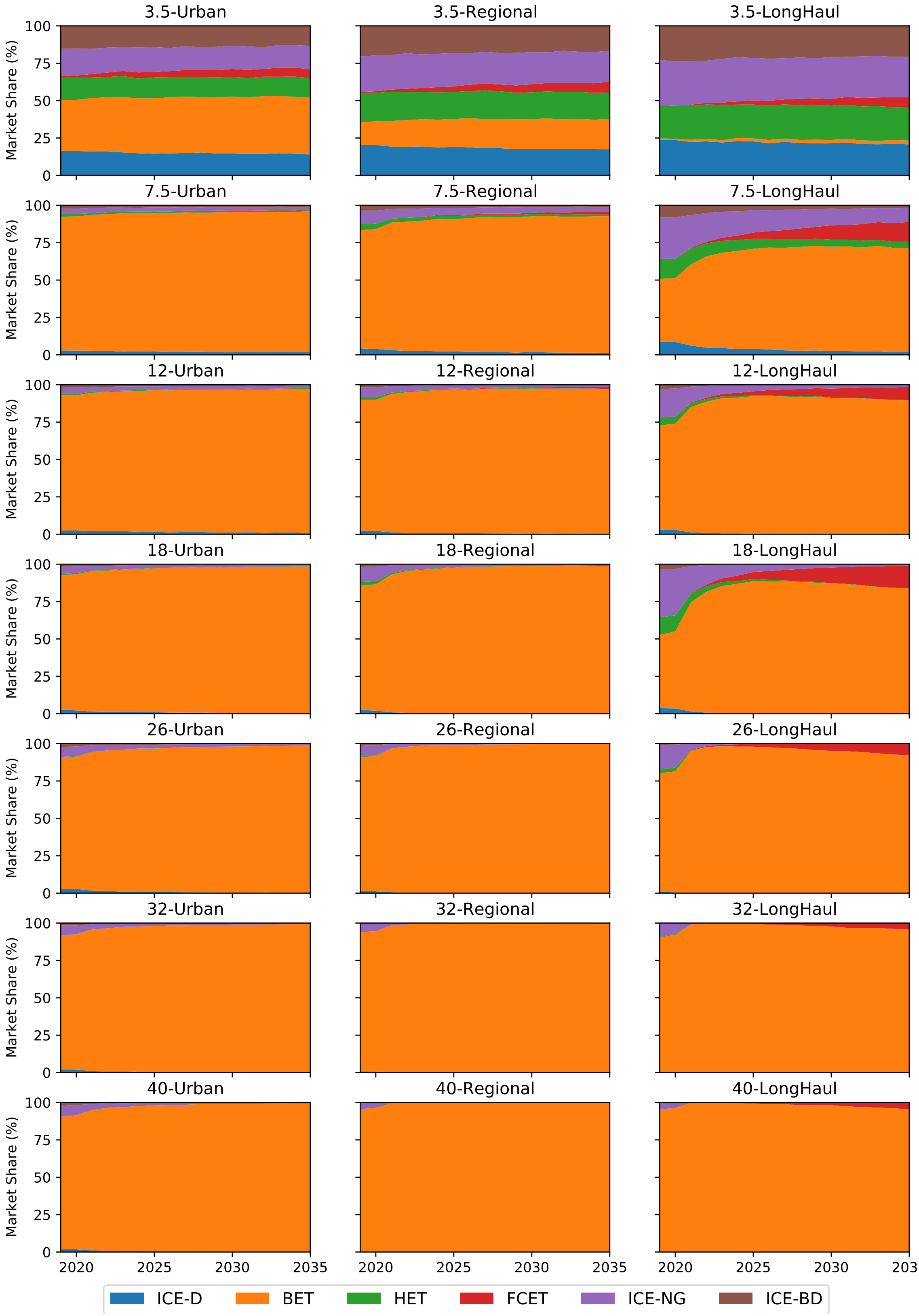

Figure A.1: "Base case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

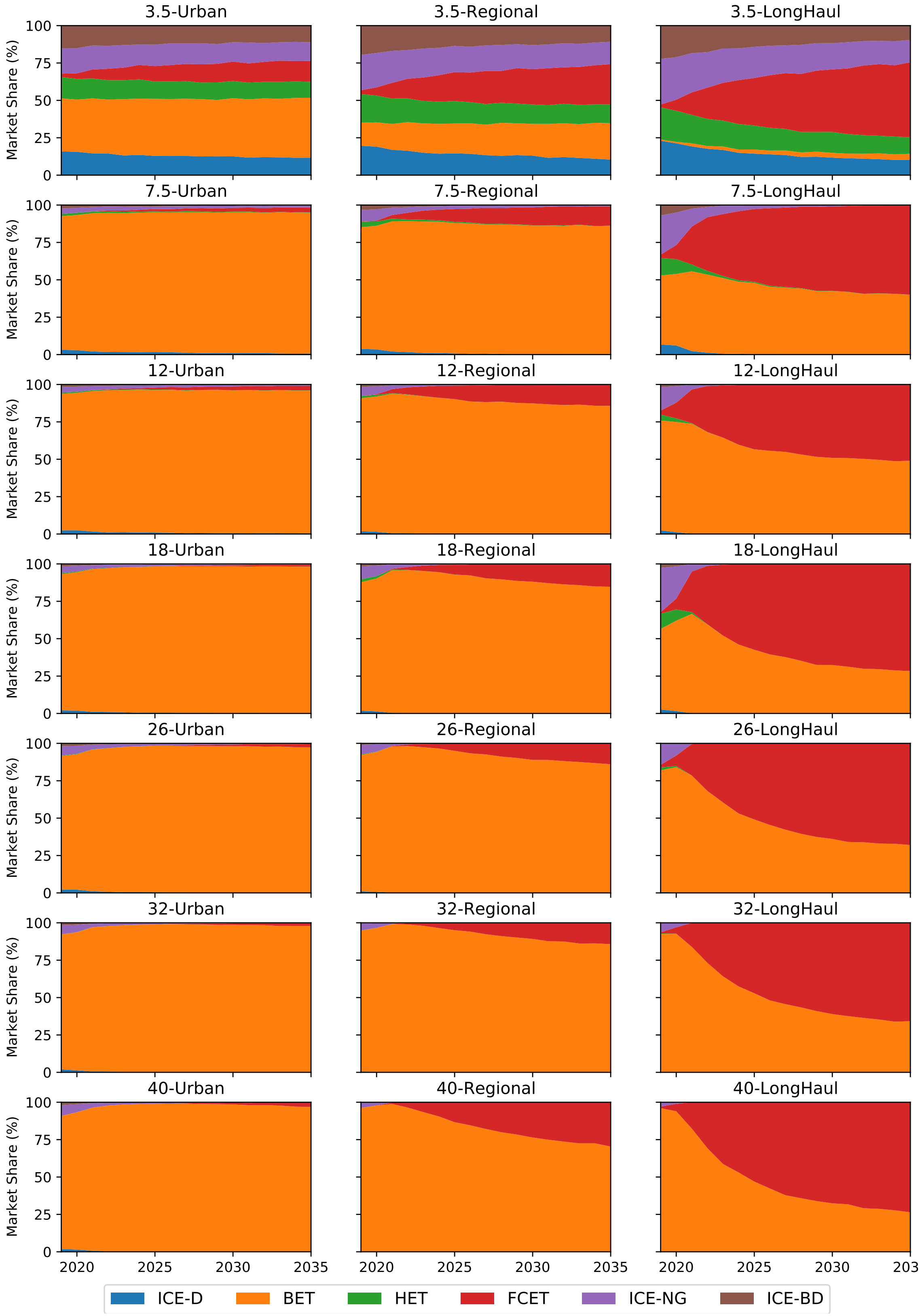

Figure A.2: "Best case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

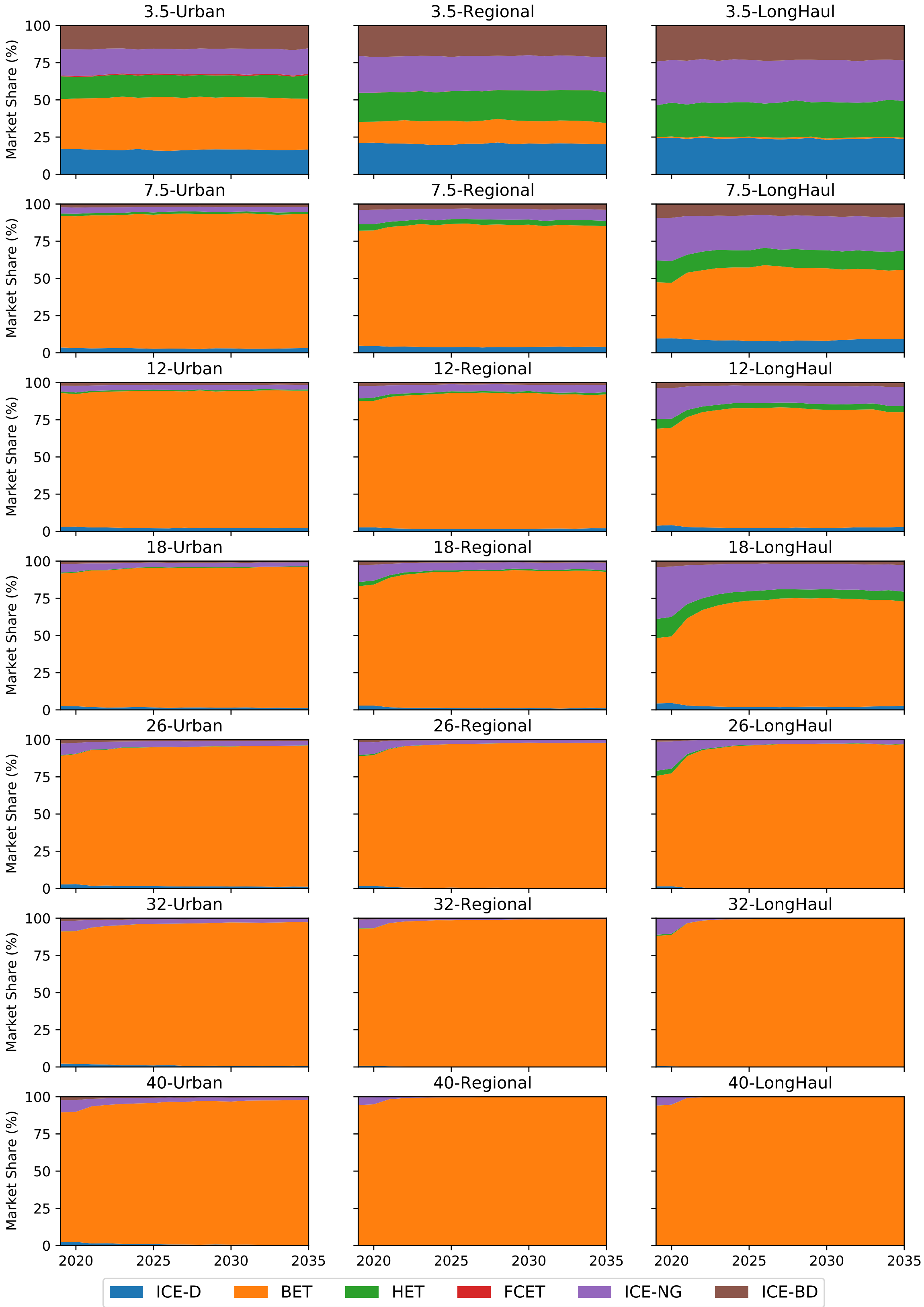

Figure A.3: "Worst case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

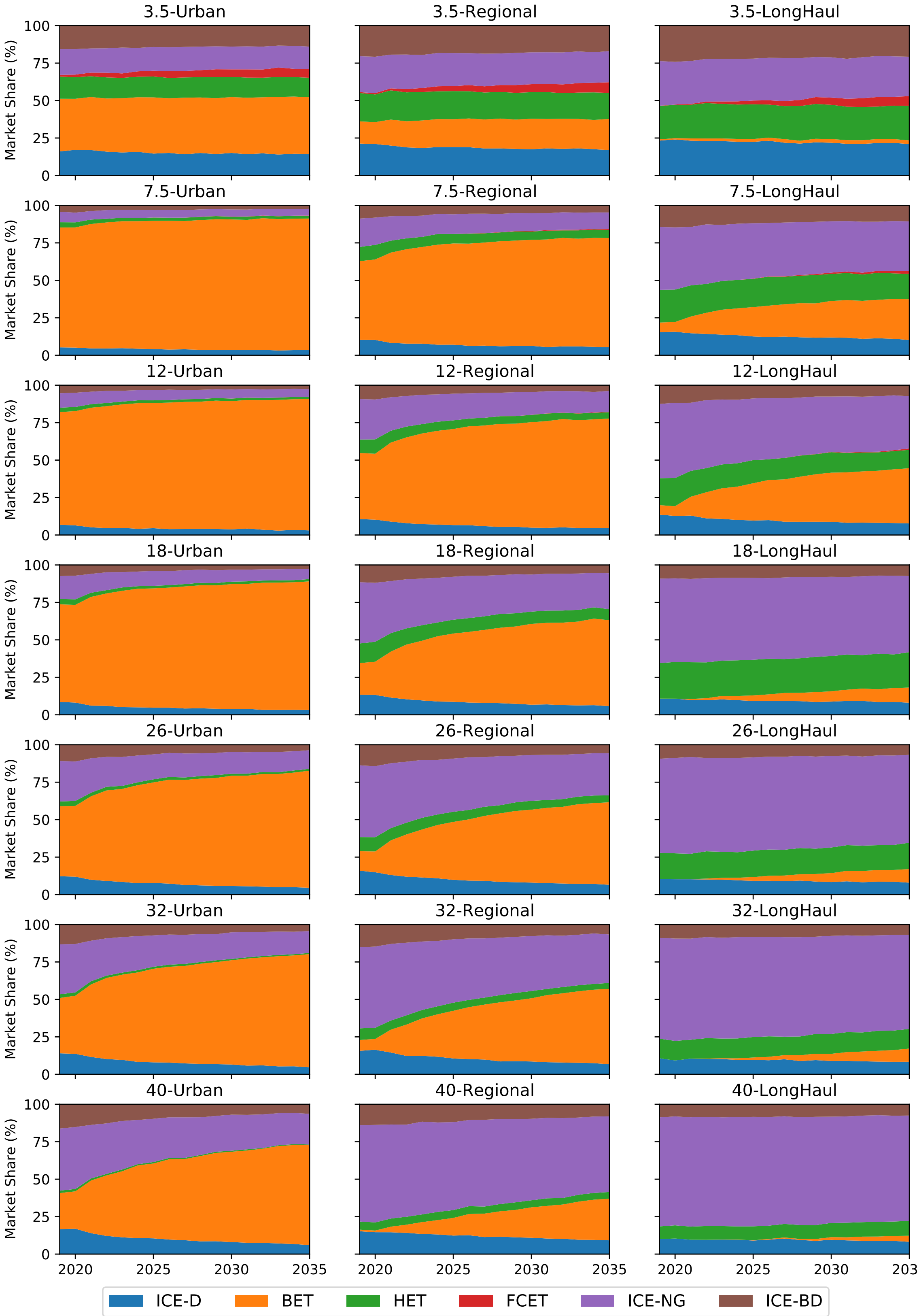

Figure A.4: "Full LSVA case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

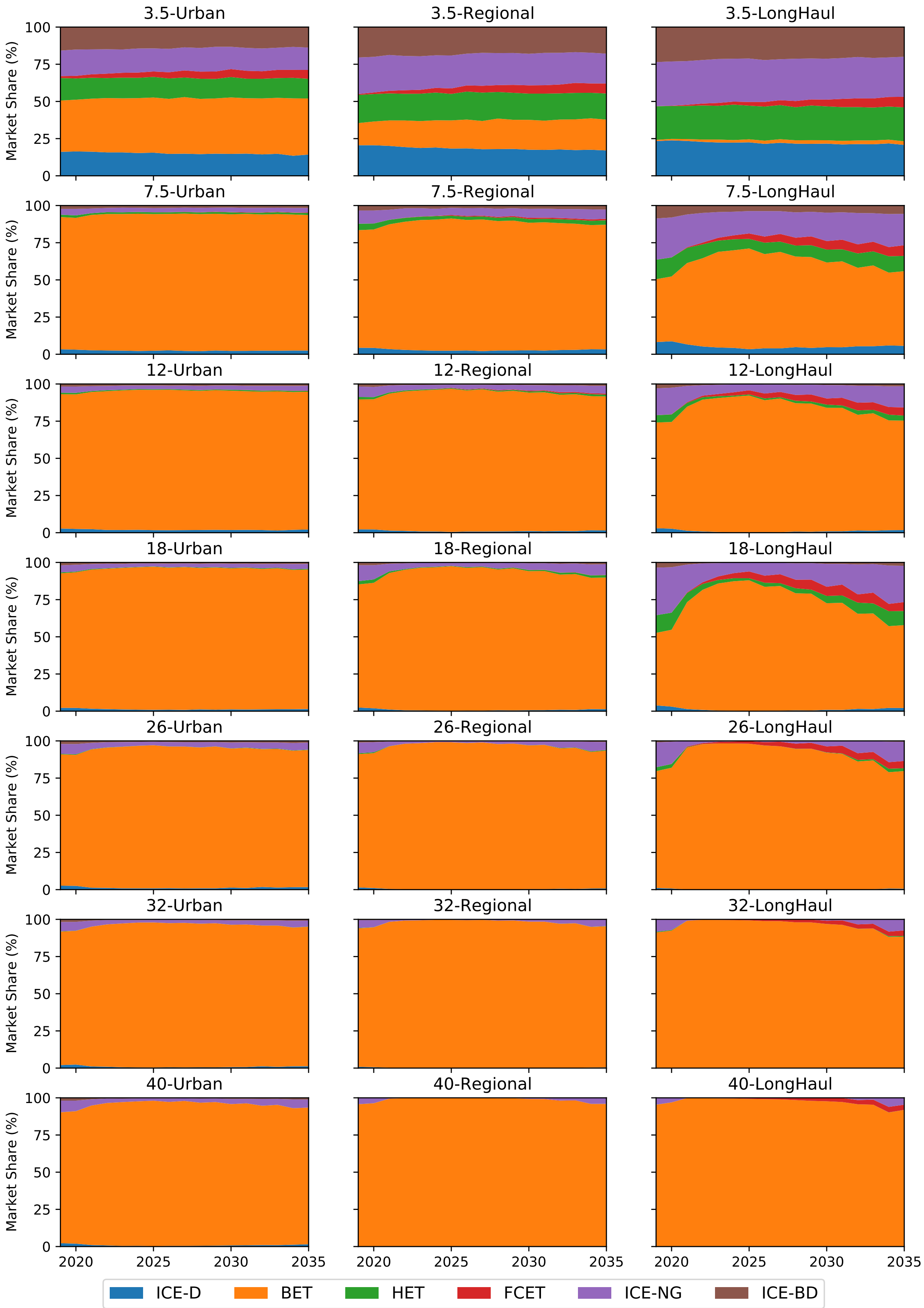

Figure A.5: "Progressive LSVA case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

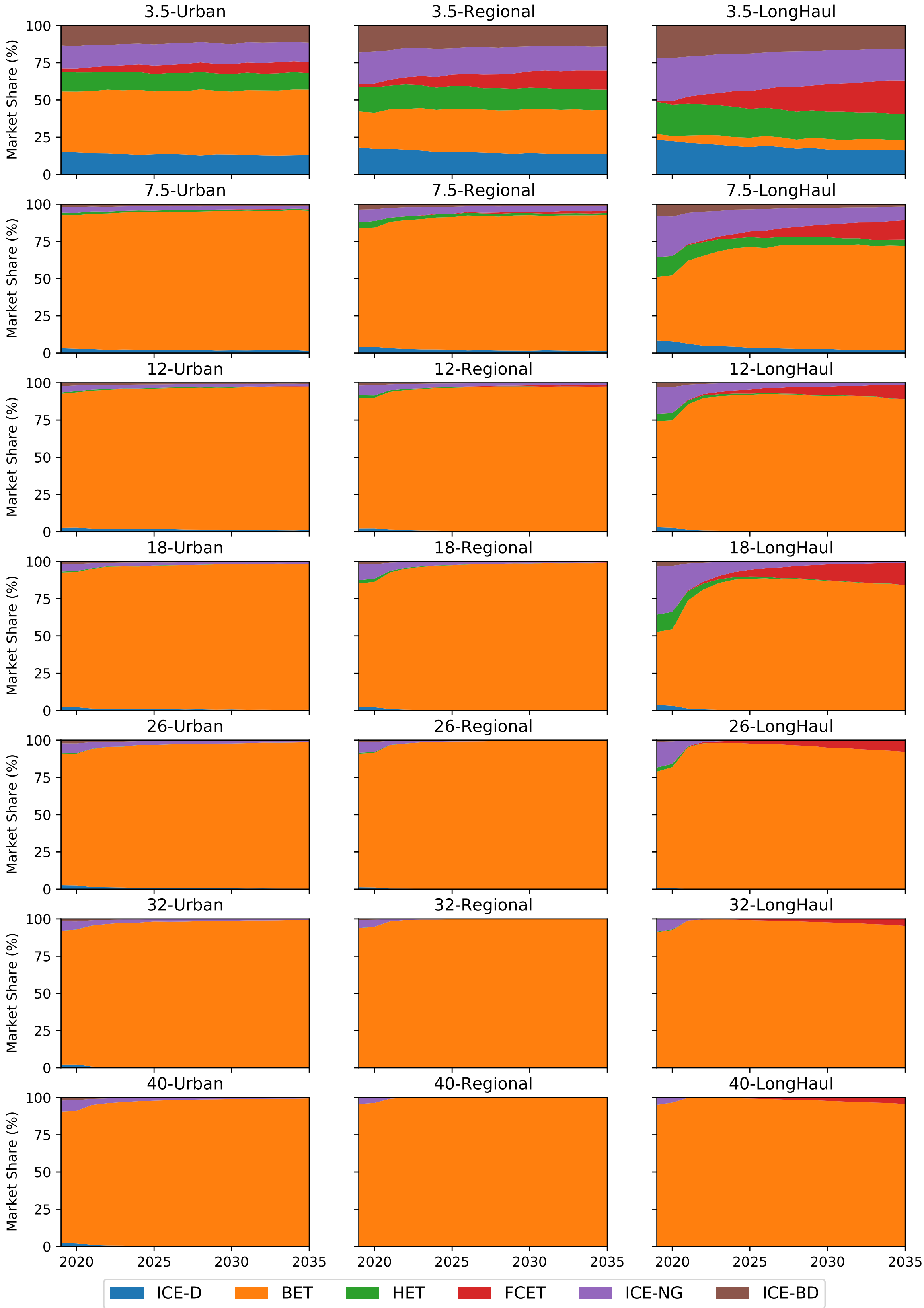

Figure A.6: "Full LSVA for LDTs case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

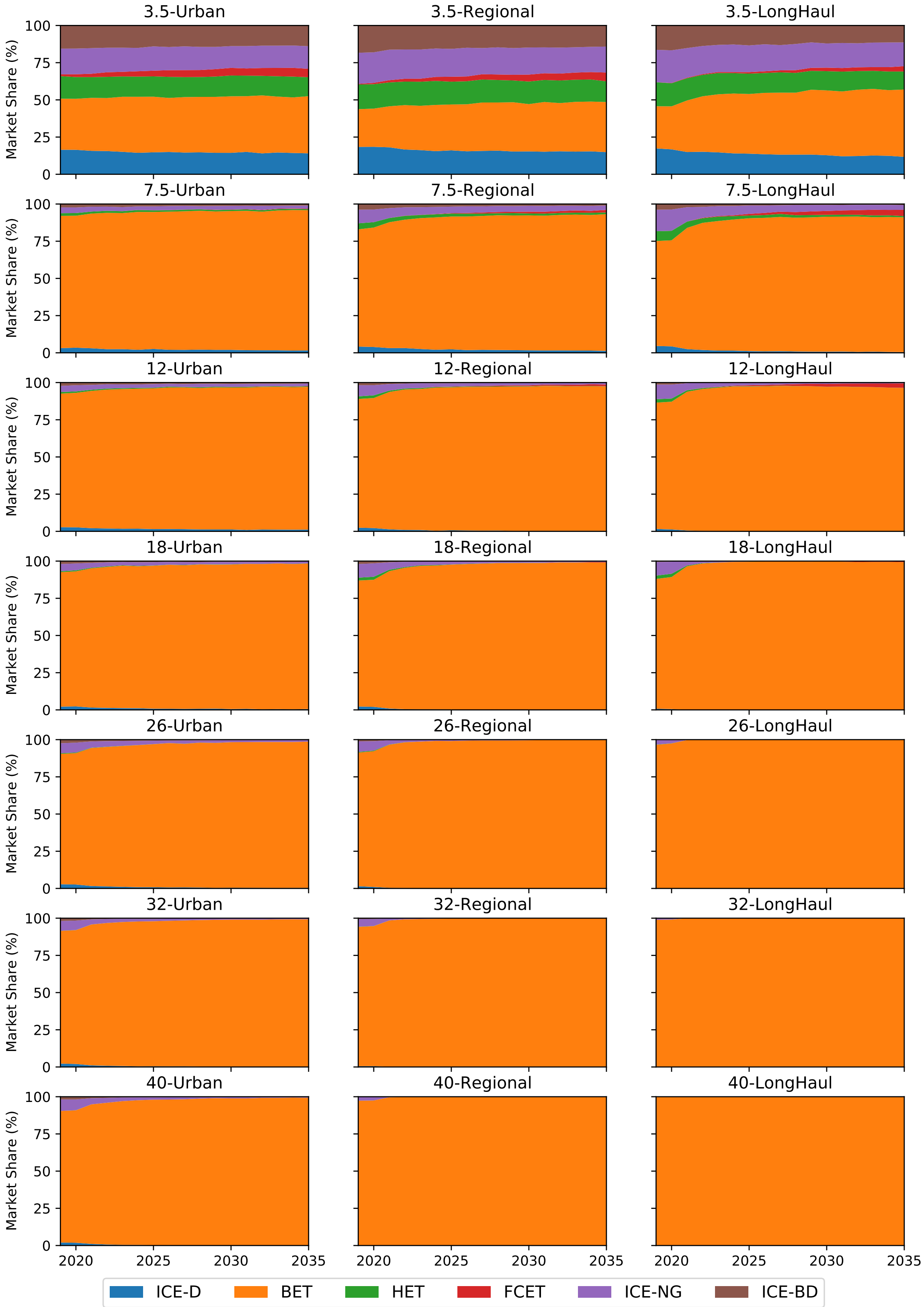

Figure A.7: "No BET penalty case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

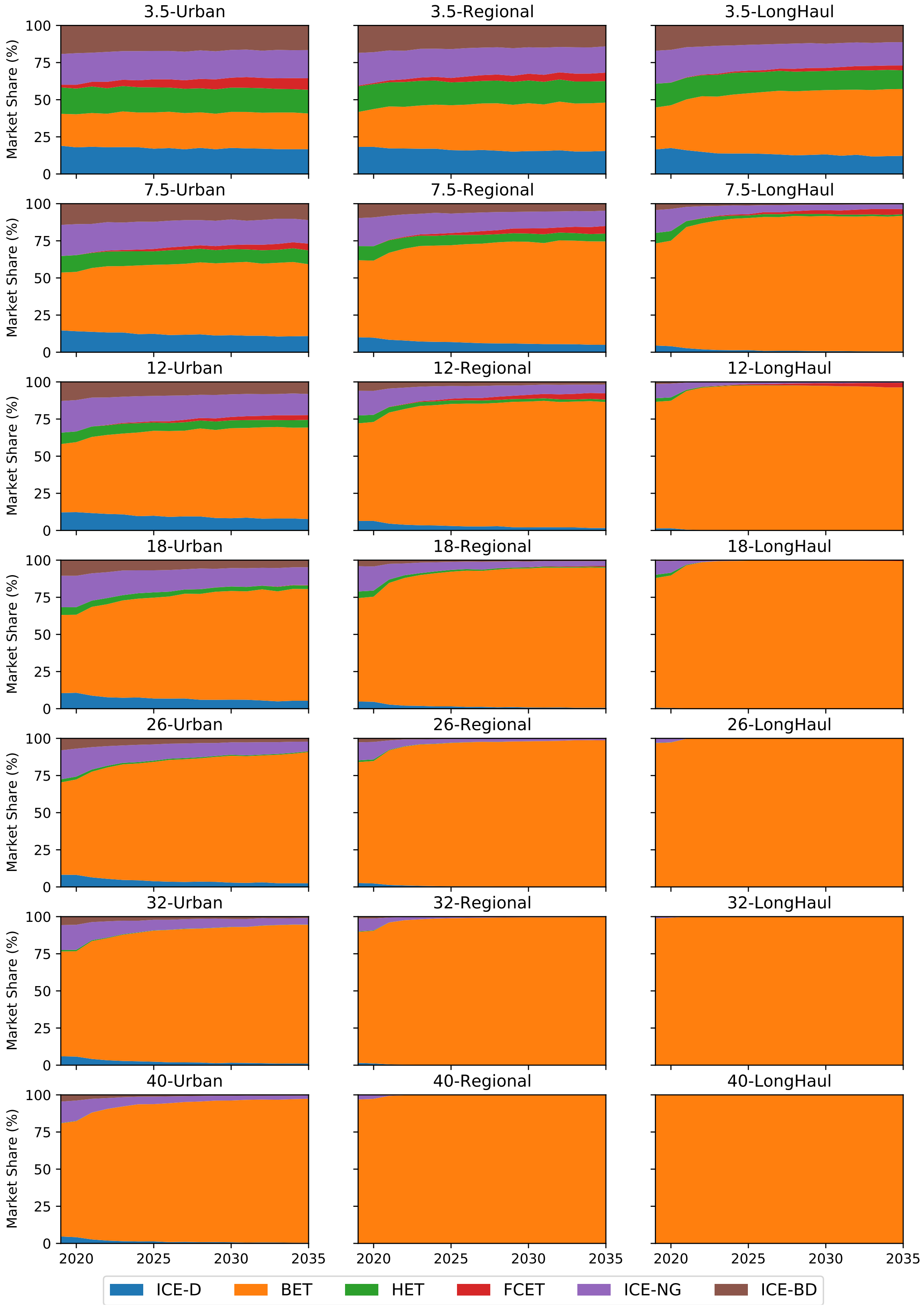

Figure A.8: "No BET penalty and no BET reward case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

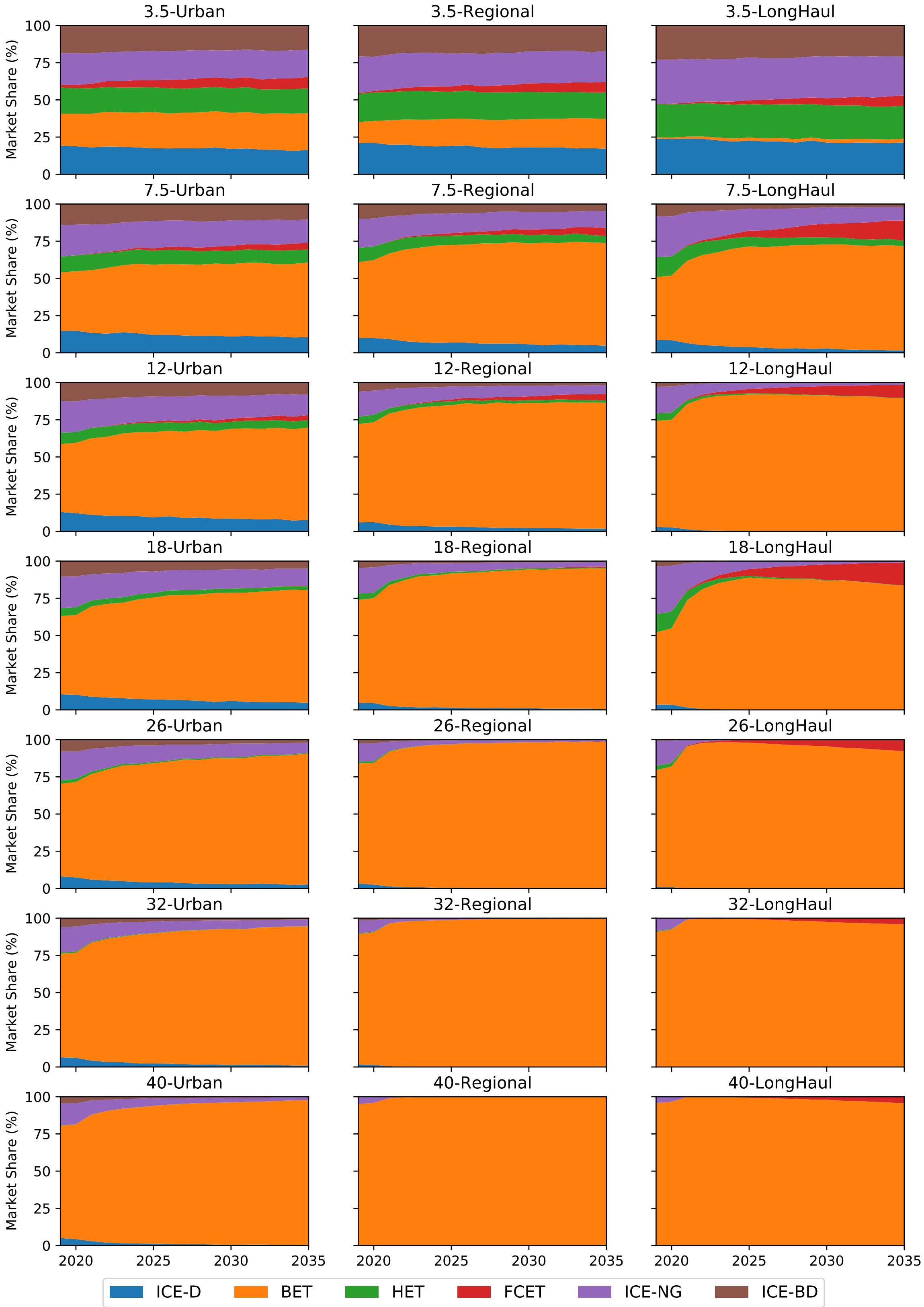

Figure A.9: "BET penalty only case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

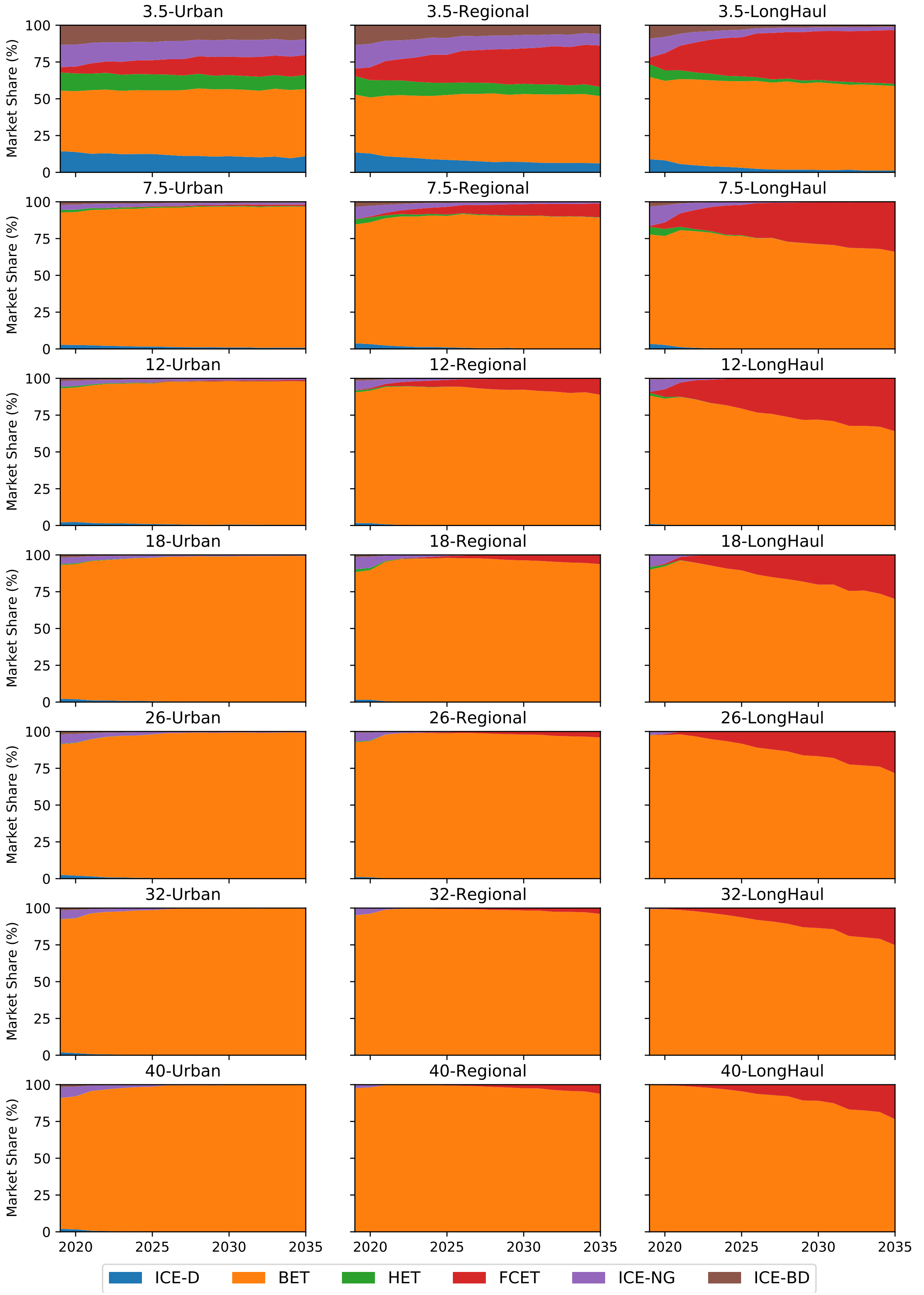

Figure A.10: "Policy-mix case" drive-technology market shares of annual, additional freight vehicles (newly registered) across 21 application segments from 2019-2035.

A.3 Sensitivity analysis

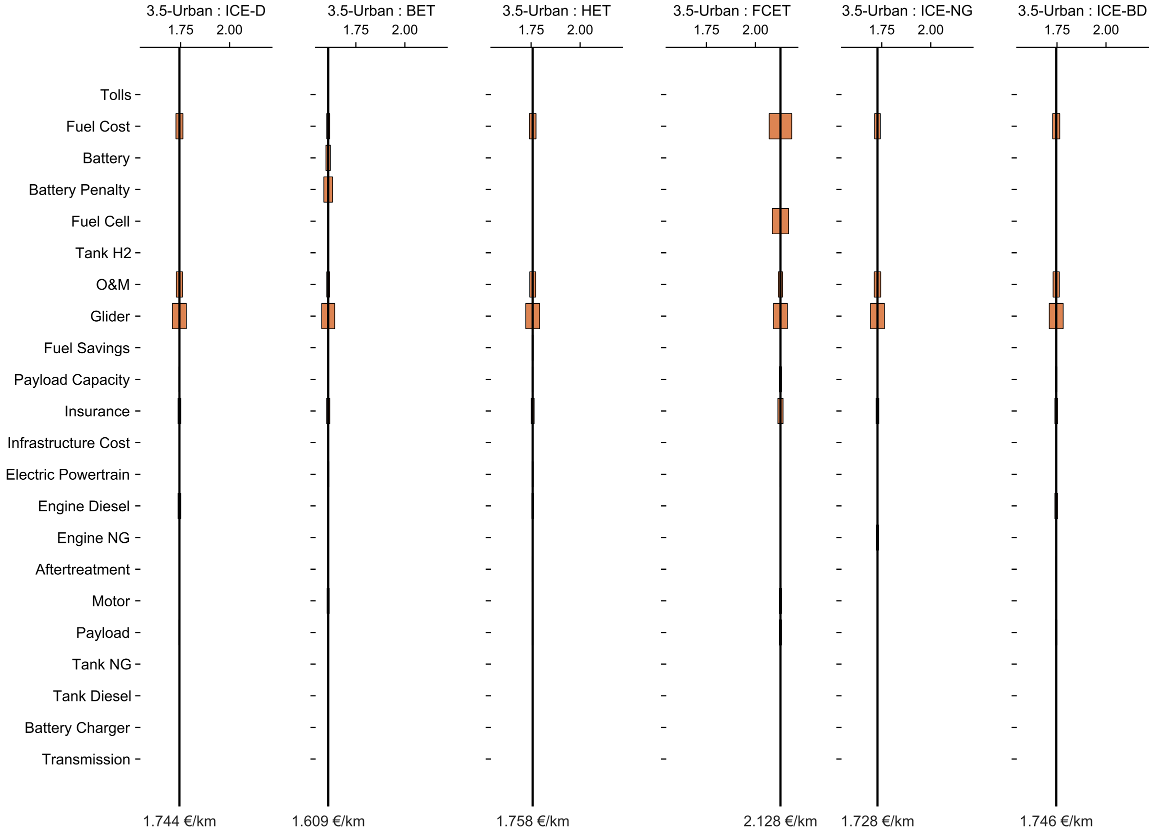

Figure A.11: Results of the sensitivity analysis for the 3.5-Urban segment.

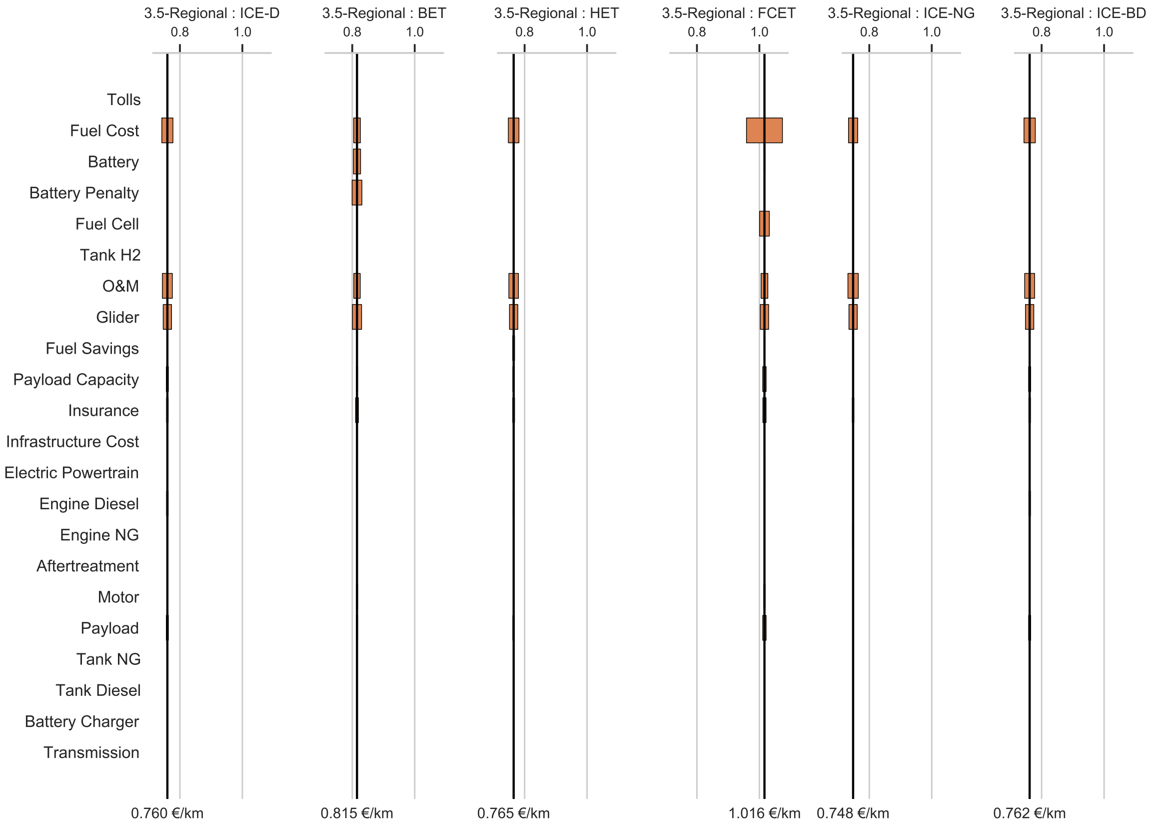

Figure A.12: Results of the sensitivity analysis for the 3.5-Regional segment.

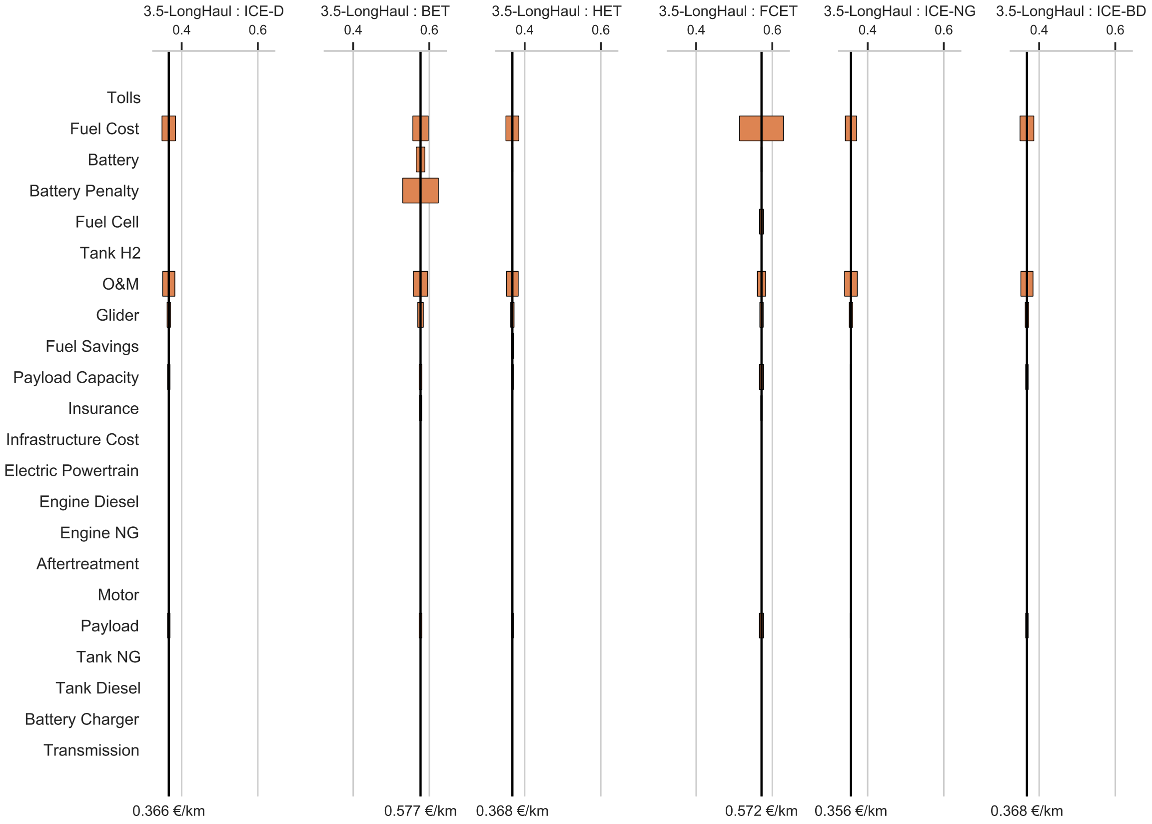

Figure A.13: Results of the sensitivity analysis for the 3.5-LongHaul segment.

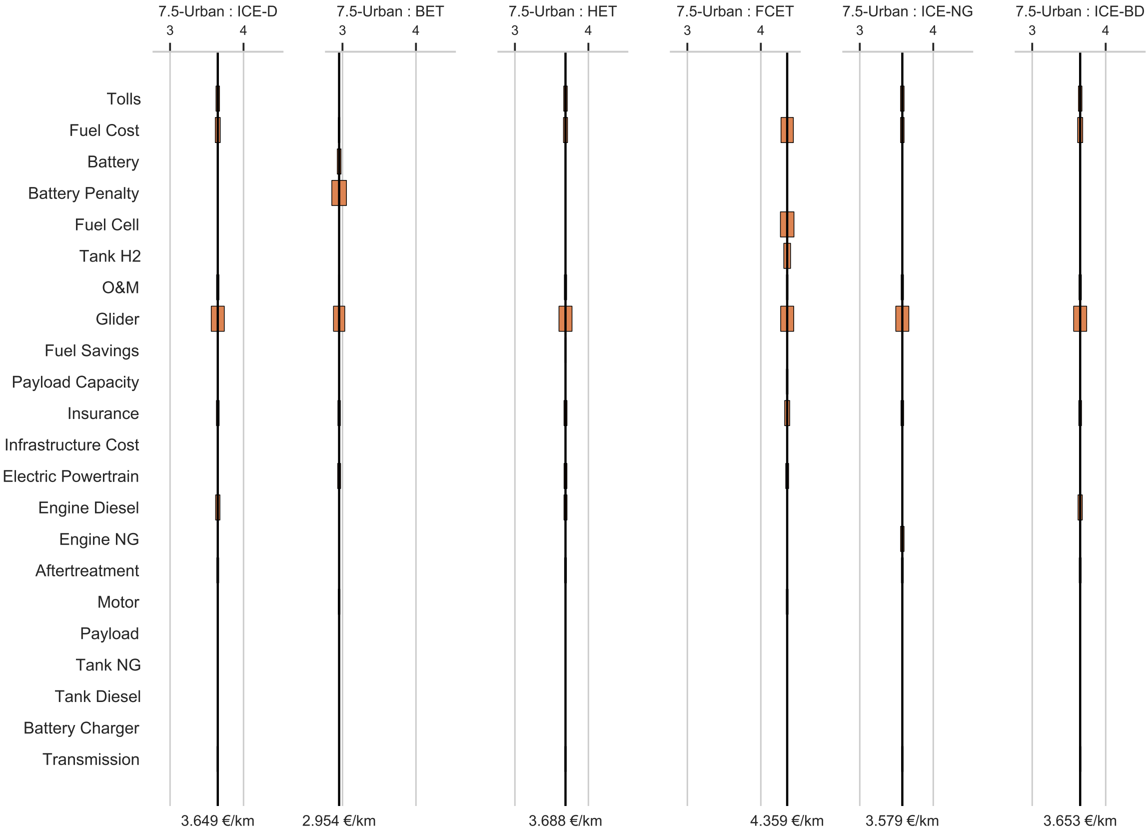

Figure A.14: Results of the sensitivity analysis for the 7.5-Urban segment.

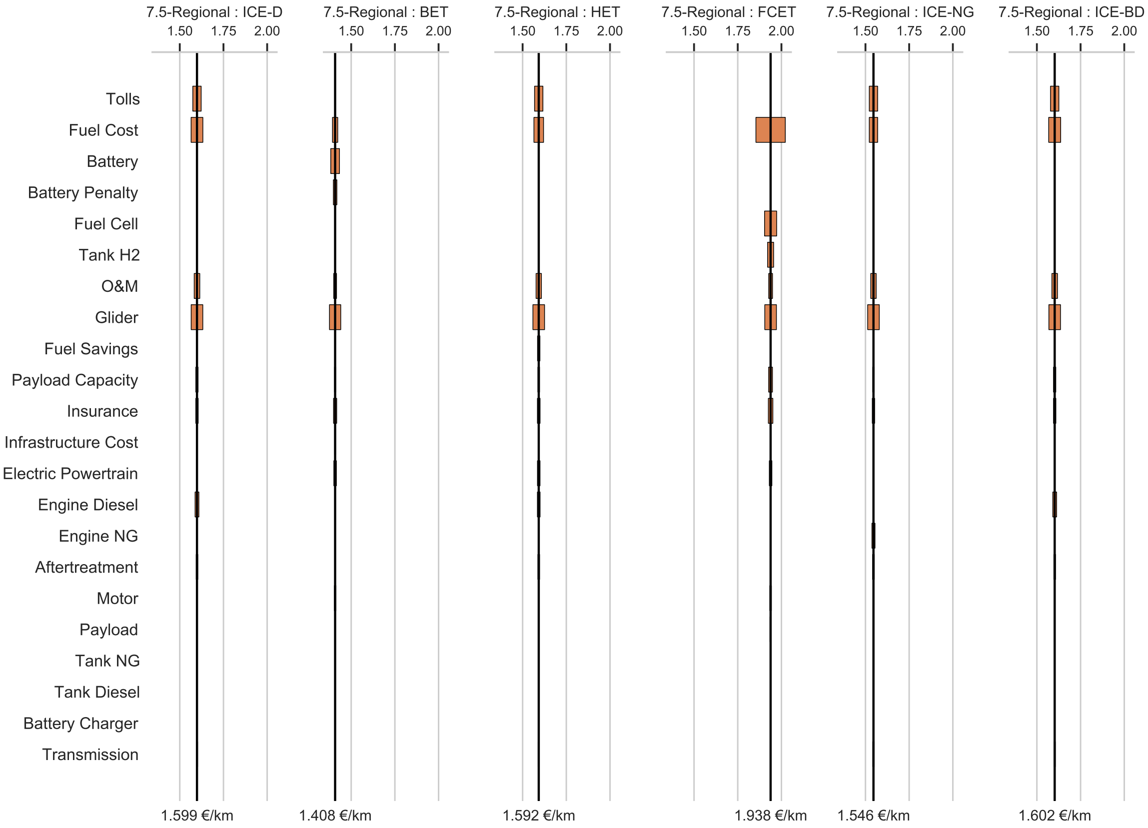

Figure A.15: Results of the sensitivity analysis for the 7.5-Regional segment.

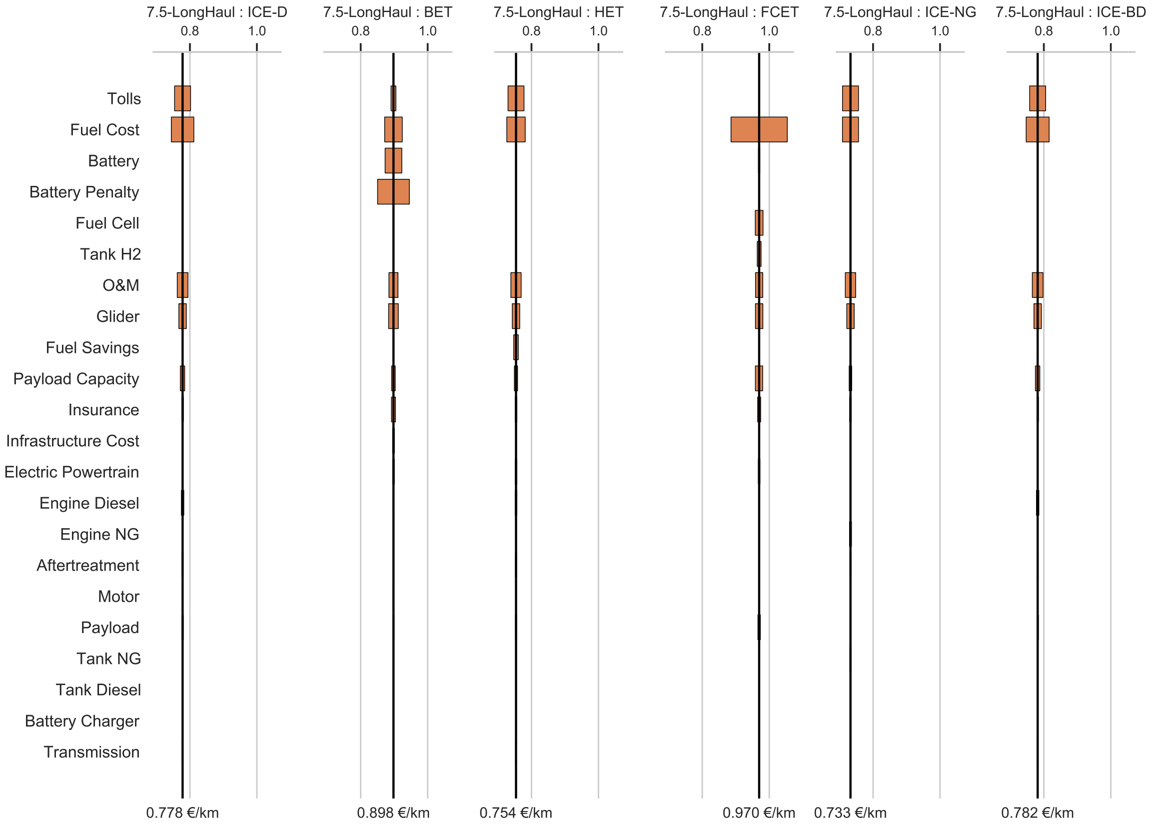

Figure A.16: Results of the sensitivity analysis for the 7.5-LongHaul segment.

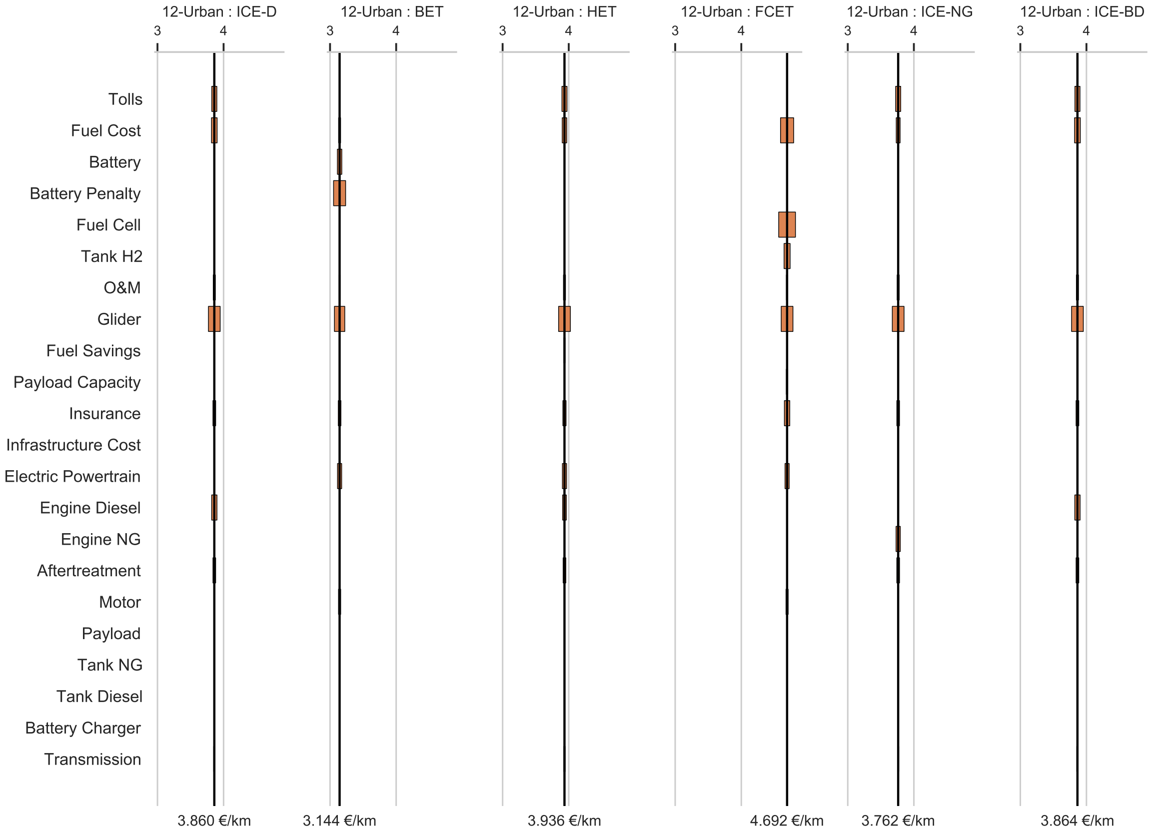

Figure A.17: Results of the sensitivity analysis for the 12-Urban segment.

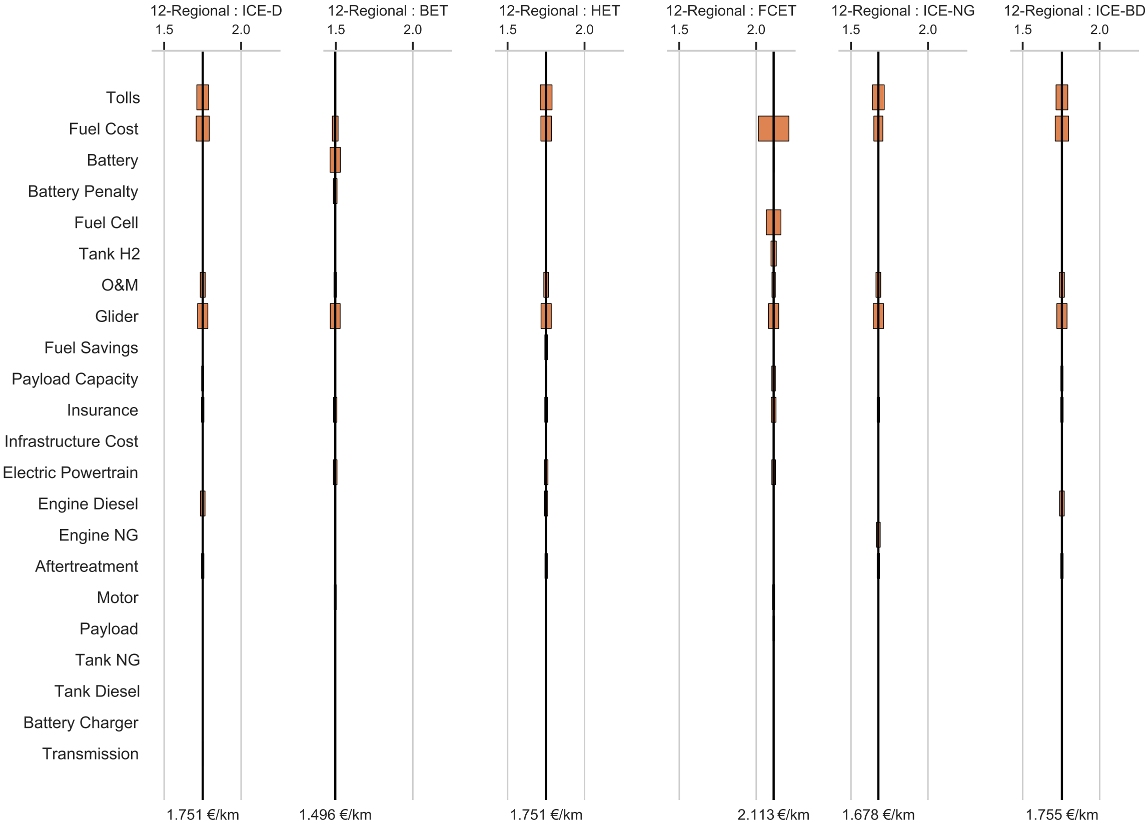

Figure A.18: Results of the sensitivity analysis for the 12-Regional segment.

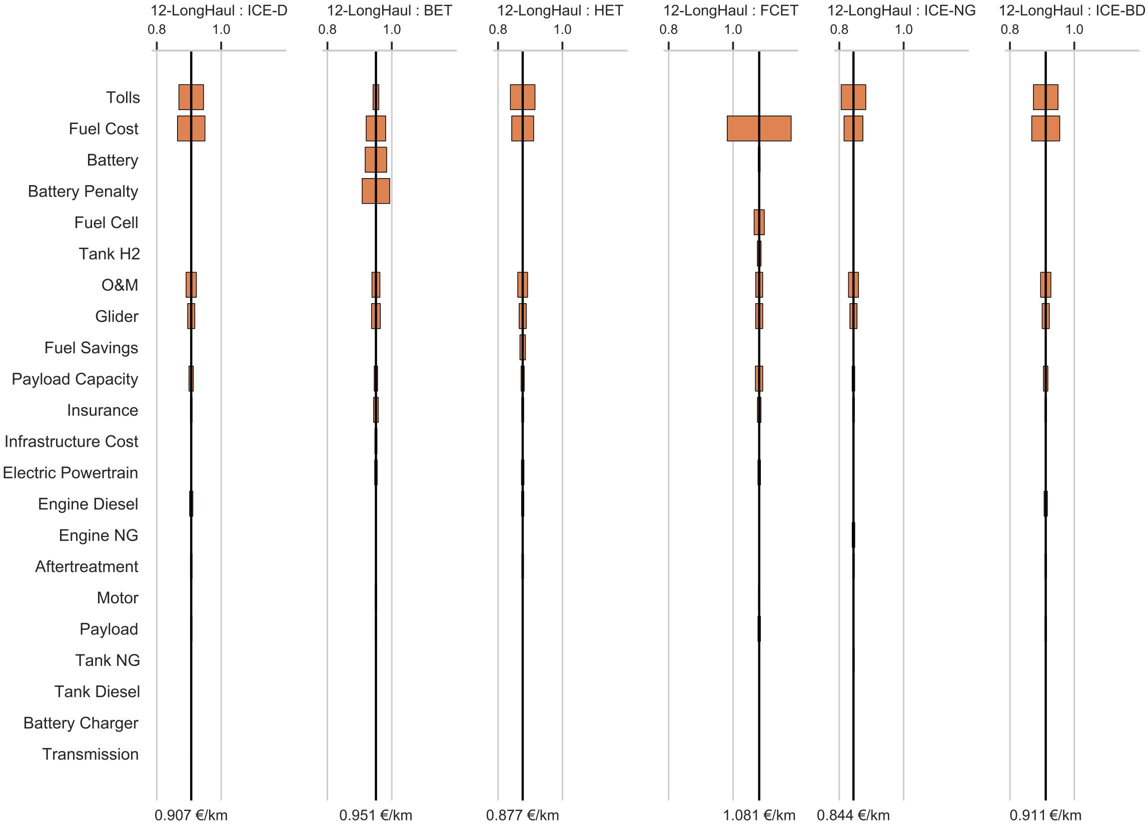

Figure A.19: Results of the sensitivity analysis for the 12-LongHaul segment.

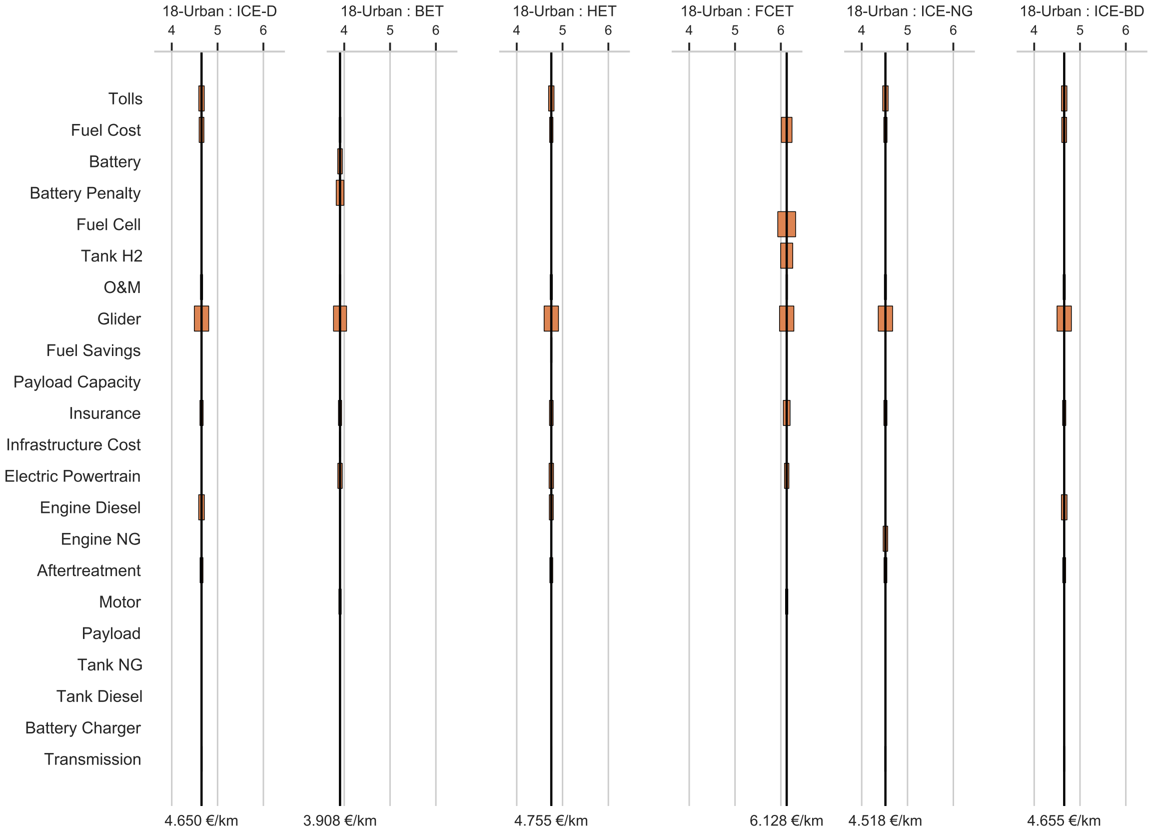

Figure A.20: Results of the sensitivity analysis for the 18-Urban segment.

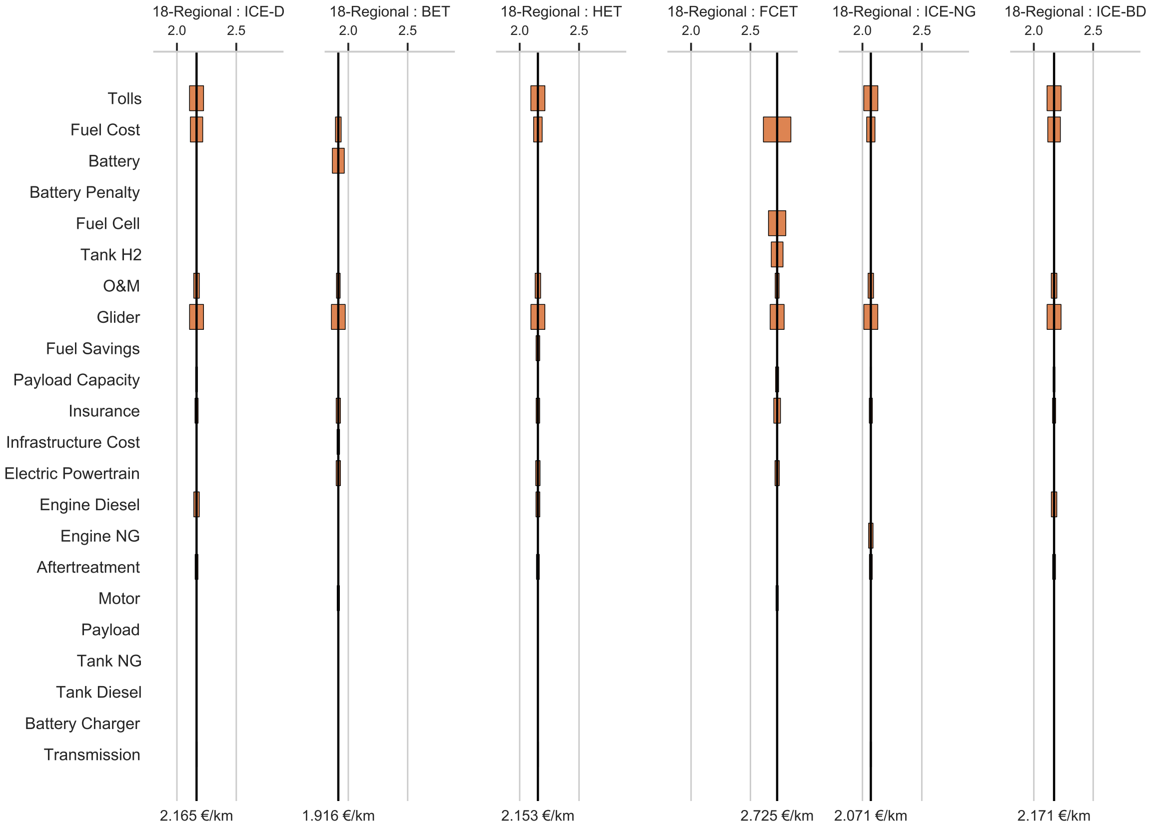

Figure A.21: Results of the sensitivity analysis for the 18-Regional segment.

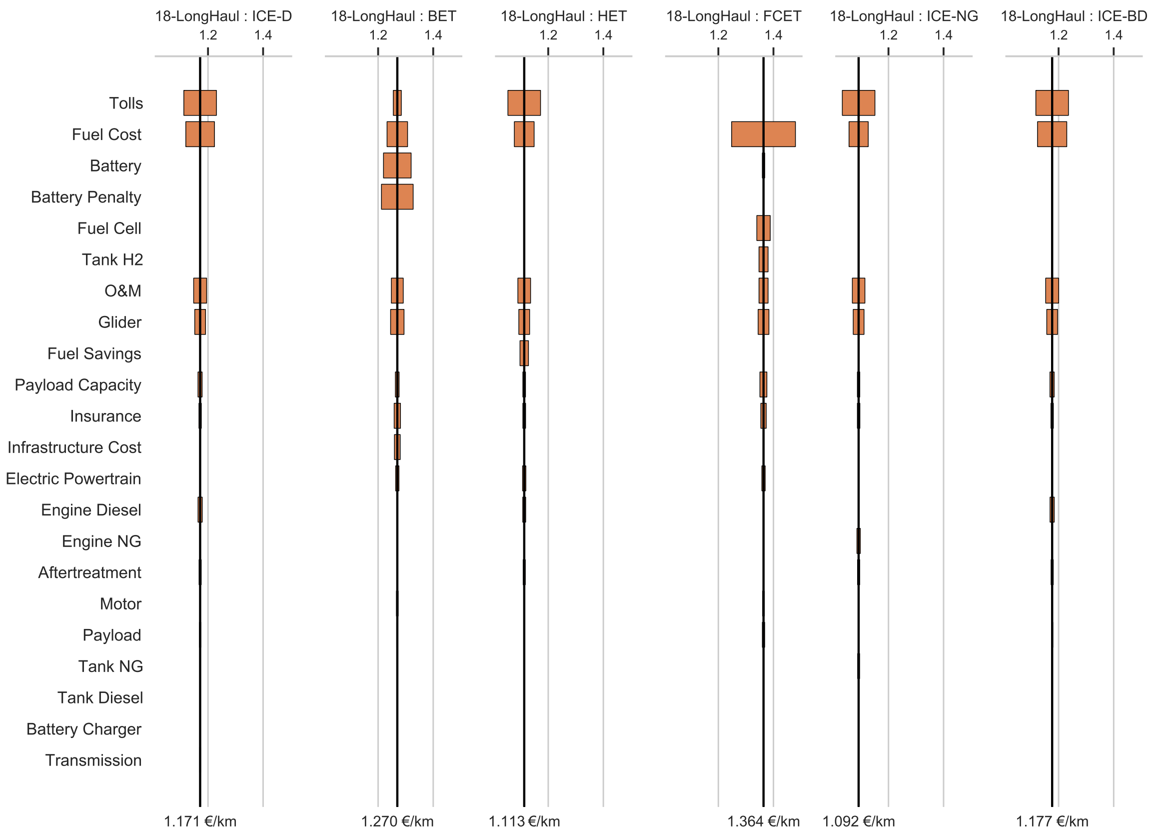

Figure A.22: Results of the sensitivity analysis for the 18-LongHaul segment.

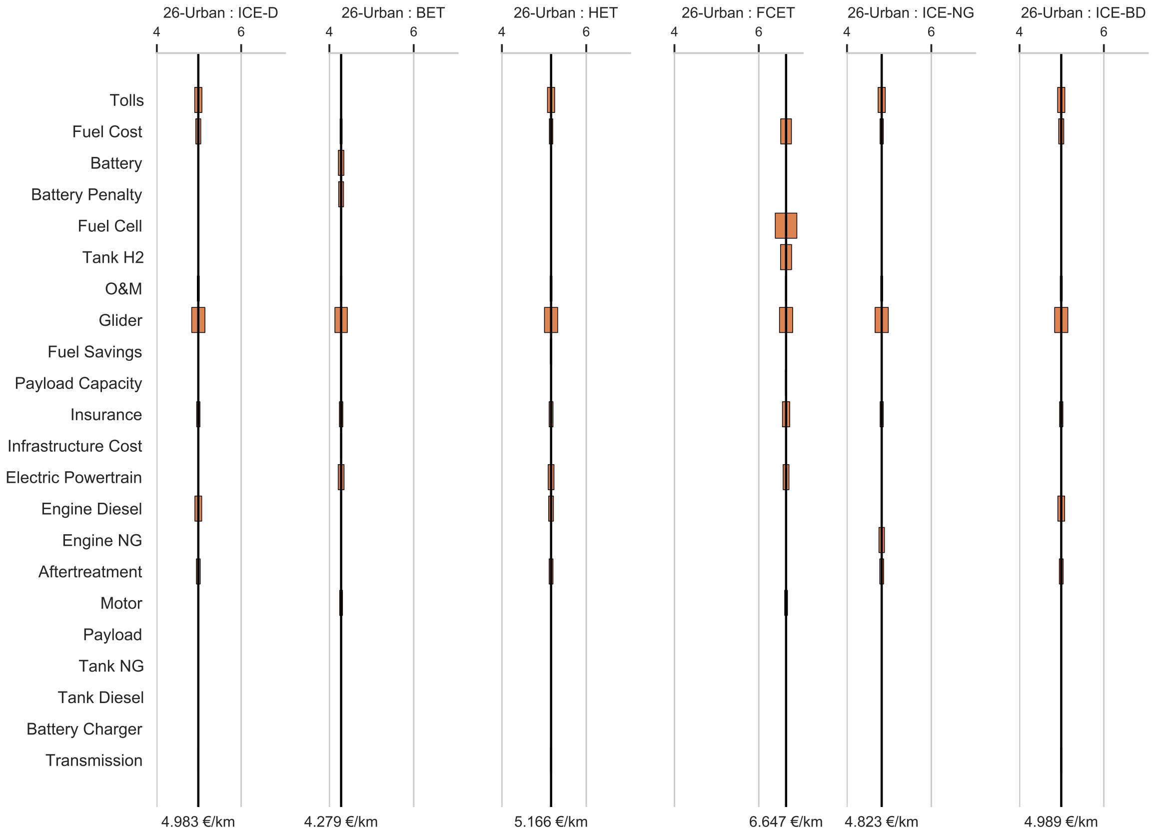

Figure A.23: Results of the sensitivity analysis for the 26-Urban segment.

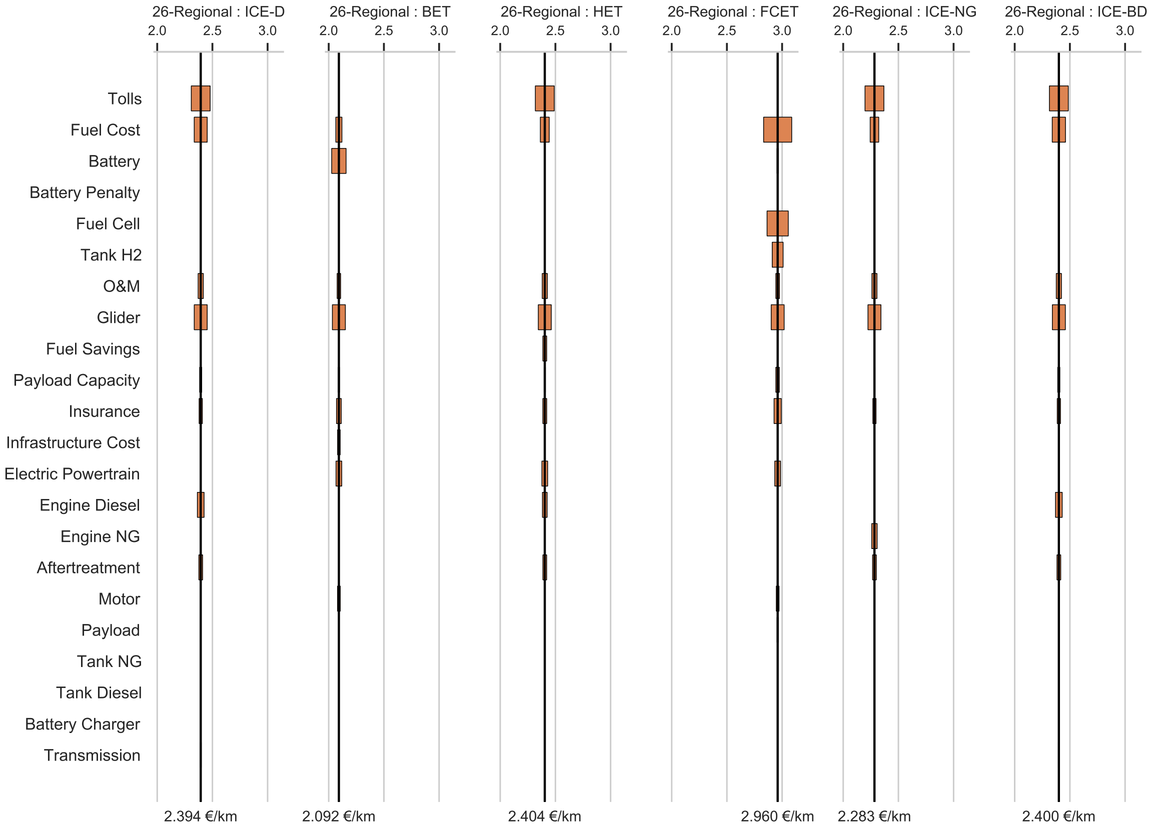

Figure A.24: Results of the sensitivity analysis for the 26-Regional segment.

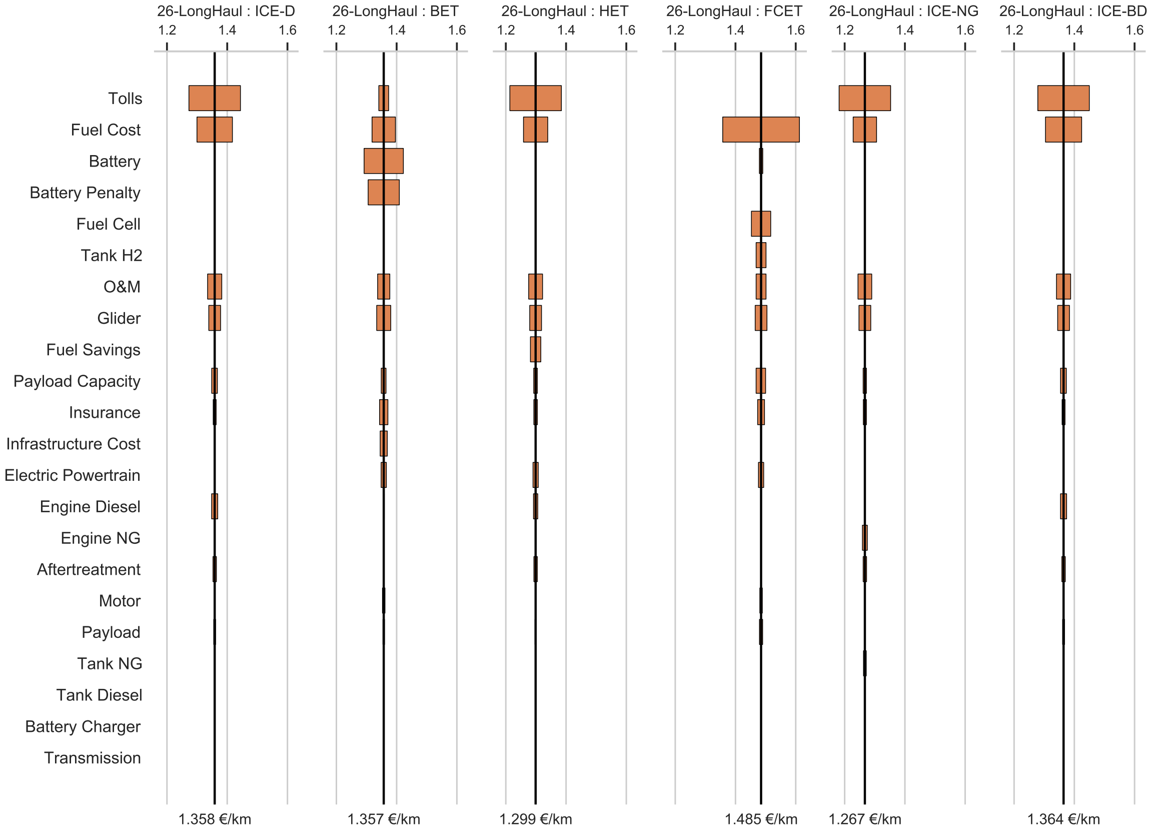

Figure A.25: Results of the sensitivity analysis for the 26-LongHaul segment.

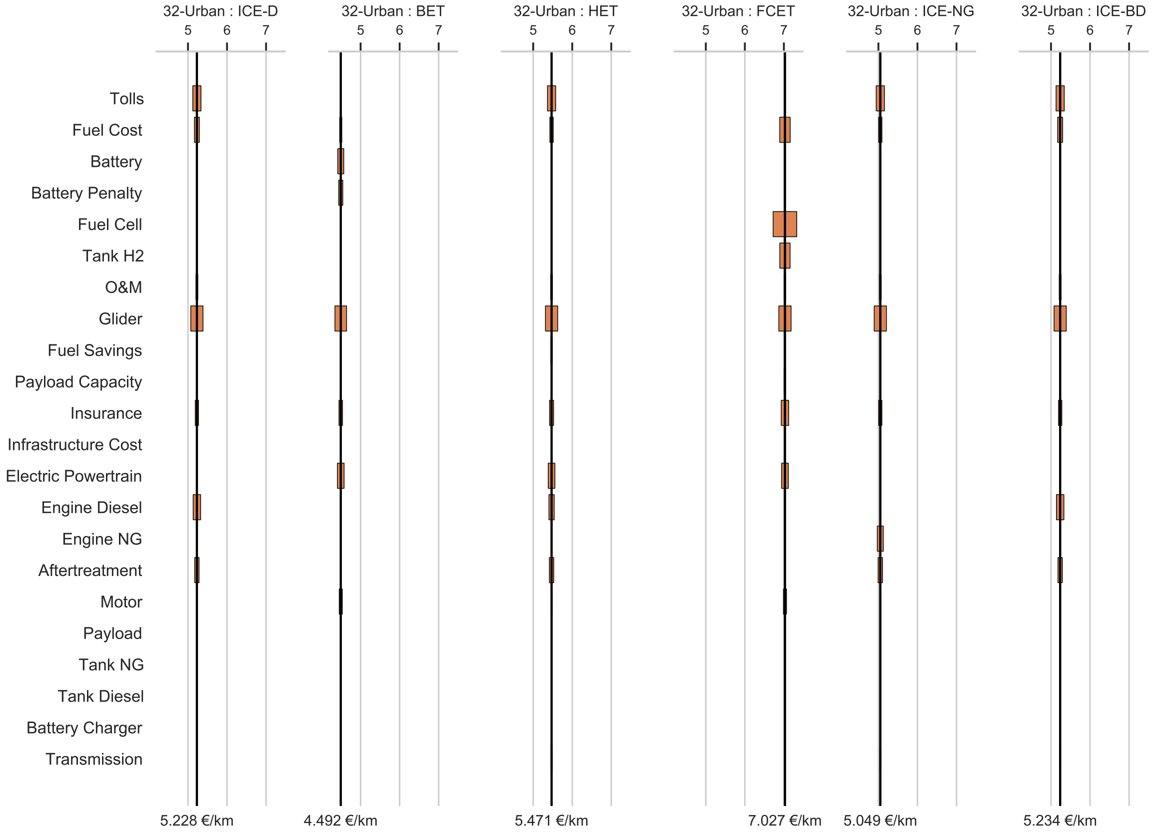

Figure A.26: Results of the sensitivity analysis for the 32-Urban segment.

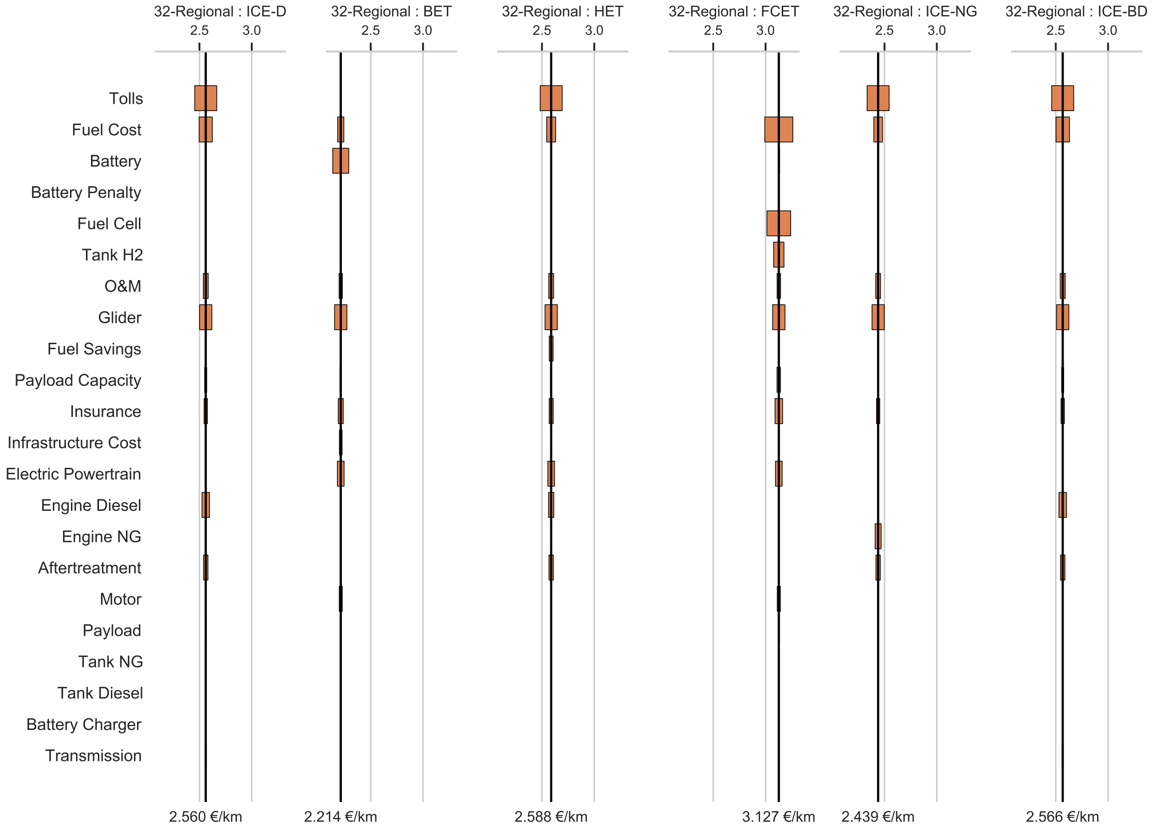

Figure A.27: Results of the sensitivity analysis for the 32-Regional segment.

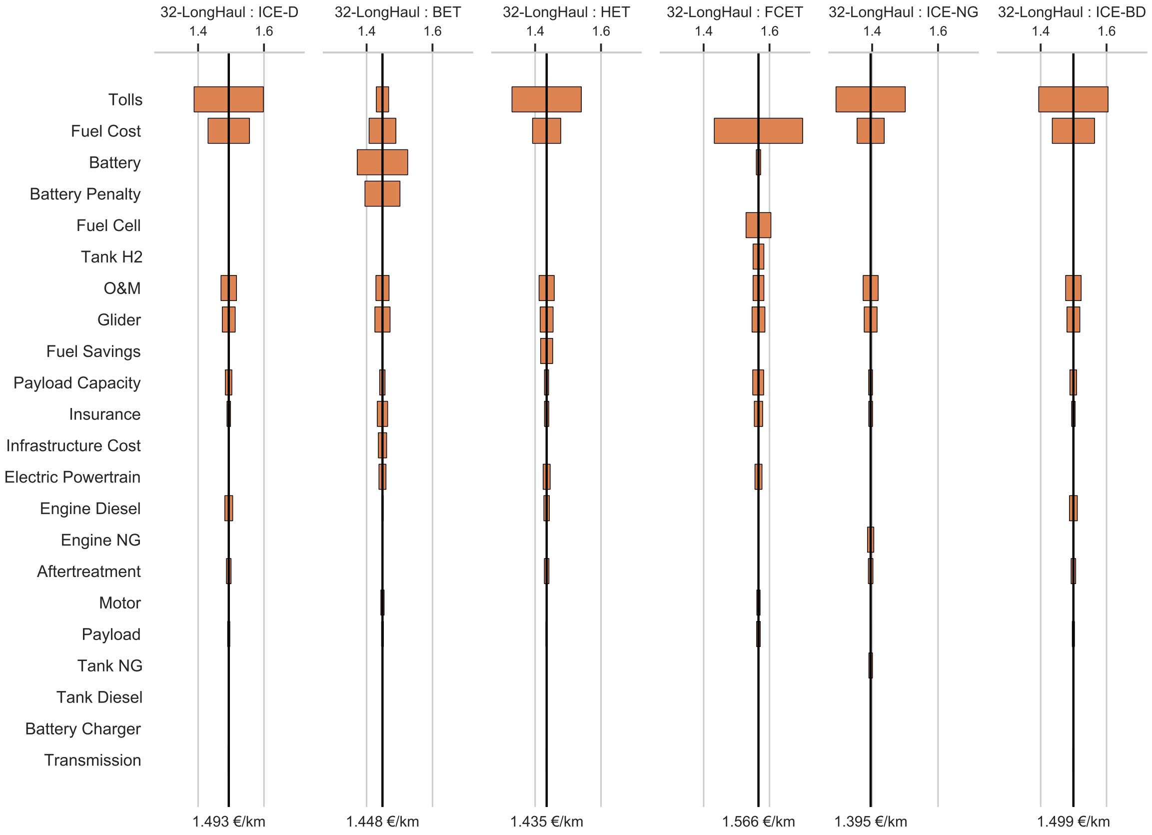

Figure A.28: Results of the sensitivity analysis for the 32-LongHaul segment.

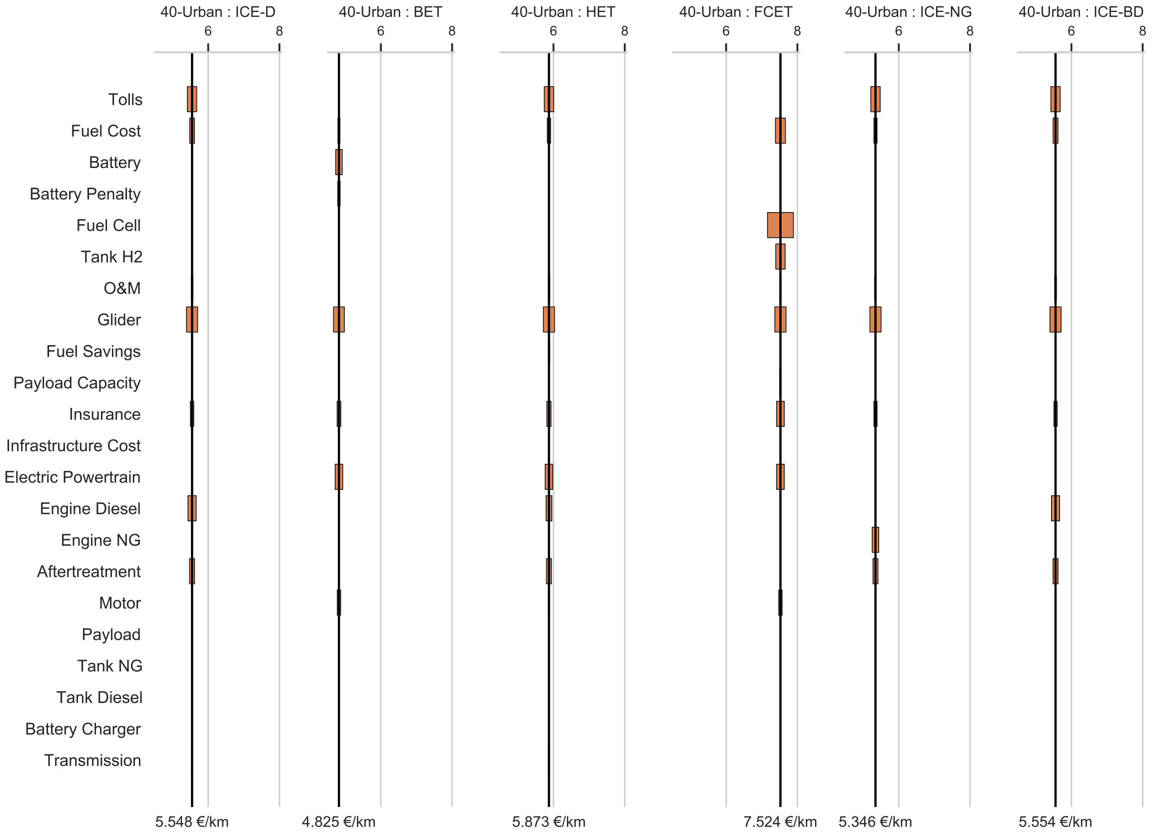

Figure A.29: Results of the sensitivity analysis for the 40-Urban segment.

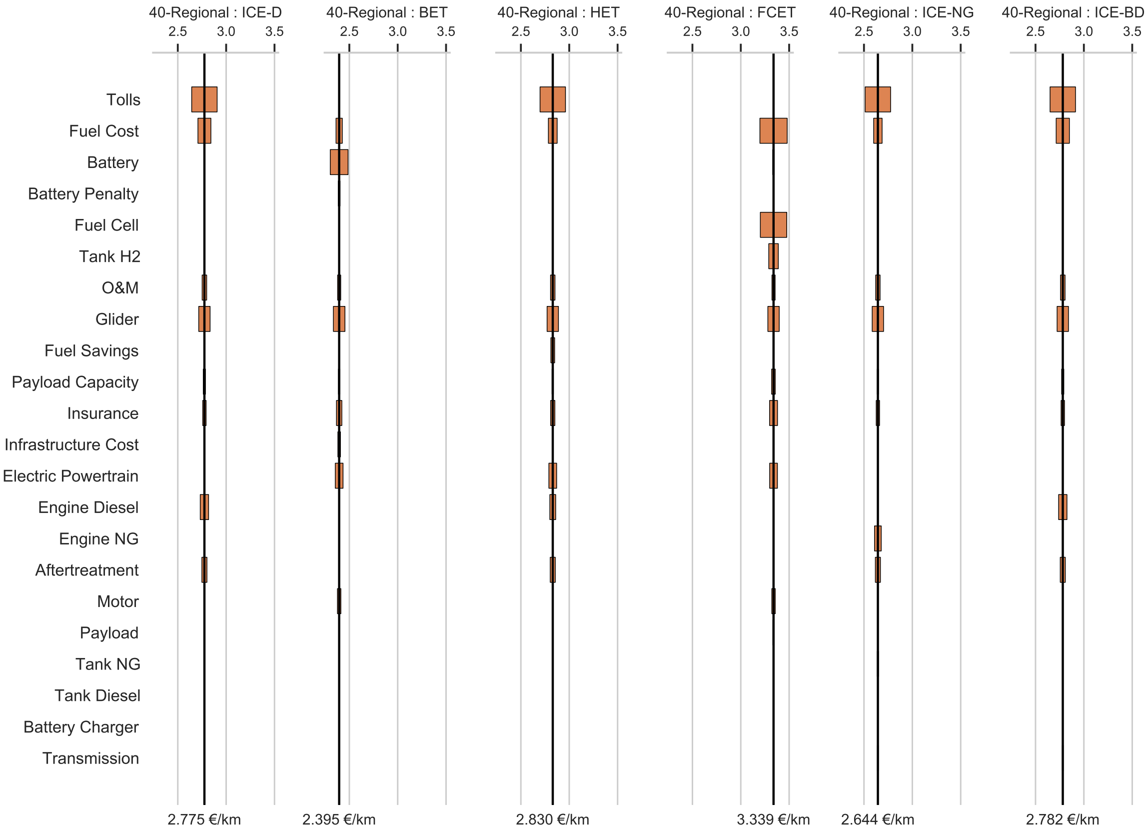

Figure A.30: Results of the sensitivity analysis for the 40-Regional segment.

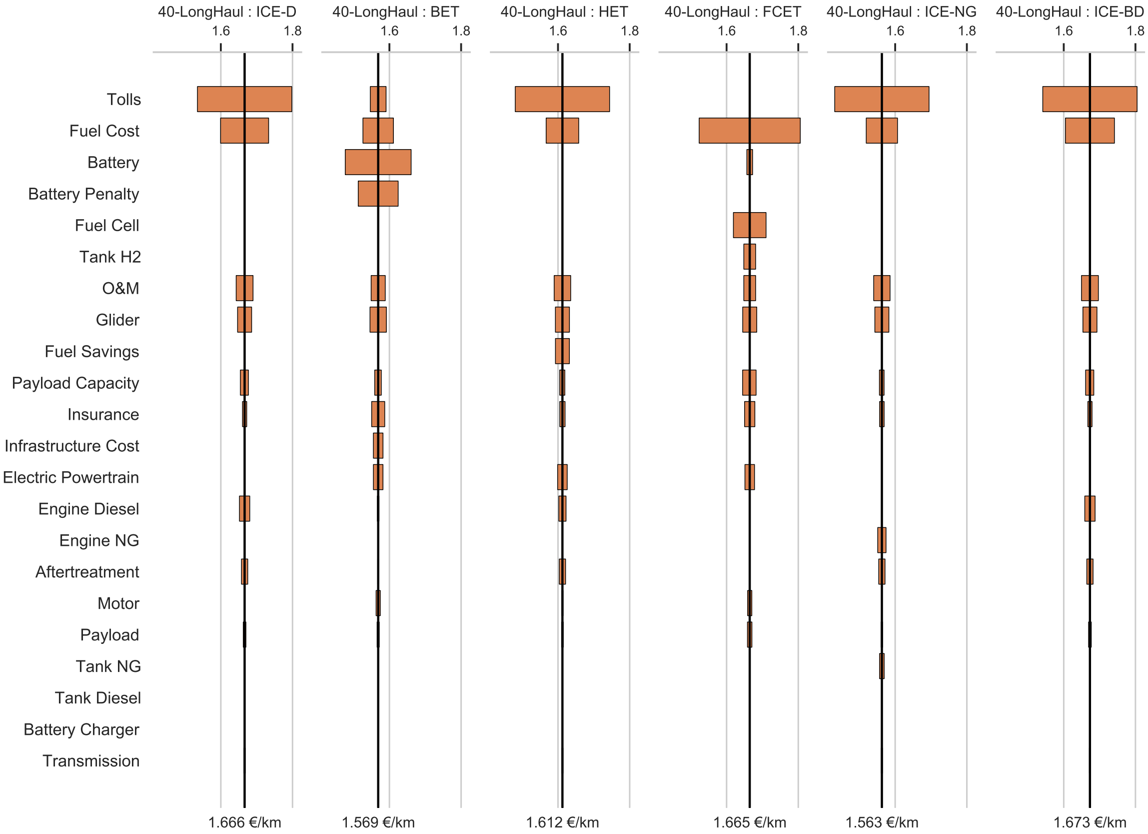

Figure A.31: Results of the sensitivity analysis for the 40-LongHaul segment.

B Appendix: miscellaneous

B.1 Digital appendix

This thesis is supplemented by a folder which contains the LSVA data and the code of the data processing end market share model along with all input data and scenario results. The folder can be found on the EPG server.

B.2 Pictures

I had the pleasure of riding along with an FCET as well as a BET during the period of my work. Being able to see the vehicles I had been working on so intensively over the past six months in action was a welcome change from desk work and an impressive experience. Many thanks to the people who made this possible. On the following page are two pictures of the vehicles I was privileged to accompany as a passenger.

Figure B.1: Fuel cell electric rigid truck at a hydrogen fueling station (Picture: Andreas Eckmann)

Figure B.2: Battery electric articulated tractor-trailer truck at a logistics center (Picture: Andreas Eckmann).