Freight Transport Decarbonization: How Policy and Logistics Trends Affect Achievement of Climate Objectives

Daniel Ruben Pinchasik

Thesis for the degree of Doctor Philosophiae (dr. philos.)
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Name: Daniel Ruben Pinchasik

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Preface

If anything has fascinated me this past year, it is processes and journeys, mistaking these with goals or results, and all nuances in between. Submitting this thesis, I took a moment to reflect on my journey, on education, interests, work, research, and climate change and the environment running like a thread through it.

My real interest was sparked earlier, but I distinctly remember watching 'An Inconvenient Truth' during a high school geography class, age 15. I ended high school with 'Brought to Light', a study into reducing energy consumption of street and shop lighting in Greater Amsterdam. Although not exactly scientific research, this project just kept on giving follow-ups, but most of all, was a lot of fun together with someone that's a close friend to this day.

Three years older and a bit more mature scientifically, I wrote my BSc thesis 'On the Role of Electricity Grids in Greening Europe's Electricity Supply'. These years also saw journeys otherwise, with a Fulbright Climate Change program in the USA, a study exchange to Oslo, and as World Student Environmental Summit delegate.

A Master's in Transport and Environmental Economics ensued, and I wouldn't be me if I'd not also this time wrote my thesis abroad – in Bergen. 'Contributions in Public Goods Experiments: Experimental Artefacts' was, indeed, on environmental public goods. However, Bergen also gave me sleepless nights, as I couldn't whole-heartedly decide between starting working life or accepting study offers in a concrete London jungle, a -9 hour time zone, or one that I'd probably still be paying loans on. A sunny-day e-mail from England resolved all this, and I got to spend an amazing, and yet ordinary M.Phil year at the University of Cambridge. My thesis? 'The role of climate-related policies in changing individual's behaviour in the developed world' – with focus on the UK, Norway and the Netherlands.

Through coincidences, I ended up working at the Dutch Central Bank. These were early days still for notions of climate and environmental risks in finance – which didn't necessarily make my job easy or rewarding. How things have changed over just a few years.

But then this drive to explore…I ended up in Norway again, this time more permanently, working at the Institute of Transport Economics (TØI). It's something that I'm proud of, especially as it would be an understatement to say that life could easily have developed differently. My first project at TØI was on reducing CO_2 emissions from Norwegian freight transport. Since, I hardly think there have been days or projects where freight and climate emissions were not a theme in some way.

The current thesis marks a culmination of this thread, at least for now. It builds on freight and climate emissions work I've done at TØI and scientific publications springing out from this. I just turned 31, am father to a little boy. Tones and messages have changed, but we still say climate change is urgent much like we did when I was 15, sitting in this high school classroom. This thesis, hopefully, provides insights that help to get on with things, faster, and in this case for the important freight transport sector.

Daniel Ruben Pinchasik,

December 2021

Acknowledgements

I didn't necessarily envision myself pursuing a doctoral degree. In fact, I didn't whatsoever – partially because I was lucky to at all be capable of working full-time again, and partially because I thoroughly enjoyed many other sides of my work and saw value in not disturbing this balance. I didn't much care for there being some between-the-lines expectations from my surroundings. It was first when I was introduced to the existence of something called a 'dr. philos' that a thought started maturing. After all, I had published several interrelated scientific articles and was working on several more, and the dr. philos path would be challenging, but nevertheless allow me to uphold more of the balances I value.

Actually writing this thesis has been a journey. There are seeds planted by my grandparents, parents and brother in terms of values and perspective, possibilities and upbringing. Much the same goes for Nelly. There have been important people throughout, cheering on, facilitating, or challenging thoughts. Some are friends, some professionals who made an impression, either generally or through some tiny thing engraining itself into my memory. To all of these: Thank you! In particular, I want to give a shout out to my colleagues at TØI and all co-authors. It's a pleasure working with you professionally. There are so many insights, knowledge and perspectives, and there is an extraordinary amount of warmth, collegiality and help for it being a place of work. Thank you Inger Beate for in many ways contributing to very rewarding years, and hopefully many to come, and thank you Kjell and Christian.

Moving from a distant thought to embarking on thesis work was a milestone, but also a commitment that I've cursed at times. There were always new projects, bigger priorities, or a seemingly endless overload of unfortunate events requiring much and urgent attention. There was family life, much for the better, sometimes for the worse. There was baby Albert turning more fun every day, growing into a unique tiny person, increasingly a daddy's boy. There was a tired mom, both ambivalent and supportive, in a role often not valued enough or taken for granted in society. Thank you. There were months of parental leave flying by without a chance of sitting down and structuring thoughts. It's also not enough to sneak into the office on 'red days' once in a while to have some thinking peace, or to have two hours here and two hours there. I ended up deciding on a big, disciplined effort. For months, I spent many hidden evening hours, weekends, holidays and birthdays included, on turning five research articles into a full, worthy doctoral thesis. Meanwhile, I told very few about what I was doing. I'm proud of much I've experienced, achieved, and found and gotten back in this process, not least the

sparkling eyes and persistence that many know me by. While I'm happy that it's a doctoral thesis that this process culminated into as result, the real value for me is broader.

Financially, work towards writing the framing introduction of this thesis was carried out with support from three sources, for which I am highly grateful:

- Det Kongelige Norske Videnskabers Selskab (the Royal Norwegian Society of Sciences and Letters).
- The Norwegian Public Road Administration's Research Program on Urban Logistics.
- My employer, TØI.

In order of appearance, the individual articles in this thesis sprang out of projects funded by:

1. The Confederation of Norwegian Enterprise and the Norwegian NOx-Fund (grant nr. 4294-2015).
2. MoZEES, a Norwegian Centre for Environment-friendly Energy Research (FME), co-sponsored by the Research Council of Norway (grant nr. 257653) and 40 partners from research, industry and public sector.
3. The Research Council of Norway (grant nr. 235859/E10).
4. A Nordic freight analysis, funded by the Norwegian Public Road Administration, Railway Administration, Coastal Administration, Avinor and Nye Veier AS; and SHIFT, a Nordic Flagship project funded by Nordic Energy Research (grant nr. 77892). Article writing was co-funded through a strategic institute program at TØI and through PLATON, a platform for climate policy knowledge, funded by the Norwegian Research Council (grant nr. 295789).
5. The LIMCO knowledge-building project for industry, funded by the Norwegian Research Council (grant nr. 283333) and collaborating with enterprises from the transport and logistics industry.

List of Publications

The current thesis builds on the research articles listed below, all of which are published in recognized, peer-reviewed scientific journals.

(1) **Pinchasik, D.R.** and I.B. Hovi (2017), 'A CO_2-fund for the transport industry: The case of Norway', *Transport Policy, Vol. 53, pp. 186-195; https://doi.org/10.1016/j.tranpol.2016.08.007*

(2) Hovi, I.B., **Pinchasik, D.R.**, Figenbaum, E. and R.J. Thorne (2020), 'Experiences from Battery-Electric Truck Users in Norway', *World Electric Vehicle Journal, Vol. 11(1), #5; https://doi.org/10.3390/wevj11010005*

(3) **Pinchasik, D.R.**, I.B. Hovi, A. Tennøy and P.B. Wangsness (2018), 'Environmental and Transport Effects of Warehouse Relocationing: Evidence from Norway', *Transportation Planning and Technology, Vol. 42(1), pp. 37-55; https://doi.org/10.1080/03081060.2018.1541281*

(4) **Pinchasik, D.R.**, Hovi, I.B., Mjøsund, C.S., Grønland, S.E., Fridell, E. and M. Jerksjö (2020), 'Crossing borders and expanding modal shift measures: effects on mode choice and emissions from freight transport in the Nordics', *Sustainability, Vol. 12(3), pp. 894; https://doi.org/10.3390/su12030894*

(5) **Pinchasik, D.R.**, Hovi, I.B., Bø, E. and C.S. Mjøsund (2021), 'Can active follow-ups and carrots make eco-driving stick? Findings from a controlled experiment among truck drivers in Norway', *Energy Research & Social Science, Vol. 75, 102007; https://doi.org/10.1016/j.erss.2021.102007*

In line with policies of the respective journals, all articles are included either as post-print versions (accepted author manuscripts before journal lay-out) or publisher's versions. All rights reserved.

Summary

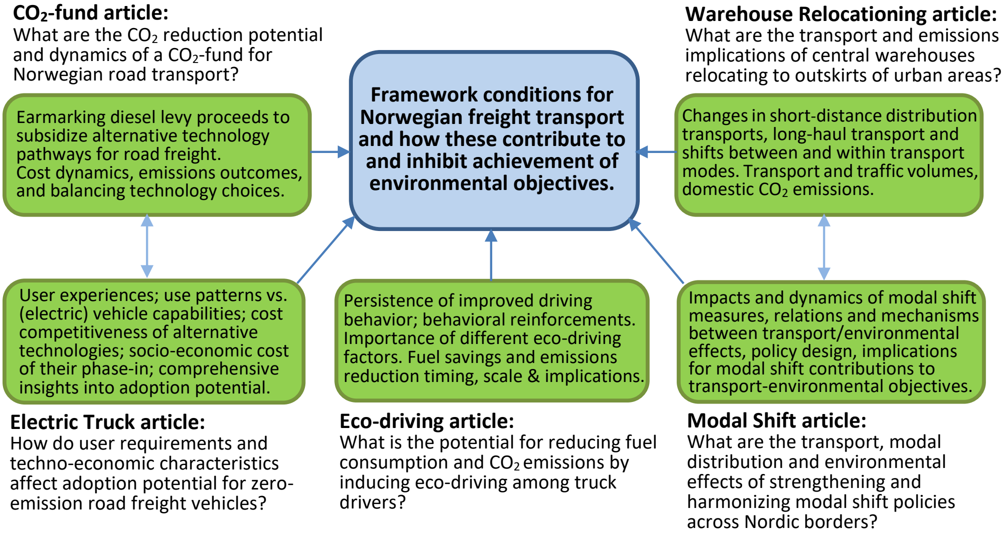
The transport sector is a major and growing contributor to climate change, requiring large and rapid emissions cuts to keep 1.5ºC global warming pathways within reach. Indeed, transport is attributed a prominent role in emissions reductions by policymakers around the world, and particularly towards 2030 targets. Within transport, freight (and particularly road freight) are increasingly important segments, but underrepresented in research, climate action, and government strategies. Freight transport is also considered particularly challenging to decarbonize, with high forecasted demand increases only adding to this problem.

Building on five research articles, this thesis discusses how changes in framework conditions for freight transport can contribute to or inhibit achieving climate objectives for transport. Although focus is on the Norwegian case and changes stemming from policy (design) and logistics trends with Norwegian relevance, the nature of the freight decarbonization challenge makes that many insights and observations will be relevant also for other countries.

I set out discussing theoretical frameworks for transport decarbonization, which I summarize into five veins: Demand intensity, Transport intensity, Modal split, Energy intensity and Energy's carbon intensity. Both between these veins and in time, there are trade-offs, dynamics and feedback effects. In practice, policymaker narratives particularly feature modal shift and technology veins (alternative technology vehicles, lower-carbon fuels and technical fuel efficiency improvements), while the first two veins discussed above, receive much less policy attention. Focusing on Norway, political discourse has made emissions cuts from transport essential, with freight being assigned an important role. Here, particular emphasis is placed on the phase-in of zero-emission heavy-duty vehicles, increased use of biofuels, and modal shift. This is reflected in the topics of my research articles, of which Figure S.1 gives an overview.

The first article finds that a CO_2-fund scheme (refunding of diesel levies through subsidies to alternative technologies) can contribute to increasing zero-emission vehicles' market share, although dynamics and the size of emissions cuts are highly dependent on technology choices made for the fund. In the Electric Truck article, we discuss how experiences from early Norwegian pilots with battery-electric trucks have largely been promising, with some exceptions. Use patterns for light distribution trucks indicate that in the short term (from 2019), electrification potential is limited to parts of some fleet sub-segments, but that in a longer run, relatively modest driving range improvements could considerably increase electrification potential. Cost competitiveness versus diesel distribution trucks is first attained when battery-

electric trucks reach mass production. Hydrogen-electric trucks can become cost competitive versus diesel in a longer term, but likely retain higher ownership costs than battery-electric trucks (making them more suitable for operations where battery-electric trucks have particular disadvantages, such as long-haul transport). Socio-economic costs of phasing in zero-emission vehicles are found to initially be highest for hydrogen-electric vehicles and lowest for biogas, but fall considerably towards mass production stages of battery-/hydrogen-electric trucks. These findings all have implications for choices of technological solutions to focus efforts on. For example, there are trade-offs and dynamics between larger, faster emissions reductions from biofuels, biofuel availability, reversibility of emissions cuts, flexibility, risks of policy lock-ins, private and social costs, timely establishment of charging/filling infrastructure, and the speeding up of technology development, production and market maturity of electric vehicles. The latter two aspects are particularly important for operational suitability and competitiveness, which are both (partially) presupposed in Norwegian transport-environmental targets. In all, incentive schemes, charging solutions, policy facilitation, and technological developments will likely remain important aspects in the years to come.



CO_2-fund article:
What are the CO_2 reduction potential and dynamics of a CO_2-fund for Norwegian road transport?

Earmarking diesel levy proceeds to subsidize alternative technology pathways for road freight.
Cost dynamics, emissions outcomes, and balancing technology choices.

Warehouse Relocationing article:
What are the transport and emissions implications of central warehouses relocating to outskirts of urban areas?

Changes in short-distance distribution transports, long-haul transport and shifts between and within transport modes. Transport and traffic volumes, domestic CO_2 emissions.

Framework conditions for Norwegian freight transport and how these contribute to and inhibit achievement of environmental objectives.

User experiences; use patterns vs. (electric) vehicle capabilities; cost competitiveness of alternative technologies; socio-economic cost of their phase-in; comprehensive insights into adoption potential.

Persistence of improved driving behavior; behavioral reinforcements. Importance of different eco-driving factors. Fuel savings and emissions reduction timing, scale & implications.

Impacts and dynamics of modal shift measures, relations and mechanisms between transport/environmental effects, policy design, implications for modal shift contributions to transport-environmental objectives.

Electric Truck article:
How do user requirements and techno-economic characteristics affect adoption potential for zero-emission road freight vehicles?

Eco-driving article:
What is the potential for reducing fuel consumption and CO_2 emissions by inducing eco-driving among truck drivers?

Modal Shift article:
What are the transport, modal distribution and environmental effects of strengthening and harmonizing modal shift policies across Nordic borders?

Figure S.1. Overview of how the articles included in this thesis relate to each other and the thesis' main theme.

With regard to modal shift, we assessed transport and environmental effects of strengthening, expanding, combining and harmonizing policy measures across Nordic borders, and of warehouse suburbanization trends (articles 3 and 4). Main findings include that even with strong policy measures for modal shift, reductions in Norwegian CO_2 emissions are limited, and that harmonizing/combining measures in some cases, but not all, can give rise to (limited) effectiveness synergies. Warehouse relocationing trends, in turn, may in fact move more freight *towards* road transport (although effects are small) and may further increase traffic and emissions particularly in the urban region, depending on case-specific trade patterns and relative geographical locations. In all, modal shift will at best be a moderate contributor to freight decarbonization, while active land use planning and curtailing transport demand might warrant more focus than is currently the case.

The above results indicate that it will take time before emissions reductions for freight transport can really become substantial. Through the last article, we therefore investigated potential shorter-term emissions reductions through improved driving behavior among truck drivers (eco-driving). Focus was on the potential for fuel savings, the persistence and reinforcement of eco-driving behavior, and the relative importance of different eco-driving factors. Findings indicate that eco-driving training can yield fuel savings of 5.2-9% for truck drivers and that active follow-ups of eco-driving training and non-monetary rewards might strengthen persistence of effects, where these otherwise tend to fade or disappear. Of different eco-driving factors, improvements in engine/gear handling seem most important. In all, eco-driving may be a way of achieving rapid, scalable and low-costs emissions reductions from freight vehicles in the period up to large-scale freight transport electrification.

On the whole, discussions in this thesis illustrate that achieving Norwegian climate objectives for transport will be challenging, particularly through freight transport. It will likely require combinations of strong efforts, both through different decarbonization veins and at different points in time. This thesis contributes to a better understanding of ways in which changes in framework conditions affect emissions reductions, into a variety of dynamics between policy, transport and environmental effects, and into (strengthening) the effectiveness of freight decarbonization approaches. It also provides perspectives on the size and urgency of the challenge, and deviations between policy narratives and achievements and potential emissions reductions in practice.

However, a main inhibitor to emissions reductions from transport in general, and freight transport in particular, remains the high projected increase in transport demand – both in Norway and in other countries. Unless this trend is reversed, the implication is that decarbonization through other veins needs to be even stronger to achieve climate objectives.

Contents

1. Introduction

1.1 Introduction, motivation, problem and scale

Transport fulfills many important functions in society, but it is also a cause of many problems. Not only is the transport sector already a major driver of climate change, but its emissions of greenhouse gases (GHG) and its share in the problem are also increasing [1,2]. Globally, transport is currently responsible for over a quarter of energy-related CO_2 emissions [3]. In fact, it is considered that global warming cannot be limited to the Paris Agreement's 1.5-2ºC without major emissions reductions from transport, and without large shares of these cuts taking place by 2030 [4,5,6,7,8,9].

Yet, despite increasingly ambitious decarbonization policies and large projected improvements in emission intensities of both passenger and freight transport, CO_2 emissions are actually set to increase due to even stronger increases in transport demand [5]. At the same time, the transport sector is assigned a prominent role in emissions cuts, particularly towards 2030 climate targets [ibid]. This is despite historical underperformance both on climate objectives generally and transport objectives specifically, and despite the emissions reduction gaps already faced by many countries [10,11].

Within the transport sector, a segment of particular interest, and the focus of the current thesis, is freight transport. Freight transport is underrepresented both in research, climate action pledges, and government strategies [e.g. 2,7,9,12,13,14], but its share in emissions and fuel consumption continues to rise rapidly, both globally and in individual countries. This is driven by demand developments and freight transport being more challenging to decarbonize than passenger transport and many other sectors [2,7,9,13,15]. Although specific estimates vary, a disproportionally large share of these emissions stems from freight transport by road, which is forecasted to also see the largest future increases [2,6,7,9,16].

In addition to focusing on freight transport, the current thesis does so for the case of Norway. Norway is chosen because of the context of projects through which this thesis' articles were written, but makes up an interesting case that warrants studying also for other reasons. For example, Norway explicitly envisions a leading role with regard to the adoption of zero-emission road freight vehicles, as it is has had for battery-electric passenger cars [17,18]. As discussed in the next chapter, Norway's political discourse has further gone to making emissions reductions from transport essential, especially towards 2030, with an important role for freight transport. Likewise, Norway faces sizable emissions reduction gaps, and all challenges discussed above are highly relevant themes.

Generally, transitions to lower-carbon societies worldwide entail large increases in demand for clean or renewable energy, another theme with particular Norwegian relevance. However, because supply of clean energy is limited, whether in terms of electricity from renewables or advanced biofuels, there is a need for curbing overall energy consumption. In other words, there is a general need for (most) energy-efficient solutions, not just from a climate perspective.

1.2 Research questions and delimitations

The above introduction indicates a need for insights that can contribute to larger and faster emissions reductions and more effective and targeted policy, while taking into account counteracting or conflicting developments. In the current thesis, this need is approached through the following overarching research question:

How can changes in framework conditions for Norwegian freight transport, stemming from policy (design) and logistics trends, contribute to or inhibit achievement of climate objectives for transport?

This formulation recognizes: A) that the framework conditions to which (Norwegian) freight transport is subject are important determinants for whether, and the extent to which, emissions reductions are induced or dissuaded; and B) that these framework conditions, in turn, are affected by developments in policy measures and logistics trends.

Throughout this thesis, I cover a selection of policy measures and developments with high relevance for Norwegian freight transport. They have in common that they are either ongoing, have recently been proposed, or are envisioned as means for reducing emissions from Norwegian freight transport, and that they are, will, or have the ability to shape Norwegian freight transport and emissions over the coming decade(s).

The selection of policy measures and developments covered in this thesis can be summarized through the main themes of each of the research articles, which I henceforth refer to as follows:

- Article 1: **CO_2-fund article**
- Article 2: **Electric Truck article**
- Article 3: **Warehouse Relocationing article**
- Article 4: **Modal Shift article**
- Article 5: **Eco-driving article**

The overarching research question of this thesis, introduced above, is operationalized through the main research questions for each of the articles. These article research questions (ARQs) can be formulated as follows:[1]

- **ARQ 1:** What are the CO_2 reduction potential and dynamics of a CO_2-fund, aimed at speeding up the adoption of alternative propulsion technologies within Norwegian road freight transport?
- **ARQ 2:** How do Norwegian user requirements and (developments in) techno-economic barriers and enablers affect the adoption potential for zero-emission road freight vehicles?
- **ARQ 3:** What are the implications of warehouse relocationing trends in Norwegian urban areas for freight transport and its CO_2 emissions?
- **ARQ 4:** What are the transport, modal distribution and environmental effects of strengthening policy measures for modal shift, and of harmonizing measures across Nordic borders?
- **ARQ 5:** To what extent and in what way do eco-driving interventions have a potential to reduce fuel consumption and CO_2 emissions by inducing more efficient driving behavior among truck drivers?

Because the current thesis builds on work spanning several different, rather than one dedicated research project, the research articles were not structured as direct follow-ups to each other, but steered by the aims, scope and delimitations of the projects they were part of. Nevertheless, as will be elaborately discussed in upcoming chapters, their analyses are in many ways interrelated, and all feed into the thesis' main theme: **how changes in framework conditions for Norwegian freight transport can contribute to or inhibit achievement of climate objectives for transport.**

1.3 Contributions and relevance beyond Norway

While the focus of the current thesis is on the Norwegian case, insights, implications and methodological approaches can be highly relevant also for other countries facing similar and related challenges; whether this is to more effectively reduce emissions, speed up the adoption of zero-emission freight vehicles, achieve more modal shift, or attain fast emissions reductions.

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[1] The reason for distinguishing between CO_2 emissions, emissions more generally, and environmental effects, is that while all research articles assess CO_2 emissions, some also consider or explicitly estimate impacts on local emissions/energy use.

For example, this thesis sheds light on dynamics of emissions reductions, the extent and urgency of the challenge, and on implications and trade-offs related to the timing of cuts. It provides insights on the extent of emissions reductions that might be achieved through different veins and on relationships between and relative contributions of different veins. These insights all come with policy lessons, e.g. on the realism behind current policy discourse and the roles assigned to different decarbonization solutions. An interesting case, for example, are Norwegian objectives on the share of zero-emission freight vehicles to be phased in by certain years. Here, policy assessments explicitly presuppose that these shares are achieved, but not necessarily how, or that this could potentially require very strong policy measures if price and technology developments are not as hoped. Similar examples can be found in many other countries. Likewise, there are themes that receive little policy attention, but might be worth considering, especially given indications that prevailing policy mind-sets do not sufficiently reflect the particular urgency of the challenge [6].

The thesis further provides insights on and a better understanding of potential advantages and disadvantages of policy design and dynamics between transport and environmental effects, on considerations of cost effectiveness, and on the specific importance and challenges of the freight transport sector. Insights are further not necessarily limited only to reducing GHG emissions, but can have implications through potential co-benefits of emissions mitigation, such as reducing the pressure on transport infrastructure or local air pollution, which is a problem many places [5].

1.4 Thesis structure

The remainder of this thesis is structured as follows: Chapter 2 provides more detailed background, elaborates on the necessity and urgency of reducing transport emissions and how they are governed, zooms in on the Norwegian case, and discusses why decarbonizing freight transport is considered particularly challenging. Chapter 3 presents the theoretical framework for this thesis, both at an overarching level and for the individual articles. In Chapter 4, I provide a detailed overview of the methods and data used, and tie together both common factors and differences between articles. Chapter 5, in turn, gives a synthesis of findings, contributions and limitations of the thesis as a whole, followed by brief summaries of the individual articles. Discussion, conclusion and implications are discussed in Chapter 6. The thesis concludes with copies of the articles.

2. Background

2.1 Climate change, CO_2 emissions and the sheer necessity of reducing transport emissions

CO_2 is a global, cumulative pollutant. This has important implications for decarbonization efforts [see e.g. 19], hereunder that "achieving the targets set for global warming is not only dependent on the outcome, but also the way this is achieved" [2, p.13]. Put very simply, what matters for global warming is the cumulative amount of CO_2 emissions over time (the emissions 'stock'). Without geoengineering (e.g. carbon capture and storage), additional emissions cause additional, relatively rapid temperature increases, which then remain rather stable for decades or centuries. For this reason, net global CO_2 emissions have to be reduced to zero before reaching a 'target temperature' [19]. These insights have contributed to increasing prevalence and use of the 'carbon budget' concept [4,20]. This concept recognizes that to stay within a certain 'target temperature' by a given year, cumulative CO_2 emissions cannot exceed a certain amount. In practice, this means that annual emissions need to peak soon and drop sharply. Waiting longer implies that emissions cuts have to be much sharper later on, and risks 'using up' the carbon budget that we have [8].

The International Panel on Climate Change [4,21,22] finds that a key and common feature of 2ºC and 1.5ºC global warming pathways is a nearly fully decarbonized power sector by 2050. However, pathways consistent with the 1.5ºC degree ambition require additional emissions reductions, primarily from transport and industry. Most pathways with very low emissions encompass transitions away from fossil fuels used in transportation. Pathways consistent with 1.5ºC global warming further require marked and rapid energy demand reductions in amongst others the transport sector, by 2030 at the latest. This illustrates both the scale and urgency of the problem, and the crucial role of the transport sector [7,23].

2.2 International governance

Because CO_2 is a global pollutant, it matters little where emissions (or reductions) take place geographically or in what economic sector. Economically, it would be optimal to reduce emissions where marginal abatement costs are lowest. From a policy perspective, however, the geographical and sectoral sources of emissions do matter. Through complex sets of rules, emissions are attributed to individual countries (the so-called territoriality principle) and sectors [24]. Similarly, countries face obligations to reduce emissions that are attributed to them, even though this is not economically optimal [25].

The overarching policy arena for international governance of climate change is formed by United Nations' Climate Change Conferences (COP meetings). The 2016 Paris Agreement (COP21) was a milestone, in that it formed a legally binding international climate change treaty setting goals to limit global warming to well below 2ºC and preferably to 1.5ºC (versus pre-industrial levels) [26]. The Paris Agreement entails that countries submit Nationally Determined Contributions (NDCs) in which they outline emissions reduction actions that will be taken. NDCs are to be progressively increased every five years and reflect the highest ambition level that is feasible for the submitting country [27].

In 2019, Norway entered into an agreement with the EU and Iceland with the aim to fulfil obligations under the Paris Agreement in cooperation. This cooperation builds on three pillars, for which the current combined ambition is to reduce emissions by at least 55% percent in 2030, compared to 1990 [28,29]:

- Participation in the European Emissions Trading System (ETS)
- Participation in the European Effort Sharing Regulation (ESR)
- Participation in Land Use, Land-Use Change and Forestry Regulation (LULUCF), prescribing net-zero emissions from land use and forestry.

The ETS covers emissions from industrial and power plants, petroleum industry and commercial aviation within the European Economic Area. The current objective is that ETS emissions for the EU, Norway and Iceland combined, are reduced by 43% in 2030 (vs. 2005), with a proposal to strengthen this objective to 61% [27,30,31]. The ESR, in turn, sets binding national targets for emissions reductions from non-ETS sectors, which include transport, agriculture, buildings, waste management and several sources not covered by the ETS.

2.3 Norwegian national setting and (freight) transport emissions

2.3.1 Governance

Overall, Norway's NDC describes a commitment to reduce GHG emissions by at least 50 and towards 55% by 2030, compared to 1990 [29]. With regard to the first pillar of Norway's cooperation with the EU, around half of Norwegian GHG emissions fall under the ETS, and hence, it is unknown and undefined what share of cuts will take place in Norway [27]. For non-ETS emissions, Norway's national target is a reduction of 45 percent in 2030, compared to 2005, in practice giving Norway a carbon budget for 2021-2030 [27,32].

Through updates to its 2017 Climate Change Act [33], Norway further engrained the commitment to reduce GHG emissions by at least 50 and towards 55 percent (2030 vs. 1990) and the carbon budget concept into national law. The Act further prescribes that Norway is to become a low-emission society by 2050, in line with the Paris Agreement. This is operationalized as a 90-95% emissions reduction compared to 1990.

Also government platforms, assessments and action plans provide guidance on how Norway intends to fulfil climate objectives. For example, it is emphasized that while international cooperation is important, it is also crucial that Norway reduces its own GHG emissions substantially, fast and sufficiently, and that the pace for reducing non-ETS emissions is increased [e.g. 18,27,34].

2.3.2 Prominence of the transport sector in Norwegian climate strategies

Norway has (or is developing) sector-specific reduction targets for non-ETS emissions [18,34]. Here, emissions cuts in the transport sector are assigned a key role [17]. Norway's current (point) target is to reduce transport emissions by half in 2030 (vs. 2005), and similarly for domestic shipping and fishery [17,27,34]. Recalling that the overall non-ETS target is a 45 percent reduction, this means that the transport sector is assigned a larger than proportional role. In fact, the Norwegian Centre for International Climate Research found that the transport sector is to contribute with the largest emissions reductions, and within transport, the road segment is likely to have to contribute larger decreases than other segments [35]. The Norwegian government, too, explicitly recognizes that without sizable emissions cuts from transport, achieving 2030 targets for non-ETS emissions will be impossible [27]. In other words, not reducing transport emissions is not an option – and on the 2030 timescale, reducing emissions from road transport will be crucial.

Key in Norwegian strategies for reducing transport emissions are transitions to zero-emission (vehicle) technologies, increased use of biofuels, infrastructure establishment for zero-emission vehicles, and taxes and levies [17,18,27,34,36]. For zero-emission vehicle adoption, policy follows targets set for shares in new vehicle sales for different segments, by 2025 and 2030. These targets presuppose improvements in technological maturity of zero-emission technology, especially for heavier vehicles [17,27]. Policy discourse is that it should be profitable to choose zero-emission vehicles, also in heavy vehicle segments [27,31]. The current and previous Norwegian government both envision Norway to remain a leading country in renewable energy and the adoption of zero-emission transport solutions, and through this to contribute to establishing markets for new zero-emission technologies and to achieve a competitive advantage for Norwegian firms [27,34]. For those vehicles that will still require diesel or petrol, (advanced) biofuels shall contribute to emissions reductions [17,27]. To this end, the current government envisions establishing an effort on Norwegian bioenergy and advanced biofuels in the transport sector, with an integrated industrial value chain [18]. In terms of taxes and levies, Norway takes a 'polluter-pays' approach, and has announced increases in CO_2-levies to around 2000 NOK per tonne by 2030 (roughly 200 EUR/tonne, or about a quadrupling of the current rate) [18,27].

Although the previous Norwegian government intended to continue work on a CO_2-fund for Norwegian land-based transport industries [34], this proposal has since been put on hold. However, in the realms of the CO_2-fund article in this thesis, the concept has again become highly relevant as recently as December 2021, when announced levy increases were met with a proposal to establish a CO_2-fund for the Norwegian maritime industry. The proposal entails that shipping firms would pay CO_2-levies into a fund, and would thereafter be able to apply for subsidies from levy proceeds, to be used on climate measures on board of ships [37].

2.3.3 Norwegian emissions from (freight) transport

Transport currently stands for around 60 percent of Norway's non-ETS emissions, or 32 percent of GHG emissions overall. In turn, over half of transport emissions comes from road transport, making it responsible for about 17% of Norway's overall emissions. Since 1990, emissions from heavy-duty transport (trucks and buses) and vans have been increasing more than those from passenger cars, and in recent years, changes in transport emissions have particularly been due to the share of biofuel use, as well as electrification of mainly the passenger car fleet. As a result, total emissions from heavy-duty vehicles and vans are now about equal to those from passenger cars [7,17,27,38]. Freight transport, in turn, makes up about 40% of Norwegian transport emissions, a share that is increasing.[2] Of freight emissions, over half comes from road freight. Figure 2.1 illustrates the above developments for different transport sub-segments in index numbers, with 2005 as base year.

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[2] Calculated as sum of emissions from light and heavy freight vehicles, shipping, and rail transport's freight share - in total transport emissions (based on Statistics Norway's Table 08940: Greenhouse gases, by source, energy product and pollutant 1990-2020).

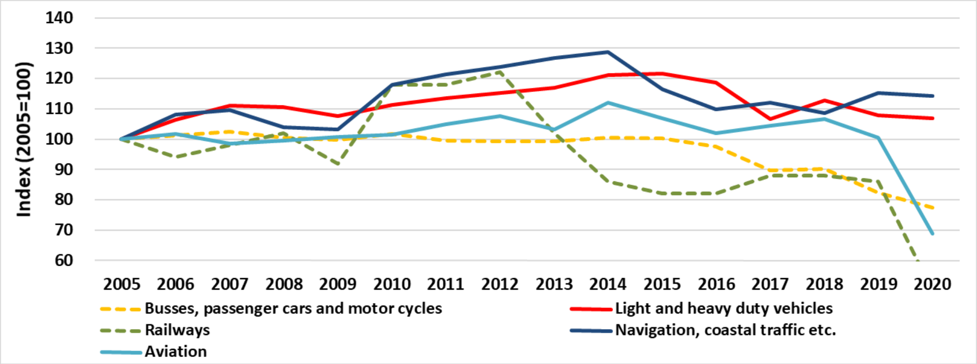

Figure 2.1. Developments in CO_2 emissions from transport sub-segments, in index numbers (base=2005).

2.4 Freight transport characteristics that make emissions reductions challenging

Freight transport is considered one of most difficult activities to decarbonize [13,39,40]. Not only are most freight transportation modes particularly dependent on fossil fuels, but transport demand is projected to increase substantially [2,9,39]. This means that the share of freight transport in total emissions is projected to increase considerably, as other sectors decarbonize faster, even when feasible efficiency and technological developments for freight transport are considered. Because of this, freight transport emissions are for example projected to surpass those of passenger transport [39].

Main current challenges include a lack of commercially available zero-emission alternatives and low-carbon operational practices. Compared to e.g. passenger transport, the freight segment sets much higher technological demands, as large quantities of goods are transported over long distances [2,9]. Much of this is done by ship, which yields lower per-unit emissions, but for which decarbonization in a short term is challenging. For freight transport by road, the availability of zero-emission heavy vans, but particularly heavy-duty vehicles, is currently still limited [17,40]. It is therefore considered unlikely that low-/zero-emission freight vehicles will dominate long-distance transport by 2030 [2].

Moreover, freight transport has relatively high abatement costs compared to many other parts of the economy [13,39,40]. This is exemplified by an assessment by the Danish Climate Council [41], in which recommendations on a cost-effective package for emissions reductions towards 2030 include few freight transport initiatives. The fact that freight transport activities largely take place in the private sector and are profit-driven, combined with fewer incentive levers being available, further makes that the role of governments is often smaller than for example for passenger transport [6]. Historically, freight transport has also received much less policy and research attention than passenger transport [6,16].

For Norway specifically, the country's geographical scope, topography, demanding weather conditions, small and scattered population, and its relative location in Europe, make employment of zero-emission transport modes particularly challenging, or particularly expensive.

3. Theory

3.1 Frameworks for reducing (freight) transport's CO_2 emissions

Strategies for reducing CO_2 emissions from transport can be categorized in different ways. Banister's 'sustainable mobility paradigm', for example, distinguishes four types of actions: 1) reducing the number of trips by reducing the need for underlying transport; 2) encouraging modal shift; 3) reducing trip distances through targeted land-use policy; and 4) increasing transport efficiency through technological innovation [42].

The ASI framework, in turn, classifies emissions reduction strategies into 'Avoid', 'Shift' and 'Improve'. Here, 'Avoid' can be interpreted as actions that reduce transport amounts (e.g. the number or length of trips), 'Shift' as transferring transport to less carbon-intensive modes, and 'Improve' as reducing carbon intensity per unit transported [e.g. 9,12,25,43].

Closely related to ASI is the Activity-Structure-Intensity-Fuel or ASIF framework, coined by Schipper and Marie [44]. Following this framework, transport emissions can be reduced by reducing transport activity, changing or shifting the modal structure of transport, reducing the amount of energy needed per unit of transport (intensity) or by reducing the carbon content of fuel or energy sources [e.g. 39,45,46]. That is, the ASIF framework breaks up energy intensity and carbon intensity, where the ASI framework combines both under 'improve'.

The Energy Transitions Commission [13] and Norwegian Center for International Climate Research [35] take approaches derived from the ASI/ASIF frameworks, with decarbonization strategies structured along curtailing transport demand or demand growth, changing modal distribution, improving energy efficiency, and application of decarbonization technologies.

However, the frameworks discussed above are either applicable to transport in general or discussed or developed in the context of the transport of people, even though they come with useful insights also for freight transport [9,13,35,42,46]. An approach more specifically considering emissions reductions from freight transport can be found in the 'Green Logistics Framework' developed by McKinnon [see e.g. 9,39,46]. McKinnon's framework constitutes an expansion of the ASI and ASIF frameworks, structuring decarbonization along five veins:[3]

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[3] In turn derived from seven key parameters: modal split, 'handling factor', length of hauls, empty running, load factor, energy efficiency and carbon intensity of the fuel/energy.

1) Reducing the level of freight movement
2) Shifting freight to lower-carbon modes
3) Improving vehicle utilization
4) Increasing energy efficiency
5) Switching to lower-carbon energy

The Green Logistics Framework, either directly or with slight adaptations, has in recent years been much adopted in both scholarly and leading policy publications on freight transport decarbonization [e.g. 2,6,15,25]. Its veins are sometimes further categorized as technology/engineering solutions, versus logistics, management or behavior solutions and regulations [15,25].

Although all frameworks discussed here may have been developed from different perspectives or with different emphasis, it can be seen that they are not very different conceptually. Most of all, the frameworks offer intuitive overviews of main veins through which CO_2 emissions from (freight) transport can be reduced. However, each vein in itself contains a plethora of sub-factors that can be addressed to achieve the vein's intention. Reducing freight movements, for example, can be approached by reducing transport demand. This, in turn, can entail everything from curtailing purchasing power, to reducing goods' transportable weight or volume, to reducing transport distances, etc. The same applies to other veins. As I will come back to, there are also many overlaps between different veins in the different frameworks, while changes in one vein can also influence others.

3.2 Conceptualization of the frameworks

3.2.1 A Kaya-identity for freight transport

Threads of the different frameworks for reducing freight transport emissions can be pulled together into a 'Kaya-identity' for freight transport. The notion 'Kaya-identity' became famous through the work of Kaya and Yokobori [47] and has been used in countless studies to analyze developments in CO_2 emissions, as well as (decompositions of) drivers of these developments [e.g. 1,9,39,45]. A main appeal of the Kaya-identity is that it can be used in many different forms and for different purposes, and can be applied both to entire economies and to small sub-segments [e.g. 40]. Because it is, by definition, a mathematical identity, it will always hold,[4] and both the original identity and adaptations can provide intuitive ways of thinking about approaches to emissions reductions.

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[4] And technically, terms of the original identity would cancel out.

Considering the frameworks discussed in the previous section, a stylized and derived adaptation of the Kaya-identity can for example be defined as follows for freight transport:

$$CO_2 = \underset{(1)}{\begin{matrix} Demand \\ intensity \end{matrix}} * \underset{(2)}{\begin{matrix} Transport \\ intensity \end{matrix}} * \underset{(3)}{\begin{matrix} Modal \\ split \end{matrix}} * \underset{(4)}{\begin{matrix} Energy \\ intensity \end{matrix}} * \underset{(5)}{\begin{matrix} Energy's \\ carbon\ intensity \end{matrix}}$$

Here, demand intensity represents the amount of goods that society demands to be transported, while transport intensity represents how much transport is generated given a certain demand (vehicle-kms/tonne-kms). These intensities are driven by many factors, including economic activity (population, affluence) and the localization of producers and consumers [9,25]. The third term, modal split, revolves around how transport is distributed between modes (e.g. road, rail and sea), but also within modes (e.g. larger trucks or vans, etc.). Energy intensity represents the energy that is needed per unit transported or per kilometer. Finally, the last term represents how much carbon is emitted per unit of energy used. Analogous to the difference discussed between the ASI and ASIF frameworks, it can be instructive to distinguish between energy and carbon intensity as two separate elements. As an example, blend-ins of biodiesel into fossil diesel will reduce emissions by reducing the average carbon intensity of the fuel, but in principal not the energy intensity of transport.[5] A transition from diesel to electric vehicles, in turn, improves the energy intensity term, as fewer kWh's worth of energy are needed per km due to electric vehicles' more efficient drivetrains. If additionally, the electricity mix becomes lower-carbon, this will act through the fifth term.

3.2.2 Implications: trade-offs in reducing CO_2 emissions and feedback effects

Even though terms in the above identity are not static, but constantly developing, the Kaya-presentation may help illustrate a number of useful insights and dynamics. Firstly, it can be instructive to get an idea of the overall potential for emissions reductions: what changes are feasible to achieve in the identity's different terms, and what would this mean for emissions in total? Secondly, it can provide an idea of the relative importance and potential contributions of different terms to emissions reductions (or increases). Thirdly, the Kaya depiction provides an intuitive starting point for reasoning how changes in one term might entail feedback effects

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[5] In reality, biodiesel generally has a slightly lower energy content per liter than fossil diesel, so that energy intensity will also be slightly affected, but I disregard this here for the purpose of this illustration.

through other terms. For example, if reducing the economy's demand for transport is unlikely, or if demand actually keeps increasing considerably, (larger) emissions reductions must be achieved through the other terms. The latter may not be feasible [see e.g. 6,9,43], meaning that either targets are not achieved, or reducing transport demand should be back on the policy table.

An important dynamic to be aware of is that improvements in one term of the identity may give rise to feedback or rebound effects through other terms. For example, energy intensity improvements may reduce transport costs, which may in turn increase transport demand [39]. Similarly, increases in road vehicle dimensions improve the energy intensity per unit transported and transport intensity (fewer vehicle-kms per unit of transport), but improve road transport's competitive edge compared to other modes and make achieving modal shift more challenging [9,39]. There are, of course, many more instances of comparable feedback effects.

Trade-offs also exist in a time dimension. Measures to achieve improvements in some terms may yield some emissions reductions in the shorter term, but can thereby postpone or hinder more substantial emissions reductions in the longer term. One example (discussed in more detail in relation to the thesis' articles) might be a short-term focus on biofuel solutions. This might slow down adoption and market maturity of electric heavy freight vehicles or result in lock-ins to biofuel policies.

In addition to feedback/rebound effects, it is important to note that improvements in the different terms are not cumulative. When one term is improved, this affects the effect of improving another term alongside, by inducing reduced marginal returns. For example, if demand intensity is reduced by 5%, this reduces emissions by 5%, all other things equal. If energy intensity is reduced by 5% on average, this also reduces emissions by 5%. If both improvements take place simultaneously, total reductions are less than 10%. In a more intuitive example: when road freight transport is electrified and yields lower emissions, reducing transport intensity will not reduce emissions as much as it would have given diesel-driven transport. These mechanisms have implications for combinations of emissions reduction measures, amongst others when effects of policy measures are assessed separately, but emissions reduction potentials of measures are thereafter added together. Another implication is that measures that on their own may be assessed as beneficial for society, might no longer be so alongside other policy measures.

It is clear that terms in the Kaya-identity can be addressed in many different ways [see e.g. extensive overviews and suggestions in 2,9]. However, in light of trade-offs and feedback/rebound effects, an important insight is that it is crucial to employ measures that complement each other, yield synergies, and achieve sufficient emissions reductions at the right time [10].

3.2.3 Decarbonization frameworks and the articles of this thesis

Table 3.1 summarizes veins of different decarbonization frameworks that are addressed through each of the articles in this thesis. In doing so, the table also illustrates the close interlinkages between different frameworks. Parentheses indicate themes that are touched upon or are affected more indirectly (e.g. the articles focusing on shifts between transport modes also address shifts within modes, such as between road vehicles with different average utilization rates, but not as main focus). Further, as exemplified in several of the articles, positively defined changes (e.g. 'improve' or 'lower-carbon modes') can also occur in opposite direction, thereby increasing rather than reducing CO_2 emissions.

Table 3.1. Overview of veins of different frameworks addressed through each of this thesis' articles.

Article	**ASI**	**ASIF**	**Green Logistics Framework**	**Kaya-term(s)**
CO_2-fund	Improve	Intensity, Fuel	Energy efficiency, Lower-carbon energy	Energy intensity, Energy's carbon intensity
Electric Truck	Improve, (Shift)	Intensity, Fuel, (Structure)	Energy efficiency, Lower-carbon energy	Energy intensity, Energy's carbon intensity
Warehouse Relocationing	Avoid, Shift	Activity, Structure	Reducing freight movement, Shift to lower-carbon modes, (Vehicle utilization)	Transport intensity, Modal split
Modal Shift	Avoid, Shift, (Improve)	Activity, Structure, (Intensity, Fuel)	Reducing freight movement, Shift to lower-carbon modes, (Vehicle utilization, Energy efficiency, Lower-carbon energy)	Transport intensity, Modal split, (Energy intensity, Energy's carbon intensity)
Eco-driving	Improve	Intensity	Energy efficiency	Energy intensity

3.3 Emissions reduction strategies in practice

Considering the veins through which emissions from freight transport can be reduced, it is instructive to take a closer look at how emissions reductions are approached in practice.

Internationally, policy proposals, measures, and narratives predominantly relate to emissions from transport in general. Despite being identified as a very challenging sector for emissions reductions, freight transport features much less prominently or explicitly [2,7,9,12,13,14]. Both for transport in general and for the fewer mentions of freight transport specifically, however, clear trends can be observed.

For example, reducing transport or transport demand is hardly mentioned or even bluntly rejected, such as through the "curbing mobility is not an option"-narrative in the EUs 2011 Transport White Paper [9,12,25,49,p.5]. Also the types of actions included in sustainable transport reports or NDCs illustrate that 'avoid' plays a rather small role [9,48]. This is attributed to the perspective that demand control runs against fundamental economic and societal principles, such as economic development, welfare, well-being and competitiveness [25,43].

Modal shift, in turn, has for many years featured very prominently among stated decarbonization strategies, for example in submissions and follow-ups to climate agreements [25,46,48]. Indeed, McKinnon [9, p.20] goes as far as stating that "politicians and policymakers around the world have long seen modal shift to rail, and to a lesser extent water-borne transport, as a panacea for many freight transport problems", because modal shift has a potential not only to reduce CO_2 emissions, but also other negative externalities. However, modal shift has shown to be very difficult to achieve, both internationally, at the EU level, and for individual countries. In fact, freight market shares of rail and water-borne transport have generally not increased significantly despite many years of modal shift policy, and in many cases actually decreased [e.g. 9,15,25,50,51,52].

Improvements through more technological veins of decarbonization frameworks also feature very prominently in policy strategies and discourse. This goes both for strategies aiming at transitions to alternative technology vehicles, the use of lower-carbon fuels, and technical fuel efficiency improvements [9,12,25,46,48,53]. The potential for the latter is considered to be rather limited for conventional vehicles with internal combustion engines (ICE) [25]. At the EU level, Dyrhauge [53] observes a development from particular focus on biofuels towards also strongly aiming at electrifying transport. Furthermore, the latter is becoming increasingly integrated with policy for infrastructure establishment and renewable electricity generation. As it stands, however, large parts of recent decreases in road freight emissions are due to increased biofuel blend-in [25].

Zooming in on Norway, policy narratives on curbing transport demand have largely been limited to passenger transport, not freight [see e.g. 17,54]. In fact, demand for freight transport is projected to keep increasing, driven by GDP and population growth, among other things

[11,17]. Modal shift, in turn, has featured in all National Transport Plans this century and in government budgets since at least 2005, with objectives to shift transport over distances longer than 300 kms away from road, and onto rail or water-borne transport [see e.g. 11,17,27,36,54]. In the past few years, for example, the (previous) Norwegian government reiterated its ambition in the latest National Transport Plan [17, translated from p.118]: "30 percent of freight transported over distances >300 km is to be shifted from road, to rail and water-borne transport by 2030". Freight modal shift similarly features as one of the measures to strengthen emissions cuts included in the (previous) government's Klimakur 2030-assessment [36], and Climate Plan 2021-2030, on how to reduce emissions in line with international commitments and obligations [27]. Strategies to achieve this modal shift revolve around improving rail and water-borne transport's framework conditions and competitiveness through infrastructure investments (capacity improvements and maintenance) and mode-specific financial incentive schemes. Similar lines seem to be followed by the current Norwegian government, through descriptions in the 'government platform' (Hurdalsplattformen) of October 2021. However, despite many years with freight modal shift ambitions, Norwegian modal shift objectives have been far from achieved, and even when implementing radical policy measures and achieving their full potential, emissions reductions would still only be very moderate [11,25,52,55,56,57].

Most policy focus in Norway, however, is on increased use of biofuels for road transport and the phase-in of zero-emission technologies, also for heavy vehicle classes [17,18,27,34,36]. For biofuels, mandatory blend-in rates have been increased year-on-year, and policy signals are that further increases will be implemented towards 2030.[6] Biofuels have the advantage that they effectively count as zero-emission in Norway's climate accounts, because in-vehicle combustion is regarded as zero-emission. Even though biofuels can yield considerable CO_2 emissions throughout their life cycle, such emissions are attributed to other sectors than transport to avoid double-counting. Additionally, because the lion's share of biofuels used in Norway is imported, emissions are further attributed to other countries [58]. Both in policy thus far, and announced future policy, focus on advanced biofuels has been increasing [17,18,27,36,58]. Advanced biofuels are subject to specific sustainability criteria that aim to ensure substantial (net) emissions cuts globally over their entire life cycle, and more so than conventional biofuels [58].

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[6] In 2021, at least 24.5% of all fuel sold to road traffic is to be liquid biofuel (in practice biodiesel/bioethanol; biogas is not included), with a separate requirement that at least 9% of all fuel is to be advanced biofuel. Advanced biofuels count double towards the main rate. This entails that the mandatory biofuel blend-in rate is effectively 15.5 percent of volume, given that the separate requirement is fulfilled.

Regarding the phase-in of zero-emission technology vehicles, Norwegian policy confirms continuation of objectives set out in the penultimate National Transport Plan [17,18,27,36,54]. Specifically, this entails that all new passenger cars and light vans are to be zero-emission by 2025, and city buses either zero-emission or using biogas. By 2030, all new heavier vans are to be zero-emission, as are 75% of new long-distance buses and 50% of new heavy-duty freight vehicles, while goods distribution in the largest city centers shall be virtually emission-free [54, p.16]. In policy documents and strategies, it is emphasized that choosing such vehicles should be profitable and attractive, with important instruments including subsidies, road toll advantages, and requirements in public procurement [17,27]. Work towards the facilitation of charging and filling infrastructure for alternative technology vehicles has also become an integrated part of Norwegian policy [17,18,27].

3.4 Article-specific theoretical background

As seen, decarbonization strategies put much focus on technology solutions and the large-scale adoption of low- and zero-emission freight vehicles, i.e. the theme of the CO_2-fund and Electric Truck articles. For freight vehicle operation with biofuels, the situation is relatively straightforward. With some exceptions, vehicles used with biodiesel or biogas largely have good and mature technical properties. Challenges, however, lie in the availability of sufficient biodiesel and biogas, and the higher relative costs of these fuels compared to regular diesel (in addition to a slightly lower energy content). For (bio)gas vehicles, capital costs are additionally somewhat higher than for diesel vehicles, both in terms of investment costs and because of more uncertain rest or resale values [e.g. 36,59].

For electric freight vehicles (battery-electric or hydrogen-fuel-cell), the situation is different. Technologies are still in (relatively) early market phases, even though developments proceed rapidly. Main advantages of battery-electric vehicles are a much higher drivetrain efficiency than ICE-vehicles, cheaper and lower-emission energy sources, and (likely) lower maintenance costs. However, battery-electric vehicles have much higher investment costs, require establishment of charging infrastructure, have limited driving ranges and substantial recharging times, and might face a payload penalty due to the weight of their batteries. Hydrogen-electric vehicles also have more efficient drivetrains than ICE-vehicles, relatively short refueling times, and yield lower emissions (depending on the method of hydrogen production). However, they also face hydrogen-related efficiency losses, are particularly expensive, lag behind in terms of technological maturity, and require much filling infrastructure [e.g. 11,60,61,62].

Most existing literature on electric vehicle adoption has naturally focused on electric passenger cars and, to some extent, vans and buses, due to their more mature market stages. Literature on electric heavier freight vehicles, in turn, is an emerging field [61], and has mostly focused on barriers and facilitators to their adoption, emissions reduction potential, and on techno-chemical improvements and developments for battery components and fuel cells. In terms of cost barriers, existing literature often applies a form of total costs of ownership (TCO) assessment or (cost) life-cycle analysis (LCA) [e.g. 61,63,64,65,66,67,68,69]. With regard to operational barriers, focus is on driving range limitations, charging requirements, and assessment and identification of feasible user cases, either theoretically or by relating limitations to current vehicle use patterns [e.g. 61,62,65]. A common factor in many studies on barriers and facilitators to electric heavy freight vehicle adoption, is that there is necessarily much uncertainty on many elements, not least on how costs and technology will develop even in the near- or medium-term future [see e.g. 61].

The Warehouse Relocationing article, in turn, builds on planning and land use theory on the traffic generation from different types of activities, and the relationship between traffic generation and (relative) locations of these activities. The theory dates back to the Dutch ABC-principle developed in the 1980s-1990s [70], where locations are categorized as A, B or C, depending on (relative) accessibility by e.g. public transport, bike, road vehicles, parking conditions, etc. These characteristics, consequently, determine the suitability of a location for different types of activities. For example, it is considered more optimal from a traffic point of view to have people-intensive activities located in central areas to reap benefits of public transport accessibility, and area-intensive activities elsewhere. The article further builds on literature on logistics sprawl, a trend observed in many developed countries, with logistics facilities moving further away from central city areas and towards the outskirts of urban regions [71,72,73,74,75,76,77]. Drivers behind this logistics sprawl include developments in logistics and supply chain costs, e.g. through costs of transport, warehousing and operation, the (increasing) footprint of warehousing functions, land prices and competition for central areas, transport infrastructure, accessibility and congestion levels, public policy, market demand, etc. [76,77,78,79]. Relocation of warehouses may increase road transport distances for local/regional transports [79], but potentially also yield modal shift on particularly longer-haul transports.

While modal shift is assessed as one of several mechanisms in the Warehouse Relocationing article, it constitutes the main theme of the Modal Shift article. As mentioned previously, the desirability of modal shift from a decarbonization perspective lies in the fact that rail and waterborne transport have considerably lower emissions per unit transported, than road transport. As it stands, road transport also dominates most other negative externalities, e.g. noise, local pollution, congestion, or accidents, while modal shift might also be desirable for other (social) political reasons [11,52,81,82]. Generally, it is considered that modal shift potential particularly lies with transport over longer distances (often operationalized as >300 km by policymakers).[7] On shorter distances, harbors and rail connections are often not available, or transferring to/from road vehicles (for first- and/or last-mile transport) is too costly or time consuming [11,52,83,84,85].

Modal choice is influenced by a range of factors. These include physical access to modes and relevant infrastructure, locations of harbors, rail terminals and transshipment sites, relative costs of performing the desired transport by different modes, properties of shipments and commodities (e.g. perishability or specific technical requirements), transit times, service quality, flexibility, punctuality, transport reliability, frequency and regularity, and price-elasticities of modes [11,15,49,50,52,57,85]. To be successful, policy measures aimed at inducing modal shift must in some way shift the balance of such modal choice factors. Strategies to do so include improvements to infrastructure, capacity, efficiency and intermodal connectivity, positive/ negative financial incentives (e.g. subsidies, taxation), regulation (e.g. vehicle dimensions, standardization, harmonization) or information initiatives [11,50,52,86]. Such strategies can, for example, improve cost competitiveness, transit times or reliability of non-road modes, especially when used in combination [52].

In terms of modal shift assessments, distinctions are made between choice models, life cycle analyses, decomposition analyses and strategic transport network models [87]. Using different terminology, distinctions can be made between market-segmentation models (simple models analyzing the share of shipments between origin-destination pairs by feasible modes), modal cross-elasticity modelling, and models using shipment or commodity data to assess determinants of mode choice [50,52]. All these approaches have advantages and disadvantages, where strategic transport network models (as used in the Warehouse Relocationing and Modal Shift articles) have high desirability but also large data demands [87]. This is described in more detail later.

Finally, the Eco-driving article builds on established theory on how to most efficiently operate a vehicle during different stages of driving, in order to save fuel. Eco-driving strategies revolve

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[7] In practice, for many traffic-intensive freight relations, rail transport is not a feasible alternative before distances are closer to or beyond 500 kms.

around improving behavior on speed choice, traffic anticipation, engine and gear use, braking, idling, and related factors [88 through 102]. Most drivers have a significant improvement potential on such elements. In scientific studies, eco-driving is induced and evaluated in different ways (as described in detail in the article), with most focus thus far on passenger car and bus drivers, and to a lesser extent on freight vehicle drivers [92,93,94,96]. For truck drivers, the literature indicates that eco-driving initiatives might induce fuel savings, with potentials often estimated to between 5-15% [93,103]. However, many existing studies are subject to some flaws, hereunder that most studies focus on relatively short time periods. Studies considering longer time periods suggest that eco-driving behavior (and thereby fuel savings) tends to fade or disappear in the medium- to longer run [88,90,91,97,99,100,101,103 through 107]. This has led to suggestions that eco-driving interventions should be reinforced to make behavioral improvements persist, for example through providing feedback and driver follow-up after initial training or by employing reward incentives or gamification [88,93,98,107]. The Eco-driving article therefore takes a longer time perspective and adds reinforcement elements.

4. Methods and data

The current chapter provides an overview of the methods and data used in the articles of this thesis, and intends to tie together both common factors and differences. The latter is done in recognition of the fact that despite their related themes and research questions, research strategies and the scope of suitable analytical approaches necessarily differ between the articles. This is driven by characteristics of their underlying projects (e.g. the projects' delimitation, objectives, or whether they entailed access to data), the types of available data and their characteristics, and many other factors. For example, when investigating themes relevant for a transition from diesel vehicles to alternative propulsion systems, aspects such as costs can be assessed using quantitative data and assumptions. Other important factors, such as operator perceptions and views on what is needed to even consider investment in zero-emission vehicles, almost by definition require more qualitative approaches.

In addition to relating the articles methodologically, this chapter also walks the reader through each of the articles' main research questions, rationale, analytical approach, methods, assumptions, and data. This is done both to provide a fuller account of research choices than was possible in the actual journal publications, as well as to introduce the reader to specifics, such as what different scenarios entail, so that this is understood when the articles' main findings are synthesized in the next chapter.

4.1 Tying together the articles

At an overarching level, all articles within this thesis build heavily on quantitative methods and data analysis, and either assess effects of policy interventions (CO_2-fund, Electric Truck and Modal Shift articles), ongoing societal change trends (Warehouse Relocationing article) or behavioral interventions (Eco-driving article). For all articles this entailed the design and definition of several scenarios for comparison. To ensure that defined scenarios were (policy) relevant in terms of e.g. existing or plausible political proposals, budgets, objectives, or the size and timeframe of measures, we carried out discussions with experts, desk research, and preparatory data analysis, to identify relevant cases and/or experimental designs.

As is discussed in more detail in the dedicated article sections, all articles build extensively on modelling (and in several of the articles additionally on simulations). In the CO_2-fund article, we developed a model covering mechanisms regarding vehicle fleet composition and usage, different propulsion technologies, investment costs, subsidies, filling/charging infrastructure, vehicle emissions, and emissions reduction pathways, in addition to other factors. In the quantitative parts of the Electric Truck article, we set up models for total costs of ownership for different propulsion technologies. Further, we developed a model extension to investigate not only cost-competitiveness (for operators) but also the socio-economic costs (for society as a whole) of phasing in zero-emission propulsion technologies, amongst others taking into account societal externalities. The Warehouse Relocationing article, in turn, revolves around freight flow modelling, after which model results are used to compare scenarios. Here, the identification of cases and the development of a rationale for defining scenario comparisons formed key inputs. In addition, while using a largely pre-established model (the NFM or National Freight Model for Norway [108]), we also developed an entirely new Excel-based model to more representatively capture transport, emission, and cost effects materializing through changes in city distribution. Similarly, the Modal Shift article builds on the same NFM for Norway, adapted to allow for assessments of envisioned future situations and policy changes (scenarios). Finally, in the Eco-driving article, the modelling approach is based partially on expectations from theory, and partially on extensive analysis of data collected from fleet management systems (FMS) on board of trucks, in order to establish suitable specifications for multiple regression analysis. Where model development and specification in the first four articles is done prior to or as integral early stages in the studies, the latter article somewhat differs in that regression models were first defined when the study's (eco-driving) experiment itself had concluded, and thus after data were collected.

In summary, modelling approaches in the articles can broadly be divided into three strands:

- Vehicle (fleet) and emission characteristics (CO_2-fund and Electric Truck articles)
- Freight/commodity flows (Warehouse Relocationing and Modal Shift articles)
- Driving behavior multiple regression analysis (Eco-driving article)

It should further be noted that, as all articles address CO_2 emissions from road freight transport (and in some articles also other modes), the overarching methodology for emissions estimation or calculation is consistent (building on standard emissions factors for fuels such as diesel). Per-liter emission factors can nevertheless differ slightly between the articles depending on developments in or announcements on mandatory biodiesel blend-in.

In addition to highly quantitative analyses, all articles employ qualitative methods. This is most apparent for the Electric Truck article, for which semi-structured interviews with early users of electric trucks were conducted. However, the collection and mapping of relevant qualitative information and cases also constitute essential inputs for the other articles. The following five sections provide more detail on the methods and data for each of the articles.

4.2 CO_2-fund article: methods and data

To recall, the main research question of the CO_2-fund article is formulated as follows:

> **ARQ 1:** What are the CO_2 reduction potential and dynamics of a CO_2-fund, aimed at speeding up the adoption of alternative propulsion technologies within Norwegian road freight transport?

The background for this research question was a proposal by a Norwegian industry consortium to approach greening of the Norwegian freight transport industry through establishing a so-called CO_2-fund. This proposal followed a similar model as the already established and positively regarded NOx-fund and received sympathy from several political parties. As such, it became a measure with feasibility of adoption in some form.

In short, the rationale behind the proposed CO_2-fund was as follows: given adopted transport-political and environmental objectives, the phase-in of low-/zero-emission freight vehicles would have to speed up, but vehicle owners and operators had little incentive to choose such vehicles, because this would entail (much) higher costs compared to conventional vehicles. In addition, lacking filling/charging infrastructure for alternative technology vehicles would pose considerable operational barriers. Prior to the CO_2-fund proposal, much policy focus had been on using ‘sticks’, such as taxes and levies, to make CO_2-intensive technologies more expensive. The CO_2-fund proposal instead proposed a form of ‘carrots’: firms participating in the fund would receive an exemption from paying a CO_2-levy on the diesel they used, and instead pay in a somewhat lower per-liter amount into the fund, thus providing a financial incentive to become a participant. In return, participants were expected to carry out emissions-reducing measures. Proceeds generated by the CO_2-fund would be refunded to industry as financial support to (part of the) investment cost premiums of low-/zero-emission vehicles and towards establishment of filling/charging infrastructure for alternative technologies, and as such help speed up their adoption. Differences in costs during the vehicles’ operational phase, however, would fall beyond the scope of the fund.

To assess the above research question, a number of methodological steps had to be performed. For example, the fund’s set-up had to be operationalized. Based on discussions about what a likely final proposal would look like, the fund was assumed to start in 2018 and operate for 10 years. The per-liter participation fee was set to 70% of the CO_2-levy rate to create a significant participation incentive. Further, industry participation was set to increase from 25% in 2018, to 80% in the fund’s final year. For investments in alternative technology vehicles, the fund’s proceeds would provide subsidies of 80% of their additional investment cost (vs. a diesel vehicle), with the alternative fully replacing a vehicle running on regular diesel with (then) 7% biodiesel content. Investments in filling/charging infrastructure, in turn, could be subsidized to up to 50% of their full costs.

Next, because the objective of the article was to gain insights into the CO_2 reduction potential and dynamics of the fund, it was necessary to establish a 'business-as-usual' or reference pathway, i.e. without a CO_2-fund. To do this, we used transport demand projections developed for the Norwegian National Transport Plan [109], as these projections form(ed) common input also for many other policy analyses. These projections were also more detailed than alternative inputs, such as the Norwegian Environment Agency's general assumptions on vehicle fleet size and driving distances in the years towards 2030. Next, we used emissions statistics for heavy vehicles from Statistics Norway. As these, even at the most detailed level, cover not just freight vehicles but also buses in the same statistic, it was necessary to separate their emission paths. This was done based on the respective transport volume shares and driving distances for buses and heavy trucks [from 110].[8] Combining historical emissions and transport statistics, we developed time-series of emissions per tonne-km, and projected these into the future assuming prescribed increases in average biodiesel content in regular diesel. Resulting emissions forecasts were similar to those by the Norwegian Environment Agency for 2020 and only slightly higher (5%) for 2030.

To be able to calculate emissions reduction effects when replacing diesel vehicles by alternative propulsion systems, we combined widely-used fuel consumption factors from the Handbook of Emission Factors for Road Transport (consistent with methods used by Statistics Norway and the Norwegian Environment Agency) and took into account annual vehicle mileages and how these change with vehicle age (from factual data stemming from periodical vehicle assessments and verifications against information compiled from two large Norwegian transport firms).

Due to the lack of publicly available price information and trucks effectively being rather custom vehicles, quantifying investment cost premiums of alternative technology vehicles was done by confidentially collecting data from several vehicle manufacturers, transport firms, and

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[8] This approach for splitting emissions from freight vehicles and buses has recently (2021) been refined towards other projects, where splitting instead is carried out based on Statistics Norway's statistics on 'Driving distances by vehicle type and age' (Table 12575). The latter method would attribute freight vehicles a somewhat lower share of emissions (and buses a somewhat higher share) than the method used in the article, although this difference is significantly smaller in more recent years vs. prior to 2010. On the other hand, Statistics Norway has in 2020/2021 also had to revise emissions statistics for freight vehicles and buses many years backward, as emissions turned out to have been underestimated by 5-6% each year (when looking at the last decade) due to a reporting mistake. Given the size of these two mechanisms, they would come pretty close to cancelling each other out in the context of the article.

firms using own vehicles running on biofuels, electricity or hydrogen. Because investment cost premiums were expected to decrease significantly over the fund's lifetime (driven by technology development, market maturity and larger-scale production), future prices were estimated based on series-production price differentials observed for passenger cars (this method has later been significantly refined, amongst others in the Electric Truck article and following works, e.g. [59]). As such, cost differentials between diesel and electric vehicles are assumed to decrease by ca. 70% by the fund's last year.

Regarding emissions for different vehicles, we primarily relied on the NEN-EN 16258 European standard for CO_2 emissions, combined with fuel consumption. Energy consumption for alternative technology vehicles was derived from operator feedback and verification of relative energy content and drivetrain efficiency vs. diesel. Because the above European standard does not distinguish between biodiesel types, we used assumptions consistent with the Norwegian Environment Agency. These imply that biofuels yield near-zero Norwegian emissions. Because this assumption can be challenged, we also performed more conservative analyses with biofuels only reducing emissions by 60% compared to fossil diesel (full life-cycle). Emissions from electricity and hydrogen are considered to be zero, in line with above European standard. Although this assumption can also be debated from a global perspective, it is consistent with prescriptions in Norwegian climate accounting.

Estimates on the costs of establishing electric charging points and filling infrastructure for biodiesel, biogas, and hydrogen were based on feedback from suppliers of the several fuels and government organization ENOVA, while the number of infrastructure points required for the different technologies was estimated taking into account characteristics of different technologies, typical infrastructure characteristics and capacity and use patterns. We presupposed that sufficient supply of energy sources is available to support the infrastructure, although it can be argued that biofuels face scarcity.

We considered six different scenarios, in four of which subsidies were exclusively given to *either* biodiesel, biogas, battery-electric or hydrogen vehicles and infrastructure. In the fifth scenario, 50% of subsidies were directed at biodiesel, and the remainder equally dispersed between the other technologies. The last scenario took into account technological maturity, using more of the fund's proceeds in early years on biodiesel vehicles and infrastructure and some on electric and hydrogen infrastructure, before gradually increasing subsidy shares directed at electric and hydrogen-based vehicles (and increasing from lighter towards heavier vehicles). In all scenarios, shares of the fund's proceeds used on infrastructure are chosen such that sufficient infrastructure is established. This implies that in the combined scenarios, which require several infrastructure types simultaneously, the share of the fund's proceeds that remains for subsidies to vehicles is smaller.

To calculate results for vehicles, we modelled emissions projections without the fund. We then calculated, based on year-on-year participation rates and developments in proceeds collected, the number of subsidies allocated (a function of investment cost premiums and therefore technology-dependent), diesel vehicles replaced, and corresponding reductions in emissions and diesel sales. We also corrected projected diesel sales under the reference scenario (forming the proceed basis) for the downward effect on future diesel sales when awarded subsidies cause a replacement of diesel vehicles. This process was reiterated until the fund's final year.

Emissions reduction effects of infrastructure subsidies are much more uncertain and difficult to assess than for vehicles. Infrastructure establishment can yield additional emissions reductions when used by passenger cars or other non-subsidized vehicles. To derive CO_2 reduction estimates, we made assumptions on how much any infrastructure would reduce the use of regular diesel annually, based on supplier feedback and sales volumes for different filling station types. This was combined with assumptions on the share of diesel reduction that could likely be attributed to non-subsidized vehicles. For electric charging infrastructure, we lacked usable data on the number of users per charging point, and had to conclude that estimates on additional emissions reductions from infrastructure could not be included in our analyses. Due to these uncertainties and gaps, we chose to present emissions reduction estimates from infrastructure only separately from vehicle results.

Finally, we recognized that emissions reduction effects do not cease after the fund's operation ceases, but continue also in years after, during which subsidized vehicles/infrastructure still yield lower emissions than would have been the case without them (until they are phased out).

4.3 Electric Truck article: methods and data

For the Electric Truck article, the main question is summarized as follows:

> **ARQ 2**: How do Norwegian user requirements and (developments in) techno-economic barriers and enablers affect the adoption potential for zero-emission road freight vehicles?

The rationale behind this question is that the adoption of freight vehicles with alternative propulsion systems is dependent on the costs of owning and operating them and on to what extent they technologically/operationally meet demands of truck owners/users.

In 2019, when the study behind this article was performed, all battery-electric trucks in Norway were converted from diesel trucks, and hydrogen-electric trucks were even some more steps behind. To provide a comprehensive assessment of the potential and costs of electrification in both the near and longer term, we carried out four related but distinctive analyses of 1) User experiences; 2) Electrification potential given typical use patterns; 3) Costs of ownership and comparisons of decomposed cost levels for different propulsion technologies; and 4) Socio-economic costs of phasing in zero-emission trucks.

The analyses focus particularly on light distribution trucks, as these seemed to be the truck segment with the largest short-term electrification potential, although some of the analyses also touch upon other segments.

To assess user experiences, we carried out semi-structured interviews with closely involved representatives from firms operating electric trucks in Norway (identified using public lists of projects receiving financial support, and the national vehicle registry). Questions were related to a broad range of themes relevant for zero-emission vehicle phase-in, with interviewees receiving a preparation questionnaire and approving final interview minutes.

The second analysis recognized that some of the largest barriers for (particularly freight) vehicle electrification are driving range limitations, long charging times, and a trade-off between heavier batteries and payload. In our analysis, we distinguish between the near term (focusing on how driving ranges and engine sizes relate to current use patterns and requirements) and the longer term, with more flexibility to distribute transport assignments between vehicles (focusing more on the influence of different vehicle-dependent obstacles for electrification).

Using base data from the Norwegian vehicle registry and 2016/2017 surveys of trucks by Statistics Norway, we compiled a dataset with information on vehicle category, engine power, age, use of trailer (in survey reporting week) and trip lengths, among other things. We then used maximum daily mileage as proxy for the minimum driving range required to suit an owner (recognizing day-to-day variation and peaks rather than averages). For vehicles with ≥ 2 daily trips starting from the same postcode, we adjusted this requirement, as this likely reflects vehicles returning to a base where some charging should be possible. Further, we set the four criteria below for trucks to be considered as having electrification potential in the shorter run (details in article). This yielded a sample of 6,150 trucks with information on static fleet data and daily use patterns and variations:

- Max. daily mileage < driving range on full battery (max. 150 km, based on existing truck specifications)
- Engine power ≤ 500 HP (based on expectations on electric truck engines by a manufacturer)
- Trucks not requiring use of trailer (except tractor units)
- Trucks up to 5 years old (i.e. the segment where requirements for new vehicle purchases are set).

For the third analysis, on cost competitiveness of different technologies, we developed models for total costs of ownership. Similar to the core of many existing studies [e.g. 111,112,113,114,115], we established cost functions with relatively detailed decomposition, as seen in the overview in Table 4.1.

Table 4.1. Overview of main cost aspects considered in Electric Truck article's TCO models.

Cost category	**Main aspects taken into account**
Time-dependent	Investment/capital costs (excl. subsidies); Depreciation; Residual values; Discount rate
Distance-dependent	Energy consumption & cost (base price + any levies); Road toll charges and exemptions (discounts) for zero-emission; Driving distances and mileages
Maintenance and repair	General maintenance; Tyre degradation; Washing, etc.
Technology-independent	Wage expenses; Admin and insurance costs; Annual weight fee

As our starting point, we used validated base parameters from the NFM for Norway.[9] For alternative technologies, cost parameters were based on (confidential) data collected in the user interviews, updates and refinements from Hovi and Pinchasik [116], feedback from transport sector actors, data from Jordbakke et al. [117], and cost development forecasts. Estimates were found to be in line with Weken et al. [118]. Depreciation was considered for typical 5-year periods, but rest values were set conservatively[10] due to uncertain remaining battery lives and second-hand markets. We further used a discount rate of 3.5%.

Energy prices were split up into base prices and applicable levies from the same sources as above, and for electricity an optional 50% base price premium was modelled for fast charging.

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[9] This model is extensively used in the Warehouse Relocationing article (and Modal Shift article) and therefore described in detail in the respective methodological section.

[10] Discounted by up to 50% depending on technology and assumed market maturity phase in 2020, 2025 and 2030, based on examples from the passenger car market.

Technology-differentiated road tolls were also included, as were maintenance costs (expected from the literature to be somewhat lower for electric drivetrains) and annual fees. Annual mileages were set to 45,000 km for trucks, based on NFM parameters and to reflect feasible use cases for battery-electric trucks, i.e. particularly urban/regional distribution.

Based on above inputs and given expected future decreases in electric truck costs [67,113,119] (detailed assumptions provided in the article, including comments on specific uncertainties of future costs), we assessed 1) An early market phase for battery- and hydrogen-electric trucks; 2) Small-scale series production, both with current and lower hydrogen prices; and 3) Mass production. For all scenarios, decomposed results were provided to illustrate the role of different components in total costs and differences between technologies.

In the last analysis, we assessed socio-economic costs of phasing in alternative propulsion technologies, as sum of public and private costs and benefits. For society, costs stem from higher investment and operational costs of zero-emission vehicles, and benefits from savings on some operational costs and from reduced negative external effects (local emissions). For the latter, we used cost factors from Rødseth et al. and Thune-Larsen et al. [120,121]. While road toll and fuel levy exemptions are benefits for truck owners in terms of cost competitiveness, these constitute transfers from the perspective of society. Following Norwegian Ministry of Finance Guidelines [122], we included a 20% tax financing cost as socio-economic cost on this transfer. Finally, we related socio-economic costs to reductions in CO_2 emissions when replacing a conventional truck by a zero-emission truck, for all scenarios (in terms of costs per reduced tonne in CO_2 emissions).

4.4 Warehouse Relocationing article: methods and data

For the Warehouse Relocationing article, we can recall the main article research question as:

> **ARQ 3**: What are the implications of warehouse relocationing trends in Norwegian urban areas for freight transport and its CO_2 emissions?

The background for this question is the previously discussed logistics sprawl trend observed in many countries, including Norway (centrally located warehouses relocating towards fringe locations). According to planning theory, this may reduce total GHG emissions from passenger and freight transport (due to central freed-up spaces becoming available for people-intensive activities, which in turn reduces emissions from passenger travel). For the transport part itself, effects are less clear, but relevant, both in terms of environmental objectives and transport and traffic objectives.

Essentially, there are three main mechanisms when centrally located warehouses relocate to fringe locations: 1) Increased distances for city distribution; 2) Changed long-haul transport distances; and 3) Modal changes (depending on locations of rail terminals/ports and costs of intermodal transports pre- and post-relocation).

In the literature, warehouse relocationing is predominantly studied from logistics or supply chain perspectives, with cost minimization as the central problem, for example through facility-location-problem and location-routing-problem analyses. Comprehensive assessments of environmental and traffic effects are more scarce, but for example studied through modelling and simulations of location, routing and delivery flows from transporters and retailers (and in some cases shopping flows by customers) [123,124,125].

The foundation of our study was formed by raw data from a Norwegian Commodity Flow Survey (CFS) by Statistics Norway. It maps domestic commodity flows (tonnes, value, shipment numbers) originating from a sample of manufacturing and wholesale trade firms and the 20 largest freight forwarders in Norway (for a total of ca. 12,000 delivering firms or 49 million shipments with postzone for both origin and receiving firm). As the survey is sample-based, Statistics Norway imputes freight flows for missing firms, but because we assess selected cases (see below), we use real data at firm level, both for case firms (outgoing flows) and for firms with deliveries to our case firms (incoming flows). For confidentiality reasons, we could not directly match commodity flows and firms, and therefore limited our CFS-dataset to commodity flows to/from localizations of relevant industries.

For our analysis, we identified two cases of hypothetical warehouse relocations from central locations to relevant locations at outskirts of two of Norway's largest cities, Oslo and Trondheim. Here, we focused on somewhat larger firms from wholesale trade and manufacturing industries (NACE-classifications 10-39; 46) as these are considered to be transport-generating. We used Statistics Norway's firm registry to identify combinations of such firms and relevant fringe locations (locations for which local municipalities actively facilitated establishment of such firms and for which relocationing trends were visible). In the Oslo case, this included 15 municipalities spread around the city of Oslo, while for the Trondheim case, this was one district slightly south of Trondheim (Heimdal). After identifying relevant current locations, we used the firm registry to identify relevant previous, more central locations.

Next, we defined two scenarios for both the Oslo and Trondheim cases: (i) warehouses remaining at central locations (likely previous locations of the types of firms in question) and

(ii) the same warehouses having moved out to their current, outskirt locations. To assess effects, we distinguished between the three main mechanisms introduced above and used two models to do so. Both models use the same set of commodity flows as input, but at different levels of aggregation.

The first model used is the National Freight Model for Norway, previously abbreviated to NFM. Because this model also features extensively in the Modal Shift article, and to avoid redundancy, this model is explained in detail in Box 4.1.

Box 4.1: The National Freight Model for Norway

The NFM is a strategic transport network model consisting of four main elements:

- Transport demand (represented by detailed commodity flow matrices)
- A network model (representing distance and transport times, including terminal/ consolidation/reloading locations)
- Cost functions, representing time- and distance-dependent costs for different modes, including loading/unloading/reloading, ordering, storage, commodity time values, etc.
- Optimization routines for shipment size, frequency and mode choice, based on minimization of logistics costs.

Commodity flows are divided into 39 types, representing different demands and requirements to transport (quality). With regard to geographical detail for Norway, origin and destination zones are largely at the municipality level, while the six largest cities are represented with four to twelve zones.

The model combines above elements to determine transshipment locations for all pairs of origin and destination zones and calculates shipment size and transport chains to select the chain with lowest logistics costs. The model is very similar to an often-used Swedish model,[11] and plays a pivotal role in policy analyses towards amongst others the Norwegian National Transport Plans.

For the current study, the NFM allows assessment of how location changes (the scenarios) affect transport cost, modal choice, tonne-kms and vehicle-kms both domestically and for imports and exports. Because the NFM's network model divides Oslo and Trondheim into 12 and 8 zones respectively, the model is most suitable for analyzing long-haul effects and modal splits, but not detailed enough to properly capture changes in distribution transports to/from

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[11] Amongst others due to involvement of common developers.

warehouses in the urban region, because changes in transport distances (from firm relocation) could be off by several kilometers given relatively aggregated zones.

The second model is an own-developed Excel-based City Distribution Model (CDM). Geographically, this model is more detailed, with zones covering geographical areas between the 'basic statistical unit' and municipality level. Oslo and Trondheim are divided in 60 and 24 zones respectively, while suburbs and the rest of Norway are also covered. For all zones, appropriate distance matrices for road transport were available. Unlike the NFM, the CDM further uses data for individual shipments, without aggregating them.

In the CDM, we distinguished between incoming/outgoing deliveries and locations pre- and post-relocation. Tonne-kms are calculated as product of weight and shipment distance (with the latter affected by warehouse (re)location). Goods category and volume of deliveries were used to define the most likely vehicle types used. Next, vehicle characteristics (costs, goods type-dependent vehicle capacity, distance, time, fuel consumption and CO_2 emissions) were used to calculate results before and after relocationing. Vehicle-kms were calculated by dividing tonne-kms for a delivery by goods type-dependent vehicle capacity, but allowing for vehicles on average not being filled to full capacity, using standard factors (70%). Finally, CO_2 emissions are a product of vehicle-kms, vehicle-specific fuel consumption, and emission factors (recognizing Norwegian mandatory biodiesel blend-in requirements, cfr. also the CO_2-fund article). While the CDM was developed to analyze effects at the urban/regional level, its extended design allowed for comparisons with NFM results at the national level. Here, it is noted that the CDM only covers road modes.

The above steps, based on CFS data, cover domestic deliveries, but warehouse relocations also affect transport for foreign trade. To also analyze effects through foreign freight flows, we used shipment-level data from the Norwegian Foreign Trade Statistics for firms identified in relevant origin/destination postcodes. These effects, however, could only be analyzed through the NFM (not CDM), and for transport costs, the NFM does not allow for distinguishing between costs accrued within and outside Norway. Otherwise, we used the same methodology as for domestic shipments.

Towards results, we distinguished between deliveries covering relatively short distances for which non-road modes are unlikely (also given the industries and goods categories analyzed), and long-haul deliveries where other modes could potentially be used (and for which the CDM thus in some cases might be less representative). Results are presented for both the NFM and CDM, except where foreign trade is involved.

An advantage of the models used is that they enable calculating isolated effects of warehouse relocations on transport performance, costs and CO_2 emissions, while taking into account full delivery patterns for the available sample. The models complement each other in terms of geographical detail at the urban level (CDM) and the capturing of modal shift effects between road and non-road modes and the possibility to also include foreign trade deliveries (NFM). In both models, estimates on CO_2-effects have their starting point in transport performance, for which data are considered rather certain. While the NFM uses average emission factors per tonne-km, the CDM takes into account capacity utilization of single shipments.

Generally, due to a much larger sample of deliveries in the Oslo case, sensitivity to e.g. a number of dominant firms accounting for a large share of observations is lower than in the Trondheim case. Finally, while not in focus, the article provides a short argument for implications that findings may have through changes in local emissions.

4.5 Modal Shift article: methods and data

For the Modal Shift article, the main research question is formulated as follows:

> **ARQ 4**: What are the transport, modal distribution and environmental effects of strengthening policy measures for modal shift, and of harmonizing measures across Nordic borders?

The rationale behind this question is years with large underperformance on modal shift objectives, and a freight analysis prepared for the National Transport Plan 2018-2029 (NTP) [126] highlighting that assessments of domestic modal shift might underestimate the full potential: it is argued that if more imported freight enters Norway by rail or sea, this increases the likelihood of further domestic transport by these modes, rather than by road. The NTP analysis therefore posed the question whether modal shift measures implemented at the Nordic level can contribute to increasing the share of foreign freight to/from Norway by sea or rail.

As discussed in the theory chapter, there are different approaches to assessing modal shift potential and effects. Strategic transport network models are considered to have important advantages [87], but require detailed data inputs which are often not available. For the current study, however, such inputs were available and the main reason for opting to use strategic transport network model analysis in our assessments of modal shift potential and effects.

In all, our methodological approach consists of three stages. In the first stage, we defined nine scenarios where existing policy measures with modal shift relevance are strengthened or expanded (summarized in Table 4.2). Scenarios were chosen based on a mapping of existing policy measures in the Nordics, analyses of volume flows and developments in foreign trade with trucks, and feedback on modal shift potential from a survey among firms with own sea terminal [update of 11, and 81,127,128]. The scenarios cover both single, mode-specific instruments, and combinations, including cross-border harmonization of measures in Norway, Sweden and Denmark. They further entail both infrastructure and efficiency improvements and financial incentives, which were studied both in isolation and combined, to assess whether measures reinforce each other or require coordination. Although we look at policy instruments in the Nordic region as a whole, analyses are primarily carried out from a Norwegian perspective and only cover effects for freight flows with origin and/or destination in Norway (both domestic and foreign trade). Similarly, while we mapped policy in the Nordics, and not just Norway, we chose scenarios so as to have (particularly) Norwegian relevance.

In the second stage, we used the previously introduced NFM to simulate the influence of policy measures on modal choice. The background for using the NFM is that important factors that decide how modal choices are made are costs, access to modes, transit time, reliability, service frequency, and different shipment and commodity characteristics [51,52,84,129,130], which the NFM all covers. To incentivize modal shift away from road, policy has to somehow change the balance of such choice factors, and this is indeed what many policy initiatives attempt. We operationalize our policy scenarios by changing parameters in the NFM (costs, available terminals, costs related to restrictions in the network model, etc.). In practice, this entails that changes are implemented in the NFM's cost functions and input files following from these, in files representing the different nodes, and in input files for the networks, with parameter changes also summarized in Table 4.2. Beyond the changes detailed there, cost developments are assumed to remain the same between modes to allow assessing the partial effects of modal shift measures.

Using abovementioned input files, the NFM estimates the distribution of transport over transport modes, as well as transport and logistics costs, for each of the nine scenarios, in addition to a reference scenario without any parameter changes. All are run for the year 2030, based on 2030 freight flow projections (PWC matrices, i.e. production, wholesale, consumption) made towards the Norwegian National Transport Plan [109]. These projections, in turn, were based on population projections by Statistics Norway and macroeconomic growth trajectories compiled by the Norwegian Ministry of Finance and spread out over regions by a spatial computable general equilibrium model (PINGO [131]). After running the scenarios, effects are found by comparing results for each policy scenario with results for the reference.

In the third stage, output from the NFM is combined with energy use and emission factors to compute also environmental effects. For road transport, we used fuel consumption and emission factors from the widely used HBEFA-model (v.3). NFM output divides transport performance into light lorries, heavy lorries and large trucks, each with several sub-categories, which we matched with truck sizes in HBEFA. Average load capacity was estimated using NFM load capacity for each commodity group, while empty trucks were assumed to constitute 30% of total distance driven, based on averages from 2016-2018 statistics for freight transport with trucks, from Statistics Norway. For freight trains, we used basic methodology from energy and emission calculation system EcoTransIT [132], based on train weight and several conversion factors. Here, we looked at 'wagon load', 'other rail' and 'diesel trains' and their NFM sub-categories. As for the HBEFA road method, NFM train sub-categories were matched with EcoTransIT, here based on capacities and tare weights. We further assumed the Norwegian electricity mix from EcoTransIT and validated this against the newest statistics available. For sea transport, ship (sub-)types in the NFM are based on data for representative ships from SeaWeb [133]. We obtained fuel consumption using specific fuel consumption data from IMO and average speeds from SeaWeb, while emission factors for air pollutants were based on Cooper and Gustafsson [134]. Finally, a continuation of the mandatory biodiesel blend-in from 2020 was assumed, because no future increases had been announced. Otherwise, we made assumptions on all vehicles complying with Euro-VI standards by 2030 and that the shares of fully electric/hybrid trucks would be negligible. For ships, significant phase-ins of low-emission technologies were not included either. These are simplifications, but including them, with very uncertain future cost levels, would not currently have been possible in the NFM and could have affected results in non-representative ways.

After carrying out the three stages of our methodological approach, we presented results for the different modes and in terms of transport volume (tonnes), transport performance (tonne-kms), energy use and emissions of CO_2, NOx and particulate matter (PM) – all compared to the reference scenario. In our presentation of transport effects, we further distinguished between effects through domestic trade flows and import and export respectively, for the part of transport taking place on Norwegian territory.

Table 4.2. Overview of scenarios and main operationalization assumptions in Modal Shift article.

Scen.	Short description	Modes influenced	Change
1	Norwegian ecobonus for sea (hypoth. annual budget: 150 million NOK)	Sea	Reduction in freight levy up to NOK 7/tonne for general cargo and container ships in Norwegian ports.
2	Norwegian ecobonus for rail (hypoth. annual budget: 150 million NOK)	Rail	Reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals.
3	Eurovignette rate increases SE, DK (fivedoubling)	Road	Increased costs of NOK 360 per truck for driving into/out of Norway.
4	Longer freight trains	Rail	740m for combi-trains into/out of Norway (from 600m). 640m on main relations in Norway (from 480m). Opening of terminals in Sweden, Denmark and Western-Europe for rail transport to/from Norway.
5	Combination of longer freight trains and Norwegian ecobonus for rail (budget as in scenario 2)	Rail	Idem to scenario 4. In addition, reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals as in scenario 2.
6	Combination of longer freight trains and rail ecobonus also applying in SE, DK	Rail	Idem to scenario 4. In addition, reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian, but also in Swedish/Danish rail terminals.
7	Combination of road measures, with rail/sea measures in Norway	Sea	Idem to Scenario 1.
		Rail	Idem to Scenario 2.
		Road	Idem to Scenario 3.
7b	Expansion of scenario 7 with terminal cost reductions in Sweden and Denmark	Sea	Idem to scenario 1, but with equal reduction in freight levy also applying in Swedish and Danish ports.
		Rail	Idem to Scenario 2, but with equal terminal costs reduction also applying in Swedish/Danish terminals
		Road	Idem to Scenario 3.
8	Combination of road, rail and sea measures (coordinated for Nordics as a whole)	Sea	Reduction in freight levy up to NOK 7/tonne for general cargo and container ships in Norwegian ports, but now also in Swedish and Danish ports.
		Rail	Reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals, but now also in Swedish and Danish rail terminals.
		Road	Increased costs of NOK 0.60/km for semitrailers and European Modular Systems in all Nordic countries

4.6 Eco-driving article: methods and data

For the Eco-driving article, the main research question was stated as follows:

> **ARQ 5**: To what extent and in what way do eco-driving interventions have a potential to reduce fuel consumption and CO_2 emissions by inducing more efficient driving behavior among truck drivers?

The rationale behind this question is that many determinants of the fuel consumption of freight vehicles are given in the short- to medium term and/or beyond the control of transport operators and drivers, while low-/zero-emission technology still faces several barriers for speedy, large-scale adoption. This leaves driving behavior as one of the main remaining determinants of fuel consumption, and potentially one that can be influenced relatively cheaply and in a short term.

Based on literature on which factors are important, we looked into ways in which eco-driving has been analyzed previously and the way eco-driving interventions tend to be set up. Here, there are many examples of set-ups or analyses with flaws that have received substantial criticism, of study data not being representative of how driving takes place in the real world, of important elements not being controlled for, or of studies considering only (very) short-term effects, without assessing longer-term implications. These are pitfalls that we sought to avoid in our own study.

The study behind our article study was performed in 2019 and designed as a randomized controlled experiment with differential treatment between two groups of seven truck drivers: a treatment- and a control group. All drivers work for the same freight forwarder firm, taking shifts on the same regional freight distribution routes in South-Eastern Norway. Unknown to them (see footnote for ethical remarks),[12] the fourteen drivers were first divided in 'pairs', driving the same routes and vehicle types, and then randomly assigned to treatment- or control group. While yielding a relatively small sample size, this design made it possible to control, to a large extent, for the same vehicles, fixed routes with generally similar loads, and fixed drivers. This way, differences in driver-independent factors with a bearing on fuel consumption were reduced to a minimum. While we did not ourselves have detailed information on the drivers, feedback from the firm was that they were part of a relatively homogeneous driver pool in terms of background and characteristics.

During the first three months of 2019, all drivers worked as normal, allowing us to establish baselines on fuel consumption and driving behavior from data logged in the FMS system (here branded 'Linx') installed in the vehicles. In early April 2019, drivers in the treatment group were subjected to an intervention: a theoretical eco-driving course taught by the supplier of the FMS solution. This course focused on seven eco-driving parameters (derived from literature and practice) logged by the FMS system, together yielding four scores ('anticipation', 'engine and gear use', 'speed adaptation', and 'idling'), in addition to a total score, all with scales from 0 to 100.

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[12] All drivers had previously been informed about and had consented to the potential use of data from their FMS system for analytical objectives. Such data utilization was, in the context of the overarching research project LIMCO, also cleared with the Norwegian Centre for Research Data.

Throughout the rest of the experiment (through December 2019), drivers in the treatment group further received monthly performance reports on their scores, which were actively followed up through individual monthly sessions with their manager. In June, non-monetary rewards were introduced for treatment group drivers in the form of clothing with texts indicating their performance levels. Both the follow-up of performance reports and the rewards were intended to reinforce eco-driving behavior. This was done because the literature [e.g. 95] suggests that making behavioral changes from eco-driving more permanent is often a challenge. The literature proposes several examples of reinforcement strategies, hereunder monetary or non-monetary rewards [98,107], with the latter having been shown to give stronger effects [100]. Drivers in the control group received neither training, follow-ups, nor rewards, and were not told about the experiment so as to have a pure control group. In retrospect, however, we became aware that they might have felt that something was going on when seeing other drivers with eco-driving clothing. We were also informed that between August and December 2019, control group drivers were sent performance reports together with their monthly pay checks. While unintended and unfortunate, control group drivers at no point received any active follow-ups, evaluations, reviews or explanations of performance report content, and were not taught or given information on eco-driving. Any changes or improvements are therefore most likely associated with drivers' own beliefs on good eco-driving.

Although many newer trucks have FMS systems, these are seldomly utilized more than superficially, lack active subscriptions, or are considered proprietary, with data being kept in-house. For the trucks covered in our experiment, these challenges were not an issue, and we received raw data for all of 2019. The data cover fifteen three-axled Volvo distribution trucks with closed chapel and max. allowed total gross weight of 27t, of which nearly all driving was done with seven, basically identical Volvo FH trucks from 2014 with 460 HP engines and the same dimensions and characteristics.

Checks of raw data resulted in removal of outliers (3.2% of observations), i.e. very short daily driving distances, likely related to vehicle rearrangement and not actual routes, or scores of 0 where these made little sense. The dataset was then expanded with several dummy variables indicating whether drivers were part of treatment of control group and whether observations were from after the course or during the baseline. We further added dummies for 6-week intervals after the course (0-6 weeks, 6-12 weeks, etc.), based on expert feedback and because changes in scores and fuel consumption over time may have different strength, direction, persistence and timing. This makes it difficult to specify suitable functional forms for regression analyses with time as metric variable. Using time period dummies further allowed testing of differences in effects at different intervals after the eco-driving course. Further, weather variables (average daily temperature and precipitation on observation day) were included as control variables. The resulting dataset contained 1,523 daily observations for all of 2019, with total driving distance >475,000 km and diesel consumption >178,000 liters. Descriptive statistics for treatment and control group suggest that routes driven were indeed similar, as intended and expected from the study design.

To analyze effects of the course and follow-ups, we constructed two multivariate regression models with average daily fuel consumption as dependent variable. The first model is meant to assess how changes in performance on different eco-driving aspects affect fuel consumption (the driving performance score model), while the second investigates differences between the treatment and control group and before and after the course (the dummy model). For both overarching models, we tested different sub-specifications through inclusion of different independent variables, and also did checks of correlations between parameters both in the experimental dataset and against larger datasets including driving and drivers outside of the experiment. By comparing with larger samples with more variability, both for vehicles and driving behavior, we sought to validate the representativeness of the study sample, which was largely satisfying, while correlation signs for eco-driving indicators also were mostly as expected from theory (with exceptions discussed in our discussions).

The driving performance score model, in its broadest specification, reads as follows:

$$\ln(FC_{i,t}) = \beta_0 + \sum_{n=1}^{7} \beta_n * ln(\chi_{i,t}) + \varepsilon_{i,t}$$

where $FC_{i,t}$ is the driver i's average fuel consumption on day t in liters per 100 km and χ_1 through χ_4 are a driver i's respective Linx-scores on anticipation, engine and gear, speed adaptation, and idling, on day t. Next, $\chi_{5;t}$ and $\chi_{6;t}$ represent control parameters for average temperature[13] and precipitation on the day of observation, $\chi_{7,i,t,}$ is the distance for driver i on day t, and $\varepsilon_{i,t}$ is a random error term. β_n represent the parameters we seek to estimate. Variables were transformed to a logarithmic scale, so as to be able to deduce elasticities constant of scale.

The dummy model, in one of its main specifications, reads as follows:

$$FC_{i,t} = \beta_0 + \sum_{n=1}^{7} \beta_n * D_{n,(i),(t)} + \sum_{n=1}^{2} \gamma_n * \chi_{n,t} + \varepsilon_{i,t}$$

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[13] Converted to Kelvin to allow a logarithmic scale.

where $FC_{i,t}$ is as above, $D_{1,i}$ is a dummy variable equal to 1 when a driver i is part of the treatment group and 0 otherwise, and $D_{2\ldots7,t}$ are different dummies equal to 1 for respective 6 week intervals after the eco-driving course (0-6; 6-12…30+ weeks) and 0 before this course has taken place. Variables χ_1 and χ_2 indicate average temperature and precipitation on day t. As before, β_n (and also γ_n) represent the parameters we seek to estimate. For regression results for the dummy model, we carried out a series of Wald tests comparing coefficients between all pairs of time period dummies. This was done to assess whether there could be any learning curve (effects increasing over time) or fading of effects (e.g. the more time has passed after the course), as is found in many studies without reinforcement mechanisms.

Based on regression results, we estimated the potential 'lower' and 'upper bounds' for reductions in fuel consumption based on improvements in driving behavior that the experiment showed could be attained (see results). We further assessed the relative importance of improvements on different eco-driving scores for fuel savings and the significance of weather conditions.

Finally, we related results from the experiment to rough baseline data on scores of other drivers at the same firm with no connection to the experiment, to give rough estimates of improvements in driving behavior scores and the related fuel savings that might be attainable.

Together, this contributed to answering four secondary research questions formulated in the published article:

- Do eco-driving interventions have the potential to reduce fuel consumption by inducing more efficient driving behavior among truck drivers, and if so, to what extent?
- Are changes in driving behavior temporary, or do they persist when an eco-driving course is reinforced with additional interventions?
- Which eco-driving strategies contribute most to reductions in fuel consumption?
- How are results affected by weather conditions?

5. Synthesis and results

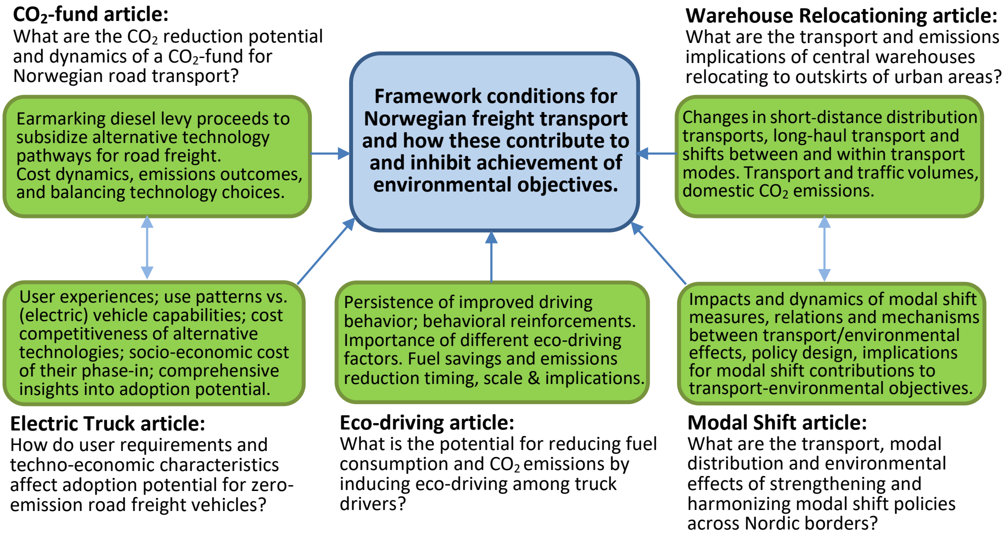
5.1 Overview, main findings and literature contributions

The upcoming sub-sections provide brief summaries of the five articles contained in this thesis. All of them provide contributions towards the thesis' main theme, **how changes in framework conditions for Norwegian freight transport can contribute to or inhibit achievement of climate objectives for transport**, although from different perspectives and using different approaches.

In the CO_2-fund and Electric Truck articles, I consider freight transport emissions reductions through the phase-in of low-/zero-emission vehicles (i.e. the Kaya's Energy Intensity and Energy's Carbon Intensity terms). Here, I look at costs, technology competitiveness, electrification potential for the vehicle fleet given vehicle use patterns, and user experiences. These factors are all important determinants for whether, when, and to what extent firms will adopt alternative technologies, of barriers and enablers of such adoption, and of the overall potential for emissions reductions. The articles also provide insights into what areas policy measures could or should focus on to achieve faster and/or larger-scale adoption.

In the Warehouse Relocationing article, I consider what an ongoing trend, of warehouses relocating from central city areas to more peripheral locations, may mean for freight transport emissions. Here, I focus on implications of warehouse relocationing through changes in the amount of transport and through modal shift between and within transport modes, e.g. between vans and trucks (i.e. the Kaya's Transport Intensity and Modal Split terms). A central element in the articles' approach is freight flow analysis, which also forms the core of the Modal Shift article. In the latter, I assess the transport, modal distribution, and environmental effects when policy measures for inducing modal shift would be strengthened and/or harmonized across Nordic borders. Modal shift is one of policymakers' go-tos in the context of transport emissions, and it is therefore relevant to put its role in perspective.

The last article, on eco-driving, approaches freight transport emissions from the notion that while reductions are urgent, most proposed solutions (including low-/zero-emission vehicles and modal shift) will first yield substantial reductions in several years' time, if at all. In the short term, where much of transport is 'fixed', reducing fuel consumption through improved driving behavior is one of the few ways in which more-than-marginal emissions reductions could potentially be achieved (i.e. the Kaya's Energy Intensity term). The article focuses on the extent to which improved driving behavior may reduce fuel consumption and thereby CO_2 emissions from trucks, on the persistence of improved driver behavior, and on which eco-driving strategies contribute most to reductions in fuel consumption. Figure 5.1 provides an overview of how the different articles relate to both each other and to the thesis' main theme.



CO_2-fund article:
What are the CO_2 reduction potential and dynamics of a CO_2-fund for Norwegian road transport?

Earmarking diesel levy proceeds to subsidize alternative technology pathways for road freight.
Cost dynamics, emissions outcomes, and balancing technology choices.

Framework conditions for Norwegian freight transport and how these contribute to and inhibit achievement of environmental objectives.

Warehouse Relocationing article:
What are the transport and emissions implications of central warehouses relocating to outskirts of urban areas?

Changes in short-distance distribution transports, long-haul transport and shifts between and within transport modes. Transport and traffic volumes, domestic CO_2 emissions.

User experiences; use patterns vs. (electric) vehicle capabilities; cost competitiveness of alternative technologies; socio-economic cost of their phase-in; comprehensive insights into adoption potential.

Electric Truck article:
How do user requirements and techno-economic characteristics affect adoption potential for zero-emission road freight vehicles?

Persistence of improved driving behavior; behavioral reinforcements. Importance of different eco-driving factors. Fuel savings and emissions reduction timing, scale & implications.

Eco-driving article:
What is the potential for reducing fuel consumption and CO_2 emissions by inducing eco-driving among truck drivers?

Impacts and dynamics of modal shift measures, relations and mechanisms between transport/environmental effects, policy design, implications for modal shift contributions to transport-environmental objectives.

Modal Shift article:
What are the transport, modal distribution and environmental effects of strengthening and harmonizing modal shift policies across Nordic borders?

Figure 5.1. Overview of how the different articles relate to each other and the thesis' main theme.

Main findings

The CO_2-fund article quantifies potential emissions reductions from a scheme that earmarks diesel levies for (partial) subsidies towards alternative technology vehicles and the filling/charging infrastructure for these technologies (biodiesel, biogas, battery- and hydrogen-electric). We find that potential emissions reductions are highest when all subsidies are targeted at biodiesel use (48% in the fund's last year, 2027, compared to business-as-usual). However, there are arguments and dynamics, for (also or instead) using the fund to target other alternative technologies, for example to avoid the risk of lock-ins or to help achieve critical masses. Further, filling/charging infrastructure that is established using subsidies from the fund, can indirectly yield additional emissions reductions when used by passenger cars or other vehicles not subsidized by the fund. Targeting multiple alternative technologies alongside each other implies that a larger share of the fund's subsidy budget is required towards infrastructure, leaving less for vehicle subsidies.

The Electric Truck article considerably develops the vehicle cost seed planted in the CO_2-fund article. However, it is not presupposed that alternative technology vehicles are indeed adopted when subsidies are thrown at it (and for which costs in the CO_2-fund article are relevant mainly because they are a determining factor for how many subsidies can be given within the fund's budget). Instead, the article considers barriers and enablers for the adoption of alternative technology vehicles. On the one hand, it looks at user experiences and use patterns for conventional vehicles that are to be replaced. On the other hand, it considers costs from the perspective that alternative technology vehicles will generally not be adopted if they are not cost-competitive in terms of total costs of ownership. We find that experiences from electric truck pilots have shown significant promise. However, typical use patterns for the fleet imply that, in a short term, fleet electrification potential is limited. In a longer run, electrification potential is considerably increased, although range improvements and electric vehicles with larger engines would be needed if the majority of the fleet is to become zero-emission. For cost-competitiveness, electric trucks would need to reach mass production stages, while hydrogen-electric vehicles likely keep higher TCO but might have suitable niche use cases. Socio-economic costs per reduced tonne CO_2 are currently considerable, but lowest for investments in biogas vehicles. Battery-electric vehicles will yield lowest socio-economic costs of emissions reductions when they reach mass production.

The two articles that use strategic transport network modelling of commodity flows, consider transport effects (volumes, modal shift) and environmental effects of a warehouse suburbanization trend and of nine scenarios where policy measures with modal shift relevance are strengthened, expanded, combined and/or harmonized across Nordic borders. The Warehouse Relocationing article finds that warehouse suburbanization can increase transport and CO_2 emissions, but overall effects are marginal to small. The strength and direction of effects also depends on specific characteristics of individual firm relocations (relative geography and firm trade patterns). Where increases happen, this is particularly through changes in shorter-distance distribution transports, implying that locally/regionally, transport and traffic may increase, as do (local) emissions. Generally, modal shift from domestic freight flows is very limited when warehouses relocate, but more pronounced for foreign freight flows. In all, the article touches mostly on transport volumes and how locations affect transport distances for ingoing and outgoing transport, on modal shift, and on changes in which road vehicles are used and efficiency implications. However, the article only looks at the transport side, not effects from how alternative use of freed-up central locations may also affect emissions. The Modal Shift article finds that even in scenarios with relatively strong policy measures to induce modal shift, reductions in Norwegian CO_2 emissions from freight are small, while local emissions might actually increase. Combining/harmonizing measures across borders is found to strengthen effects of modal shift policy and positive environmental effects (synergies) in some scenarios, but not all.

The fifth article, on eco-driving, considers emissions reduction potentials from fuel savings from improved driving behavior, as the other articles imply that diesel vehicles will still make up much driving for years to come. We find that eco-driving training can give fuel savings for truck drivers of between 5.2-9% and that effects, unlike in some studies, can persist over time. This persistence is possibly helped by behavioral reinforcements from active driver follow-ups and non-monetary rewards. As such, eco-driving may contribute to short-term and low-cost emissions reductions, which might be rather scalable and transferable. Eco-driving may therefore play a not insignificant part of emissions reduction strategies, until other solutions, such as alternative technologies, are technologically and economically feasible at a meaningful scale. It can also reduce transport operators' costs.

Literature contributions

In the upcoming sections, literature contributions of the individual articles are discussed in more detail. Here, I want to relate their main contributions to each other and provide some thoughts on the overall literature contribution of this thesis. As a whole, this thesis' primary overarching contributions are improved understanding of how framework conditions for Norwegian freight transport can contribute to or inhibit achievement of climate objectives for transport, of dynamics between different framework conditions, and of (policy) areas that might be more and less worthwhile to focus on in the bigger emissions picture. These contributions are achieved through both development of new methodological approaches and extensions of existing methodology, and by looking into several of the main veins for reducing transport emissions as discussed in the literature.

The CO_2-fund article provides new insights into dynamics and potential of earmarking diesel levy proceeds to subsidize adoption of low-/zero-emission vehicles and establishment of filling/charging infrastructure. Assessments of policies that combine 'sticks' and 'carrots' are few, and while many different set-ups and combinations can be devised, our observations and framework design can be useful for studies concerned with emissions, alternative pathways, trade-offs, and policy pitfalls in other settings. This includes the recent proposal for the Norwegian maritime sector (cfr. section 2.3.2).

The Electric Truck article contributes to the literature by improving understanding of barriers and enablers for the adoption of alternative technology freight vehicles. An important element is that our study is comprehensive, covering both operator experiences, technology suitability given what operators need, cost competitiveness of alternative technologies, and socio-economic costs of reducing CO_2 emissions by their phase-in. We extend and develop cost modelling frameworks (hereunder from the CO_2-fund article), and in doing so ensure high flexibility for future analyses when more becomes clear on developments in important cost drivers. We further develop a framework for exploiting truck survey data on vehicle use patterns to assess fleet electrification potential, which can be adapted and updated in other countries where such data is available. These analyses point out technical improvements that are needed to meet real-world use patterns with battery-electric trucks.

The Warehouse Relocationing article documents effects of warehouse relocationing on freight traffic and CO_2 emissions and provides insights on dynamics. Despite being a trend in many countries, with significant relevance for long-term policymaking, existing literature has gaps and rather takes a logistics or supply chain perspective. Our methodological framework and modelling approach, combined with dynamics we point out, can help advance similar analyses for cases in other countries and thereby provide insights with planning and land use policy relevance.

The Modal Shift article contributes to the literature by studying modal shift measures over country borders and whether measures complement each other. Most existing modal shift studies are limited to measures in one country or only cover selected freight flows. Moreover, we comprehensively combine assessments of transport and environmental effects and trade-offs and dynamics between these. In many studies, the latter is not possible. Further, we build our framework upon high-quality granular data, which are usually challenging to attain, but desirable for comprehensive analyses. The rationale behind our study and approach can provide a basis for related assessments for other regions, while implications and dynamics of our observations can provide researchers and policymakers relevant insights.

The Eco-driving article adds to the limited literature on truck eco-driving and the scarcity of real-world, controlled studies on long-term effects and use of reinforcement mechanisms. We also overcome several main limitations of existing studies and demonstrate how upcoming large data volumes from FMS systems can be used for insightful analyses, as well as registering areas for improvement.

Overall, the articles cover both ‘carrots’ and ‘sticks’ for reducing freight transport emissions.

Limitations and future research

Both in the CO_2-fund and Electric Truck articles, main limitations are related to uncertainties on investment costs. While the latter article uses a more refined approach and benefited from somewhat more available data points and literature, developments in investment costs for particularly battery- and hydrogen-electric freight vehicles are uncertain and dependent on many factors. It was further necessary to utilize several rough assumptions, such as on vehicle residual values. Deviations from our assumptions will necessarily impact results, although it depends on the type of deviation how large these impacts will be. Refinements in work that is currently in progress include sensitivity analyses on the most important parameters. For the CO_2-fund article, a limitation is that the proposal presupposes that subsidies entail vehicle adoption, without taking into account TCO. A further limitation is that estimates on additional (indirect) emissions reductions from filling infrastructure are based on rough assumptions and could not be calculated for electric charging infrastructure. This also means that total effects of the CO_2-fund (emissions reductions through vehicle transitions and infrastructure establishment) could not be comparably presented in sum, nor could results tell us how efficiently the modelled CO_2-fund contributes to emissions reductions, compared to different set-ups or other measures. In the Electric Truck article, technological progress and offerings from vehicle manufacturers can have a bearing on the experiences of users and on relative improvements in vehicle capabilities compared to user demands, and thereby on estimates on the fleet electrification potential.

The Warehouse Relocationing and Modal Shift articles both build on commodity flow modelling. The models used entail a degree of stylization and therefore, deviations from some explicit or implicit assumptions may affect results. For example, if transport cost developments deviate from assumptions (whether through fuel prices, driver wages or different phase-in paths of more expensive vehicle technologies than assumed), this may influence both transport and environmental effects. The same goes for deviations from assumptions on how/which vehicles are chosen, their average utilization rates, and how distribution transport and return trips take place, among other parameters. Other limitations of the Warehouse Relocationing article include that we only consider effects through freight. These effects are obviously highly relevant for transport-environmental objectives, but ideally, policymakers and analyses should consider net effects, both through freight and other changes (e.g. in passenger travels) when the central previous warehouse location has become available for other uses. A follow-up article [135], where I am co-author, does just this. Further, our analyses implicitly assume that e.g. warehouse size and trade patterns remain the same, while in reality, warehouses might become more efficient or consolidated into fewer but larger warehouses. It can be reasoned that such concomitant changes will make the found effects more pronounced. Further limitations of the Modal Shift article include that analyses only cover effects through freight flows with origin and/or destination in Norway, even though e.g. Danish/Swedish flows might indirectly also be influenced. Finally, scenarios studied have different policy costs, such as e.g. high investment costs where infrastructure improvements are involved.

Limitations of the study in the Eco-driving article include a relatively limited sample size, some attrition in the control group, and spill-over effects that might be related to the control group figuring out that something was going on. Further, despite aiming to control for many factors, such controls are not perfect, and while payload and route differences between comparisons should have been limited as intended by our design, perfectly controlling for this is challenging with the current state of FMS systems. Despite studying drivers from a rather homogenous pool, the ability to control for several (potentially moderating) driver and situational characteristics would have strengthened our study.

Studies carried out in the articles of this thesis can be followed-up, expanded and improved in future research. For the articles on alternative technology vehicle adoption, the basis for cost parameters can be further refined (as we are currently working on) and different sensitivity analyses can be insightful and improve the studies' usefulness. The Warehouse Relocationing article has already been followed up with abovementioned study of net effects, but can further benefit from modelling refinements and larger samples. The study's approach can also be applied to cases in different countries. The Modal Shift article can inspire similar future research on effects of country-overspanning policy measures, including the harmonization of levies and incentives over country borders, and through simultaneous assessments of effects through other countries' freight flows. Also here, scenarios and modelling can be refined. Finally, the Eco-driving article can inspire future research, both for validation of results found regarding longer-term effects and by overcoming some of the remaining challenges of our study. Amongst others, larger sample sizes could be achieved (which should be or become more feasible with fast-increasing numbers of trucks with detailed FMS systems), and factors such as weight on board could be better controlled for when weaknesses of current (2021) FMS-data are resolved.

5.2 Article summaries

The intention behind the brief individual article summaries in the next sub-sections is that they can largely be read stand-alone. Because I provide short summaries of what the articles do, what they build on, what they allow us to do, what we find, what the implications are, and their limitations, the summaries will necessarily contain some repetition of previously discussed aspects.

5.2.1 Article 1: A CO_2-fund for the transport industry: The case of Norway

Co-authored with Inger Beate Hovi
Status: Published in Transport Policy

This article assesses the CO_2 reduction potential and dynamics of a CO_2-fund, depending on which low-/zero-emission freight vehicle technolog(y)ies the fund is directed at.

Our study draws on a proposal to establish a CO_2-fund for Norwegian land-based transport industries. It uses numerical modelling, emissions forecasting, and estimates on future developments in investment costs of alternative technology freight trucks for detailed analysis of CO_2 emissions reductions in six scenarios. Four of these scenarios entail that subsidies from the fund are exclusively used on either biogas, biodiesel, battery-electric or hydrogen-electric vehicles and required filling/charging infrastructure. The latter two entail combinations of several technologies alongside.

The article contributes to the literature by quantifying emissions reduction effects of measures financed within the Norwegian framework for CO_2 levies on fuel used by trucks, under different scenarios. In addition, we do this for a proposal that combines positive and negative measures (subsidies and levies), which are usually assessed in isolation. Particularly the 'refunding' or earmarking of levy proceeds to finance subsidies has received little attention. Because the rationale and mechanism behind the CO_2-fund can be (and in a few cases has been) applied to other sectors and/or in other countries, overarching insights can also be relevant beyond freight transport and the transport literature.

The numerical model developed in our study allows us to estimate emissions reductions and to compare scenarios not only in emissions terms but also in terms of dynamics. This includes when (how fast) emissions reductions take place and how emissions add up cumulatively, rather than just in a target year (noting that many emissions reduction objectives effectively are point targets). Also other dynamics can be investigated, such as how the fund's proceeds develop depending on technology choices and the timing and extent of diesel sales decreases. Together, this allows us to draw insights on more and less efficient aspects of the rationale represented by the CO_2-fund and on the importance of different elements, which all have potential relevance for related initiatives.

Overall, we find that a CO_2-fund can yield considerable emissions reductions and contribute to increasing market demand for zero-emission vehicles. Which technolog(y)ies the fund is directed at, and these technologies' (development in) investment costs, has important implications for how the fund's proceeds develop over time and for the number of vehicles that can be subsidized within its budget (replacing conventional diesel vehicles). As a consequence, emissions reduction effects are also highly dependent on which alternative propulsion technolog(y)ies the fund's proceeds are directed at. At the most (scenario with full reliance on biodiesel) we find emissions reductions from vehicles of 48% in the fund's last year (2027). This is higher than in full biogas, battery-electric and hydrogen-electric scenarios and in scenarios where subsidies are given to multiple technologies alongside each other. Subsidies to establishment of filling/charging infrastructure can yield considerable additional emissions reductions depending on the extent of use by non-fund participants, but estimates are more uncertain and not feasible for electric infrastructure. In scenarios with focus on multiple alternative technologies, larger shares of the fund's proceeds are needed towards infrastructure establishment, meaning that the number of vehicles that can be subsidized is lower.

Our results and observations have several implications. One of these revolves around which technology or technologies to focus efforts on. For example, targeting biodiesel is shown to give the largest emissions reductions. Given (advanced) biodiesel availability and potential applications, however, it may be more sensible for use in sectors where decarbonization through other veins is harder to achieve, such as air transport. It can also be argued [e.g. 59] that since biodiesel and fossil-based diesel have effectively become interchangeable, vehicle operators can easily switch back again and increase emissions. Because of the latter, it might also be difficult to later reduce incentives for use of biodiesel, meaning that policy can become 'locked-in'. Similar arguments apply for biogas. Further, both for biodiesel and biogas, (life-cycle) emissions reductions can be debated. At the same time, targeting battery- and/or hydrogen-electric technology or several technologies alongside entails that fewer diesel vehicles will be replaced due to the higher technology costs. The more expensive technology options, however, entail less reversible emissions reductions and might contribute to speeding up production stages, market maturity and cost reductions. A further consideration is that infrastructure establishment for some technologies, e.g. through electric chargers, might yield considerable positive externalities also for vehicles not covered by the fund, and these may deviate from our assumptions.

Further, while the fund's set-up incentivizes participation and will likely meet less resistance than other types of measures, it does not provide participants incentives to follow through with actual emissions reductions or adoption of alternative technology vehicles. This is because such actions still entail increased costs for firms, as the subsidies only partially cover cost premiums. Moreover, subsidies do not change that, in the short term, operational and technical limitations of alternative technology vehicles make them unsuitable for many use cases. Again, this disincentivizes firms to follow through on emissions reductions. The question is whether credible enforcement mechanisms can be established. In this regard, it is also relevant that Norwegian land transport industries have many more and smaller actors to control, than e.g. a similar fund targeting the largest NOx emission sources. Further, effectively reducing fuel levies makes transport cheaper and may induce increased transport demand, while it also reduces government income from levies, the more so the more participants the fund attracts. On the other hand, the fund may provide positive contributions through coordination of individual action, knowledge build-up and possibly improved bargaining power, with implications for cost-effectiveness and the achievement of critical masses.

While we were able to use actual data or educated estimates on many factors, and were supplied with concrete input on parameters for the fund's likely set-up, we were also forced to make several important assumptions. One of these is on the investment costs of alternative technology vehicles and future developments of these, which necessarily come with much uncertainty, but are important for results. Further, estimates on CO_2 reductions from infrastructure are uncertain and should be interpreted with caution. Because such estimates could not be included for electric charging points, the study does not allow fully comparing scenarios in terms of combined effects from subsidies to vehicles and subsidies to infrastructure. Although providing some insights, results do not tell us either whether the fund's set-up is most efficient compared to other set-ups, or other measures, such as not setting up a fund but earmarking existing fuel levies for subsidies provided by government. While several of these limitations entail that emissions results are sensitive to deviations from e.g. assumed developments in investment costs, the *types* of dynamics found are more robust, not directly apparent, and therefore insightful.

5.2.2 Article 2: Experiences from Battery-Electric Truck Users in Norway

Co-authored with Inger Beate Hovi, Erik Figenbaum and Rebecca J. Thorne
Status: Published in World Electric Vehicle Journal

This article presents four related analyses on barriers and enablers for the adoption of electric and lower-emission trucks. The first analysis investigates user experiences from early Norwegian pilots with battery-electric trucks and builds on semi-structured interviews with pilot firms, focusing on factors identified in the literature as important for electric truck adoption [64,67,69,136]. The second analysis estimates the potential for electrification of freight trucks in the near term and longer run. It does so by quantifying use characteristics and requirements for the existing Norwegian vehicle fleet in terms of factors highlighted as important barriers for adoption [from e.g. 64,65,137], and then relating these to technical capabilities of electric vehicles. The third analysis assesses competitiveness of vehicles with different propulsion technologies in terms of total costs of ownership, drawing on a branch of research revolving around total costs of ownership modelling [64,65,66,67,68,119] and considerably extending and developing parts of the work started through the CO_2-fund article. The last analysis assesses the socio-economic costs of phasing in alternative technology vehicles, per vehicle and per tonne CO_2 reduced.

The study contributes to the literature on the adoption of electric trucks, which, at the time of publication, was much more limited than for e.g. passenger cars and buses (and still is). This applies both to studies on user experiences and on drivers of adoption, comprehensive assessments of electrification potential, and to studies on TCO of medium- and heavy-duty electric freight vehicles. This is not surprising, as the number of electric trucks was still small and at an early stage of market maturity and only recently has started to substantially increase with delivery of series-produced electric trucks.

Together, the analyses allow us to compile (policy- and industry-relevant) insights on the restrictiveness of different barriers and implications for the adoption of alternative technology trucks. This includes insights into factors such as purchasing processes, technology, vehicle choices, user experiences and various performance aspects. Estimates on electrification potential within different heavy-duty vehicle segments, in turn, are based on use patterns and elements such as battery weight vs. unutilized payload, trailer use, daily mileages, etc. The TCO-models allow us to compare cost competitiveness and gain detailed insight into the relative importance of different cost drivers for different technologies for 1) an early market phase for battery- and hydrogen-electric trucks, 2) small-scale series production both with current and lower hydrogen prices, and 3) mass production. The models also allow sensitivity analyses given changes in vehicle prices and assumptions, including levies set by authorities.

Overall, we find that experiences from battery-electric truck pilots have been promising (especially for waste and recycling trucks), despite requiring considerable route/location choice tailoring and both small and more severe technical or performance issues experienced by operators. Typical use patterns for light distribution trucks indicate that in the short term (from 2019), electrification potential is limited mainly to only small parts of some fleet sub-segments and of mileages (particularly closed chapel trucks and special trucks (waste/recycling)). Depending on day-to-day variation in driving and charging opportunities, electric operation will also require considerable route tailoring and daytime charging. This assessment is supported by observations on truck types covered by early pilots. In a longer run, relatively modest driving range improvements could considerably improve electrification potential, but larger range improvements are needed for remaining fleet and driving segments. In terms of costs, battery-electric light distribution trucks will first become competitive with diesel trucks at the mass production stage, but will then no longer require advantages such as road toll exemptions. Hydrogen-electric vehicles can at mass production stages become cost-competitive versus diesel, but likely keep higher TCO than battery-electric trucks and are therefore likely more suitable for niches where range limitations and charging times of battery-electric vehicles are limitative (e.g. long-haul transport). Socio-economic costs of phasing in zero-emission technologies are highest for hydrogen-electric vehicles and lowest for biogas, but fall considerably towards mass production stages. At that point, socio-economic costs per tonne reduction in CO_2 emissions are estimated to EUR 170 for battery-electric light distribution trucks versus EUR 340 for biogas and EUR 580 for hydrogen-electric trucks.

With regard to implications, electric trucks with engine power of up to 600 HP would have to become available if the majority of Norwegian road freight is to be carried out electrically, and driving ranges of (in some cases considerably) higher than 300 kms must be supported, in part depending on whether trucks are driven with or without trailer. Simultaneously, establishment of charging infrastructure will be required. Given payload utilization in practice, most trucks would further have considerable room for batteries, especially given additional weight allowances for zero-emission vehicles. This implies that the battery-payload trade-off is not as restrictive as often thought.

In cost terms, TCO for electric trucks has to come down, and electric trucks have to achieve considerable market and technological maturity to be able to compete on TCO. Generally, capital costs remain the main cost driver for electric trucks in the foreseeable future, with lower energy costs and to a lesser extent toll exemptions constituting main savings. All in all, it is likely that in the years to come, incentive schemes (financially or e.g. through environmental weighting in tenders), charging solutions, policy facilitation, and technological developments will remain important aspects for zero-emission adoption. Such adoption is also important to create demand, in order to speed up production and its scale. Finally, although socio-economic costs of reducing CO_2 emissions are currently lowest through the adoption of biogas vehicles, this is no longer the case when battery-electric trucks reach mass production. Further, focusing on biogas risks lock-ins similar to those discussed in the context of the CO_2-fund article and allows operators to switch to natural gas.

Main limitations of our study include uncertainty on future developments of important costs drivers, for which developments in practice may deviate from assumptions. Estimates on investment cost premiums of alternative technology vehicles in early stages are for example based on the interviews, feedback from manufacturers, and limited literature sources, while estimates for future maturity stages are based on a first, rough approach. Both for battery- and hydrogen-electric vehicles, we have in progress more elaborate and detailed techno-economical approaches for expected developments in costs of alternative technologies, in order to improve our estimates in future studies [see e.g. 59,138]. Also mileages (in our analyses chosen to reflect mostly urban/regional distribution patterns in light of what battery-electric trucks are most suitable for) can in practice differ considerably between cases. To reduce these natural limitations of data availability (given the low number of battery- and hydrogen-electric trucks), our TCO-model set-up is designed for easy incorporation of improved estimates for all parameters, when these become available with increasing vehicle adoption.

5.2.3 Article 3: Environmental and Transport Effects of Warehouse Relocationing: Evidence from Norway

Co-authored with Inger Beate Hovi, Aud Tennøy and Paal Brevik Wangsness
Status: Published in Transportation Planning and Technology

In many developed countries, large-scale urban development trends are observed of warehouses moving from locations in central city areas to more peripheral locations. This article assesses transport, cost, environmental, and modal effects from such warehouse relocations around Oslo and Trondheim (Norway).

The study draws on planning and land use theory claiming that replacing centrally located warehouses with urban development (e.g. housing, workplaces, shopping) will contribute to reduced transport volumes and GHG emissions in total. We build on real data (detailed commodity flow data and base data from Norway's foreign trade statistics), as inputs in a strategic network transport model and an own-developed model with particular suitability for studying city distribution effects.

Our study contributes to the literature by investigating and documenting effects of developments in land use (warehouses relocating within the urban region) on freight traffic and CO_2 emissions. While these developments are hotly debated by policymakers, comprehensive studies on environmental and traffic effects of location choices are relatively scarce, and there are gaps in our understanding of effects through freight traffic and emissions dynamics. Indeed, academic literature predominantly approaches warehouse relocations from logistics or supply chains perspectives, considering facility location problems and location-routing problems aimed at identifying cost-minimizing locations and route plans. Particularly limited are studies building on highly granular data as we use here, as such data are often not available or hard to attain. In all, the study's design and more general insights and observations can help advance similar analyses for cases in other countries.

Using modeling tools, rather than e.g. surveys on firms' perceptions on transport and emissions effects of relocating, allows for bottom-up calculations of driving distances, fuel consumption, and emissions, taking into account full delivery patterns for the available sample. This makes it possible to empirically investigate three main mechanisms: 1) increased transport distances for city distribution, 2) changed distances for long-haul transport, and 3) changes between and within transport modes, using two models with characteristics that complement each other.

Studying two cases, we find that for Oslo, transport performance increases when warehouses relocate from central to fringe locations, both through short-distance (+2.3-4.8%) and long-distance domestic trade (+1.6-1.8%). Partially offset by decreases in transport performance from foreign trade flows, this yields a total increase of just below 1%. Further, we find increases of around 2.6% for CO_2 emissions and between 1 to 4.6% for transport costs. For Trondheim, transport (+0.3%) and CO_2 emissions (+0.49%) increase less when warehouses relocate, while transport costs decrease marginally. Generally, modal shift from domestic freight flows is very limited when warehouses relocate, but more pronounced for foreign freight flows, mostly from maritime to road transport. Specific characteristics of individual firm relocations are important in determining the strength and direction of effects on transport, costs and emissions.

Examples include trade patterns and the relative geography of (re)locations, which explain the slightly more pronounced results in the Oslo case.[14]

In terms of implications, our findings are consistent with some, but challenge other conclusions from the relatively scarce literature. However, caution should be exercised, as conclusions in the literature are mixed and not necessarily directly comparable due to how studies are designed, what elements they cover, and how (see more detailed discussion in the article). Also our own study indicates that results are rather dependent on specific characteristics of individual relocations. All in all, we find marginal-to-small increases in CO_2 emissions from warehouse relocations. The fact that increases predominantly materialize in the urban region, due to longer-distance driving with smaller vehicles and on more trips, suggests that urban areas could see relevant increases in local emissions and traffic. Further, differences in effects through domestic trade and foreign trade have some implications given that policymakers might care most about what part of emissions takes place on Norwegian territory. Finally, while we find transport costs increases in the Oslo case, firms' logistics costs in total may nevertheless decrease due to e.g. lower land prices at fringe locations, centralization of stockholding, or more efficient operation.

One main limitation of our study is the simplified way in which distribution transports and return trips are modelled. These are in fact very difficult to model, and indeed, knowledge gaps on how distribution transports are carried out in practice, and lack of data, are challenges experienced by transport modellers throughout the world [139]. Ideally, such transports should have been modelled as a travelling salesman problem. Another limitation of our study is that it only covers the freight side, and not total effects through urban development at freed-up central sites. The latter may, according to planning and land use theory, counteract urban sprawl and contribute to minimizing passenger road traffic. The previously mentioned follow-up article [135], where I am co-author, quantifies such net effects and concludes that total emissions decrease when centrally located warehouses relocate to fringe locations, and freed-up sites are used for urban development. An important further limitation of our study is the implicit ceteris paribus assumption. In reality, warehouse relocations will yield concomitant developments, such as warehouses increasing in size and/or consolidation of several warehouses into one, when the cost savings of doing so outweigh increases from increased

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[14] Most Oslo relocations are in eastward direction, introducing extra distances/diversions to existing delivery routes. Relocation distances are also somewhat larger than for Trondheim, where locations further happen more along existing transport routes and in directions where most deliveries come from/go to, thus not adding as much extra distance.

transport distances. This aspect will likely lead to more pronounced transport and environmental effects than found in our analyses. Other limitations include some uncertainty in matching commodity flows and firms due to confidentiality reasons, although commodity flows should be representative for firms of relevant industries and relevant (re)locations. While the two models used are complementary (the strategic transport network model allowing inclusion of foreign trade and covering also other modes than road, and the city distribution model being more geographically detailed for particularly urban distribution and expected to yield more precise estimates on CO_2 emissions), they yield some deviations in vehicle sizes that short-distance shipments are assigned to, and thereby in transport costs. As such, for most results, lower and upper bounds are presented, rather than one number.

5.2.4 Article 4: Crossing borders and expanding modal shift measures: effects on mode choice and emissions from freight transport in the Nordics

Co-authored with Inger Beate Hovi, Christian S. Mjøsund, Stein Erik Grønland, Erik Fridell and Martin Jerksjö
Status: Published in Sustainability

This article assesses transport and environmental effects for nine scenarios in which existing policy measures with relevance for modal shift are strengthened, expanded, combined and/or harmonized across Nordic borders (detailed in methodology section 4.5). The relevance of this is years of underachievement on modal shift objectives and modal shift being attributed an important emissions reduction role in policymaker narratives.

The study builds on strategic transport network modelling; one of four main strands for studying modal shift and the strand with generally larger data demands, but also best suitability for assessing environmental effects [e.g. 87]. This modelling, carried out through the existing NFM for Norway and using detailed commodity flow data, allows for simulating transport effects from changes in important determinants of freight modal choice.

Our article contributes to the literature by studying modal shift measures over country borders, where most existing analyses are primarily country-specific or comprise narrow cases or only limited parts of total freight flows. Further, our study combines investigations of transport and environmental effects and provides insights in dynamics between changes in the two. In this regard, it overcomes the challenge that sufficiently granular high-quality data are rarely available, inconsistent, or limited to country- or commodity-specific freight activities. Such data are, however, desirable, as both transport and environmental effects are highly dependent on, amongst others, freight flow origins, destinations, and proximity to intermodal terminals. While differences in e.g. geographical conditions and transport mode availability will affect results for comparable scenarios in other countries or regions, results, methodology and particularly implications will still contribute with relevant insights for researchers, policymakers and other stakeholders.

The study's model simulations allow us to assess the potential for modal shift in feasible future policy scenarios and to compare resulting changes in energy use and emissions of CO_2, NOx and PM from freight transport with Norwegian origin and/or destination. As such, we can investigate whether the full modal shift potential is higher if freight, instead of arriving or leaving Norway by road, uses other modes. This question is based on a hypothesis of public policymakers working closely with analyses underlying the Norwegian government's National Transport Plans. Their reasoning is that implementing measures at the Nordic level could contribute to increasing the share of foreign freight to/from Norway by sea or rail and could reduce operational disadvantages, thereby increasing the competitiveness also for upstream and downstream transports by these modes. Our study further allows assessing which policy measures might be more effective than others, potential complementary effects, and whether international harmonization might increase effectiveness.

Overall, we find that even in scenarios with relatively strong policy measures to induce modal shifts, reductions in Norwegian CO_2 emissions from freight do not exceed 3.6%, while in some scenarios yielding increased local emissions. A Norwegian ecobonus for rail yields larger modal shift away from road than a similar ecobonus for sea transport and also yields positive environmental effects (small reductions in emissions of CO_2, NOx, PM), rather than small increases in the sea ecobonus scenario. Modal shift effects from increases in Eurovignette rates in Sweden and Denmark reduce road transport, but, as a whole, modal choice and environmental effects are limited. Facilitating longer freight trains yields more (but still limited) modal shift but has high policy costs. Combining/harmonizing measures across borders is found to strengthen effects of modal shift policy and positive environmental effects (synergies) in some scenarios, but not all, depending on transit traffic.

In terms of implications, results indicate that modal shift can only be a moderate contributor to the decarbonization of freight transport, although there may be other (political) reasons that make modal shift desirable. Moreover, maximizing modal shift is not necessarily optimal from a CO_2 emissions perspective (in line with findings in e.g. [140]). Further, because environmental effects are mode-specific, policymakers can face trade-offs between local and global emissions.

More indirectly, dynamics behind environmental effects might give policymakers a perverse interest in choosing or designing measures yielding the largest emissions reductions within their own countries' territory, but not necessarily overall. It can also be pointed out that designing measures such that money is not spent on freight already going by sea or rail, can be challenging. Finally, other policy measures, such as larger allowances for vehicle dimensions, might improve road transport's competitiveness, thereby disincentivizing modal shift. At the same time, expected developments towards low-/zero-emission road vehicles reduce many of the negative externalities that (currently) make modal shift desirable.

With regard to limitations, it is noted that despite the Nordic perspective, analyses only cover effects for freight flows with Norwegian origin and/or destination and scenarios with (particularly) Norwegian relevance. Impacts on Swedish and Danish freight flows are not analyzed, even though measures could reduce road transport also there or e.g. give rise to new shipping or rail routes attracting freight from all Nordic countries. Further, results do not take into account policy costs, e.g. that rail infrastructure investments will be much more expensive than budgets for rail/sea ecobonuses. This is something to weigh by policymakers. Also, developments on some points may prove different than assumed, e.g. with regard to relative costs of modes, phase-in rates of new technologies or biofuels, levies/duties changes, or several societal trends discussed in the article, not captured by model simulations. Such hypothetical deviations were not assessed, in order to be able to distinguish the partial effects of modal shift measures. Large-scale introduction of lower-emission vehicles or higher biofuel blend-ins would, however, make environmental benefits of modal shifts away from road, smaller. Deviations from projected commodity flow developments (volumes, origins/destinations or relative changes between commodities) may imply both increases and decreases in transport performance and environmental effects overall, and for different modes. However, for many factors, impacts of such uncertainties are likely not very large from a modal shift perspective.

5.2.5 Article 5: Can active follow-ups and carrots make eco-driving stick? Findings from a controlled experiment among truck drivers in Norway

Co-authored with Inger Beate Hovi, Eirill Bø and Christian S. Mjøsund
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This article investigates the potential of eco-driving interventions for fuel savings by truck drivers, assesses the persistence and reinforcement of eco-driving behavior, and looks into the relative importance of eco-driving factors.

The study builds on existing eco-driving theory and insights on how vehicles are driven most efficiently during different driving stages. The study's design and assessments draw on one of the (underutilized) methodological strands through which eco-driving is studied: naturalistic experiments. In our case, we designed a randomized controlled experiment with differential treatment of two groups of truck drivers (treatment/control) and with the aim to control for fixed vehicles, routes, drivers and weather to the extent possible. To reinforce effects of eco-driving training, the treatment group was subjected to two reinforcement mechanisms (active monthly follow-ups and non-monetary rewards), based on literature suggestions. Analyses are carried out using data on eco-driving indicators from in-vehicle FMS systems for all of 2019.

Our article contributes to the relatively limited literature on truck eco-driving and particularly the scarce real-world studies on long-term effects and use of reinforcements. We manage to overcome much of the trade-off between controlling for fixed elements and still studying driving under real-world conditions, thereby increasing external validity. We also address main limitations of existing studies (particularly within the relatively few truck studies), such as the lack of control groups, limited periods of investigation, artificial settings, or not controlling for weather. We further show how (often underutilized) data from FMS systems can be used in improving driving behavior, noting that availability of such data is increasing with it becoming a 'standard' in new trucks.

The study's design and data availability allow us to investigate developments in driving behavior and fuel consumption for individual drivers and at the group level, and to assess developments and dynamics in eco-driving performance after interventions, compared to a control group. Two overarching multiple regression models allow us to estimate a potential for fuel savings (and thereby reduced CO_2 emissions) given observations on eco-driving improvements, and to look into the relative importance of different eco-driving factors.

Overall, we find that eco-driving training can yield fuel savings for truck drivers, with literature-consistent estimates of 5.2-9% (lower and upper bounds), controlled for significant effects of weather conditions (both temperature and precipitation). Results indicate that drivers follow a learning curve after training, and, contrary to several literature findings, that effects do not fade significantly or disappear over time. This suggests that active follow-ups of eco-driving training and non-monetary rewards might strengthen persistence of effects. Of eco-driving factors, improvements in engine/gear handling seem most important. We further find spill-over effects through significant fuel savings for control group drivers (undergoing no interventions). These are likely the result of them becoming aware that 'something eco-driving related' was going on.

A main implication of our results is that eco-driving may contribute to short-term and low-cost emissions reductions from freight vehicles, which are not unlikely to have scalability and an extent of transferability to other settings. As such, eco-driving may play a not insignificant part of strategies towards (urgent) emissions reductions from road freight, until other emissions reduction solutions are technologically and economically feasible at a large enough scale. Fuel savings estimates also imply a potential for significant cost savings for operators. The study further demonstrates that significant eco-driving effects and fuel savings can be maintained longer than is often assumed and suggests that active monthly follow-ups and non-monetary rewards may be promising behavioral reinforcement mechanisms. Insights into the relative importance of eco-driving factors may contribute to targeted focus in eco-driving interventions. Further, if spill-overs to the control group indeed took place, this strengthens the view that eco-driving might be a rather low-hanging fruit. While not our focus, study observations suggest that real-world fuel consumption may deviate considerably from values often used in research and policy analyses, with increasing availability of FMS-data yielding a potential for improving this.

Limitations of our study relate to potential spill-overs of effects, once treatment group rewards became visible or after control group drivers unintentionally received feedback reports. This implies that the control group might not fully reflect behavior without any interventions (although spill-overs are unlikely to have affected the treatment group). Further, despite aiming to control for many factors, signs on some estimated coefficients are not as expected. We believe this to be the result of some important factors not being included due to lacking data availability (e.g. dynamic on-board cargo weight, topography and curvature of roads in areas where transports were carried out). While experimental design and selections likely reduce these deficiencies, there will still be some variations in payload and occasionally in routes. Controls for topography could be addressed in future studies by ensuring sufficient (driver-set) frequency of GPS-logging, but payload data from FMS systems still has large deficiencies, while other potential data sources are either rarely available or not easily coupled to vehicle data. Attempting to control for vehicles, routes, and drivers further put a natural limit on our attainable sample size (exemplified by some attrition). Similarly, comparing drivers at the exact same time was not possible because routes were driven in shifts. Another limitation of our research is that we were unable to consider several driver and situational characteristics, which are thought to potentially moderate effects, even though differences were expected to be small due to a homogeneous driver pool. Increasing prevalence of FMS systems might contribute to future studies being able to study driving behavior over longer time periods, and at larger scale.

6. Discussion, conclusions and implications

Today's transport sector is a major source of GHG emissions, and both emissions and the sector's relative share in the climate change problem are increasing. Based on current knowledge, not reducing emissions from transport and doing this fast, is not an option if global warming is to be kept within the targeted 1.5-2°C range. Indeed, transport is assigned a prominent role in emissions reductions by policymakers around the world. This applies both to absolute reduction targets, but also to the sector's relatively higher targets than other important sectors, particularly towards 2030.

Within the transport sector, an increasingly important segment is freight, and particularly road freight, which stands for a disproportionally large share of emissions and is forecasted to see the largest future increases. Freight transport is underrepresented both in research, climate action pledges, and government strategies, and is considered particularly challenging to decarbonize. High forecasted increases in freight transport only add to this problem. Challenges in decarbonizing freight apply both at a global level and the individual country level, including Norway, the focus of this thesis.

Considering different theoretical frameworks for (freight) transport decarbonization, I discussed that although developed from different perspectives or with different emphasis (e.g. transport in general or passenger transport), they are not very different conceptually, and all point to veins through which emissions can be reduced. McKinnon's Green Logistics Framework stands out as being specifically developed for freight transport, with frequent adoption in both scholarly and leading policy publications on freight transport decarbonization. Pulling threads of the different frameworks together, I defined a stylized 'Kaya-identity' for reducing freight transport emissions, revolving around five veins: Demand Intensity, Transport Intensity, Modal Split, Energy Intensity and the Energy's Carbon Intensity. Approaching freight decarbonization this way may help provide a more intuitive idea of overall emissions reduction potential, the relative importance and potential contributions of different veins, and trade-offs and feedback effects. I further discussed potential trade-offs in a time dimension and the implications of improvements in different veins not being cumulative.

Internationally, policymaker narratives on freight decarbonization particularly feature modal shift and technological improvements (alternative technology vehicles, the use of lower-carbon fuels, and technical fuel efficiency improvements), with much less acceptability for strategies to reduce transport or transport demand.

In Norway particularly, political discourse has gone to making emissions reductions from transport essential, especially towards 2030, with an important role for freight transport. Most policy focus is on the phase-in of zero-emission technologies also for heavy vehicle classes, where Norway envisions a similar leading role as for zero-emission passenger cars. Also increased use of biofuels for road transport and modal shift feature very prominently in Norwegian decarbonization strategies. In this light, the articles of this thesis cover a selection of policy measures and developments with high relevance for Norwegian freight transport.

With regard to the adoption of low-/zero-emission freight vehicles and biofuels, the CO_2-fund article assessed the emissions reduction potential and dynamics of a proposed CO_2-fund. This fund combines carrots and refunding of levies (sticks) through subsidies, to speed up the adoption of alternative technology vehicles and establishment of necessary filling/charging infrastructure. Meanwhile, the Electric Truck article focused on how Norwegian user requirements and (developments in) techno-economic barriers and enablers affect the adoption potential for zero-emission road freight vehicles.

In the first article, we found that a CO_2-fund can contribute to increasing market demand for zero-emission vehicles and to achieving critical masses. However, both the development of the fund's proceeds over time and the number of vehicles it can subsidize, are highly dependent on the choice which technolog(y)ies to subsidize. The same goes for the size of emissions reductions that can be achieved and the timing of their materialization. We find that emissions reductions are largest in a scenario with exclusive focus on biodiesel, alongside smaller estimated reductions in scenarios with exclusive focus on biogas, battery-electric or hydrogen-electric technology respectively, and scenarios with combinations of technologies alongside. Further, subsidies towards establishment of filling/charging infrastructure can yield considerable additional emissions reductions, depending on their use by non-fund participants. However, these estimates are more uncertain and not feasible for electric infrastructure. In scenarios where the fund is used to target multiple technologies alongside, larger shares of fund proceeds are needed to support sufficient infrastructure establishment, reducing the number of vehicles that can be subsidized.

In the Electric Truck article, we found that experiences from early Norwegian pilots with battery-electric trucks have largely been promising, despite often requiring considerable route/location choice tailoring, and some technical or performance issues. Use patterns for light ICE-distribution trucks in Norway indicate that in the short term (from 2019), electrification potential is limited mainly to parts of some fleet sub-segments, thereby often requiring considerable route tailoring and daytime charging. In a longer run, relatively modest driving range improvements could considerably increase electrification potential. In terms of costs, competitiveness of battery-electric light distribution trucks versus diesel is first attained at the mass production stage, but might at such point be attainable even if advantages such as road toll exemptions would be reduced, and actually become a financially attractive choice for the private sector. Hydrogen-electric vehicles can in the longer term become cost-competitive vs. diesel, but will likely keep higher TCO than battery-electric trucks and are therefore more suitable for niches (e.g. long-haul transport). Socio-economic costs of phasing in zero-emission technologies are highest for hydrogen-electric vehicles and lowest for biogas, but fall considerably towards mass production stages.

Findings from these articles on the adoption of low-/zero-emission freight vehicles and biofuels have several implications, including for choices of technological solutions to focus efforts on. For example, trade-offs exist between emissions reductions from biofuels, which in the short term can be larger, cheaper, and be achieved faster than through freight electrification. This is relevant in light of the carbon budget notion discussed in chapter 2. However, limited availability of (advanced) biofuels may make it more sensible to use biofuels for harder-to-decarbonize applications. A disadvantage of biofuels is further that operators can switch back to fossil fuels, entailing a risk of emissions cuts being reversed and of lock-ins to policies that incentivize biofuel use. Biofuels are also debated, both with regard to their lifecycle impacts, and because of dynamics of international emissions accounting.

While battery- and hydrogen-electric technologies are (currently) more expensive, they entail less reversible emissions reductions. Early efforts might further contribute to speeding up technology development, production and market maturity, and bring down their costs. User experiences and use patterns indicate that technology development is essential for increasing the proportion of the Norwegian freight vehicle fleet with electrification potential. Payload penalties from high battery weight, in turn, are likely not as limitative.

Technology development and reaching more mature stages is also needed for electric trucks to reach cost competitiveness, especially as capital costs remain their main cost driver in the foreseeable future. The same goes for reducing the socio-economic costs of reducing emissions through forcing the adoption of electric trucks. Technology choices are also relevant with regard to sufficient and timely establishment of filling/charging infrastructure. Balancing all these considerations is challenging, and although pathways pursuing multiple technologies alongside have their disadvantages, they can also yield flexibility during a transition towards large-scale freight electrification. All in all, it is likely that in the years to come, incentive schemes (financially, through tender requirements, or otherwise), charging solutions, policy facilitation, and technological developments will remain important aspects. It should also be considered that different freight transport segments have different requirements, affecting the feasibility of using different technologies. For example, electrification will in early phases be particularly relevant for urban and regional transports, while long-haul transport will require alternatives in a transition phase. Also the replacement rate for the road vehicle fleet is something to consider. Compared to other modes (e.g. especially ships), road vehicles are shifted much more frequently, but still, investments in conventional vehicles have emissions impacts many years into the future. For example, used Norwegian trucks are often exported to lower-cost countries in Europe, and may later be exported further to developing countries. Because of this, Norwegian technology choices also have a bearing on global emissions in a more long-term perspective.

Discussions on strengths and weaknesses in the CO_2-fund article (e.g. on enforceability, the many actors involved, and perverse incentives) further provide useful policy insights for weighing alternative policy designs and measures against each other. A case in point is also that subsidies by themselves do not automatically remove the technological and operational barriers for many use cases. Indeed, current Norwegian policies explicitly presuppose that technological developments progress such, that concrete zero-emission vehicle adoption targets are feasible.

As a final remark regarding technology-focused decarbonization, it should be highlighted that clean energy, both electricity from renewables and advanced biofuels, will be in high demand also in other transitioning sectors. This entails a need for curbing overall energy consumption (which more efficient electric vehicle drivetrains also contribute with). In other words, there is a general need for (most) energy efficient solutions, not just from a climate perspective.

With regard to modal shift, we assessed transport and environmental effects of strengthening, expanding, combining and harmonizing policy measures across Nordic borders, and of warehouse suburbanization trends. In the Modal Shift article, we found that even in scenarios with strong policy measures to induce modal shift, reductions in Norwegian CO_2 emissions are limited ($\leq 3.6\%$), while some scenarios feature increases in local air pollution. This indicates that modal shift can only be a moderate contributor to the decarbonization of Norwegian freight transport. Maximizing modal shift is also shown to not necessarily be optimal for reducing CO_2 emissions, consistent with findings in e.g. [140]. We further found that a Norwegian ecobonus for rail yields larger modal shift away from road than a similar ecobonus for sea transport and yields better environmental results. Increases in Eurovignette rates in Sweden and Denmark reduce road transport, but with limited modal change and environmental effects overall. Facilitating longer freight trains yields more (but still limited) modal shift but has high infrastructure costs. Further, we found that combining/harmonizing measures across borders in some, but not all cases, positively strengthens transport and environmental effects, depending on transit traffic and border-crossing dynamics.

In the Warehouse Relocationing article, we found that warehouse suburbanization yields very limited modal shift from domestic freight flows, but more pronounced shifts for foreign freight flows (mostly from maritime to road transport). This is likely due to the fact that warehouse relocations to outskirts of Oslo and Trondheim entail movements further away from relevant ports, making sea transport less attractive (e.g. more time-consuming or costly).

Also our findings on modal shift have various implications, not least when comparing the decarbonization role that it is assigned in policy narratives and strategies with limited achievements in practice, and with what can be regarded as realistic emissions reduction potential. The thesis also discussed dynamics between transport and environmental effects of modal shift, how these can complement each other but also entail trade-offs, and that modal shift can be desirable also for other reasons than decarbonization. Similarly, policymakers can face trade-offs between local emissions and traffic safety considerations vs. global emissions, and between maximizing emissions reductions domestically versus for the whole transport chain. In terms of increasing policy effectiveness, this thesis provides lessons relevant for how policy is designed, the relative potential of different modal shift measures, and how harmonizing/combining measures can in some cases give rise to synergies, albeit limited. However, our articles also point to ongoing trends that may counteract modal shift objectives. This includes logistics sprawl and measures that make road transport more efficient and competitive, thereby counteracting modal shift (e.g. increased weight and length allowances in many countries, including Norway). We further pointed out that expected developments towards alternative propulsion road vehicles (and safer and more automated road transport) reduce many of road transport's negative externalities, and more rapidly than for other modes [cfr. 50], e.g. with regard to noise, traffic safety, possibly congestion (better driving flows) and some local emissions. This will reduce the relative benefits of and need for modal shift.

In addition to modal shift, the Warehouse Relocationing article focused on **changes in distribution and long-haul transport**. Here, we found that for Oslo relocations, transport performance both through short- and long-distance domestic trade increases, and is only partially offset by decreases in transport performance from foreign trade flows. Further, CO_2 emissions and transport costs (but thereby not necessarily total logistics costs) increase by a few percent. For Trondheim, transport and CO_2 emissions increase less when warehouses relocate, while transport costs decrease marginally. In all, we conclude that specific characteristics of individual cases (geography of locations and trade patterns) are important in determining strength and direction of effects on transport, costs and emissions. The observation that increases in CO_2 emissions predominantly materialize in the urban region suggests that urban areas could see relevant increases in local emissions and traffic.

Active land use planning and curtailing transport demand receive relatively little focus for freight transport (where passenger transport by car for example has a zero growth objective in several Norwegian cities). Our results suggest that increasing this focus might be useful. Mechanisms, such as through where changes in transport take place, also have relevance for transitions to alternative technology freight vehicles. Increases in distances for distribution transports may for example have a bearing on their electrification potential.

One thing that all the above articles illustrate, is that it will take time before emissions reductions for freight transport can really become substantial. Through the Eco-driving article, we investigated a more immediate way for reducing emissions. Focus was on the potential for fuel savings, the persistence and reinforcement of eco-driving behavior, and the relative importance of different eco-driving factors. Here, we found that eco-driving training can significantly reduce fuel consumption of truck drivers, with literature-consistent estimates of 5.2-9% reduction (lower and upper bounds, controlled for significant effects of weather conditions). Findings further indicate that active follow-ups of eco-driving training and non-monetary rewards might strengthen persistence of effects. This is important, as literature findings suggest that improved eco-driving behavior otherwise has a tendency to fade or disappear over time. Further, improvements in eco-driving behavior follow a learning curve, and improvements in engine/gear handling seem most important among different eco-driving factors.

Implications of this article include that targeting eco-driving may be a way of achieving rapid, scalable and low-cost emissions reductions from freight vehicles, and might warrant more (policy) focus than it is currently given. The article further provides suggestions on how initiatives can be designed to achieve larger and more persistent fuel savings. Eco-driving can in fact be rational and profitable for firms by reducing fuel expenses, which constitute a major cost driver. It is also a decarbonization vein that to a lesser extent requires government action and can be initiated by industry. This contrasts decarbonization through alternative technology adoption, biofuels and modal shift, where public authorities have important roles in initiating, facilitating and accommodating emissions reductions.

Implications and contributions

Together, the articles and framing introduction contribute towards this thesis' overarching research question: **"How can changes in framework conditions for Norwegian freight transport, stemming from policy (design) and logistics trends, contribute to or inhibit achievement of climate objectives for transport?"**

Overall, discussions in this thesis indicate that achieving Norwegian climate objectives for transport will be challenging, particularly through the freight transport segment. It will likely require combinations of strong efforts, both through different decarbonization veins and at different points in time. Recognizing the limitations outlined for the different articles, we demonstrate the potential decarbonization contribution and dynamics of a CO_2-fund with different set-ups. Such a fund improves framework conditions for the use of low- and zero-emission vehicles, and may speed up their adoption. Through a comprehensive discussion of user experiences, user requirements and vehicle use patterns, cost competitiveness, and socio-economic costs of phasing in alternative technology vehicles, we provide insights into a range of factors that contribute to or inhibit adoption of alternative technology vehicles. We also point to important considerations for policymakers and firms to improve this balance to increase and speed up emissions reductions.

Logistics trends such as urban sprawl of warehouses, in turn, may entail counteracting effects by increasing transport demand, counteracting modal shift, and potentially delay electrification feasibility. Although transport and environmental effects are very case-specific, we argue that these trends should not be neglected by policymakers, as currently seems the case. With regard to modal shift, we demonstrate that the potential for emissions reductions is limited and provide policy lessons on measure design, effectiveness, dynamics, and different trade-offs. We also highlight developments in other veins that make road transport more competitive, thereby disincentivizing modal shift, and developments that reduce the general desirability of modal shift. Related to this discussion, also another observed trend should be mentioned: a movement towards large, centralized Nordic warehouses, many of which are located in Southern-Sweden. The common European labor market has generally caused many transport firms to use foreign drivers to reduce costs. With central warehouses located abroad, cabotage rules allow for cheaper road transport between warehouse and recipient (e.g. in Norway), using trucks and drivers from low-cost European countries. The latter would not have been possible permanently from warehouses located in Norway. However, the Covid-19 pandemic has also highlighted several vulnerabilities related to this dependency on foreign drivers.

Because changes in most framework conditions will first yield sizable emission cuts in a few years' time, we further discussed potential short-run emissions reductions from eco-driving initiatives, and design lessons.

In all, a main inhibitor to emissions reductions from transport in general, and freight transport in particular, is the high projected increase in transport demand. Unless this trend is reversed, the implication is that decarbonization achievements through other veins need to be even larger to fulfil objectives.

On the whole, by providing a better understanding of ways in which changes in framework conditions contribute to or inhibit emissions reductions, this thesis provides insights into the effectiveness of relevant freight decarbonization approaches in a Norwegian context and into the potential for strengthening this effectiveness. As such, the thesis can contribute to better-informed future policy.

While the focus of the current thesis is on the Norwegian case, insights, implications and methodological approaches in this thesis can be highly relevant also for other countries facing similar and related challenges. This includes general and specific dynamics that are discussed, for example between different decarbonization veins and between transport and environmental considerations, but also a better understanding of the extent and urgency of the challenge, and on implications and trade-offs related to the timing of cuts in light of the carbon budget notion. These insights all come with policy lessons, e.g. on the realism of current policy narratives and solution strategies, but also on advantages and disadvantages of policy design, cost effectiveness considerations and freight-specific challenges. Likewise, I identify themes that receive little policy attention, but might be worth considering also in other country settings, and provide insights beyond just CO_2 emissions (e.g. on policy implications for local air pollution, which is a relevant theme in many cities).

Limitations and further research

All articles in this thesis necessarily come with limitations, which were discussed in detail in Chapter 5, both overall and for the individual articles. In short, these include uncertainties and investment costs and the use of several important, and in some cases rough assumptions. Both articles using commodity flow modelling entail a degree of stylization, while commodity flow data both yield some uncertainties and can become outdated due to societal trends and future changes in today's delivery patterns. Main limitations of the Warehouse Relocationing article are the implicit ceteris paribus assumption (whereas relocationing for example often will entail consolidation), the simplified way in which distribution transports are modelled (in reality very complex), and the fact that the article only covers emissions effects from changes in freight transport, and not from freed-up central areas being put to use for other activities. Regarding the latter limitation, I referred to a follow-up article that considers net effects and concludes that emissions from passenger and freight transport combined, decrease when central warehouses relocate to fringe locations and freed-up sites are used for urban development. The Modal Shift article, in turn, only covers effects through freight flows with Norwegian origin and/or destination, and while benefits can be compared, policy costs in different scenarios cannot, and can differ much. The Eco-driving article has its main limitations in the relatively limited sample size, potential spill-over effects from treatment to control group, and the inability to perfectly control for payload and route differences (although these should be limited by our experimental design).

For the thesis as a whole, a limitation is that effects found in the different articles cannot be added up. While the five articles consider one or several veins alongside, emissions reductions through different veins are not independent of each other. As discussed, there are many feedback effects between veins, e.g. through more efficient transport inducing increased transport demand, savings in one mode inducing modal shift to this mode, etc. Comprehensive assessments of total emissions effects are challenging to establish. A case in point is the important Norwegian Klimakur assessment, where it can be argued that emissions effects found for different policy measures are too easily summed into an overall emissions reduction potential, without sufficiently taking into account these potential feedback effects.

In Chapter 5, I also discussed how studies included in this thesis can be followed-up, expanded and improved in future research. For the articles on alternative technology vehicle adoption, cost analyses can be further refined, and some progress has already been made in Pinchasik et al. [59], where we also move to user experiences from the first *dedicated series-produced* battery-electric trucks in Norway. Before the summer of 2020, all battery-electric Norwegian trucks were converted vehicles. The Warehouse Relocationing article has been followed up with abovementioned study of net effects and can be further improved through modelling refinements, larger samples, and by looking at different settings, also in other countries. Also the Modal Shift article can be improved and expanded to new cases, by covering freight flows in multiple countries and to/from multiple countries, and by model refinements. For example, today's strategic transport network model could be expanded by implementing cost models for alternative propulsion modes. This would allow more long-term projections and also generally provide improved strategical tools for long-term planning and policy analysis. The Eco-driving article can be followed up with studies using larger samples and refining controls for factors such as payload.

Appendix to introductory chapter

Art.	Research question	Theory	Data	Methods	Key findings
I	What are the CO_2 reduction potential and dynamics of a CO_2-fund, aimed at speeding up the adoption of alternative propulsion technologies within Norwegian road freight transport?	Combining carrots and sticks to incentivize alternative propulsion vehicle adoption. **ASI:** Improve **ASIF:** Intensity, Fuel **Green Logistics Framework:** Energy efficiency, Lower-carbon energy **Kaya-terms:** Energy intensity, Energy's carbon intensity	Transport demand projections, emissions statistics for heavy vehicles, transport volumes for heavy vehicles, mileage data by vehicle age from periodical vehicle assessments, applicable CO_2-levy rates and biodiesel blend-in requirements, emission factors, confidentially collected data from vehicle manufacturers, suppliers of several fuels and ENOVA, proposed parameters for the fund's set-up and estimates on participation.	Numerical modelling and scenario analysis, solving for fund dynamics, number of vehicles and infrastructure points subsidized, diesel consumption replaced and emissions offset compared to reference.	A CO_2-fund can contribute to increasing market demand for zero-emission vehicles and to achieving critical masses. Choice of technology focus for the fund and (developments in) investment costs vs. ICE-vehicles, have important implications for proceeds development over time and the number of vehicles that can be subsidized. As a consequence, emissions reductions are also highly dependent on the fund's technology choice. At the most (scenario with full reliance on biodiesel) we find an emissions reduction from vehicles of 48% in the fund's last year (2027). This is higher than in full biogas, battery-electric and hydrogen-electric scenarios and in scenarios where subsidies are given to multiple technologies alongside. Subsidies to establishment of filling/charging infrastructure can yield considerable additional emissions reductions when used by non-fund participants, but estimates are more uncertain and not feasible for electric chargers. In scenarios with focus on multiple alternative technologies, larger shares of the fund proceeds are needed to support establishment of sufficient infrastructure, meaning that the number of vehicles that can be subsidized is lower.

II	How do Norwegian user requirements and (developments in) techno-economic barriers and enablers affect the adoption potential for zero-emission road freight vehicles?	TCO and alternative technology vehicle barriers and facilitators theory, theory on feasible use cases. Social cost-benefit theory. User perception theory. **ASI:** Improve, (Shift) **ASIF:** Intensity, Fuel, (Structure) **Green Logistics Framework:** Energy efficiency, Lower-carbon energy **Kaya-terms:** Energy intensity, Energy's carbon intensity	Base data from Norwegian vehicle registry and Statistics Norway's surveys of trucks, lists of zero-emission vehicle projects receiving financial support, interview feedback, validated base parameters from NFM, (confidential) cost data collected in interviews and from transport sector actors, data from Jordbakke et al. [117], updates of Hovi and Pinchasik [116] and literature.	Semi-structured qualitative interviews, quantitative analysis of typical vehicle use patterns, total costs of ownership modelling and cost decomposition, socio-economic cost-benefit analysis.	Experiences from early Norwegian pilots with battery-electric trucks have been promising (especially for waste and recycling trucks), although requiring considerable route/location choice tailoring and despite operators facing both small and more severe technical or performance issues. Typical use patterns for light ICE-distribution trucks indicate that in the short term (from 2019), electrification potential is limited mainly to parts of some fleet sub-segments (and particularly within special truck and closed chapel truck segments). Depending on day-to-day variation in driving and charging opportunities, substantial route tailoring and daytime charging is required. In a longer run, relatively modest driving range improvements could considerably improve electrification potential, while reductions in payload from heavy batteries are likely not critical. In terms of costs, battery-electric light distribution trucks will first become competitive with ICE-trucks at the mass production stage, but at such point, competitiveness is possible even when advantages such as toll exemptions would be reduced. Hydrogen-electric vehicles can in the longer term become cost-competitive vs. ICE, but likely keep higher TCO than battery-electric trucks and are therefore more suitable for niches (e.g. long-haul transport). Socio-economic costs of phasing in zero-emission technologies are highest for hydrogen-electric vehicles and lowest for biogas but fall considerably towards mass production stages.

III	What are the implications of warehouse relocationing trends in Norwegian urban areas for freight transport and its CO_2 emissions?	Planning and Land Use theory, Logistics sprawl theory. **ASI:** Avoid, Shift **ASIF:** Activity, Structure **Green Logistics Framework:** Reducing freight movement, Shift to lower-carbon modes, (Vehicle utilization) **Kaya-terms:** Transport intensity, Modal split	Raw data from Commodity Flow Survey and Foreign Trade Statistics, data from Norway's firm registry (for case selection), parameters from NFM, emission factors, mappings of relevant policy measures.	Numerical modelling and scenario analysis, solving for changes in transport performance, costs and CO_2 emissions.	Studying two cases, we find that for Oslo, when warehouses relocate from central to fringe locations, transport performance both through short- and long-distance domestic trade increases and is only partially offset by decreases in transport performance from foreign trade flows. Further, CO_2 emissions and transport costs increase by a few percent (but not necessarily total logistic costs). For Trondheim, transport and CO_2 emissions increase less, while transport costs decrease marginally. Generally, modal shift from domestic freight flows is very limited when warehouses relocate, but more pronounced for foreign freight flows (mostly from maritime to road). Specific case characteristics (relative geography of locations/trade patterns) are important in determining the strength and direction of effects on transport, costs and emissions. The observation that emissions increases predominantly materialize in the urban region (due to longer-distance driving with smaller vehicles and on more trips), suggests that urban areas could see relevant increases in local emissions and traffic.
IV	What are the transport, modal distribution and environmental effects of strengthening policy measures for modal shift, and of harmonizing measures across Nordic borders?	Modal choice and modal shift theory. Barriers and facilitators. Improvement hypotheses. **ASI:** Avoid, Shift, (Improve) **ASIF:** Activity, Structure, (Intensity, Fuel)	PWC input matrices for NFM (based on population projections and (regionalized) macroeconomic growth trajectories). NFM parameters (and adjustments representing the scenarios). Energy use and emission	Numerical modelling and scenario analysis, solving for changes in transport performance, costs and emissions of CO_2, NOx, PM and energy use.	Even in scenarios with strong modal shift policies, reductions in Norwegian freight's CO_2 emissions do not exceed 3.6%, while sometimes increasing local air pollution. Modal shift can only be a moderate contributor to freight transport decarbonization, and maximizing modal shift is not necessarily optimal for reducing CO_2 emissions. Countries may further face trade-offs between emissions reductions

		Green Logistics Framework: Reducing freight movement, Shift to lower-carbon modes, (Vehicle utilization, Energy efficiency, Lower-carbon energy) **Kaya-terms:** Transport intensity, Modal split, (Energy intensity, Energy's carbon intensity)	factors from HBEFA, EcoTransIT, NFM, statistics for freight transport with trucks, specific ship fuel consumption and emissions.		within their territory vs. for entire transport chains. A Norwegian rail ecobonus yields larger modal shift away from road than a similar sea ecobonus and also yields positive environmental effects (small reductions in emissions of CO_2, NOx, PM), rather than small increases. Increases in Eurovignette rates in Sweden and Denmark reduce road transport, but as a whole, modal choice and environmental effects are limited. Facilitating longer freight trains yields more (but still limited) modal shift but has high policy costs. Combining/harmonizing measures across borders in some, but not all cases, strengthens effects of modal shift policy and positive environmental effects, depending on transit traffic/border-crossing effects.
V	To what extent and in what way do eco-driving interventions have a potential to reduce fuel consumption and CO_2 emissions by inducing more efficient driving behavior among truck drivers?	General eco-driving theory. Theory on behavioral reinforcement. **ASI:** Improve **ASIF:** Intensity **Green Logistics Framework:** Energy efficiency **Kaya-terms:** Energy intensity	Data from FMS systems onboard distribution trucks, weather data, vehicle characteristics from the Norwegian vehicle registry.	Randomized naturalistic controlled experiment with differential treatment of control and treatment group. Eco-driving course, active monthly performance report follow-ups and non-monetary rewards. Multivariate regression analyses.	Eco-driving training can significantly reduce fuel consumption of truck drivers, with literature-consistent estimates of lower and upper bounds of 5.2-9% reduction (controlled for significant effects of weather conditions). Active follow-ups of eco-driving training and non-monetary rewards might strengthen persistence of effects, which is important as several existing studies find that effects otherwise have a tendency to fade or disappear over time. Further, improvements in eco-driving behavior follow a learning curve. Of different eco-driving factors, improvements in engine/gear handling seem most important. In all, eco-driving may contribute to short-term, scalable and low-cost emissions reductions from freight vehicles.

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Abstract

Emissions from heavy trucks constitute a large and increasing share of Norwegian CO_2-emissions. The Norwegian Green Tax Commission recently presented recommendations for emission reductions, largely confined to 'sticks', in the form of taxes and levies. Another way to reduce emissions and to force the phase-in of alternative propulsion systems on heavy trucks, is the use of more positive measures for the industry. In Norway, establishment of a CO_2-fund for the industry, modelled after the existing Norwegian NOx-fund, has been proposed. Rather than paying a levy on every litre fuel consumed, participants to the fund will pay a (lower) participation fee in exchange for committing to emission reducing measures. The fund's proceeds will then be used on (partial) subsidies towards the additional investment costs for renewable-based rolling stock and infrastructure. The analysis in this study shows that it is most cost-effective to direct the fund's subsidies towards biodiesel alternatives, but that the availability of sustainable fuel might become a challenge. A fund should therefore also consider subsidizing more expensive renewable technologies based on biogas, electricity, or hydrogen. Although some of these alternative technologies still face several techno-economic barriers, a CO_2-fund can contribute to increasing market demand and to achieving critical masses.

1. Introduction

Norway has committed to cutting greenhouse gas (GHG) emissions by 40 percent in 2030, relative to its 1990 level. Although the transport sector currently falls outside the scope of the Emissions Trading Scheme (ETS), demanding emission targets are expected to be implemented in line with the European Union (EU). At the EU-level, emissions from sectors outside the ETS in 2030 are to be reduced by 30 percent relative to 2005, with targets for individual countries varying between 0 and 40 percent (Norwegian Environment Agency, 2015).

With transport making up over 30 percent of Norwegian national emissions, and transport demand set to increase, these targets imply that measures are needed to keep emissions in check. This particularly applies to emissions from heavy trucks, which constitute a large share, and keep rising. The present study therefore focuses on (heavy) trucks that are used for long-haul transport and local distribution.

Generally, measures to curb emissions from road transport aim at reducing transport demand and/or increasing the use of renewable technologies (e.g. Callan & Thomas, 2010), of which biofuels, hydrogen and electricity are deemed the most promising (e.g. Connolly et al., 2014). These measures often take the form of levies or duties ('sticks') that make (conventional) transport more expensive. Such approaches are also recommended in a recent report by the Norwegian Green Tax Commission (2015).

In this study, we assess a proposal for a CO_2-fund for the industry, which instead uses 'carrots' to incentivize the phase-in of renewable technologies. We contribute to the existing literature by quantifying the emission reduction effect of measures financed within the current Norwegian framework on CO_2-levies for trucks, under different scenarios. In addition, we do this for a scheme which combines positive and negative measures, where these are often assessed in isolation. Particularly the direct 'refunding' of levies to finance subsidies has received little attention before (Hagem et al., 2015). Although our study primarily focuses on emissions from Norwegian heavy truck transport, similar measures can be applied to different sectors and in other countries as well.

Norwegian agents currently pay a CO_2-levy for every litre fuel used. In return for mandatory emission reductions, participants to a CO_2-fund would be exempt from this CO_2-levy and instead pay a (lower) per litre participation fee into the fund. The fund's proceeds are then used on partial subsidies towards the additional investment costs of renewable-based propulsion systems and infrastructure, such as filling stations and charging points. By stimulating and speeding up the adoption of renewable technologies for road transport, a CO_2-fund intends to achieve emission reductions in the years going forward.

This study first discusses the methodology, assumptions, and scenarios of our analysis in section 2. In section 3, we discuss the development of CO_2-emissions, provide a survey of measures and instruments and alternative technologies, and discuss the NOx-fund after which the proposed CO2-fund is modelled. Section 4 presents the results of a scenario analysis in terms of fund proceeds, cost effectiveness, and the potential for CO_2-reductions from Norwegian road transport. In section 5, we discuss the strengths and challenges of a CO_2-fund and our analyses. Section 6 concludes and identifies avenues for further research.

2. Methodology and assumptions

In this section, we will first address the calculation of our emission forecasts under 'business as usual'. We then discuss the underlying assumptions, considerations, values, data sources, and scenarios used in our calculations. Finally, we explain how this information is combined to assess the possible effects of a CO_2-fund, where we distinguish between effects from subsidies to rolling stock and subsidies to infrastructure.

2.1 Emission forecasts

Forecasts on the development of CO_2-emissions under 'business-as-usual' form the reference for an assessment of a CO_2-fund, and are presented in section 3.1. Our forecasts distinguish between vans, heavy trucks, buses, construction equipment, coastal shipping, and fishery, and are largely in line with projections by NEA, the Norwegian Environment Agency (2015).

For heavy trucks, we decided to use forecasts based on transport demand projections (Hovi et al, 2015) developed for the National Transport Plan, rather than NEA's general assumptions about the number of vehicles and driving distances between 2020-2030. We then derived emission factors from data on GHG-emissions from heavy vehicles (Statistics Norway, 2016) and used transport volumes and driving distances for buses and heavy trucks (Farstad, 2015) to calculate and distinguish separate emission paths. We further related historical emissions to transport performance in order to develop a time series of emissions per ton-km. Finally, we took into account that the biodiesel content in regular diesel is legally prescribed to increase from the current 5.5 percent to 7 percent from 2017 (NEA, 2015, p.152). The resulting forecasts are similar to NEA's for 2020, and only somewhat higher for 2030 (5 percent in total for heavy trucks).

2.2 The fund's set-up

The proposed CO_2-fund receives proceeds, and uses these on subsidies. The fund's proceeds are a function of the per litre participant levy, the participation rate, and the yearly diesel sales accounted for by the fund's participants. To provide a sufficient participation incentive, the participant levy is proposed to be set at NOK 0.80 (EUR 0.085/USD 0.095) per litre diesel, which is 70 percent of the current CO_2-levy. The fund is proposed to operate for ten years, starting in 2018. Based on discussions with the NOx-fund, participation is assumed to increase from 25 percent in the first year to 80 percent in the fund's final year. Estimates on the yearly diesel use by participants are derived from the projected CO_2-emissions in section 3.1, while accounting for the downward pressure that the fund's subsidies put on fossil fuel consumption, relative to 'business as usual'

Subsidies from the fund are intended to (partially) cover the additional costs of renewable-based rolling stock and infrastructure, compared to conventional combustion technologies. For investments in rolling stock, the fund provides subsidies of 80 percent of additional investment costs, while infrastructure is subsidized up to 50 percent. Subsidies are only given for investments in new vehicles, as modifying existing vehicles is more expensive, and therefore less cost-effective. Subsidized vehicles are further assumed to fully replace existing vehicles running on fossil diesel with a biodiesel content of 7% (B7). In our analysis, subsidies do not cover the potentially higher operating expenses for renewable-based rolling stock or infrastructure. This is, however, an area worth exploring.

2.3 Vehicle characteristics

The average per kilometer fuel consumption at average loads was calculated based on the model from the Handbook Emission Factors for Road Transport (HBEFA, 2014). This method is consistent with approaches used by Statistics Norway (SSB) and NEA. The results in table 2.1 also correspond well with data from a large Norwegian transport firm.

Table 2.1. Average diesel consumption in litres per km for different vehicle types. Calculation based on HBEFA-model, consistent with approaches by SSB and NEA.

Vehicle types (aggregated)	Litres/km
Vans	0.08
Distribution trucks (gross weight 3.5-12 tons)	0.34
Long-haul trucks (gross weight >12 tons)	0.40
Tractor units	0.40

Given that subsidized measures result in larger CO_2-reductions, the longer the driving distance of replaced vehicles, we also took into account the distribution of driving distances over lifetime. Data was based on periodical vehicle assessments by the Norwegian Public Roads Administration. For vehicles with a gross weight over 7.5 tons, we extrapolated data from the Norwegian Road Traffic Information Council (Opplysningsrådet for Veitrafikken) and checked the resulting estimates against data collected from two large Norwegian transport firms; see table 2.2. As the remainder of this study focuses on alternative technologies on distribution trucks and long-haul trucks, other categories are only depicted as illustration.

Table 2.2. Assumptions on vehicle lifetimes and total driving distances during average lifetimes. Source: periodical vehicle assessment data by the Norwegian Public Roads Administration (gross weight ≤7.5 tons); extrapolation of data from the Norwegian Road Traffic Information Council, checked against data from two large Norwegian transport firms (gross weight >7.5 tons).

	Assumed lifetime (years)	Driving distance over average lifetime (in 1000 km's)
Vans	17	280
Distribution trucks (gross weight 3.5-12 tons)	21	350
Long-haul trucks (gross weight >12 tons)	10	475
Tractor units	10	750

2.4 Additional investment costs

To estimate the additional costs of different types of renewable-based vehicles, we collected data from several vehicle manufacturers, transport firms, and other firms using own vehicles running on biofuels, electricity or hydrogen. As these data were collected confidentially, figure 2.1 presents index numbers, where fossil diesel with a biodiesel content of 7% (B7) = 100. Compared to conventional fossil-based vehicles, additional investment costs are lowest for biofuels, while hydrogen and electric vehicles are currently still expensive due to small-scale production, individual orders, and the lack of a critical mass. However, these costs are expected to fall throughout the fund's lifetime (Anandarajah et al., 2013) and technologies are expected to become ready for use on heavy trucks. In our analysis, we therefore estimated the additional costs at a stage of serial production, based on current price differentials between conventional and electric passenger cars, taxes excluded. As a result, additional costs for electric and hydrogen vehicles are assumed to decrease by roughly 70 percent from today's level, by the fund's last year.

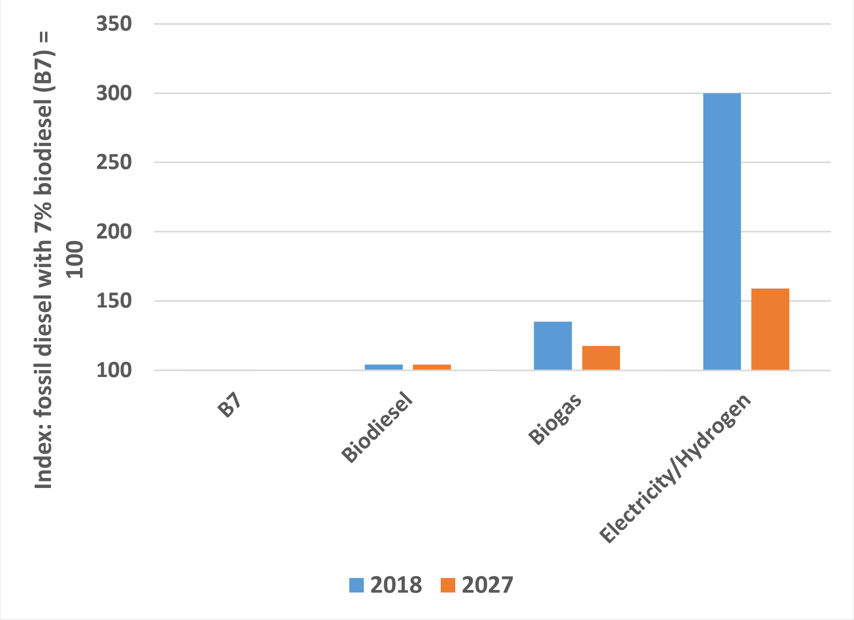

Figure 2.1. Additional investment costs for alternative technologies in 2018 and 2027 (in index numbers with diesel containing 7% biodiesel (B7) =100).

Figure 2.2, in turn, illustrates the cost efficiency of the different technological alternatives over time, given our assumptions. This is done by looking at the number of index points above 100 (as measure for additional investment costs), required for a one-ton reduction in CO_2-emissions. Despite cost efficiency improvements for electricity and hydrogen, biodiesel (and to a lesser extent biogas) remain more cost effective throughout the fund's entire lifetime.

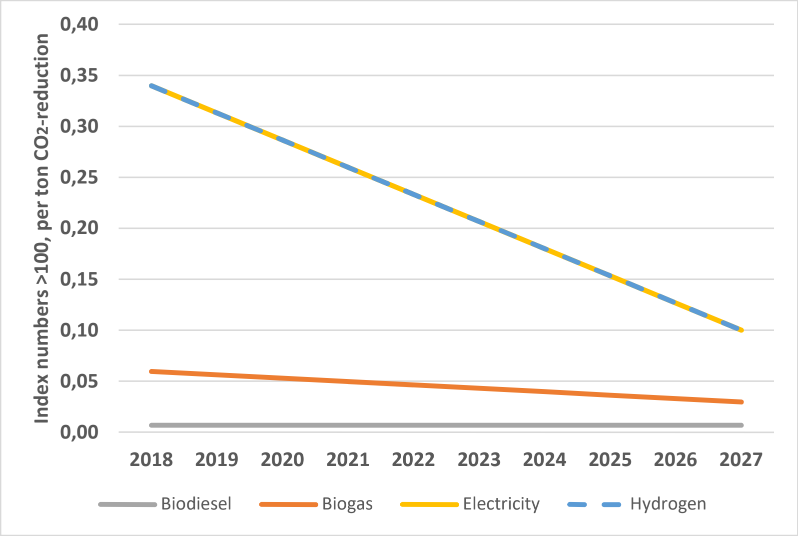

Figure 2.2. Developments in cost efficiency: number of index points above the 100 baseline (i.e. index of additional costs), that are required for a one-ton reduction in CO_2-emissions.

2.5 Emissions and climate accounting

The adoption of biofuels is surrounded by controversy. Besides ethical concerns (e.g. food security, biodiversity reduction, employment, consequences for subsistence farming), the total lifecycle of some biofuels involves higher, rather than lower global CO_2-emissions, compared to fossil counterparts (e.g. Pimentel & Burgess, 2014). The climate impact of biofuels will primarily depend on the type of biomass used, its sourcing and production, and the distribution of the fuel. In this study, we assume the use of biodiesel for which total lifecycle CO_2-reductions are more generally accepted (see e.g. Weber & Amundsen, 2016).

To calculate emissions for different vehicles, we considered the fuel consumption per kilometer and the CO_2-intensities per energy unit for both the conventional fuel and the alternative energy source ($in\ {}^{l}/_{km} * {}^{MJ}/_{l} * {}^{CO_2}/_{MJ}$). To the extent feasible, we used emission factors from a European standard for CO_2-emissions from renewable fuel sources (NEN-EN 16258; Nederlandse norm, 2012), which accounts for cultivation, processing, transport, and distribution. As this standard does not distinguish between different types of biodiesels, we further used the same assumptions as the Norwegian Environment Agency in its climate measures evaluations and emission projections towards 2030 (NEA, 2015).

According to NEA, the production of biofuels currently largely takes place abroad. From a climate accounting perspective, replacing fossil fuels with imported biofuels therefore results in Norwegian emission reductions of almost 100 percent. Although our main analysis will follow this reasoning, we also carried out more conservative analyses assuming that biofuels only reduce emissions by 60 percent globally (over the full life-cycle). This is based on prescriptions (NEA, 2015) that biofuels only qualify as 'sustainable' if they reduce emissions by at least 50% for 2017, and 60% for 2018, the fund's first year, and on the European Renewables Directive (European Parliament, 2009).

Emissions from electric or hydrogen vehicles, in turn, are also considered to be zero – again in line with NEN-EN 16258. During the production phase of these fuels, the use of hydropower implies that Norwegian emissions are zero from a climate accounting perspective, while during the use phase, CO_2-emissions are also zero. Table 2.3 summarizes the CO_2-emissions per kilometer for alternative fuel types and vehicles.

Table 2.3. CO_2-emissions (kg) per kilometer for different fuel types and vehicle categories. For biofuels, we show emissions under both the climate neutrality assumption and the more conservative 60%-reduction assumption. Sources: European standard NEN-EN 16258 and assumptions NEA (2015).

	B7	**Biodiesel**	**Biogas**	**Electric**	**Hydrogen**
Vans	0.25	0 / 0.10	0 / 0.10	0	0
Distribution trucks	1.06	0 / 0.44	0 / 0.44	0	0
Long-haul trucks	1.24	0 / 0.52	0 / 0.52	0	0
Tractor units	1.23	0 / 0.52	0 / 0.52	0	0

Climate change is, however, a global problem, for which it does not matter whether emission reductions take place in Norway or elsewhere. A rising domestic electricity demand for powering transport may, for example, reduce the export of 'clean' Norwegian electricity to other European countries, which in turn could increase fossil fuel use and CO_2-emissions in those countries. Assuming that the use of hydropower or imported biofuels results in zero emissions does therefore not account for the full global climate effects. It is, however, the leading approach in per country climate accounting and political discussions, and therefore the method presented in this paper.

2.6 Infrastructure

Estimates on the costs of developing and constructing different types of filling stations were based on information from suppliers of different fuel types and information from Enova (in: Norwegian Public Roads Administration, 2013). Given the characteristics of the different technologies, filling stations, and use patterns, we assumed that a sufficient infrastructure for heavy vehicles in Norway consists of:

- Ca. 60 hydrogen stations
- Ca. 140 biogas stations
- Ca. 700 biodiesel stations
- Ca. 500 electrical fast-charging points, suitable for trucks

Unlike electric passenger cars, which can typically be charged overnight, restrictions posed by operation schedules for trucks will generally require special, fast chargers. Such charging networks should not be confined to larger urban areas, but also cover locations in between, at rest areas, etc. This critical need is reinforced by the (currently) relatively short driving ranges for trucks with electrical propulsion.

2.7 Biofuel availability

Our analysis presupposes that sufficient sustainable biofuels are available to accommodate the subsidies under each of the scenarios in the following paragraph. This assumption may be critical, as the potential for emission reductions will in many cases be driven by the availability of biofuels (which is restricted by the area of cropland that is available for biomass production, without leading to adverse land-use impacts).

Campbell et al. (2009), for example, carry out life-cycle assessments for bioethanol and bioelectricity, and find that bioelectricity yields considerably higher CO2-offsets than cellulosic ethanol, for several types of biomass, production technologies, and vehicles. Given the limited area for producing this biomass, the authors therefore argue that efficiency should be maximized by choosing bioelectricity applications, rather than bio-combustion fuels. Our analysis facilitates this line of thought by allowing scenarios in which electricity and hydrogen applications gradually receive larger subsidy shares, once they have become techno-economically viable for larger-scale use on freight vehicles.

2.8 Scenarios

We constructed six scenarios to analyze the costs and effects of a possible CO_2-fund. Four of the scenarios were based on 'extremes' with full reliance on either biodiesel, biogas, electricity or hydrogen. In the fifth scenario ('Combined 1') we allocated the share of the subsidies going to rolling stock as follows: 50% to biodiesel vehicles, and the remaining part equally dispersed with 16.7% to hydrogen, electricity and biogas respectively.

In the last scenario ('Combined 2'), we took into account the maturity of electric and hydrogen technology: During the first years of the fund, most emphasis is put on subsidizing biodiesel vehicles and infrastructure, with some of the fund's proceeds going to investments in electric and hydrogen infrastructure. After a few years, emphasis shifts from biodiesel to electric and hydrogen; first to lighter distribution trucks, later also to heavier trucks, facilitating the argument by Campbell et al. (2009).

In addition, the shares of the fund's proceeds going to infrastructure are chosen such that in all scenarios, sufficient infrastructure is constructed for all applicable technologies. This assumption is important for our results: in the four 'extreme' scenarios, only infrastructure for one technology is constructed. This leaves a larger share of proceeds available for subsidies to rolling stock. In the fifth and sixth scenario, a larger share of the fund's proceeds is required for subsidizing the construction of several types of infrastructure.

2.9 Results calculation for rolling stock

Above assumptions, data, and scenarios are used to assess the effects of a CO_2-fund in chapter 4. We started out with the projections for emissions and diesel sales given 'business as usual'. Using the fund's assumed participation rate, we then calculated the fund's proceeds in year 1 by multiplying the fuel consumption of the fund's participants with the per litre participation fee.

The allocation of these proceeds and the costs of different measures then determines the number and types of subsidies in the different scenarios. The fuel and vehicle characteristics described above were used to calculate the corresponding reductions in emissions and diesel sales. We then corrected the projected diesel sales (being the proceed basis) under 'business as usual' for year 2, for the downward effect of previously awarded subsidies. This process was reiterated until the fund's last year. Although no more subsidies are given after this last year, previously awarded subsidies continue to have an effect until the last subsidized vehicle reaches the end of its lifetime.

2.10 Results calculation for infrastructure

Because effects from the construction of infrastructure are difficult to estimate and more uncertain than for rolling stock, results for infrastructure are calculated separately. The development of infrastructure results in CO_2-reductions if expanded distribution networks for alternative fuels are also used by passenger cars or other vehicles not subsidized by the fund (CO_2-reductions from vehicles that have received subsidies are already included in our calculations).

To arrive at CO_2-reduction estimates, we assume that hydrogen, biodiesel and biogas stations reduce the use of regular diesel (B7) by respectively 500,000, 1,500,000 and 2,000,000 litres yearly. For hydrogen and biogas, these assumptions are based on information from suppliers of hydrogen and biogas for fuelling purposes, while estimates for biodiesel are based on sales volumes for different types of filling stations from Madslien et al. (2013).

For hydrogen stations, we assume that 75% of the reduction in regular diesel sales can be attributed to unsubsidized vehicles, and therefore regarded as additional CO_2-reduction. For biogas- and biodiesel stations, we used shares of 50% and 25% respectively. Although these shares are based on judgement, hydrogen stations are expected to cover the passenger car market to a larger extent, as hydrogen is a less mature technology for heavy vehicles than biofuels.

For electrical charging points, it is difficult to estimate the additional CO_2-reductions resulting from constructing public fast charging points. Figenbaum et al. (2013) point out that new charging points do not necessarily result in more people using electric cars, but that owners of electric cars will be able to use their cars for longer trips. As we lack data on the number of users per charging point, we have not included electric infrastructure in our calculations.

In order to estimate additional CO_2-reductions from the construction of infrastructure, we took into account the allocation of proceeds in the different scenarios. Here too, it should be emphasized that filling stations result in CO_2-reductions beyond the year they are built, and after the fund's lifetime.

3. CO_2-emissions, measures, and technology for reducing emissions

3.1 Emission developments and forecasts

Given existing measures and policies, Norwegian CO_2-emissions from transport are expected to increase considerably towards 2030. Based on forecasts for transport demand for the Norwegian National Transport Plan 2017-2029 (Hovi et al, 2015) and the Norwegian Environment Agency's projections[1] (NEA, 2015), emissions from the industry's transport will rise from roughly 9 million tons CO_2 in 2014 to almost 10.6 million tons in 2030. Figure 3.1 shows these projections, divided over different transport segments. Although emissions from coastal shipping might be somewhat underestimated (DNV GL, 2015), the figure illustrates that particularly road transport is a driving force behind emission increases. For heavy trucks, which are the primary focus of this study, emissions are expected to rise from 2.4 million tons CO_2 in 2014 to 2.9 million tons in 2030.

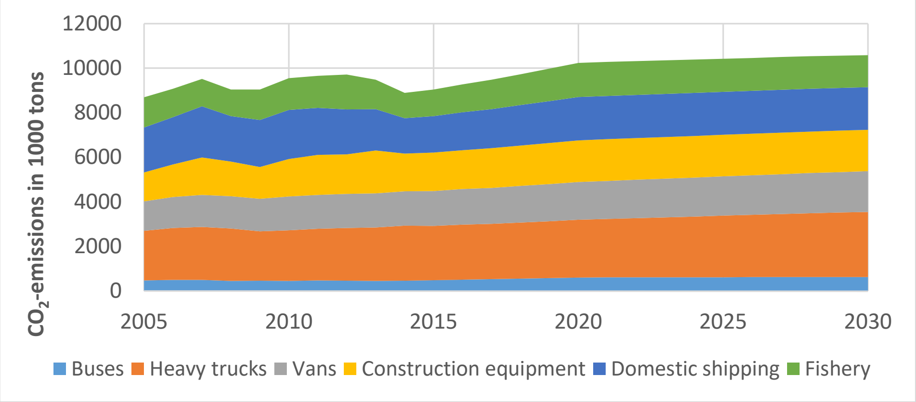

Figure 3.1. Emissions in CO_2-equivalents from the industry's domestic transport. Figures up to 2014 come from Statistics Norway (SSB); figures for 2020 and 2030 are projected by Hovi et al. (2015) for heavy trucks, and the Norwegian Environment Agency (other categories). Figures in 1,000 tons.

3.2 Current measures and instruments

The rising emissions illustrated above illustrate the need for additional measures and instruments. At present, Norway employs a range of measures and instruments aimed at influencing infrastructure usage, vehicle fleet composition, and negative external effects from road transport. The most important ones are summarized from Hovi et al. (2014), and described below.

The first measure is a road use levy, which is differentiated by fuel type, and collected at the point of sale. For diesel, this levy is 3.44 NOK (ca. EUR 0.37/USD 0.41) per litre for 2016. In addition, fuel is charged with a per litre CO_2-levy, again dependent on the fuel type. For diesel, this levy currently amounts to 1.12 NOK (ca. EUR 0.12/USD 0.13) per litre. These measures provide incentives for reductions in the consumption of fuel, by driving less, choosing technologies that use less fuel, and/or choosing fuel technologies that produce fewer negative externalities, and hence face a lower levy rate (Bragadóttir et al., 2015).

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[1] After pointing out that some of their original numbers were incorrect, we received corrected numbers from NEA.

In addition, vehicles over 7,500 kg are charged a yearly weight levy, divided into two parts. The first part is differentiated by weight and number of axels, whilst the second part is differentiated based on the vehicle's environmental characteristics (euro-class).

Besides these taxes and levies, Norway has a range of toll roads, concentrated around large(r) cities and on the major roads network. Heavier vehicles pay higher toll charges, and in some cities an additional rush-hour levy, which disadvantages transport by road. Switches to other modes are also incentivized with a strategy that recently passed Norwegian Parliament. This strategy aims at transferring 30% of (primarily longer-distance) goods transport by road, to transport by ships and trains. This will be done by implementing subsidies for ship transport, and also by prioritizing these transport modes in other ways (Stortinget, 2016).

3.3 Use of alternative technologies

Despite the measures and instruments described above, the adoption of alternative technologies remains slow. For heavy trucks, diesel remains the dominant choice. Of the ca. 66,000 trucks registered in Norway in 2014, over 93% used diesel, while virtually all remaining trucks relied on gasoline (Opplysningsrådet for veitrafikken, 2015).[2] Additional data from Statistics Norway (2015) indicates that new truck sales, including 2015, are also still directed at diesel-technology, and that only a negligible number of new trucks employs alternative technologies.

To illustrate, the diesel share for vans is also very high, with over 92% in 2014 (OFV, 2015), but the number of electric vans has recently shown a clear upward trend following incentives and improved maturity. At the same time, the number of electric passenger cars has also shown a marked increase (Statistics Norway, 2015). Fully electric passenger cars are exempt from toll charges, registration tax, annual taxes and VAT on their purchase. Combined with several practical advantages, this has made Norway Europe's market leader for electric vehicle adoption in both market share and absolute numbers. An evaluation of the contribution and importance of different electric vehicle incentives by Fearnley et al. (2015), suggests that attractive incentive structures can considerably contribute to the adoption of alternative technologies, given that their technologies have sufficiently advanced for practical use.

3.4 'Carrots' and 'sticks'

As described earlier, the Norwegian Green Tax Comission (2015) identifies taxes and levies as the primary means to reduce emissions from transport. At the same time, little to none attention is given to more positive instruments, such as subsidies for stimulating research, development, and the adoption of new technologies. In theory, axes and levies could be cost-effective instruments for reducing emissions (Musso & Rothengatter, 2013). However, in practice, environmental taxes and levies are often set at levels that do not result in socially optimal outcomes, for example because they are also motivated by fiscal or other reasons (e.g. Carlén (2014), and often attract resistance.

One way of making taxes or levies more politically acceptable, is to earmark or 'refund' the proceeds towards publicly desirable objectives, as is done in the proposed CO_2-fund. Hagem et al. (2015) describe three of the few real-life examples where (NOx)-

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[2] The diesel share for the ca. 8,600 tractor units was 99.9%.

levies and subsidies are combined. While combinations of taxes and subsidies are addressed in a number of papers, the authors point out that set-ups like for the Norwegian NOx-fund, where tax proceeds on emissions are refunded through direct subsidies on abatement measures, have hardly been analyzed before. One of the contributions of the present assessment is therefore the quantification of the environmental effects of a CO_2-fund, which allows for comparisons with other measures aimed at emission reductions.

3.5 The NOx-fund in practice

The NOx-fund was established in 2008 and consists of an agreement between the Norwegian Ministry of the Environment[3] and a consortium of industry organizations on the reduction of NOx-emissions. Industry actors who join the NOx-fund see their NOx-levies reduced in exchange for concrete emission reduction measures. After a slow start, the fund has so far helped reduce Norway's NOx-emissions by 30,000 tons, with a side effect of also reducing CO_2-emissions by half a million tons (NHO, 2015).

Although it can be argued that NOx-emissions have been going down in Europe regardless of method, this is different for Norway, where marked NOx-reductions only picked up around the establishment of the NOx-fund in 2008 (see figure 3.2). Norway's oil & gas and domestic shipping & fishery industries together made up between 52-56% of domestic NOx-emissions in the years 2008-2014 (Statistics Norway, 2016). Although contributions to the NOx-fund have to a large extent come from the oil & gas-sector, subsidies have primarily been aimed at domestic shipping & fishery, for which emission reductions of over fifty percent were achieved during this period. Meanwhile, NOx-emissions from the oil & gas industry have remained relatively stable (Hagem et al., 2014 & Eurostat, 2016).

Regarding NOx-emissions from road transport, Norway did largely follow the European downward trend (figure 3.2). A driving force behind particularly these reductions in NOx-emissions is the Euro Directive (see also Caspersen and Hovi, 2015).

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[3] Now the Ministry of Climate and Environment

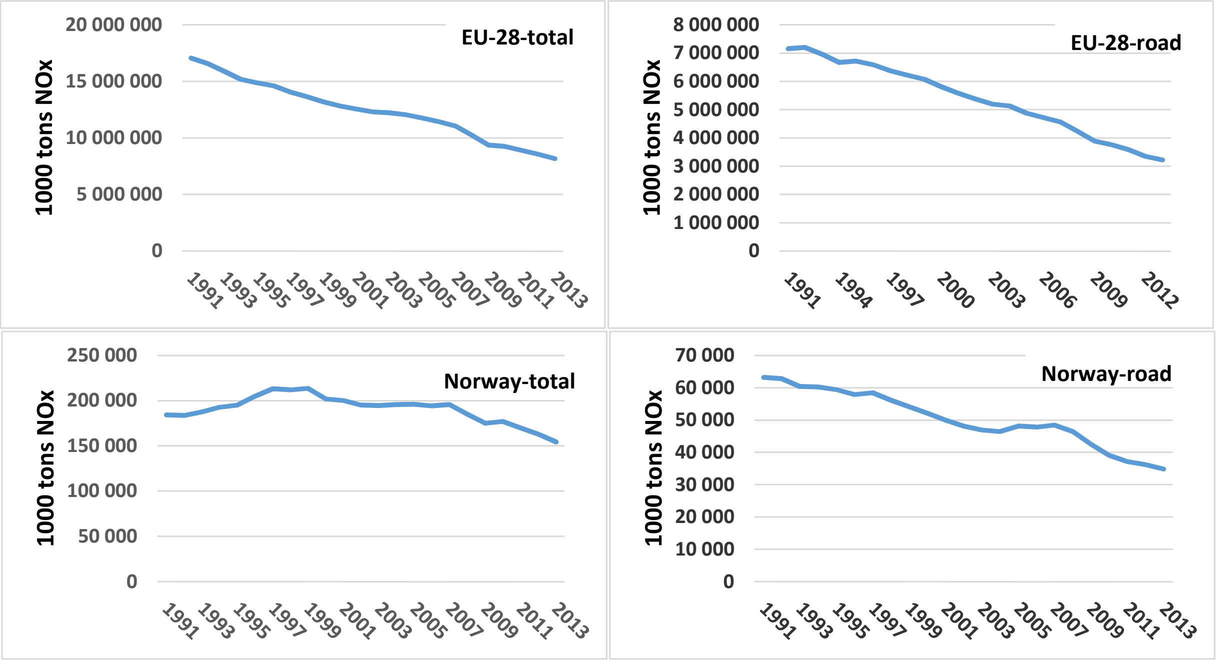

Figure 3.2. Yearly NOx emissions between 1991-2013 in total (upper left: EU-28, lower left: Norway), and confined to road transport (upper right: EU-28, lower right: Norway). Figures in 1000 tons. Source: Eurostat and Statistics Norway data on NOx emissions divided by source.

3.6 Challenges of a CO_2-fund

The proposed CO_2-fund works on a similar premise as the NOx-fund: it accommodates and speeds up the adoption of alternative technologies that result in lower emissions. Instead of a CO_2-levy, industry actors joining the fund pay a (lower) participation fee in return for committing to a plan for taking emission reducing measures. The fund's proceeds are returned through subsidies towards the additional costs of renewable-based rolling stock and infrastructure. As a result, important cost-barriers for the transition to alternative technologies are greatly reduced.

An important difference between the NOx-fund and a CO_2-fund is that the NOx-fund has 900 members and a participation rate of almost 100% within its relevant sectors. In addition, two thirds of its proceeds come from the oil- and gas industry. A CO_2-fund for the private sector for heavy truck transport would require a considerably higher number of members, which could make controlling and enforcing commitments by participants more difficult. According to Statistics Norway, there are about 9,200 firms within road transport, of which 15%, or some 3,400 firms, are responsible for 70% of employment. These numbers should be reasonably good proxies for the share of transport these firms are responsible for. Additionally, several large firms that manage their own transport solutions could also be potential participants of a CO_2-fund.

Other differential factors that may affect the success of a CO_2-fund are mostly of a techno-economic nature. Technological alternatives that result in lower CO_2-emissions for example require relatively large changes to vehicles and infrastructure, compared to the NOx-fund case. In addition, these technologies are still expensive, result in higher depreciation rates, and may not yet be practically viable. Electric trucks, for example, currently still face short driving ranges, which, combined with an underdeveloped infrastructure for fast chargers, does not make the technology practicable for use by most firms. Despite abovementioned differences, the primary reasoning behind the NOx-fund can also be applied to the transport sector.

3.7 Alternative technologies

When it comes to transitions to alternative technologies for road transport, biofuels (e.g. biodiesel or biogas), hydrogen, and electricity are considered most promising (Connolly et al., 2014). The extent to which these alternative technologies result in emission reductions depends on the production methods and raw materials used.

Biodiesel, for example, exists in several varieties and generations and can, amongst others, be based on reactions between vegetable oils and methanol, the hydro treatment of vegetable oils, or raw materials from forests. Biogas can also be produced using many sources, such as sewage sludge or food waste, or livestock manure. In Oslo, biogas from sewage sludge is for example used for waste disposal trucks.

Hydrogen can be produced by splitting water into hydrogen and oxygen through electrolysis. Hydrogen produced in this way is climate neutral if produced from non-fossil sources, and can potentially be produced by many power producers around Norway. On an industrial scale, hydrogen is currently often produced using natural gas. Unless combined with carbon capture and storage, such hydrogen is not climate neutral.

Some types of pure biodiesel can directly replace fossil fuels in newer combustion engines, and adaptation costs or additional costs for new vehicles are relatively low. Using biogas, in turn, usually requires larger and considerably more expensive vehicle adaptations.

Hydrogen requires even larger and more expensive adaptations. Although hydrogen use is still in an early stage, Toyota is expected to introduce a passenger car onto the Norwegian market this year, and several other car manufacturers are also working on hydrogen cars. Public transport company Ruter currently runs a pilot project in Oslo, where 5-8 hydrogen buses are operated at relatively high capacity. This indicates that hydrogen technology can also be feasible for use on heavy vehicles.

For heavy vehicles running on electricity, range limitations are still a pressing issue (Pelletier et al., 2016). While smaller electrical trucks are gaining some market share, larger trucks are still only built on a small scale or individual orders. Although this currently leads to high additional costs, these costs are expected to decrease as market demand increases following technological progress (e.g. Anandarajah et al., 2013).

3.8 Infrastructure

In addition to cost issues and technological limitations, insufficient distribution networks and infrastructure may also pose a barrier for the adoption of above technologies. Although driving ranges for biofuels and their fossil counterparts are similar, there are about 1,600 regular filling stations in Norway (Norwegian Petroleum Institute, 2016), but currently only 5-6 filling stations for pure biodiesel. For biogas, AGA (a large supplier) has only established 15 stations in Norway so far (Melby, 2015).

Although hydrogen vehicles generally have larger driving ranges, there are still only 5 hydrogen stations in Norway, concentrated around greater Oslo. However, there are indications of developments: a hydrogen supplier announced plans to construct 20 more stations by 2020, and hydrogen infrastructure has in recent years seen large expansions in amongst others Germany (Ehret and Bonhoff, 2015). For electric vehicles, the current electric infrastructure consists of 1,875 charging stations with about 7,700 charging points (about 720 non-specialized fast-chargers of ≥43 kW (NOBIL, 2016), and is almost exclusively catering the passenger car market.

A large-scale adoption of electric trucks will therefore particularly require the expansion of networks for fast charging and locations for induction charging. Due to trucks' use patterns and the driving range of electric trucks, these fast chargers need to be built also outside of urban areas, e.g. at resting points.

The expansion of some or all of these infrastructure types entails large costs. At the same time, the construction of distribution networks may also speed up the adoption of alternative technologies by other vehicles, like passenger cars, and contribute to breaking barriers and achieving critical masses.

4. Results

4.1. Rolling stock

Previously, we saw that yearly emissions from heavy truck transport are expected to rise from 2.4 million tons CO_2 in 2014 to 2.9 million tons yearly by 2030, given current developments and instruments.

The potential emission reductions resulting from a CO_2-fund depend on the type and number of measures implemented, and at which segments of the transport market these subsidies are directed. Subsidies to long-haul trucks will for example result in larger CO_2-reductions than subsidies to local distribution vehicles.

Table 4.1 illustrates how subsidies are allocated in every scenario, over the fund's entire lifetime. As explained earlier, the 'combined' scenarios require a considerably larger share of proceeds going to infrastructure than the 'extreme' scenarios. In the 'extreme' scenarios, proceeds are allocated such that sufficient distribution networks will have been established after 6-7 years. In the combined scenarios, the construction of (a higher number of) filling stations is more spread out over the entire fund's existence.

Other noteworthy results include the number of different types of vehicles that can receive subsidies in the different scenarios. In the biodiesel 'extreme', the total number of subsidized vehicles is for example much higher than in the hydrogen scenario. These differences are largely due to the cost differences between investments in different alternative technologies. For all scenarios, subsidies were allocated such that the total number of subsidized vehicles would remain plausible relative to the total number of registered vehicles.

Table 4.1. Number of subsidies in each scenario over the fund's entire lifetime, as well as the distribution of the fund's revenues over infrastructure and rolling stock.

	Number of subsidies, filling stations					Number of subsidies, rolling stock		Share of revenues to		Of which	
	Hydrogen	Biogas	Biodiesel	EL	**TOTAL**	Long-haul	Local distribution	Infra-structure	Rolling stock	Long-haul	Local distribution
Hydrogen	51				51	1,610	4,277	12%	88%	29%	59%
Biogas		110			110	6,452	12,905	10%	90%	30%	60%
Biodiesel			536		536	13,255	26,510	17%	83%	28%	55%
Electricity				425	425	1,686	4,482	8%	92%	31%	62%
Combined 1	38	118	544	399	1,099	12,092	12,204	48%	52%	26%	26%
Combined 2	67		675	449	1,191	7,278	13,211	36%	64%	29%	35%

With above allocations, the following results are obtained:

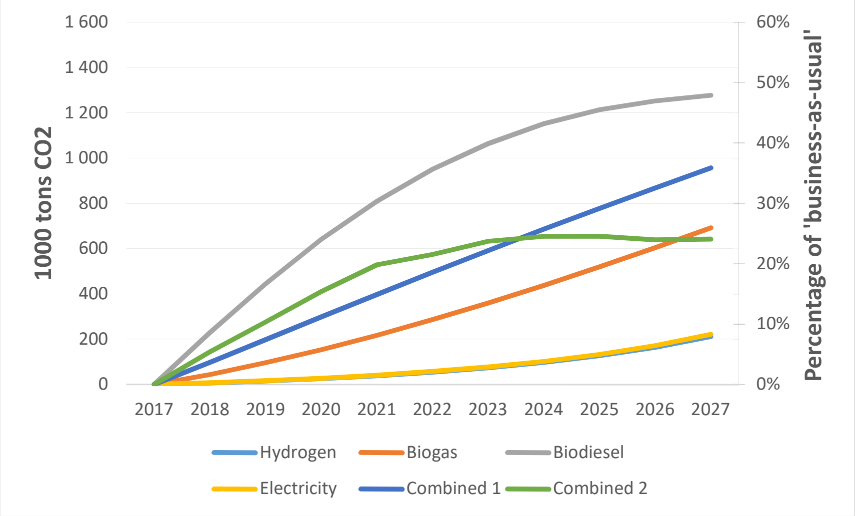

Figure 4.1. Yearly CO_2-reduction in each scenario from subsidized rolling stock, relative to 'business as usual'. Figures in 1,000 tons CO_2 (left axis), and as percentage of 'business as usual' (right axis).

Figure 4.1 shows the yearly CO_2-reductions resulting from a CO_2-fund, relative to 'business as usual'. The left axis shows CO_2-reductions in thousand tons, while the right axis expresses reductions as a percentage of emissions under 'business as usual'. Emission reductions are largest when all of the fund's proceeds are used for subsidies towards biodiesel technology, and amount to 48% in the fund's last year. This is due to biodiesel adaptations being relatively cheap, which makes these subsidies relatively cost-effective. In the two 'combined' scenarios, a considerable share of subsidies goes to biodiesel vehicles as well. This explains why the 'combined' scenarios also yield larger emission reductions than full reliance on biogas, electricity or hydrogen vehicles. In 'Combined 2', yearly emission reductions start to fall during the last years of the fund. This is due to more cost-effective subsidies to biodiesel slowly being replaced by less cost-effective subsidies to electric and hydrogen vehicles in later years.

Figure 4.2., in turn, shows the development of the fund's yearly proceeds, which are determined by the participation rate, the per litre participation fee, and the fuel consumption by the fund's members.

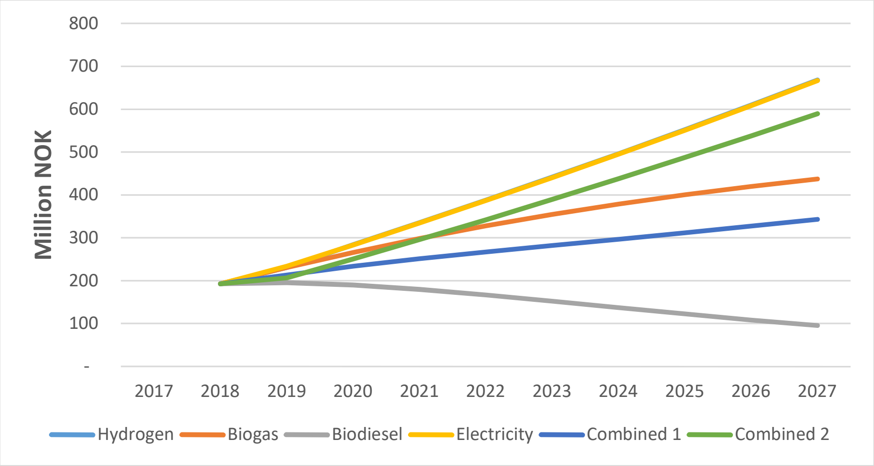

Figure 4.2. The fund's yearly revenues in each scenario. Figures in million NOK.

The figure illustrates that yearly proceeds decrease rapidly in the biodiesel scenario, while proceeds increase for all other scenarios. As biodiesel adaptations are relatively cheap, the number of conventional vehicles replaced in the fund's early years is relatively large. This leads to a reduction in the consumption of (fossil) fuels that are subject to a levy. As a consequence, the proceed basis for the fund diminishes faster than the participation rate increases. The opposite is true for the hydrogen and electricity scenarios; here, the fund's proceeds increase steadily, driven by increasing participation rates and relatively small reductions in diesel sales.

After the fund's final year, annual CO_2-reductions start to decrease year by year until 2048, when the last vehicles that received subsidies reach the end of their lifetime. Annual CO_2-reductions decrease because the driving distance of a vehicle is generally highest in the first year of its use, and then decreases over time. Nevertheless, the fund still achieves CO_2-reductions in the 20 years after its final year: figure 4.3 shows that the accumulated CO_2-reduction in the scenario with full reliance on biodiesel is 13 million tons in 2027, but 18 million tons in total. In other words, almost a third of the CO_2-reduction materializes after the fund's final year. Similar results are found for the other scenarios.

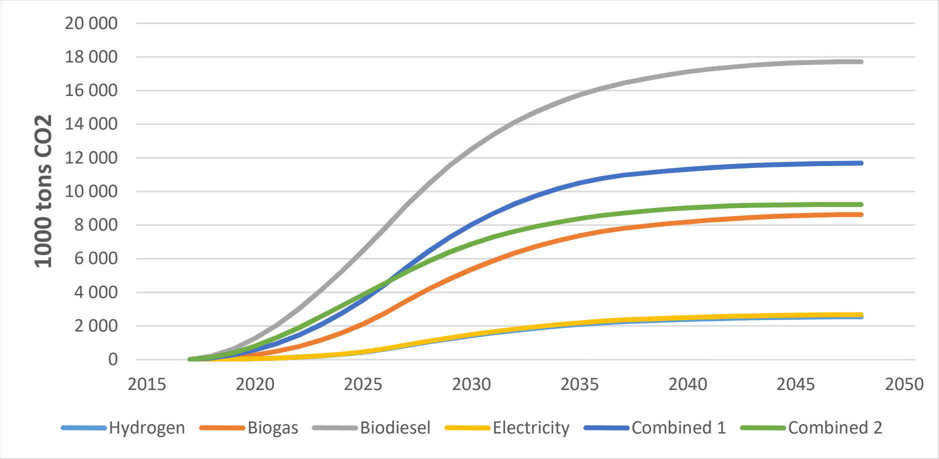

Figure 4.3. Accumulated CO_2-reduction in each scenario from subsidized rolling stock, relative to 'business as usual'. Figures in 1,000 tons CO_2.

4.2. Infrastructure

The previous section discussed CO_2-reductions from subsidies to rolling stock, relative to 'business as usual'. In addition, the construction of corresponding infrastructure is not only necessary for the use of vehicles with alternative technologies, but it also yields additional (indirect) CO_2-reductions. Ideally, one would compare different scenario results based on CO_2-reductions from both rolling stock and infrastructure. As estimates for infrastructure are more uncertain than for rolling stock, and as we lack estimates on electric infrastructure, we chose to separate these results.

Figure 4.4 shows the yearly additional CO_2-reduction resulting from subsidizing investments in infrastructure, based on assumptions described earlier. CO_2-reductions are highest in the two combined scenarios, amounting to between 0.73 and 0.88 million tons CO_2 in the fund's last year. These results are not surprising: as the combined scenarios require sufficient distribution networks for several technologies, a larger share of the fund's revenues is allocated to infrastructure, resulting in much higher numbers of filling stations than in the 'extreme' scenarios.

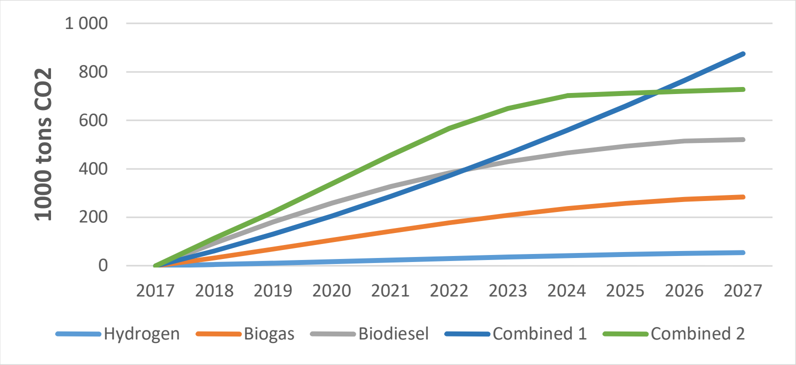

Figure 4.4. Yearly CO_2-reduction in each scenario from subsidized infrastructure, relative to 'business as usual'. Electrical infrastructure not included. Figures in 1000 tons CO_2.

Figure 4.5 shows the accumulated CO_2-reduction during the fund's lifetime. Due to its large number of filling stations, the biodiesel 'extreme' also yields considerable additional CO_2-reductions behind the two 'combined' scenarios. Given unchanged use, the yearly additional CO_2-reduction per station after the fund's last year is equal to the reduction in this last year, until the last life year of the infrastructure. The accumulated additional CO_2-reduction therefore continues to rise after the fund's resolution.

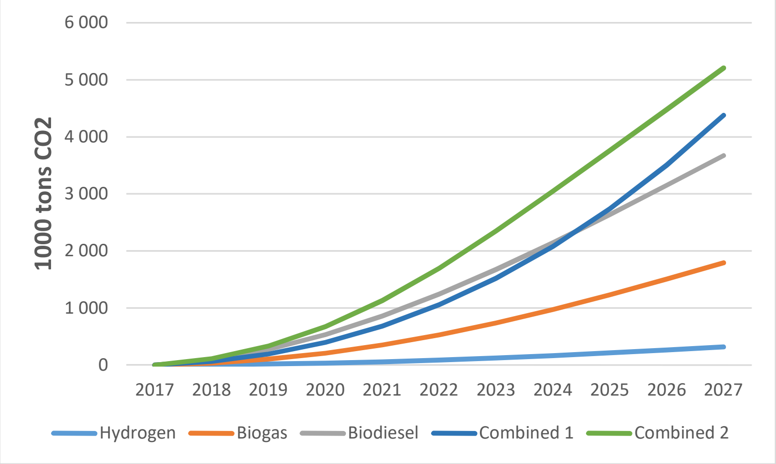

Figure 4.5. Accumulated CO_2-reduction in each scenario from subsidized infrastructure, relative to 'business as usual'. Electrical infrastructure not included. Figures in 1000 tons CO_2.

It remains important to emphasize that no potential additional CO_2-reductions from electric infrastructure were included. Results might therefore underestimate the CO_2-reduction in the full electric 'extreme' and the combined scenarios.

5. Discussion

The idea of a CO_2-fund is not new, and has both upsides and downsides. By employing 'carrots' in the form of reduced CO_2-levies, implementation will likely meet less resistance from the industry and public than when only 'sticks' or stringent command-and-control regulation are used. An additional advantage of a centralized fund is that it can be used to coordinate individual action, build up expertise, and possibly to use its scale to improve bargaining power. Together, these aspects may increase cost-effectiveness and contribute to achieving critical masses.

A CO_2-fund like the one analyzed in this study, however, also faces several downsides. Firstly, participation makes transport cheaper, as the participation fee is set below the prevailing CO_2-levy. Although this provides an incentive to participate, it does not provide participants an incentive to follow through with their mandatory plans for emission reducing measures. The fund will therefore need effective enforcement mechanisms in order to achieve actual emission reductions, particularly given the high number of participants. These challenges are aggravated if reduced driving costs results in higher transport demand than under 'business as usual', resulting in a 'leakage'.

Secondly, the analyzed fund only (partially) covers additional investment costs. Besides higher investment costs, renewable-based propulsion systems and infrastructure often face higher operating and maintenance costs, and currently face several techno-economic barriers. In addition, the lack of a developed second-hand market results in low residual values and higher depreciation rates for vehicles with alternative technologies. Altogether, these factors make investing in alternative vehicles less attractive. It might therefore be worth considering including such factors when awarding subsidies, and performing further analyses, taking into account the sum of investment and operating costs over a vehicle's lifetime.

A third downside to the fund is that it reduces the proceeds from CO_2-levies, implying that more government income will have to be sourced elsewhere.

An alternative could be to earmark current CO_2-levies for use towards subsidies, without first giving a participation 'discount'. This way, per litre proceeds are higher than is the case for the fund, and a larger number of subsidies can be awarded. In addition, there would be no 'leakage' from increases in (cheaper) transport demand, and no incentive to 'free-ride' without intention to act.

However, giving no (or smaller) 'discounts' on current CO_2-levies provides a lesser incentive to participate. In the end, a balance will probably have to be found between participation incentives, financial consequences, and effectively reducing emissions.

Our calculations, in turn, are based on thorough analyses on the development of transport demand, and in addition on real-life experiences from the NOx-fund. For many aspects, we were able to use actual data and educated estimates (e.g. distribution of driving distances over lifetime). Nevertheless, we were also forced to make several important assumptions. Particularly the estimates on CO_2-reductions from infrastructure investments are more uncertain, and subject to assumptions. This uncertainty, combined with lacking data for estimating the effects from constructing electrical infrastructure, made us unable to compare the total effects of every scenario.

6. Conclusions and final remarks

Given current measures and policies, Norwegian emissions from transport are expected to rise from almost 9 million tons CO_2 to 10.6 million tons in 2030. The largest drivers behind this increase are road transport, and in particular heavy truck transport. For heavy trucks, emissions are expected to rise from 2.4 million tons CO_2 in 2014 to 2.9 million tons CO_2 in 2030 under 'business as usual'. This implies that there is a considerable reduction potential for emissions from transport by heavy trucks.

While the Norwegian Green Tax Commission recently confined itself to recommending 'sticks' to achieve emission reductions, our study assesses a CO_2-fund using both 'sticks' and 'carrots'. The fund is modelled after the Norwegian NOx-fund, and rewards participants by charging a lower fee per litre fuel than the current CO_2-levy. In return, participants commit to emission reducing measures that can (partially) be subsidized using the fund's proceeds.

This study analyzed the effects of a CO_2-fund using four 'extreme' scenarios with full reliance on either hydrogen, biogas, biodiesel, or electricity, and two 'combined' scenarios, in which the implementation of different technologies is pursued alongside.

Looking only at the effects of subsidies to rolling stock, full reliance on biodiesel results in the largest CO_2-reductions in the fund's last year (1.4 million tons annually or 48% of the emissions under 'business as usual'). This is due to the relatively low costs for adapting vehicles for the use of biodiesel. The two combined scenarios also achieve considerable CO_2-reductions, which, again, is driven by large shares of (cost-effective) subsidies directed at biodiesel adoption. At the same time, full reliance on biogas results in a CO_2-reduction of about 24% of emissions under 'business as usual', while both hydrogen and electricity achieve reductions of some 8% in the fund's last year. However, the fund's effects don't cease after its last year; in most scenarios, about a third of total CO_2-reductions materializes thereafter.

Ideally, one would compare the different scenarios based on CO_2-reductions resulting from both subsidies to rolling stock and subsidies to infrastructure. This distinction is important, as in the 'extreme' scenarios a considerably larger share of proceeds is allocated to infrastructure. However, as estimates on CO_2-reductions from the construction of infrastructure are more uncertain, these should be interpreted with more caution. Particularly for electrical infrastructure, it is uncertain to what extent the development of infrastructure can or will lead to additional CO_2-reductions. We therefore refrained from adding up CO_2-reductions from subsidies to both rolling stock and infrastructure.

Altogether, our analysis indicates that it is most cost effective to allocate subsidies to vehicles using biodiesel, but that the availability of sustainable biofuels may pose a challenge. This is, however, a critical assumption on which the potential for emission reductions in many cases will depend. A potential CO_2-fund should therefore also consider allocating subsidies to more expensive technologies based on biogas, electricity, and hydrogen. Technologies for the latter two options are still immature for use on heavier trucks, but a CO_2-fund may contribute to increasing demand for these technologies and speed up the achievement of a critical mass. There are also indications that the limited area of available cropland for biomass production, warrants a pathway towards bioelectricity, rather than bio-combustion fuels.

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Article

Experiences from Battery-Electric Truck Users in Norway

Inger Beate Hovi *, Daniel R. Pinchasik, Erik Figenbaum and Rebecca J. Thorne

Institute of Transport Economics, NO-0493 Oslo, Norway; drp@toi.no (D.R.P.); efi@toi.no (E.F.); rth@toi.no (R.J.T.)
* Correspondence: ibh@toi.no; Tel.: +47-9884-7002

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Abstract: This paper presents experiences from pilot-projects with battery-electric trucks in Norway, focusing on purchasing processes, technology, vehicle choices, user experience and various performance aspects. Furthermore, we discuss the electrification potential for battery-electric trucks and compare their total costs of ownership and associated socio-economic costs with internal combustion engine (ICE) trucks for a range of technological maturity scenarios. The results show that experiences have generally been positive but tailoring of use patterns is often required. Furthermore, at their current maturity level, battery-electric trucks could, to some extent, replace typical use of Norwegian ICE trucks, depending on the situation. In terms of costs, we expect that battery-electric light distribution trucks will first become competitive with ICE trucks when technology reaches mass production.

Keywords: BEV (battery-electric vehicle); case study; truck; electrification potential; TCO (total cost of ownership); ZEV (zero-emission vehicle)

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1. Introduction

Norway's National Transport Plan for 2018–2029 sets ambitious targets for the introduction of zero-emission commercial vehicles as a means to fulfil CO_2 reduction objectives towards 2030. By 2025, all new lighter vans are required to be zero-emission vehicles. By 2030, the same applies to all new heavy vans and 50% of new Heavy Goods Vehicles (HGVs) [1]. Achieving these targets, however, is not straightforward. The Nordic Council of Ministers [2], for example, finds that given current policy, Norway (and other Nordic countries) faces sizable emission reduction gaps in freight transport in light of the 2030 climate objectives, and that major trend changes are needed in the production and adoption of alternative propulsion systems and lower-carbon fuels.

Although several manufacturers have announced intentions to start series production in 2019–2020 [3], the market for zero-emission electric trucks (e-trucks) has, to date, largely consisted of pilot tests, meaning that most trucks with battery-electric powertrains (BE-trucks) are converted versions of standard diesel trucks. In Norway, the first BE-truck became operative (registered) as late as September 2016, and when the current study began in April 2018, this had only increased to three trucks. By July 2019, the Norwegian fleet still counted only 15 e-trucks, all utilizing battery-electric technology, including heavy vans that are registered as light lorries due to their high battery weight. With these numbers, freight vehicles lag behind compared to electric vans and buses, for which production stages are somewhat more mature [3].

By the autumn of 2019, all e-trucks in Norway are still conversions from diesel trucks and heavy vans. Volvo seems to be among the first manufacturers opening sales of small-series BE-trucks from week 42 in 2019, with expected delivery in the first half of 2020, while MAN will be able to deliver a small handful of BE-trucks to the Norwegian market during late 2019 or the start of 2020. For fuel cell hydrogen-electric trucks (FCHE-trucks), there still seems to be some way to go before series-produced vehicles reach the market. In the fall of 2019, however, four FCHE-trucks, converted from diesel truck chassis', will be phased into operation for a major distributor of groceries in central Norway.

The aim of the present paper was to identify and present experiences gained by pilots with BE-trucks in Norway so far. Building on information from pilot users, this work further provides insights into the potential and costs for electrification in both the near term and longer term. This is done by (1) looking at how pilot vehicles are used and what adjustments have had to be made in daily use patterns compared to similar patterns for ICE trucks, (2) analysing user patterns for different vehicle segments, (3) developing cost models that compare total costs of ownership of BE- (and FCHE-) trucks versus ICE-trucks in a number of scenarios for technology maturity, and (4) assessing socio-economic costs of phasing in zero-emission trucks. While the first two analyses thus focus on BE-trucks, in the latter two, it was possible and insightful to also consider FCHE solutions. Understanding user experiences and technological and economic barriers and enablers perceived by operators is crucial for achieving the ambitious uptake of zero-emission vehicles that Norway envisions over the next decade. Particularly for freight vehicles, there seems to be a knowledge gap regarding these topics.

2. Literature Background

To date, research on the adoption of e-trucks has been relatively limited compared to what is the case for passenger cars, and to a lesser extent, buses. This applies both to research on user experiences and on reasons behind the adoption (by firms) of electric vehicles e.g., [4]. For TCO analyses, there are also particularly few studies for medium and heavy-duty vehicles [5]. The main reason for this is that the number of e-trucks is still small and in an early phase. This is caused by prohibitively high purchase prices compared to ICE-vehicles, and by technological and operational limitations and uncertainties, such as short driving ranges, operational stability, resale prices, etc. [6–8].

Although battery-electric heavy-duty vehicles (HDVs) have, to date, reached higher technological readiness levels than their FCHE counterparts and therefore, dominate pilots [7,9], the small number of battery-electric HDVs that are currently in use are largely conversions from diesel vehicles [8]. From 2019, however, several manufacturers have started up selected pilots [8].

When it comes to user experiences, a case study based on interviews of frontrunner companies in Amsterdam [4] revealed that important factors for adoption are positive social and environmental effects, as well as strategic considerations. Respondents reported positive experiences using electric vehicles, but at the same time, technological limitations were identified as adoption barriers. Firms successfully adopting BE-vehicles also reported having to carry out significant adjustments of e.g., route planning. Kleiner et al. [7] reported similar findings in an overview of the status for electric logistics: common experiences across countries are that drivers are generally well-accepting of e-trucks, but that e-trucks have operational limitations compared to ICE trucks, and that the availability and choice of vehicles has, to date, been limited. Kleiner et al. [7] also found that few business cases are provided, and that from these, it becomes clear that specific local characteristics are very important for success (e.g., topography, temperature and availability of (financial) incentives).

With regard to the feasibility of e-trucks in terms of cost competitiveness and technical capabilities, findings are mixed [8]. On the one hand, there are significant extra costs for investing in e-trucks compared to those with ICE. In TCO analyses assessing the current situation, these are generally either calculated by summing cost estimates for different components [10] or based on a small number of observations. This situation leads to estimates that, thus far, are uncertain and vary widely between studies. Estimates of capital cost premiums of electric propulsion systems in the future also vary considerably, particularly for FCHE-trucks [9]. However, there seems to be a consensus that capital cost premiums compared to conventional vehicles will decrease considerably with larger scales of production, with BE-trucks remaining cheaper than FCHE-technology, and reaching cost-competitiveness vis-à-vis ICE at a faster rate e.g., [11–13].

On the other hand, there are operating costs which, due to longer mileages, are more significant for TCO of trucks than for passenger cars [9]. Operating costs for electric propulsion tend to be lower than for diesel vehicles due to, amongst other reasons, higher energy efficiency for electricity and savings on energy costs and general maintenance [5,6,14]. This emphasizes the idea that high utilization may be key for recovering the cost premium of investment, and thereby, for the competitiveness of e-trucks.

Nevertheless, according to Plötz et al. [9], it is this degree of utilization, due to range challenges, that makes the potential for electrifying heavy freight transport by road controversial. Indeed, technological barriers stemming from limited driving ranges and long recharging times are lower for trucks with shorter yearly mileages. This is also the reason why e-trucks are starting to get deployed in urban use cases. For larger trucks and trucks with high annual mileages, barriers for electrification are larger [15].

Comparing BE- and FCHE-propulsion, Mulholland et al. [15] found that BE-systems yield higher energy efficiency but are currently most suitable for shorter-distance driving, due to limited battery capacity and long recharging times. As a potential motivator for the adoption of FCHE-trucks, compared to BE-trucks, a selection of German experts identified the longer driving ranges. However, there are concerns about insufficient fueling infrastructure becoming available [8].

Overall, it is likely that the operational and economic feasibility of electric HDVs is currently still highly dependent on characteristics of the specific use case, not least the public policy instruments.

3. Methodology

The current paper builds on four interrelated analyses: (1) User experiences, (2) Electrification potential in light of typical user patterns, (3) Models for cost of ownership and comparisons of decomposed cost levels for different propulsion technologies, and (4) Socio-economic costs of phasing in zero-emission trucks. The results from the first analysis are presented for different vehicle segments (light and heavy distribution trucks, tractors for semitrailers, refuse collection vehicles, and to a lesser extent, vans). A similar analysis for zero-emission buses in Norway was presented at EVS32 in Lyon [16]. In the other analyses, the presentation of results will focus on light distribution trucks, which seems to be the vehicle segment with the largest electrification potential in the short term (in addition to electric vans, which are already a commercial product category).

3.1. User Experiences

To assess user experiences, we carried out a case study based on semi-structured interviews of enterprises with experience in operating e-trucks in Norway. Sample selection is based on the list of projects [17] that have received support from ENOVA (the Norwegian Government Agency for the transition towards a low-emission society), the Norwegian Public Road Administration's vehicle registry Autosys, as of December 2018 [16], and the project list of 'Klimasats', which is the Norwegian Environment Agency's climate initiative for transitions to low-emission solutions in the public sector. In addition to truck operators, such as freight forwarders, a number of relevant government/public policy bodies and manufacturers were also interviewed.

The interviews were open-ended and conducted as Skype meetings (in Norwegian) with representatives closely involved in investment or policy decisions of each of the identified organizations. As preparation, subjects were sent a questionnaire, after which the open-ended interview questioning allowed them to articulate perceptions freely. To allow clarifications and correction of any misunderstandings, subjects were sent the interview minutes for comments and approval. Although specifics varied, interview questions were related to the vehicle purchase process and supplier, trial experiences (technology choice, design, feedback from owners/drivers/passengers, energy use, range, vehicle performance, service/maintenance, charging performance and use of existing fleet), decomposed investment and operation costs, as well as public frameworks and incentives that could contribute to faster diffusion of zero-emission vehicles into the Norwegian market.

3.2. Electrification Potential Given Typical Vehicle User Patterns

Given the current state of technology, the most important barriers for the electrification of vehicle fleets are driving range limitations and long charge times of larger BE-vehicles. These barriers are especially relevant for freight transport by road. Compared to buses, freight vehicles generally cover larger service areas and have less predictable daily driving patterns, which often also complicates daytime charging. In addition, owners of freight vehicles rely on their vehicles to generate income. Loss of cargo capacity due to large and heavy batteries or time required for daytime charging translates directly into higher costs, and may also lead to needs for increased vehicle-km to perform the same level of services compared to a vehicle with combustion engine.

In our analysis, we look at the Norwegian potential for electrifying freight vehicles, distinguishing between the near term (with particular focus on how technological limitations such as driving ranges and engine size relate to current use patterns and requirements) and the longer term (where we focus more on the influence of different vehicle-dependent obstacles for electrification) given that transport assignments can be distributed between vehicles with more flexibility.

The main sources for our analysis are base data from both the Norwegian vehicle registry, Autosys [18] and Statistics Norway's survey of trucks for 2016 and 2017 [19]. In the latter, samples of truck operators report all transport assignments for one week, and sample selection is done such that all weeks of the year are represented. Combining these two sources, we constructed a dataset including information on amongst others, vehicle category and age, engine power, use of trailer (during reporting week) and trip length.

We also aggregated data from trip level to daily mileages, using maximum daily mileages as a proxy for the minimum driving range that electric vehicle alternatives should have to be suitable for the user. Using the maximum daily mileages ensures that we take into account day-to-day variations, which may pose challenges with respect to battery sizing, predictability, and charging requirements (see, e.g., an analysis of the potential for use of BE-vans by Norwegian Craftsmen in Figenbaum [20]). In cases where vehicles have two or more daily trips starting from the same postcode (as approximation for vehicles returning to a base with a charging opportunity), daily mileages were adjusted to reflect that requirements for driving ranges would be lower.

Furthermore, we set a number of criteria for trucks to be considered as having electrification potential in the shorter timeframe:

- Maximum daily mileage is shorter than the driving range on a fully charged battery (the latter is set to a maximum of 150 km based on specifications of and pilot experiences with current electric alternatives; this also agrees with Anderhofstadt and Spinler [8] who identified upcoming e-trucks by Daimler and MAN having maximum driving ranges of up to 200 km, which must be derated somewhat for Norwegian winter driving, and similarly, Volvo's announced FE Electric-truck)
- Engine power ≤500 HP (according to a major manufacturer interviewed, there are currently effectively no alternatives to diesel or biodiesel for higher engine powers; this is supported by none of the current battery-electric trial vehicles having engine powers >500 HP)
- Not requiring the use of a trailer, except tractor units (due to the high engine power required for driving with heavier trailers and following the above manufacturer's feedback)
- Trucks up to five years old (i.e., the fleet segment where transport actors and manufacturers report that requirements for new purchases are set, and taking into account that annual mileages decrease with vehicle age)

Altogether, this yielded a sample of 6150 trucks with information on static fleet data, daily user patterns and variations.

3.3. Cost Competitiveness of Electric vs. ICE Operation

To investigate the cost-competitiveness of electric trucks with trucks with ICE, we developed models for total costs of ownership. Similarly to the core of many existing studies e.g., [5,13,21,22], we established cost functions that are decomposed into relatively detailed cost components. We distinguished between technology-dependent costs (which vary between technologies and are divided further into time-dependent, distance-dependent and maintenance costs), and technology-independent costs (equal or assumed equal for all technologies). The cost aspects considered in our model are summarized in Table 1.

Table 1. Overview of main cost aspects considered in the cost-comparison model. All cost comparisons exclude VAT, since firms can subtract this on incoming goods and services. Exchange rate used: 1 EUR = 9.8 NOK.

Cost Category	Main Aspects Taken into Account
Time-dependent	Investment/capital costs (excl. subsidies); Depreciation; Residual values; Discount rate
Distance-dependent	Energy consumption & cost (base price + any levies); Road toll charges and exemptions (discounts) for zero-emission; Driving distances and mileages
Maintenance and repair	General maintenance; Tyre degradation; Washing, etc.
Technology-independent	Wage expenses; Admin and insurance costs; Annual weight fee

The starting points for the technology-dependent cost functions are validated base parameters from a National Freight Model for Norway, hereafter referred to as NFM [23,24]. An advantage of starting with this model is that the technology-dependent cost functions can later be used for analyses of different future scenarios using the same model.

With regard to investment/capital costs, we distinguished between ‘reference investment costs’ for the diesel alternative (from the NFM) and investment cost premiums of alternative technologies. For e-trucks, cost parameters (hereunder investment cost premiums) are based on (confidential) data collected in the user interviews, updates and refinements of cost parameters from Hovi and Pinchasik [25], feedback from actors in the Norwegian transport sector, data from Jordbakke et al. [3], and cost development forecasts e.a. [12]. We found that estimates for cost premiums of converted heavy-duty trucks are in line with Weken et al. [26]. Subsidies towards cost premiums were not included in our calculations, as these are granted only in a limited number of cases and because one of the study’s objectives was to illustrate when alternative propulsion vehicles can be competitive on their own.

Furthermore, TCO calculations are done considering a depreciation period of 5 years (the typical leasing period), with depreciation based on the counter-balance principle. Hereby, it is expected that batteries last at least the entire typical leasing period without requiring replacement, in light of lifetime estimates spanning between 6.6 and 11 years [5,22,27].

However, due to uncertainty around remaining battery lifetime after the leasing period, and due to the lack of a second-hand market (in particular for the early-phase market for BE- and FCHE trucks), the availability of data on resale prices is limited [8,22,28,29] and is set conservatively. For e-trucks, this entails that we use the same residual value share as for diesel vehicles (using NFM parameters), but with an additional ‘uncertainty’ discount, depending on the production maturity phases, i.e. discount of 50% under the early market phase scenario, 25% under small-scale series production, and no discount under mass production. The latter is based on examples from the market for BE-passenger cars which found that Norwegian leasing firms initially operated with low residual values due to uncertainty, but that these values have normalized with market maturity [30].

As in most TCO analyses see, e.g., [21,27], or [29] costs and savings occurring at different stages in the vehicle’s lifetime are discounted to their present value. We used a discount rate of 3.5% (upward adjustment from the NFM representing commercial cost of leasing).

Regarding distance-dependent costs, energy prices are split into a base price and any applicable levies, using the same sources as above. For electricity, costs are further split into regular charging, and a cost premium of 50% per kWh in case of fast charging (representing additional costs of requiring charging at higher power/effect, e.g., connection upgrades). While we include road toll charges and their exemptions for zero-emission vehicles, ferry costs and exemptions are not included in the analysis due to limited data availability and particularly high dependence on use location.

Driving distances and mileages are set to 45,000 km/year for trucks, based on NFM parameters and adjusted to reflect mileages feasible for BE use cases, i.e., particularly urban/regional distribution patterns.

Regarding maintenance, we assume that costs for e-trucks are 50% lower than indicated for ICE trucks by NFM parameters. This is based on conclusions by Huismans [5], and by Zhou [22], who suggested that maintenance costs for electric trucks are about 30–50% of the level for similar diesel vehicles, and Jadun [31], who expects savings on maintenance to increase with larger-scale adoption.

Other cost aspects in the table are based on NFM parameters. The annual weight fee is treated as a technology-independent cost component, because its environmental component is only marginal.

Not presented here are costs related to infrastructure establishment, charging/filling time, any need for back-up capacity, any decreases in cargo capacity given heavy batteries, and any decrease in operating hours during the day because of range limitations and/or lack of access to fast charging throughout the day. These themes are discussed later in our analysis of electrification potentials and use patterns.

It should also be noted that for BE- and FCHE-trucks, available data on cost premiums and operation are currently still limited and uncertain in many studies e.g., [5,10,27], amongst others, because manufacturers are cautious about sharing detailed information. However, data availability is expected to improve with future adoption, and our flexible model set-up is designed to allow easy incorporation of new estimates for all parameters.

Based on the inputs above, and given expectations that cost premiums of electric trucks will decrease materially with technology maturity e.g., [4,12,13], we assessed three scenarios to illustrate implications for cost-competitiveness: (1) today's early market phase for BE- and FCHE-trucks, (2) small-scale series production, both with current and lower hydrogen prices, and (3) mass production. For today's early phase, our assumptions on cost premiums of electric vs. ICE vehicles are based on the sources above. For small-scale series production, we assume that battery-electric vehicles cost twice as much as corresponding ICE vehicles; hydrogen-electric vehicles three times as much. Under mass production, battery-electric vehicles are assumed to cost 50% more than ICE vehicles; hydrogen vehicles about double. The latter is in line with estimates on system cost reductions for MD trucks at production scales of 100k systems a year [32], page 15, and which imply a cost premium of ca. 95%. For all scenarios, we present a decomposed analysis to illustrate the role of different cost components for competitiveness and differences between ICE vehicles and BE- and FCHE-trucks. For reasons of space, cost decompositions are only presented for light distribution trucks, but reference is made to equivalent analyses for heavy distribution trucks and tractors for semitrailers. Today's retail pump price of hydrogen is 72 NOK/kg excl. VAT (~€ 7.35) [33] can potentially be halved with self-production (operator interview) or moderate production scale increases [34].

3.4. Socio-Economic Costs of Phasing-in Zero-Emission Technologies

To complement the assessment of cost competitiveness, we carried out an assessment of the socio-economic costs of phasing in alternative propulsion technologies, i.e., the sum of public and private costs and benefits. For society as a whole, costs can be expected from the investment premium of zero-emission vehicles, while benefits stem from savings on fuel/energy costs and general vehicle maintenance compared to diesel vehicles. In addition, society can expect benefits through reduced negative external effects (local emissions), for which cost factors are based on Rødseth et al. [35] and adjustments in Thune-Larsen et al. [36].

In our TCO analysis, road toll and fuel levy exemptions for zero-emission vehicles are treated as a benefit for the private firm. Because these exemptions simultaneously entail revenue losses for the state, they are considered neither as a cost or benefit, but as a socio-economic transfer. Following guidelines from the Norwegian Ministry of Finance, we do, however, include a 20% 'tax financing cost' as a socio-economic cost on this transfer.

Finally, by relating the sum of social-economic costs to the reduction of CO_2-emissions when replacing an ICE vehicle by a zero-emission truck, we arrived at socio-economic costs per reduced tonne in CO_2 emissions for the different maturity scenarios.

4. Results

4.1. User Experiences

4.1.1. The Trials

A technical summary of the characteristics of early Norwegian trials with e-trucks, and whose operators formed the core of the interviews, is shown in Table 2. Trials were operated in the South East of Norway, and were implemented in food distribution, household and business refuse collection and recycling service segments. The e-trucks operated vary in power and total weight, and were mostly registered in 2018. All trucks operated five days a week and with expected annual mileages ranging from 18,000 to 120,000 km, divided into about 250 business days per year, and one to three working shifts per day.

Table 2. Electric heavy-duty vehicle trials beginning 2017/2018 in Norway, upon which interviews were based. Source: Autosys [17] and interviews with the operators. [a] At the time of the interview, the operator only had experience from a test-vehicle. [b] Average fleet value. [c] Actual km/y driven at time of interview. [d] For a similar (existing) ICE fleet. [e] LIB = Lithium ion. [f] $NaNiCl_2$ = Sodium nickel chloride.

Variable:	**A**	**B**	**C**	**D** [a]	**E**	**F**	**G**
Sector	Distri-bution	Waste collection	Waste collection	Recycling	Manufacturing	Waste collection	Waste collection
Vehicle type	Truck (freight)	Truck (waste)	Truck (waste)	Tractor (recycling)	Heavy van	Truck (waste)	Truck (waste)
Manufacturer	MAN/Emoss	Dennis Eagle/PVI (Renault)	MAN/ Emoss/Allison	MAN/Emoss/Allison	Iveco	DAF/Emoss/ Geesinknorba	DAF/Emoss/ Geesinknorba
Expected annual driving distance (km/y)	50,000 [b]	18,000 [c]	80,000 [d]	120–130,000	30,000	20–26,000 [d]	16,800 [d]
Range, full charge (km)	180	140	200	178	160	120–130	100–140
Number of vehicles tested	1	2	1 (+1)	2	5	1	1
Registration year	2016	2018	2018 (19)	2018	2018	2018	2018
Total weight (t)	18.6	26.8	28.0 (50.0)	40.0–45.0	5.6	12.0	12.0
Payload (t)	5.5	9.7	18–19	15–20	2.6	3.5	3.5
Length (m)	9.0	9.5	7.8	7.4	7.2	7.0	7.0
Battery technology	LIB [e]	LIB	LIB	LIB	$Na\text{-}NiCl_2$ [f]	LIB	LIB
Battery capacity (kWh)	240	240	200 (300)	300	80	120	130
Depot charging (kW)	2 × 44	44	44	44	22	22	44
Opportunity. charging (kW)			150	2 × 150			
Charge time (h) to 80%	5	8	4.5 (to 100%)	4–6 (slow)/0.3 (fast)	8	2–8	3.5

In addition to the vehicles in the table, two operators using BE-light commercial vehicles were interviewed for comparison. These companies currently do not have regular operations of heavy-duty e-trucks, but one of them had tested a heavy BE- van for 14 days.

4.1.2. Procurement Process

In the procurement process of the BE-pilot trucks, one important incentive was financial support from the authorities through a Norwegian Environment Agency municipality support program ('Klimasats'), or more commonly, the ENOVA scheme. ENOVA is a government instrument financed by an energy fund and can provide support for 40–50% of the additional costs of zero-emission trucks, in addition to the full costs of a charging station, depending on the size of the applicant firm. Another incentive for electric vehicles are specific requests in public tenders, but it was emphasized that environmental characteristics must be weighted more than price if a bid in public tenders with e-trucks should be competitive. Long and sometimes uncertain vehicle delivery time, relative to the often limited time between tender results and start of contracts, was identified as a potential risk by operators. In addition, although it was not difficult for the operators to find potential suppliers, a challenge for the first operator was that the supplier did not have agents in the Norwegian market. This situation contrasts with the electric LDV operators interviewed who commented that they have a framework agreement with all major vehicle suppliers.

4.1.3. Battery/Charger Technology

Battery choices for the trucks were based on requirements set by the operating purpose of the vehicles. For the larger trucks in the pilots, battery capacities chosen ranged between 200 and 300 kWh, with a corresponding range (on full charge) of between 140 and 200 km. This contrasted to the LDV operators interviewed, where the battery size was smaller (56 kWh). Lithium-ion battery technology was mostly chosen, while the heavy vans from Iveco have sodium nickel chloride batteries of 80 kWh installed.

Regarding charging technology and solutions, most operators charged trucks overnight and during lunch breaks at the depot, due to challenges with establishing fast chargers. Similarly, the LDV operators interviewed utilized overnight depot charging. A summary of the selected battery capacity (including for vans), associated range on full charge, and charger solution chosen by the operators, is shown in Figure 1.

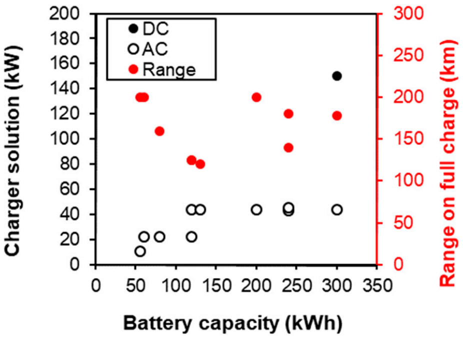

Figure 1. Summary of the battery capacity (kWh) and charging solution (AC or DC, kW) used by the operators. The range on full charge is also shown (in red).

4.1.4. Experience from Operation

Operator feedback related to different aspects of trial operation is outlined below. Due to the limited number of operators who currently have e-truck experience in Norway and thus, could be interviewed, feedback is deliberately described only in general terms and not analyzed further.

Design

Although the design of the e-trucks did not convey major issues, some user comments were made about a lack of focus on reducing the specific vehicle weight of the chassis, to better accommodate the associated weight increases due to battery, cooling aggregate, and insulation. Other comments encompassed the limited availability of different vehicle size alternatives. In general, much of the design knowledge for e-trucks has been transferred from buses, with the most important difference being battery dimensioning due to different possibilities for opportunity charging. This means that the trucks must carry more energy on board (ideally to cover one shift, or about 200 km per day for distribution). A failure in, e.g., overnight charging, thus becomes critical for truck operations the next day because of the (often) long charging time.

Owners/Drivers

Despite initial reservations, both managers and drivers were generally pleased with the e-trucks. Several operators commented that the trucks contribute to a good working environment, and when working properly, are pleasant and fun to drive. The main challenge, according to operators was trusting a new technology and overcoming range anxiety. Other specific issues included changes in driving license requirements (for the heavy vans, due to increased total weight and changes in vehicle classification), which limited the ability to recruit drivers to those holding such licenses.

In general, the pilottrucks were reported to produce less noise and vibrations than regular ICE vehicles, although in some cases, mechanical noise became more noticeable. Reduced noise/vibrations were received positively by owners/drivers, both in terms of a positive impact on the work environment, but also because operators recognized a potential for operation during night times in densely populated areas where noise restrictions preclude ICE operation.

Nearly all operators interviewed said that the e-trucks give a positive environmental profile to their enterprise. Several operators reported high public interest for both customers and media, and that their client also felt a sense of pride.

Energy Use

According to operators, the energy use of the e-trucks under real-life conditions proved significantly lower than for ICE vehicles per km (~1–1.5 kWh/km vs. ~3–8 kWh/km with ICE). Operators also noted that energy used for waste compressors, heating and cooling, if derived directly from the battery, reduces the driving range for the vehicle. In some cases, this was solved by using an external HVO-based generator. Issues were also reported due to the lack of soft start functions of cooling units.

Range/Route

Despite the fact that most e-truck trials were intended to directly replace routes of ICE vehicles, in practice, this has not always been the case. Some vehicles have been put in operation in central areas, where topographical differences and range requirements are relatively low and where they are most useful due to low noise and reduction of local emissions. Other operators optimized routes for charging during pick-ups/deliveries or breaks. However, it was noted that where a fleet has varying daily driving requirements, the e-trucks are particularly vulnerable to unexpected transport assignments in the afternoon.

A number of operators further reported that driving ranges did not live up to their expectations, both in terms of manufacturer/supplier specifications and display readings in the vehicle. This variation has meant that in some cases, ranges used for planning have had to be significantly adjusted downwards, and in general, very conservative values for route planning are used. Such issues were also reported for LDVs, assumed to be due to the number of stops en route coupled with a relatively low driving speed, cargo loadings, and variable route topography. Range differences between summer/winter have so far not been apparent, but there has been little experience with operation during cold days as of yet.

Vehicle Performance

Experience with the technical/general performance of the trucks has been mixed. One truck operator reported major technical issues and extensive vehicle downtime. For LDVs and the refuse collection trucks, operators were generally happy with technical performance, and most of the issues reported were relatively minor and attributed to the conversion from diesel to electric powertrains, and teething problems. Noteworthy general performance comments included mixed experiences with braking capacity, vehicle traction and engine power. For some (but not all) operators, adjustments fixed these issues.

Most operators reported reduced freight capacity for the e-trucks compared to the equivalent ICE vehicles, which, in some cases, was considered by the operator to be a major issue affecting operation. Reasons for the reduced capacity are the significant battery weight and, in some cases, battery position in the vehicle.

Charging

The availability and possibility of charging along the routes were found to be highly restrictive factors by operators. In addition, various technical issues were also reported relating to charging problems and/or lack of experience. Examples include difficulties with problem diagnostics, charging restrictions specified by the manufacturer during a 'run-in' period before putting the vehicle in operation, and some issues related to the cold Norwegian winter climate. A number of other more minor technical issues were mostly resolved quickly.

For BE-LDVs, the operators interviewed mentioned challenging power peaks when charging many vehicles simultaneously. Challenges also occurred relating to the availability of grid power when building new terminals, and incentives for the development of charging infrastructure at rented locations. Some operators called for a form of central coordination for smarter charging for the business sector, and load distribution/capacity utilization.

Ownership Costs

The interviews provided information on different cost components, such as for the chassis, energy, maintenance, chargers, and operation. For reasons of confidentiality, these are not explicitly discussed here, but were an important input for modelling total cost of ownership for different propulsion systems. In general, however, the interviews suggested that at current cost levels, BE-vehicles had purchase costs of between ~1.5 and 4 times the cost of corresponding ICE-vehicles, depending on vehicle classes. Operators agree that BE-vehicles have significantly lower costs of operation than ICE vehicles. This is particularly due to savings on energy costs and road toll charges; maintenance costs, too, are reported to be lower than for ICE vehicles. However, the largest maintenance costs usually occur after 4 to 5 years. Battery changes were not expected to be required during the effective vehicle lifetime, but it is known that these may be expensive. Overall, due to, e.g., the high purchase costs, many operators expect that the e-trucks will be more expensive over their lifetime than a corresponding ICE truck.

4.2. Electrification Potential Given Typical Vehicle User Patterns

4.2.1. Potential for Electrification in the Near Term

The main barriers for the adoption of BE-HDVs in the near term stem from driving range limitations of battery-electric (pilot) vehicles, limited engine power, and, as a result, limitations to the possibility to drive with a trailer. To assess the extent of these barriers, we looked at use patterns and the composition of the Norwegian commercial vehicle fleet.

From an analysis of base data from Autosys and Statistics Norway's survey of trucks, we found that the majority of Norway's commercial vehicle fleet (ca. 75%) consists of trucks of up to five years old, of which most have engines ≥500 HP and are driven with a trailer. In light of limitations in terms of power and availability of alternatives to diesel, this suggests that near term electrification of this segment of trucks is unlikely.

For trucks with engines <500 HP, the trucks not using trailers in the reporting week (which are considered most suitable for electrification) constitute 16.6% of the total fleet, while those using trailers equate to another 7.5%. For the latter, trailer use often encompasses lighter city trailers, i.e., leaving some potential for electrification.

In terms of mileage, we found that newer trucks constitute an even larger share (85%) than in terms of vehicle number. Further, over 70% of mileage with newer trucks is carried out with engines

≥500 HP, mostly with a trailer attached. This is noteworthy since it is largely the segment for newer trucks where user requirements are set. These observations also confirm that based on current use patterns, electrification in the near term seems unlikely for a large part of the Norwegian commercial vehicle fleet.

Regarding segments where near-term electrification is most likely, and taking into account also variations in daily use, we found that trucks with engine power <500 HP and maximum daily mileages up to 200 km constitute only 3% (without trailer) and 1% (with trailer) of the total mileage driven with newer trucks. This indicates that with current technological limitations, the electrification potential in terms of vehicle-km that can be electrified is currently small. The potential might increase when access to charging infrastructure improves, supporting longer daily driving distances.

After our assessment of engine power and trailer use, we focused on differences between categories of trucks (with engines <500 HP, up to 5 years old, and without trailer (except for tractors for semitrailer). In this segment, trucks with closed chapel make up the largest share of mileage (ca. 50%), particularly for the driving of shorter daily distances. Tractor units with semitrailer constitute about a quarter of total mileage, but are mostly used on longer distances. Special trucks (e.g., refuse collection trucks and crane truck), in turn, stand for 20% of total mileage, in part, over shorter daily distances, while trucks with platform body and tank trucks make up only small shares of driving in this segment.

To investigate range limitations, we further looked at the maximum daily mileage for each truck, as reported in the reporting week for the survey of trucks. Figure 2 shows an illustration of these maximum daily mileages in ascending order for different truck categories. Where daily mileages of a vehicle are below 150 km (the assumed all-electric driving range on a full battery without requiring daytime charging), vehicles are assumed to have potential for electrification (green-shaded area). For daily mileages between 150 and 250 km, we consider that a certain additional electrification potential exists, provided the availability of sufficient daytime charging opportunities or improved batteries (blue-shaded area).

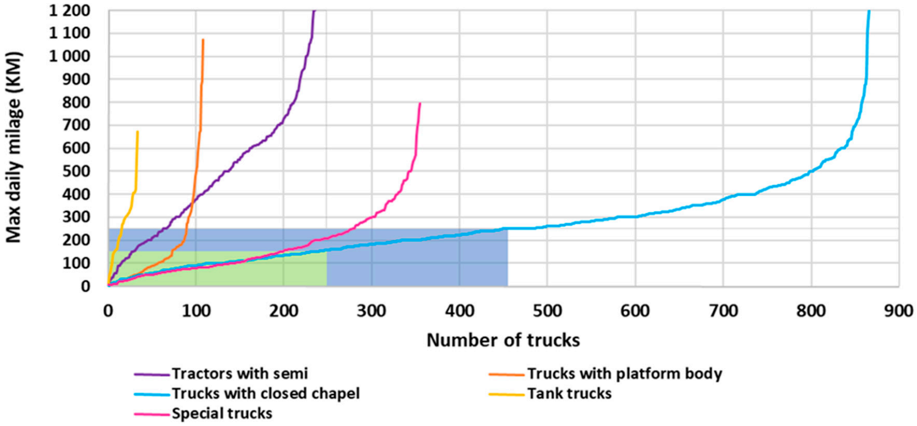

Figure 2. Maximum daily mileage (km) for individual trucks in different truck categories in the sample of Statistic Norway's truck survey. For trucks up to five years old, with engines up to 500 HP, and without trailer, except for tractors with semitrailer. Green area: potential for electrification; all-electric driving range, no daytime charging, blue area: electrification can under some circumstances be possible with current battery electric truck status. Source: Base data of Statistics Norway's 'survey of trucks' for 2016 and 2017 and NPRA's Autosys registry.

Figure 2 shows that special trucks and trucks with closed chapel have most vehicles in the segment with potential for electrification, thereby constituting the main market for near-term electrification. This is confirmed by our case study, as early pilots with e-trucks were carried out with distribution and refuse collection trucks. For the other vehicle categories, maximum daily driving distances exceed what can currently be supported by battery-electric alternatives.

4.2.2. Potential for Electrification in a Longer Term

In a longer term, firms owning multiple trucks might have some flexibility to redistribute transport routes between vehicles, e.g., by assigning BE-trucks more to shorter-distance transport of volume goods. This flexibility is not easy to quantify because the transport industry is very fragmented and further consists of both hire-transporters (with many small firms) and own-transporters. Although we do not have data on the share of firms carrying out own transport, in our sample, own-transport constitutes 27% of trucks but only 18% of mileage. This suggests that on average, own-transport is carried out with smaller vehicles driving shorter mileages than hire-transport, implying that own-transport is more suitable for electrification. Own-transport vehicles are also more likely to be operated from only one terminal and can thus more easily be charged overnight. The fact that vehicles used for own-transport are, on average, older, however, works in the opposite direction.

Even with route redistribution and more abundant charging opportunities in the longer term, several challenges for the electrification of trucks remain, in particular relating to engine power, driving ranges, the trade-off between battery weight and payload, and limitations to the use of trailers.

Most driving is carried out by trucks having an engine power between 500 and 600 HP (53% of trips, 54% of vehicle-km and 66% of tonne-km), while driving with larger engines makes up relatively small shares. This suggests that if the majority of transport assignments are to be carried out with e-trucks in Norway, e-trucks with and engine power of up to 600 HP would be have to be available in the market.

With regard to driving ranges, Table 3 illustrates the distribution of daily mileages for newer trucks, for different engine powers.

Table 3. Distribution of daily mileages for trucks ≤5 years old, for different engine powers. Shares in total vehicle mileage. Source: Base data of Statistics Norway's 'survey of trucks' for 2016 and 2017 and Autosys registry. Color-coding indicating good and reasonable potential for electrification with current technology (green shades), reasonable potential, some potential with extensive charging opportunities (blue), some potential when higher engine powers become available for battery-electric trucks (yellow), and less feasible in shorter term (red).

Engine Power (HP)	Up to 100 km	100–200 km	200–300 km	300–400 km	400–500 km	500 km and Over	Total
100–199	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.2%
200–299	2.5%	2.2%	1.1%	0.6%	0.2%	0.2%	6.8%
300–399	2.8%	2.8%	1.1%	0.7%	0.2%	0.2%	7.7%
400–499	4.7%	4.4%	2.9%	1.0%	0.6%	2.2%	15.7%
500–599	12.4%	8.3%	6.6%	4.1%	5.3%	17.6%	54.2%
600–699	2.1%	1.1%	0.9%	0.6%	0.8%	2.7%	8.2%
700+	2.0%	0.9%	0.7%	0.5%	0.7%	2.4%	7.3%
Total	26.6%	19.8%	13.2%	7.5%	7.6%	25.3%	100.0%

The table shows that more than a quarter of all driving with trucks in Norway is carried out by vehicles with daily mileages of up to 100 km, a fifth by vehicles with daily mileages between 100 and 200 km, and around 13% by vehicles with daily mileages between 200 and 300 km. Although a sizable share of driving is done with (much) higher daily mileages, this suggests that if batteries of e-trucks could support a vehicle range of 300 km (alongside engine powers up to 600 HP), this could give a potential for electrification for a large share of transport.

With regard to the weight of batteries, we looked at mileages driven with and without trailer for trucks ≤5 years old. Here, we found that for almost 79% of mileage with cargo, it is volume and not weight that fills up capacity and constitutes the capacity dimensioning factor. This suggests that the extra weight of batteries might not be as critical as is sometimes assumed. Furthermore, a proposal adopted by the European Parliament in April 2019 opens up for a two-tonne additional total vehicle weight allowance for zero-emission trucks [37,38]. This corresponds to the weight of about 200 kWh of batteries, and possibly more in the future, as the energy density of lithium-ion battery cells has been increasing by around 5–7%/year [39].

Next, we looked at the distribution of total mileage without trailer attached (as it is the vehicle, not trailer, that is most crucial) by capacity utilization and vehicle's maximum allowed total weight. Here, we found that, respectively, three quarters and a fifth of total mileage is driven by vehicles with maximum total weights between 10 and 20 tonnes and 20 and 30 tonnes. Driving with smaller vehicles only constitutes a fraction of total mileage. More importantly, for over 80% of total mileage driven with cargo, at least 20% of the vehicles' weight capacity is unutilized. Particularly for vehicles with payloads over 10 tonnes, which constitute most of mileage with cargo, this indicates that there would often be sufficient 'weight capacity' to carry several tonnes of battery.

Finally, we looked at limitations on the use of trailers. Here, we found that 45% of trips are driven without trailer attached, particularly by trucks with engines between 200 to 600 HP, and of those, particularly with largest engines in this interval. In terms of mileage, rather than trips, the share of driving without trailer is only 28%. This indicates that trips without trailer are on average considerably shorter than trips where trailers are used.

There may be variations in how a vehicle is used over a year that may reduce the potentials described above. The datasets used only cover 1 week of trucking. A truck that is not fully utilizing the capacity during this week could potentially be doing it another week of the year. BE-trucks may thus reduce the flexibility of some operators to take on different transport assignments over the year.

4.3. Cost Competitiveness of Electric vs. ICE Operation

In Section 3.3., we described the development of a model for comparing decomposed ownership costs of different propulsion technologies. For readability, results from our comparisons are presented in two tables. Table 4 shows decomposed ownership costs for light distribution trucks based on the current early stage of technological maturity for BE- and FCHE-alternatives, while Table 5 presents a similar decomposition for the scenarios with small-scale series production and mass production of electric vehicles, including a reduction hydrogen fuel prices. For conciseness, several smaller cost components were aggregated. Components that differ significantly between technologies or that might be used to create policy incentives, however, are presented separately. Wage costs are shown to illustrate their magnitude compared to other cost drivers.

Table 4 illustrates that in today's early stage, ownership costs for light distribution vehicles with electric propulsion are considerably higher than for ICE-based propulsion systems. Compared to diesel vehicles (0.95 EUR/km), ownership costs for BE-vehicles (1.48 EUR/km) and FCHE-trucks (2.23 EUR/km) are, for example, 57% and 136% higher, respectively. Although not shown in further detail here, our calculations show that these figures are 55%/128% for heavy distribution trucks and 92%/161% for tractors for semitrailers. Compared to light distribution trucks, differences stem primarily from differences in investment cost premiums and fuel/energy consumption. It can further be seen that at 0.93 EUR/km, wage costs are of a similar order of magnitude as vehicle-ownership costs for light distribution vehicles with ICE. Our estimates on operational costs for both battery- and hydrogen-electric trucks fall within the ranges identified in a review of different studies by Plötz et al. [9].

Table 5, in turn, shows that small-scale series production considerably reduces ownership costs for electric trucks. For FCHE light distribution trucks, per-km costs fall to 1.54 EUR (at current hydrogen prices), or 1.41 EUR if prices of hydrogen were to fall by half (driven by higher demand and larger-scale production). Even at these prices, however, ownership costs for FCHE vehicles remain considerably higher compared to ICE-trucks. For BE-trucks, in turn, ownership costs under small-scale series production, at 0.98 EUR/km, approach those of diesel trucks at typical mileages.

Table 4. Decomposed ownership costs for light distribution trucks. Base scenario/early stage. Figures in EUR/km. Costs are based on a period of analysis of 5 years and annual mileages of 45,000 km.

Cost Component	Diesel	Biodiesel	Biogas	FCHE	BE
Base investment	0.35	0.35	0.35	0.35	0.35
Investment premium	-	0.00	0.10	1.46	0.90
Wage costs (incl. social/holiday)	0.93	0.93	0.93	0.93	0.93
General levies	0.00	0.00	0.00	0.00	0.00
Insurance + admin	0.05	0.05	0.05	0.05	0.05
Fuel/energy, excl. Levies	0.14	0.28	0.25	0.25	0.05
CO_2-levy	0.03	-	-	-	-
Road use levy	0.09	-	-	-	-
Premium in case of fast charging	-	-	-	-	0.02
Tyres, wash, consumables, etc.	0.08	0.08	0.08	0.08	0.08
General maintenance	0.07	0.07	0.07	0.03	0.03
Road toll	0.14	0.14	0.14	-	-
Total incl. wage costs	1.88	1.91	1.96	3.16	2.41
Total excl. wage costs	0.95	0.97	1.03	2.23	1.48
Index incl. wage costs	100%	101%	104%	168%	128%
Index excl. wage costs	100%	103%	109%	236%	157%

Table 5. Decomposed ownership costs for light distribution trucks. For small-scale series production with current and reduced hydrogen (fuel) prices, and for mass production. Figures in EUR/km. Costs are based on a period of analysis of 5 years and annual mileages of 45,000 km.

Cost Component	Small-Scale Series Production				Mass Production	
	Diesel	FCHE	FCHE (Lower Fuel Price)	BE	FCHE (Lower Fuel Price)	BE
Base investment	0.35	0.35	0.35	0.35	0.35	0.35
Investment premium	-	0.77	0.77	0.40	0.35	0.17
Wage costs (incl. social/holiday)	0.93	0.93	0.93	0.93	0.93	0.93
General levies	0.00	0.00	0.00	0.00	0.00	0.00
Insurance + admin	0.05	0.05	0.05	0.05	0.05	0.05
Fuel/energy, excl. Levies	0.14	0.25	0.13	0.05	0.13	0.05
CO_2-levy	0.03	-	-	-	-	-
Road use levy	0.09	-	-	-	-	-
Premium in case of fast charging	-	-	-	0.02	-	0.02
Tyres, wash, consumables, etc.	0.08	0.08	0.08	0.08	0.08	0.08
General maintenance	0.07	0.03	0.03	0.03	0.03	0.03
Road toll	0.14	-	-	-	-	-
Total incl. wage costs	1.88	2.47	2.34	1.91	1.92	1.69
Total excl. wage costs	0.95	1.54	1.41	0.98	0.99	0.76
Index incl. wage costs	100%	131%	125%	102%	102%	90%
Index excl. wage costs	100%	163%	149%	104%	105%	80%

For the scenario with mass production, we found that ownership costs for battery-electric vehicles fall below those of ICE-vehicles. At this point, FCHE-trucks are still more expensive at annual mileages of 45,000 km, but may nevertheless have potential in specific use cases, e.g., within long-haul transport, where BE-operation yields more limitations.

When focusing on individual cost components, we see that capital costs, albeit decreasing with technological maturity stage, remain the main cost driver for electric trucks in the foreseeable future. Administration and insurance costs and general levies such as Norway's annual weight fee, are only minor costs drivers. Even though the weight fee has an environmental component, this component plays such a small role that its effects are marginal at most. Costs for washing, consumables, and tyres, too, are only moderate cost drivers, and not expected to differ between technologies. Costs for general maintenance, in turn, are expected to be lower for electric vehicles than for ICE, but savings make up a minor share of TCO.

Looking at energy-related expenses, however, we found considerable differences. For diesel vehicles, in addition to fuel costs, operators pay a CO_2-levy and road use levy (together equaling ~0.26 EUR/km), while energy costs for biodiesel and biogas vehicles are of a similar order. On top of this come road toll charges of around 0.14 EUR/km. Energy costs for BE-vehicles, in turn, are much lower, at under 0.05 EUR/km (or around 0.07 EUR/km with only fast charging). For FCHE-vehicles, energy costs at current prices are still relatively high, but could fall towards 0.13 EUR/km. These results show that savings on operation costs for electric vehicles increase with annual mileage, particularly due to lower energy costs per km, but also due to toll savings and to a lesser extent, savings on maintenance.

Just as distance-dependent costs decrease with increasing annual mileages, capital costs (derived from the investment base and premium cost) will also decrease with annual driving distances. To illustrate this, Table 6 summarizes at what annual mileages BE- and FCHE-trucks may become cost-competitive with corresponding ICE-trucks. Results are presented for light distribution trucks, heavy distribution trucks, and tractors for semitrailer.

Table 6. Annual mileages (km) at which battery-electric vehicles (utilizing fast charging) are calculated to achieve cost-parity with other technologies. Rounded to the nearest thousand km.

Vehicle Size	Fuel Technology	Early Market Phase	Small-Scale Series Production	Mass Production
Light Distribution Trucks	Diesel	Unrealistically high mileages	52,000 km	21,000 km
	Biodiesel		47,000 km	19,000 km
	Biogas		37,000 km	11,000 km
	FCHE	Battery-electric always cheaper		
Heavy Distribution Trucks	Diesel	144,000 km	58,000 km	23,000 km
	Biodiesel	129,000 km	52,000 km	22,000 km
	Biogas	131,000 km	40,000 km	11,000 km
	FCHE	Battery-electric always cheaper		
Tractors for Semitrailers	Diesel	Unrealistically high mileages	43,000 km	19,000 km
	Biodiesel		39,000 km	17,000 km
	Biogas		35,000 km	10,000 km
	FCHE	Battery-electric always cheaper		

The table shows that in the current early market phase, e-trucks cannot compete with the costs of ICE-based vehicles, except for when mileages would be unrealistically high in light of limitations to the driving range set by current battery technology.

In the scenario assuming small-scale series production, our calculations show that BE-vehicles become cost competitive compared to diesel vehicles at mileages between 43,000 and 58,000 km. The reason for BE-light distribution trucks reaching cost-parity versus diesel at lower mileages than heavy distribution trucks is that the cost premium of investment is relatively high compared to savings on energy costs. Again, it is important to remember that estimates on cost premium and fuel consumption are uncertain, and that fuel consumption is affected by load weight and topography. Data on vehicle usage, e.g., from Statistics Norway's Survey of Trucks, indicate that such annual mileages are not unusual for newer diesel-based trucks. Provided that limitations to range, payload etc., are reduced, e-trucks may thus become a feasible alternative.

Finally, in the scenario assuming mass production, we found that BE-vehicles become cost-competitive compared to diesel operation starting from annual mileages between 19,000 and 23,000 km, and at even lower mileages compared to biodiesel and biogas vehicles. These findings indicate that even when advantages such as toll exemptions would be reduced, BE-vehicles may prove cost-competitive alternatives.

For FCHE-trucks, in turn, we find that ownership costs are higher than for BE-trucks in all scenarios, because both cost premiums of investment and energy costs per km are expected to remain higher, even when hydrogen prices are reduced by half. Compared to ICE-based trucks, we find that FCHE-operation may become cost-competitive in a stage of mass production at annual mileages between 50,000 km (tractors) and 65,000 km (heavy distribution trucks). Such mileages are not uncommon in many use cases (particularly for tractors). Even though BE-operation might be cheaper, limitations might, therefore, make hydrogen the alternative of choice in cases with, e.g., intensive use, long-haul unsuitable for BE-trucks, or when cost premiums for FCHE trucks are reduced more than is assumed here.

4.4. Socio-Economic Costs of Phasing-in Zero-Emission Technologies

With regard to the socio-economic costs of phasing-in zero-emission technologies, Section 3.4. describes components that constitute public and private costs and benefits. Table 7 shows how these public and private costs and benefits sum to socio-economic costs, and what this implies for society's costs per tonne reduction in CO_2-emissions. Figures are for light distribution trucks and compared to a diesel truck, assuming today's early phase of technological maturity (and cost levels) for electric vehicles. To illustrate the role of mileage, figures are further presented both for typical annual mileages of 45,000 km and lower mileages of 20,000 km.

Table 7. Socio-economic costs per vehicle under a transition from light distribution trucks using diesel to other propulsion technologies. For annual mileages of 45,000 and 20,000 km respectively, assuming the scenario for today's early phase of technological maturity. Figures in EUR, rounded.

Fuel Technology	**Socio-Economic Costs vs. Diesel**	**Cost in EUR/Tonne CO_2 Reduction**	**Socio-Economic Costs vs. Diesel**	**Cost in EUR/Tonne CO_2 Reduction**
	Annual Mileage: 45,000 km		**Annual Mileage: 20,000 km**	
Biogas	43,000	340	31,000	550
Hydrogen	353,000	2760	340,000	5980
Battery-electric	184,000	1440	194,000	3420

From the table, it can be seen that a transition to alternative propulsion technologies yields socio-economic costs of between EUR 43,000 and 353,000 per truck when assuming typical mileages. Consequently, the costs of reducing CO_2-emissions by one tonne vary from EUR 340 for biogas to 2760 for FCHE trucks, while it is EUR 1440 for BE-trucks.

At low annual mileages, socio-economic costs from a transition to biogas and hydrogen are slightly lower, while for electric propulsion, they are somewhat higher. These differences are due to external damage costs from diesel operation being lower at lower mileages, but also savings on energy costs and maintenance from a transition to alternative propulsion being lower. Since reductions in CO_2-emissions are much lower with less intensive vehicle use (while cost premiums of alternative propulsion trucks remain the same), the socio-economic costs per unit CO_2 reduced are considerably higher at lower mileages.

Figure 3 illustrates how socio-economic costs per reduced tonne in CO_2-emissions go down in future scenarios with larger scales of production (i.e., lower investment cost premiums) and at typical mileages.

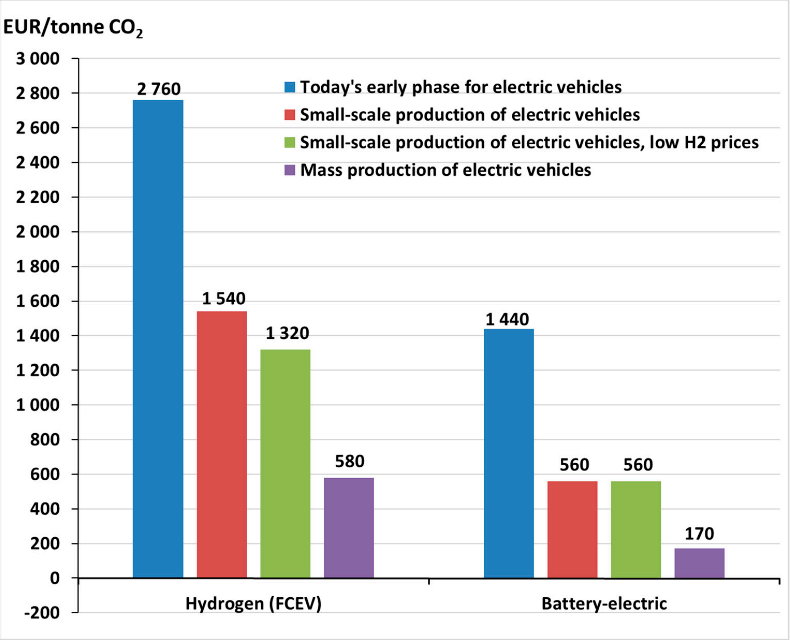

Figure 3. Socio-economic costs for reducing CO_2-emissions by one tonne, under a transition from light distribution trucks using diesel to electric propulsion. For annual mileages of 45,000 km and for multiple scenarios of production phase/technological maturities of electric trucks. Figures in EUR.

The figure clearly shows that socio-economic costs for reducing CO_2-emissions towards alternative technology trucks become lower when electric propulsion systems reach more mature stages. At the same time, it is assumed that the costs of FCHE-vehicles will remain higher than for BE-vehicles. This is due to both higher cost premiums of investments and lower savings on energy costs compared to conventional trucks. Moreover, Weken et al. [26] concluded that although FCHE technology is considerably more expensive and less technologically mature than BE-trucks, it could prove a solution to the range and charging time challenges of BE-trucks.

5. Discussions and Conclusions

Currently, the adoption of zero-emission commercial vehicles in Norway is limited in light of the ambitious targets for the phasing in of these vehicles stated in Norway's National Transport Plan for 2025 and 2030, and the contribution that is needed from road transport to be able to meet Norway's CO_2-reduction objectives by 2030. At the present time, only a few BE-trucks are in operation in Norway, and all of these are conversions of vehicles with diesel engines, with purchases being driven mostly by strategic considerations (such as image, having an early mover advantage etc.). It is expected that a limited number of small-scale series-produced BE-trucks will be delivered to the Norwegian market during the first half of 2020. These are expected to be distribution trucks with 2 and 3 axles. According to Weken et al. [26], most battery-electric trucks announced for market introduction are for lower weight classes.

Experiences from the few pilots in Norway with BE-trucks have been promising (especially for waste and recycling trucks), but not in all respects. Although operators are positive about working conditions, energy savings and lower operating and maintenance costs, they have generally had to perform considerable tailoring of route/location choices. Weken et al. [26] also found that transport firms, drivers and customers generally give positive feedback on their experience with electric trucks.

Nonetheless, a number of issues for the Norwegian e-trucks have also been experienced, varying from minor teething problems to a couple of major issues requiring battery/part changes. A number of challenges were, for example, indicated with regard to lower traction than the operators need, and challenges with charging, range and vehicle capacity reductions. Experience with use in (cold) winter periods has, so far, been limited, but could bring to light additional challenges.

Looking at typical user patterns for light distribution trucks with ICE for base data from Statistics Norway's truck survey, we found that the majority of newer trucks have annual mileages that considerably exceed the current capability of a BE-alternative. Nonetheless, there is also a sub-segment where there is potential for electrification, if daily driving patterns are relatively uniform or the truck is operating in a fixed shuttle service between two locations, giving an opportunity for fast charging connected to loading and unloading. The same opportunity will occur if the truck is visiting the same terminal, storehouse or refuse plant during the day. Looking at day-to-day variation, however, indicates that in many cases, BE-operation using current technology levels will require considerable route tailoring and daytime charging.

If a transition to electric heavy-duty transport is to be made, charging infrastructure must be further developed. Although most operators currently use depot charging, an emphasis is increasingly being placed on fast charging. One operator, for example, suggested that the Norwegian Public Roads Administration should establish fast chargers for HDVs at all vehicle control stations (weighing stations) in the main road network.

It should be noted that cost estimates for the current early production phase are based on the interviews, feedbacks, and information discussed in Section 4.1, while for future stages of production maturity, cost estimates (and thus results) are based on a first rough approach, as described in Section 3.3. Particularly for FCHE-electric vehicles, cost development paths are necessarily uncertain, since very limited information is available, and information that is available is based on a very early development stage, characterized by small production volumes of all components. Both for BE- and FCHE-vehicles, we have in progress a more elaborate and detailed techno-economical approach for expected developments in costs of alternative technologies, in order to improve our estimates.

Weken et al. [26] found that without subsidies, BE-trucks are so far not economically feasible because of cost premiums, which are high due to expensive low-volume niche production (largely conversions). Furthermore, higher mileages yield higher savings on operation costs, but achieving higher mileages is often hindered by technological limitations. From our analysis of cost-competitiveness of different propulsion technologies and different maturity levels, it also appears important to keep incentives to foster further diffusion of zero-emission trucks, such as ENOVA-support schemes and exemptions of road toll charges. This will reduce the barrier that zero-emission vehicles have significantly higher investment costs than similar vehicles with ICE. The same applies for having an emphasis on environmental characteristics in public (and private) tenders, as electric solutions might otherwise not be selected due to their current higher cost. Access to bus lanes for zero-emission trucks will additionally help make these more attractive, because it makes driving times during rush hours in urban areas shorter and more predictable, thus helping to reduce time-dependent costs for such trucks.

Incentives for zero-emission trucks are also important to create demand, in order to speed up the manufacturers' start-up of series productions. Altenburg et al. [4] also considered that larger-scale production of electric vehicles is needed to lower the price, improve the business case, and increase adoption. Our analysis of ownership costs illustrated that reductions in investment premiums of electric vehicles, through cheaper series and mass production, go a long way to improving the cost-competitiveness of zero-emission solutions compared to ICE-trucks.

In the short term, several of the operators interviewed for this study intend to expand the use of BE-vehicles. Driven by the Norwegian Government's 'Klimasats' initiative for transitions to low-emission solutions in the public sector and tender requirements for zero-emission operation, a number of BE-refuse collection vehicles have for example been ordered, with delivery in 2020 (rebuilt from ICE). In addition, multiple operators have placed pre-orders for Tesla tractor units, but emphasize that these are very preliminary given a number of yet unanswered questions on specifications and (tracking) capacity.

In summary, findings in this paper suggest that there might be a growing potential for electrification of commercial vehicles in Norway. Nevertheless, in the years to come, incentive schemes, charging solutions, policy facilitation, and technological developments will remain important aspects for zero-emission adoptions.

With regard to the socio-economic costs of phasing-in zero-emission technologies, we found that costs are currently highest for FCHE-vehicles, and lowest for biogas. At typical mileages, socio-economic costs per tonne CO_2 reduced versus diesel operation, lie at EUR 340 for biogas, EUR 1440 for BE-, and EUR 2760 for FCHE-trucks. In a scenario with mass production and lower cost premiums of electric vehicles, these costs are calculated to fall to EUR 580/tonne for FCHE-vehicles to EUR 170/tonne for BE-vehicles.

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Environmental and Transport Effects of Warehouse Relocationing: Evidence from Norway

Abstract

Reducing traffic volumes and CO2-emissions from freight transport has proven difficult in many countries. Although the increasing suburbanization of warehouses is seen as a relevant land use trend, comprehensive analyses remain scarce. This study uses real data in modelling transport, costs, environmental and modal effects from warehouse relocations around Oslo and Trondheim (Norway). Results indicate that for Oslo, traffic performance (ton-km), CO2-emissions, and transport costs increase following warehouse suburbanization. For Trondheim, transport performance and CO2-emissions increase less, while transport costs decrease marginally. We conclude that specific case characteristics (geography and trade patterns) are important in determining the strength and direction of effects, and expect that common concomitant developments (warehouse centralization and consolidation) would lead to more pronounced results. Our findings confirm some, but challenge other findings from the relatively scarcely available literature. Finally, the study's more general insights and observations can help advance similar analyses beyond Norway.

Keywords: land use, warehouse relocationing, road freight transport,
transport modeling, CO2-emissions, transport performance

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1. Introduction

Large-scale societal transformations are necessary if Norwegian climate objectives are to be achieved. This has proven difficult within the transport sector, where traffic volumes and greenhouse gas (GHG) emissions are steadily rising. Current planning and land use theory claim that replacing centrally located warehouses with urban development (housing, workplaces, shopping) will contribute to reduced transport volumes and GHG-emissions in total. This understanding is often referred to as the Dutch ABC-principle (Verroen et al., 1990). Despite a general agreement on this hypothesis, comprehensive empirical studies remain scarce.

This study aims to bridge this gap by empirically investigating several important mechanisms that affect GHG-emissions from transport, when centrally located warehouses are relocated. Three of these mechanisms, after relocation to fringe-locations, are 1) increased transport distances for city distribution, 2) changed transport distances for long haul transports, and 3) modal changes, depending on geographical locations of rail terminals and ports, and the relative cost of intermodal transports given old and new warehouse locations.[1]

The way and extent to which these mechanisms act, and whether they affect GHG-emissions, depends on the context. Using data from a commodity flow survey and Foreign Trade Statistics, we define and investigate two cases of hypothetical warehouse relocations from central locations to relevant locations at the outskirts of cities (Oslo and Trondheim). For both cases, we define two scenarios. In scenario *i)* warehouses are located at central locations (likely previous locations of the types of firms in question), while in scenario *ii)* warehouses are located at the outskirts. Using both the Norwegian National Freight Model, and a City Distribution Model, we compare transport performance (ton-km), modal shares, and transport-related GHG-emissions for the different scenarios, and discuss differences in results between both models used. We then analyze and discuss which contextual factors contribute to explain the effects and differences found, and compare results with existing literature.

The current study will contribute to the literature by investigating and documenting effects of land use and transport-system development on traffic volumes and GHG-emissions with respect to the relocation of warehouses (for freight transport) within the urban region. This issue is highly relevant as it is a part of on-going large-scale urban development trends, it can strongly affect traffic volumes and GHG-emissions, it is heatedly debated, and our knowledge of it is not well enough documented. While this study's analysis is based on Norwegian data, several observations are made that apply more generally and will help advance similar analyses for cases in other countries.

The remainder of this paper is organized as follows: section 2 discusses the background and context for reducing GHG-emissions from transport in Norway,

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[1] Relocations may also give rise to an indirect mechanism in the longer term: relocations open for urban developments on the site, which may counteract urban sprawl tendencies and hence contribute to minimise passenger road traffic. This indirect mechanism lies beyond the scope of this current paper.

followed by a review of the literature. Section 3 describes the methodology and assumptions used in our analysis, while elaborate results are presented in section 4. Section 5 provides a discussion and identifies avenues for further research, after which section 6 concludes.

2. Background and literature

2.1 Objectives

Stopping traffic growth and reducing GHG-emissions from traffic are clear and stated objectives in the Norwegian Parliament's climate agreement, the Norwegian National Transport Plan, and in many county- and municipal plans. A main strategic objective is to steer developments of land use and transport-systems in directions that contribute to reducing transport demand, to changing the modal split towards less car use, and to reduce emissions from goods distribution (see e.g. European Commission, 2011 & Transport Departments (Transportetatene), 2016).

Empirical studies during the last decades present overwhelming evidence that most activities (e.g. housing, workplaces, shopping) generate less traffic, the more centrally they are located (see e.g. Næss, 2012). Hence, in order to minimize car-use and traffic volumes, activities attracting the most people (employees, visitors) per square meter should be located in the most central parts of a city. For such reasons, it is understood that area-intensive activities (such as warehouses) should not be located in the more central parts of cities.

Based on such insights, there seems to be a relatively widespread agreement regarding how land use and transport-systems ought to be developed in order to reduce urban road traffic volumes: *i)* land use developments as central, urban densification rather than sprawl; *ii)* physical and fiscal restrictions on road traffic; *iii)* improved public transport services and improved conditions for walking and cycling (see e.g. Downs, 1962; Strømmen, 2001; Banister, 2011; Næss, 2006, 2012).

2.2 Failing practice

Despite this widespread agreement, a long history of such planning efforts, and initiatives intended to take developments in traffic-reducing directions, traffic volumes have in practice only kept rising (EEA, 2006; Furu, 2010). GHG-emissions from road traffic in Norway increased by 32% from 1990 to 2014, and road traffic accounted for 19% of Norwegian GHG-emissions in 2014 (Statistics Norway, 2016).

An implementation gap thus seems to exist in practical policy. With respect to factors explaining this gap, Tennøy (2012) found that weaknesses in the knowledge on how some combinations of land use and transport-systems developments affect traffic volumes, and lack of relevant knowledge among professionals, are important. Scientific knowledge can consequently be excluded or ousted from planning processes (see also Krizek et al., 2009). This problem is aggravated by the fact that several cause-effect relationships are counter-intuitive, and that different mechanisms may be active simultaneously. The latter means that even if strategies actually contributing to reducing traffic volumes are implemented (such as improving public transport services), traffic volumes may still increase due to other developments that contribute to traffic increases (e.g. urban sprawl or increased road capacity). This can be highly confusing for non-specialists. It may contribute to doubts, unfounded beliefs, and myths concerning how land use and transport-systems developments affect traffic volumes, and may hamper transitions towards more climate-friendly cities. These challenges particularly apply to complex issues that are hard to investigate empirically and are not well enough documented, such as the relocation of centrally located warehouses.

2.3 Literature

Indeed, when it comes to the location of warehouses, the academic literature predominantly takes a logistics or supply chain perspective, by identifying locations and route plans that minimize costs. This literature goes back to Weber (1909), who studied the minimization of total travel distances between a set of customers and a facility. Askin et al. (2014) refer to this problem as the Facility Location Problem (FLP), and provide an overview of 29 FLP-studies with varying dimensions and solution approaches. They then design a generic algorithm for optimizing the entire supply chain system and minimizing total costs, including fixed location costs, inventory costs, and transport costs.

Related to the FLP is the Location-Routing Problem (LRP). Prodhon and Prins (2014) analyze 72 articles on LRP between 2007 and 2013, and discuss how the LRP is a core decision in designing distribution systems. The location choice (e.g. for a warehouse) is a strategic decision, while vehicle routing to serve customers consists of tactical and operational decisions.

Despite established bodies of literature on both location and routing choices, only few studies to date provide comprehensive analyses and evaluations of the environmental and traffic effects of location choices (e.g. Nuzzolo and Comi, 2015).

One such example is Koç et al. (2015), who approach the LRP by looking at the impact of warehouse locations, truck fleet composition, and vehicle routing on emissions from urban freight distribution. The authors run a range of scenarios with regards to e.g. warehouse costs and urban distribution of customers. In most scenarios, they find that it is most cost and environmentally efficient to minimize the number of warehouses and to locate them outside the city center, oftentimes in the outer zones or suburbs. Although various authors claim that relocating warehouses to suburbs results in higher emissions, Koç et al. (2015) find that for a range of assumptions, this does not have to be the case.

Nuzzolo et al. (2014a) present a modelling framework for jointly simulating urban logistics for shopping flows (consumers) and delivery flows (freight transporters and retailers). They then test how land management can be used to improve the efficiency of urban logistics systems, and run model simulations of shopping and delivery flows for the midsize metropolitan of Padua in northern Italy. The authors test three scenarios:

1) A large share of retailers is relocated from the city center and first ring, to the second ring (larger outlets).
2) A large share of warehouses is relocated from the city center and second ring, to the first ring.
3) A large share of retailers and warehouses from the city center and second ring, relocate to the first ring.

For the first scenario, simulation results show a decrease in vehicle-km for freight distributors, but an increase in consumer-km, resulting in a net increase in equivalent vehicle-km of 2.9%. The second scenario resulted in a net reduction of 0.1% in vehicle-km, and scenario 3 in a net reduction of 12.7%, thus scoring best in terms of emission reductions. However, isolated effects of centralization on one hand (second ring to first ring), and sprawl on the other hand (city center to first ring) are less clear. The three scenarios also resulted in changes to the distribution between light, medium, and heavy vehicles (modal choice).

In Nuzzollo et al. (2014b), a similar simulation framework is discussed, again for the city of Padua. While demographic and economic developments towards 2025 are assumed to be identical, scenarios differ in other respects: in the first two scenarios, e-shopping increases moderately and dramatically respectively. In the third scenario, e-shopping also increases dramatically, but in addition, a large share of warehouse activity is relocated from both the city center and second ring to the first ring, while a large share of retail activity is relocated from the second to the first ring.

In this third scenario, the isolated effects of warehouse and retail relocation are a reduction in vehicle-km of 3.5%, 5.2% and 8.6% from light, medium, and heavy goods vehicles respectively. No change was observed in the number of vehicle-km for private cars. However, again it is unclear whether these results are driven by more or less centralization.

A different study is carried out by Allen et al. (2012), who investigate how geographical, spatial, and land-use factors correlate with key variables for land transport for 14 urban areas in the UK. The authors analyze their data in light of several trends in commercial land use and warehousing in urban areas: de-industrialization, spatial centralization of stockholding and the “squared root law of inventory” (McKinnon, 2009), rising land prices and increasing traffic congestion, and the suburbanization of warehousing (e.g. documented by Cidell (2010) for the USA). As such, Allen et al. find that commercial and industrial land use patterns affect the characteristics of freight transport, e.g. that larger urban areas have larger proportions of internal road freight trips than smaller ones, and that warehouses have become larger and increasingly suburbanized. The authors also find that trips within urban areas are less efficient (fewer ton per trip) than trips to and from urban areas, and that trips from urban areas are less efficient than trips to urban areas. Finally, the authors find that transport intensity (kilometers per ton lifted) is lower within urban areas than to and from urban areas.

2.4 Trends

The study by Allen et al. (2012) points out that the suburbanization of warehouses is part of a trend, and that relocated warehouses are often larger than original warehouses. This is largely due to lower land prices and opportunities for spatial centralization, for example by replacing multiple regional warehouses by one larger, central warehouse, when the cost savings of doing this compensate for potentially higher transport costs.

Dablanc and Rakotonarivo (2010) also observe this suburbanization trend, in studying how parcel and express terminals have gradually moved from central locations in Paris, to the outer suburbs, from the 1970s. The authors call this suburbanization "logistics sprawl". For the 17 largest parcel and express transport companies, the standard distance from terminals to the center of Paris increased from 5 km to 16 km between 1974 and 2008. On average, this logistics sprawl has led to an increase of 400 vehicle-km per terminal per day, resulting in about 15,000 tons of additional CO_2 per year for deliveries in Paris. While not negligible, this effect seems marginal compared to the 6.45 million tons of CO2 emitted from freight transport in Paris annually (Mairie de Paris, 2007).

Sakai et al (2015) follow studies like Dablanc and Rakotonarivo (2010), Dablanc and Ross (2012), and Dablanc et al. (2014), and find that, for Tokyo, the average distance between logistics facilities and the city center has increased by 2.4 km between 1980 and 2003 (4.1 km excluding the coastal area). The authors not only find an increase in the average distance for "last-mile-delivery", but also an increase in the average distance for the entire shipment. Based on the Tokyo Metropolitan Freight Surveys, they calculate the optimal location for logistics facilities that minimizes the distance from shipments' origins to their destinations. It turns out that the difference between the optimal locations of facilities and their actual locations increases as their distance from the city center increases. However, several exceptions also suggest that many facilities are located close to their optimal location, even if this is far from the city center.

3. Methodology and assumptions

The above discussion identified gaps in the understanding of the effects on traffic volumes and GHG-emissions with respect to the relocation of warehouses (for freight transport) within the urban region. As this study aims to bridge some of these gaps, this section will first provide background on the data used in our analysis. We then discuss and illustrate the selection of relevant cases and scenarios. This is followed by a description of our method of analysis. Finally, we discuss the models, characteristics, and assumptions used in our analysis.

3.1 Data

The foundation of this paper is formed by raw data from the most recent Norwegian Commodity Flow Survey (CFS), which was carried out by Statistics Norway in *2015*, and maps domestic commodity flows (measured in tons, value, and number of shipments) originating from a sample of firms in the manufacturing and the wholesale trade industries in *2014*. In addition to this sample, Statistics Norway collected data on all deliveries for the 20 largest freight forwarders in Norway. This addition yields data on deliveries for many more firms (and industries) than the ones mentioned above. In total, the CFS contains data on approximately 12,000 delivering firms or 49 million shipments. Commodity flows are mapped at post zone level for both the originating and receiving firm. Since the survey is based on a stratified sample, Statistics Norway imputed freight flows for missing firms, based on information about domestic turnover and delivery patterns from neighboring firms within the same industry. However, since we consider data for selected cases (more below), we use real data at the firm level. Because the CFS only maps outgoing freight flows, it is necessary to include both firms in the study areas, and externally located firms, from which deliveries to the study areas originate, to capture the full effects of any changes.

3.2 Case selection

In order to analyze the mechanisms described earlier, we are interested in (particularly) somewhat larger distribution firms in the urban regions of Oslo and Trondheim, for which relocations to fringe locations could be a relevant issue. By this, we mean that they have a history of 'recently' (2008-2014) moving to a fringe location, or have newly been established at such a location.

We therefore used Statistics Norway's firm registry (bedrifts- og foretaksregister)[2] to identify combinations of relevant manufacturing and wholesale trade industries (NACE-classifications 10-39; 46) and relevant fringe locations, for which municipalities have facilitated for the presence of firms from these industries.[3] Figures 3.1.a and 3.1.b illustrate locations of 'newly' established warehouses in the Oslo and Trondheim regions between 2000-2013. These figures indicate that newer developments take place mostly towards the outskirts of the urban regions (and often yield easy access to the E6-highway), while the current stock of warehouses is predominantly located centrally in the urban areas (not shown here).

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[2] The firm registry includes data on, amongst others, firm names, industry classification (NACE), location, number of employees, registration number, year of establishment, etc.

[3] I.e. Akershus county, municipalities Enebakk, Frogn, Gjerdrum, Lørenskog, Nes, Nittedal, Oppegård, Rælingen, Skedsmo, Ski, Sørum, Ullensaker, Vestby and Ås for the Oslo case; the Heimdal district for the Trondheim case.

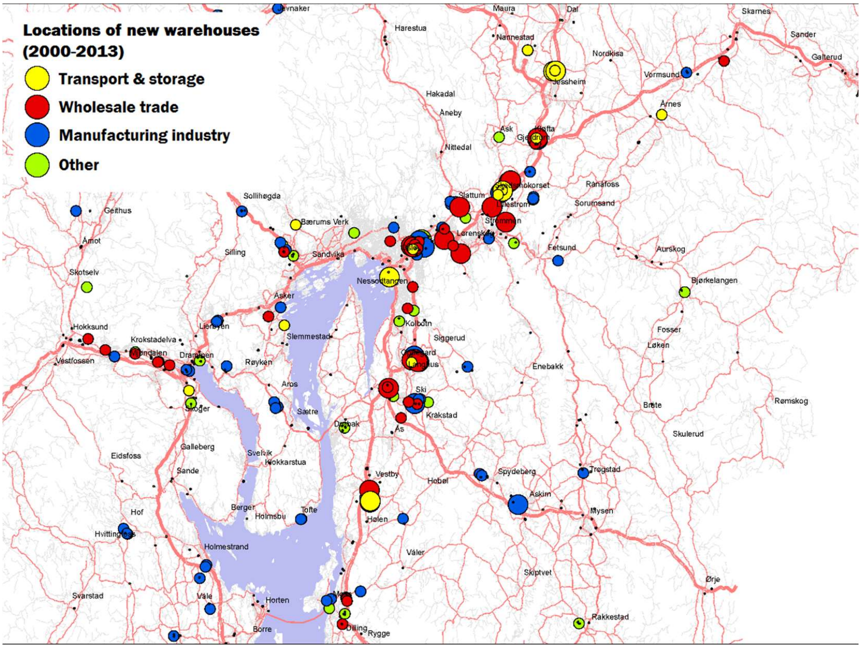

Figure 3.1.a. Locations of 'newly' established warehouses in the Oslo region.

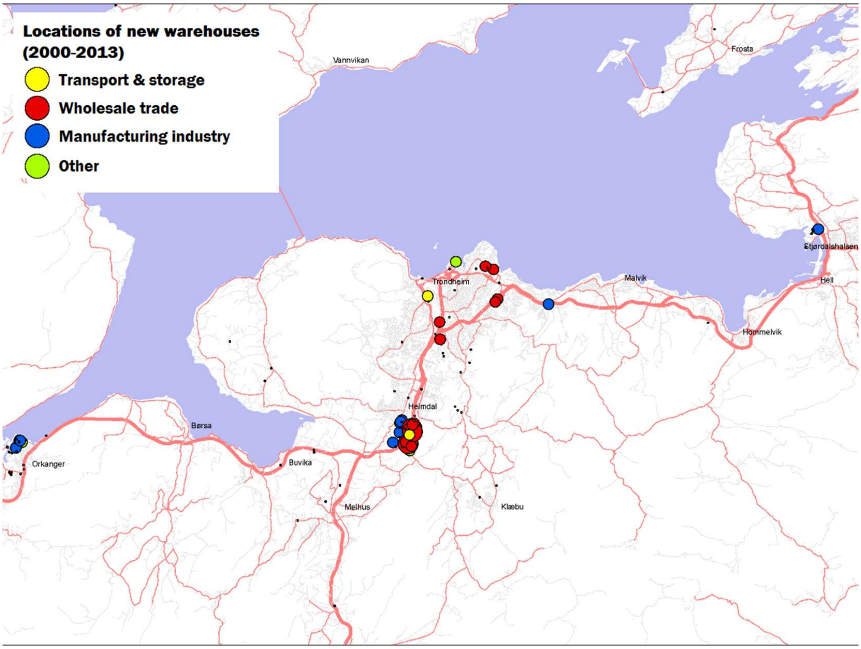

Figure 3.1.b. Locations of 'newly' established warehouses in the Trondheim region.

After identifying relevant current locations, we used the firm registry to also identify relevant previous, more central locations. Due to confidentiality reasons, we couldn't directly match commodity flows and firms, and therefore limited our CFS-dataset to commodity flows to/from localizations of relevant industries. This data-subset was then used for the analyses in this study. The relocations included in this study are illustrated in figure 3.2.

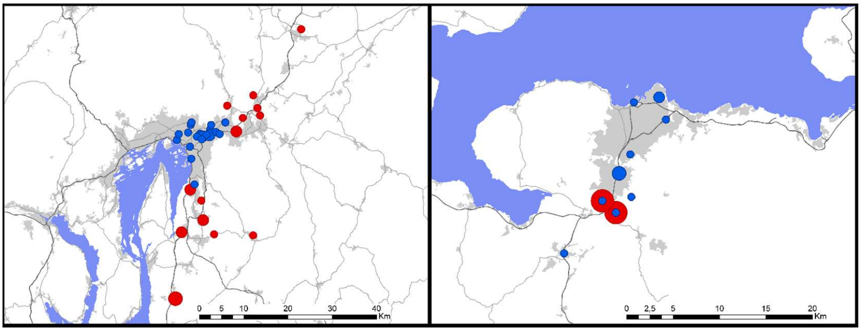

Figure 3.2. Analyzed relocations in the Oslo region (left panel) and the Trondheim region (right panel). Blue points indicate locations before moving, red points indicate locations after moving, dimensioned by number of firms.

3.3 Scenarios

As mentioned before, we defined two cases for both scenarios. In scenario *i)* warehouses are assumed to remain at central locations (likely previous locations of the types of firms in question), while in scenario *ii)* these same warehouses have been moved out to locations at the outskirts (their current locations).

3.4 Analysis

In our analysis we distinguish between effects on long-haul transport, city distribution, and modal split. In doing so, we employ two models. Both models use the same set of commodity flows (PC-matrices) as input, but at different levels of aggregation.

3.5 Long-haul transport: National freight model

Long-haul transport and modal split are most suitably analyzed using a national freight model (NFM) developed for Norway (de Jong et al., 2013; Grønland, 2015; Hovi, Caspersen and Grue, 2015; Madslien et al., 2015). This model allows for assessing how changes in locations (the scenarios) affect transport costs, modal choices, and transport performance (ton-km and vehicle km) both domestically, and for import and export. The model looks at aggregate yearly commodity flows, based on which optimal delivery frequencies, shipment sizes, and transport chains are calculated that minimize yearly logistics costs. An extension to the model additionally allows for estimating effects on CO2-emissions, based on modal splits and the CO2-intensities per ton-km for the different modes of transport.

The national freight model geographically divides Oslo and Trondheim into 12 and 8 zones respectively. While this is sufficient for analyzing long-haul effects and modal splits, it is too broad for properly capturing changes in distribution transport to/from warehouses in the urban area.

3.6 City distribution: detailed geographic level

Primarily to analyze the effects on city distribution, we therefore developed an Excel-based City Distribution Model (CDM), based on the CFS. Compared to the NFM, this model employs a geographically more detailed zone system, and divides Oslo and Trondheim in 60 and 24 zones respectively, while also covering the suburbs and the rest of the country. Because the same system is used in the Norwegian National Passenger model (see e.g. Steinsland and Fridstrøm, 2014), appropriate distance matrices for road transport are easily accessible. Another difference with the NFM is that the CDM utilizes data for individual shipments, rather than aggregating them.

In the CDM, we distinguish between outgoing and incoming deliveries and between locations before and after relocation. The vehicle-independent number of ton-km is calculated by multiplying the distance of a shipment with its weight. CFS-data on goods category and volume are used to derive the most likely vehicle for a delivery, and consequent calculations then make use of the characteristics of this assigned vehicle (capacity given goods type, distance, time, (un)loading costs, fuel consumption and consequently, CO2-emissions).

Forwarding costs are calculated by multiplying distance- and time-specific vehicle costs, while taking into account that vehicle capacity is not always fully utilized. Where relevant, we also took ferry costs into account. (Un)loading costs were calculated similarly, based on vehicle-specific cost factors.

Vehicle-km were calculated by dividing the number of ton-km of a delivery by the vehicle's capacity, taking into account the goods type transported, again under the assumption that vehicles are not always filled to capacity.

Finally, CO2-emissions were calculated by multiplying vehicle-km by the vehicle specific fuel use, the number of vehicles per delivery, and a constant of 2.62 kg CO2 per liter diesel.[4]

While the CDM was primarily developed to analyze effects at the level of the urban region, its extended design allows for comparisons with the NFM at the national level.

3.7 Foreign trade

Besides effects from warehouse relocations through domestic deliveries (captured using the Norwegian CFS), relocations also affect transport for foreign trade. This was analyzed by identifying firms in relevant origin/destination postcodes, and

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[4] This takes into account the mandatory blending in of biodiesel in Norway. See e.g. Pinchasik and Hovi (2016)

relating this information to data from the Norwegian Foreign Trade Statistics on shipment-level. These data could only be analyzed using the NFM, and results are limited to effects on transport performance, mode choice, and CO2-emissions. For transport costs, the NFM did not allow for a distinction between costs accruing within and outside Norway.

4. Results

4.1 Introduction

The main focus of this study is the effect of warehouse relocations on transport performance and CO2-emissions as a result of the three main mechanisms described. In discussing our results, we distinguish between the cases for Oslo and Trondheim. We further distinguish between deliveries covering relatively short distances for which modal choices other than road are unlikely (given the industries and goods categories analyzed), and long-haul deliveries. This distinction is illustrated in figure 4.1.[5] Where possible, result tables in this chapter show results from both the NFM and the CDM. As effects through foreign trade could only be calculated using the NFM, these results are only presented for the NFM. Consequently, totals combining effects from domestic trade and foreign trade are necessarily also only available from the NFM.

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[5] For the Oslo case, shorter distance/likely road transport is considered to include the counties Østfold, Akershus, Oslo, Hedmark, Oppland, Buskerud, Vestfold, Telemark and Aust-Agder, and for the Trondheim case the counties Hedmark, Oppland, Møre og Romsdal, Sør-Trøndelag and Nord-Trøndelag.

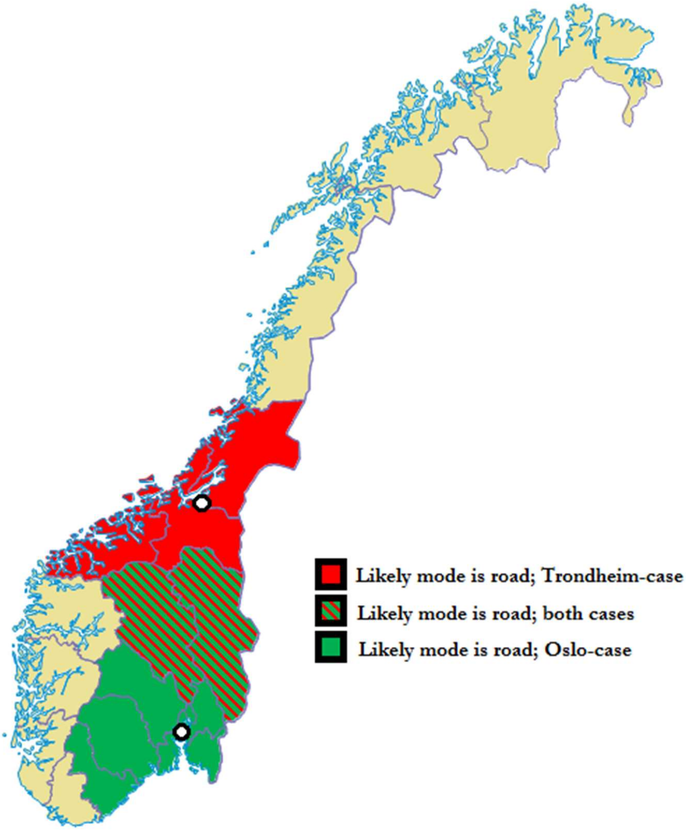

Figure 4.1. Norway divided by counties. For green counties (red counties), transport to/from Oslo (Trondheim) is predominantly done by road. Striped coloring indicates an overlap: for these counties, both transport to/from Oslo, and transport to/from Trondheim is most likely done by road.

4.2 Transport performance (ton-km)

4.2.1. Oslo

In both the NFM and the CDM, transport performance is calculated by multiplying the distance and weight of shipments. For the Oslo case, Table 4.1 presents results before and after warehouse relocations, for both models, and also includes effects through foreign trade.

Table 4.1. Comparison of transport performance before and after warehouse relocation (Oslo), divided by model used and county subsets. Figures in 1,000 ton-km per year.

	DOMESTIC						FOREIGN	TOTAL
	Short distance / likely mode = road		Long-haul / other modes also likely		All counties		Foreign trade	Total domestic (CFS) + foreign trade
	NFM	CDM	NFM	CDM	NFM	CDM	NFM	NFM
Before relocation	54,074	53,733	257,036	250,064	311,044	303,797	58,612	369,656
After relocation	55,290	56,283	261,013	254,531	316,315	310,814	56,728	373,043
Change	1,216	2,550	3,977	4,467	5,271	7,071	-1,884	3,387
%-change	2.25%	4.75%	1.55%	1.79%	1.69%	2.31%	-3.31%	0.92%

Several points can be noted from these results. First of all, both models show that the relocation of warehouses leads to an increase in the transport performance from domestic trade of several percent. Secondly, this increase is observed for both shorter distance transport (2.25-4.75%), and for long-haul transport (1.55%-1.79%), although relative increases are somewhat larger for shorter distances. Thirdly, estimates on transport performance tend to be slightly higher in the NFM than in the CDM. This is due to the fact that the CDM uses more geographically detailed distances and weighs these distances more accurately than the NFM.

For the foreign trade part, however, transport performance decreases by over 3%. Combining effects through domestic and foreign trade, the relocation of warehouses therefore results in a transport performance increase of just under 1% in the Oslo case. Causes for the decrease in transport performance through foreign trade are discussed in more detail in the upcoming section on modal shares.

4.2.2. Trondheim

For the Trondheim case, results are presented in Table 4.2.

Table 4.2. Comparison of transport performance before and after warehouse relocation (Trondheim), divided by model used and county subsets. Figures in 1,000 ton-km per year.

	DOMESTIC						FOREIGN	TOTAL
	Short distance / likely mode = road		Long-haul / other modes also likely		All counties		Foreign trade	Total domestic (CFS) + foreign trade
	NFM	CDM	NFM	CDM	NFM	CDM	NFM	NFM
Before relocation	2,546	3,207	33,656	35,903	39,880	39,111	26,103	65,983
After relocation	2,522	3,195	33,643	35,850	39,858	39,045	26,345	66,203
Change	-24	-13	-13	-53	-22	-66	242	220
%-change	-0.94%	-0.40%	-0.04%	-0.15%	-0.06%	-0.17%	0.93%	0.33%

Compared to Oslo, the relocation of warehouses in the Trondheim region results in smaller effects, and minor reductions in traffic performance through domestic trade. With reductions of 0.40%-0.94%, relative effects are somewhat larger for short distance shipments than for long-haul ones.

Several explanations can be provided for these results being less pronounced than for Oslo. As is seen from Figures 3.1. and 3.2. above, relocations in the Oslo region take place mostly to locations east of the city. For many deliveries with origin or final destinations in the city of Oslo, relocations therefore introduce extra distances or diversions to existing delivery routes. Compared to Trondheim, the relocation distance is also generally somewhat larger, which also implies somewhat larger effects. In addition, for Trondheim, the lion's share of deliveries comes from, or goes to places south of Trondheim. Firms moving from more central locations in Trondheim, to Heimdal, essentially move along an existing transport route, thus not adding much extra distance.

For the foreign trade part, however, transport performance in the Trondheim case increases somewhat (0.93%). As foreign trade constitutes a non-negligible part of total trade, the total effect therefore amounts to a marginal increase in transport performance (0.33%).

4.3. Modal shares

After presenting changes in transport performance, this section discusses underlying causes and modal shares.[6]

4.3.1. Oslo

For Oslo, the NFM indicates that virtually all shorter distance transport is done by road. Long-haul transport is also predominantly done by road (±90%), and the relocation of warehouses only causes very marginal increases (decreases) in the share of road and sea transport (rail transport).

Changes in modal shares are much more pronounced for the foreign trade part: while the share of rail transport increases only marginally, the share of road transport increases from 24.9% to 30.6%, largely at the expense of maritime transport. This is also where explanations for the decrease in transport performance through foreign trade have to be sought: firstly, the relocation of some warehouses means that shipments can arrive through different ports (e.g. Moss), for which shipping distances are shorter. Secondly, for firms relocating in northern direction, the distribution distance from intermodal terminals increases. Thirdly, relocations further away from ports may lead to goods flows shifting from ship to road, and fourthly, relocations in the direction of Sweden imply shorter domestic distances for some import and export, and therefore a decrease in transport performance.

Zooming in on road transport, we find that the NFM has a tendency to assign shipments to larger vehicles, relative to the CDM, on shorter distance shipments. This tendency is even more pronounced after relocation, and is one reason for the NFM arriving at lower transport costs than the CDM. With the transport performance of short distance deliveries making up ca. 17% of total transport performance in the Oslo case, this difference is non-negligible. For long-haul shipments, the NFM and CDM assign virtually all road transport to equivalent large vehicles, and warehouse relocations only cause marginal changes.

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[6] Shares across different modes can only be derived from the NFM, as the EM only allows for road transport.

4.3.2. Trondheim

For Trondheim, short distance transport is predominantly done by road (±90%). Compared to the Oslo case, maritime transport now makes up a share of almost 10%, while short distance transport by rail is virtually non-existent. For long-haul shipments, in turn, road transport makes up roughly two thirds of domestic transport performance, with maritime and rail transport having shares of 16%-17%. Same as in Oslo, the relocation of warehouses only leads to marginal changes in modal shares for domestic trade.

Unlike for Oslo, where modal changes for the foreign trade part were quite dramatic, such changes are not found for Trondheim. The shares of road transport (ca. 6.5%) and rail transport (ca. 8%) increase only marginally, and the share of maritime transport also only changes marginally. This also explains why changes in transport performance through foreign trade in the previous sections were relatively minor.

When exclusively looking at road transport in the Trondheim case, the NFM anew tends to assign short distance shipments to larger vehicles than the CDM does. Again, this will be one of the reasons for the NFM showing higher transport costs than the CDM (the other main reason being Trondheim's geographical characteristics). However, for Trondheim, shorter distance deliveries make up less than 7% of total transport performance, so that effects will be smaller. For Trondheim, vehicle assignment on long-haul shipments is close to identical in the NFM and CDM, and just like for Oslo, warehouse relocations only cause very marginal changes.

4.4. CO2-emissions

4.4.1. Oslo

When it comes to CO2-emissions, calculation approaches between the models differ. By basing CO2-estimates on the number of ton-km, the NFM assumes fixed average capacity utilization rates for different modes. As described before, the underlying capacity utilization in the CDM can vary for different shipments, as the model uses data on shipment-level, rather than calculating optimal shipment sizes and frequency per year (like the NFM). Despite these differences, both models indicate that total CO2-emissions from domestic shipments increase when relevant warehouses are relocated (Table 4.3).

Table 4.3. Comparison of CO2-emissions before and after warehouse relocation (Oslo), divided by model used and county subsets. Figures in ton CO2 per year.

	DOMESTIC						FOREIGN	TOTAL
	Short distance / likely mode = road		Long-haul / other modes also likely		All counties		Foreign trade	Total domestic (CFS) + foreign trade
	NFM	CDM	NFM	CDM	NFM	CDM	NFM	NFM
Before relocation	6,702	6,999	28,186	25,337	34,879	32,336	1,757	36,636
After relocation	6,875	7,445	28,830	25,790	35,717	33,235	1,922	37,639
Change	173	445	644	453	839	899	165	1,003
%-change	2.58%	6.36%	2.29%	1.79%	2.40%	2.78%	9.41%	2.74%

Although absolute numbers differ somewhat between the models, this effect persists both for shorter distance and long-haul deliveries. Again, relative increases are highest for shorter distance deliveries (2.58%-6.36% vs. 1.79%-2.29%). The relatively higher increase in CO2-emissions for shorter distance shipments in the CDM can be explained by the CDM assigning a larger share of deliveries to smaller vehicles than in the NFM (see the previous section).

For the foreign trade part, CO2-emissions increase as well, despite the reduction in transport performance. The total effect from the relocation of warehouses therefore amounts to an increase of CO2-emissions of just under 3%. The cause for this increase lies with the changes in modal shares discussed above: as the share of road transport increases at the expense of maritime transport, average CO2-emissions per ton-km increase.

4.4.2. Trondheim

In the Trondheim case, the effect of warehouse relocations on CO2-emissions is relatively small (Table 4.4).

Table 4.4. Comparison of CO2-emissions before and after warehouse relocation (Trondheim), divided by model used and county subsets. Figures in ton CO2 per year.

	DOMESTIC						FOREIGN	TOTAL
	Short distance / likely mode = road		Long-haul / other modes also likely		All counties		Foreign trade	Total domestic (CFS) + foreign trade
	NFM	CDM	NFM	CDM	NFM	CDM	NFM	NFM
Before relocation	285	357	3,055	3,172	3,417	3,529	543	3,960
After relocation	282	356	3,066	3,168	3,429	3,524	553	3,982
Change	-2	-1	11	-4	12	5	11	22
%-change	-0.84%	-0.10%	0.36%	-0.14%	0.34%	-0.13%	1.95%	0.56%

While the NFM shows an increase in emissions of 0.34% for the country as a whole, the CDM indicates a minor decrease of 0.13%. For the shorter distance deliveries, CO2-emissions are estimated to decrease, but by no more than 0.84%, while for long-haul transport, estimated effects are also very small (-0.14% to 0.36%).

For the foreign trade part, however, which is predominantly done over sea, CO2-increase by just under 2 percent. The effect of domestic and foreign trade combined therewith amounts to an emissions increase of 0.56%.

4.5. Transport costs

Estimating transport costs is often challenging because of imbalances in freight flows in different directions. Consequently, transport modes are on average not filled to capacity. In the NGM, this challenge is addressed through adjustments to capacity utilization rates and by adding a mobilization distance for some specialized modes, while the CDM addresses this challenge by capping capacity utilization rates at 70%.

4.5.1. Oslo

Results on transport costs estimates differ significantly between the two models, as both models employ their own cost functions and cost elements. In addition, the assignment of deliveries to different modes plays a material role in the freight model, with transport costs constituting an important factor. Together with the NFM’s tendency to assign deliveries to larger vehicles, and to optimize the number and size of deliveries, this leads to transport costs in absolute terms being significantly lower in the NFM than in the CDM, which only allows for transport by road. Another point worth mentioning is that for cost effects through foreign trade, the NFM does not distinguish between costs accruing in Norway and costs accruing abroad. Results are therefore limited to domestic trade.

Nevertheless, both models show that transport costs in the Oslo case increase as a result of warehouse relocation. This increase is moderate in the NFM (0.32% and 1.35% for shorter distances and long-haul transport respectively, for a combined increase of 0.97%). In the CDM, the increase in transport costs is more significant (4.58% in total).

4.5.2. Trondheim

For Trondheim, results also differ significantly between the two models, for the reasons described above. For Trondheim, however, both models show that transport costs decrease as a result of warehouse relocation.

The NFM indicates a decrease of 0.50% on short distance shipments, and a decrease of 1.36% for long-haul transport, for a combined decrease of 1.22%. The CDM, in turn, indicates almost no change in transport costs, with decreases not exceeding 0.1%.

5. Discussion

Using modelling tools, rather than e.g. surveys asking firms about perceived transport and CO2-effects of relocating, allows for a bottom-up approach to calculating driving distances, fuel consumption, and CO2-emissions. The models used in this study also make it possible to calculate isolated effects of warehouse relocations on transport performance, costs, and CO2-emissions, and in doing so, take into account full delivery patterns for the available sample.

To a certain extent, the NFM and CDM complement each other in doing so. An important strength of the NFM is that it allows for modal shifts following relocation, and includes maritime and rail transport, in addition to road transport. This might also make its estimation of transport costs more realistic than in the CDM, where road transport is the only mode considered, even when this is considerably more expensive between certain origins and destinations.

A weakness of the NFM in the realms of this study, however, is its aggregated geographical level. This particularly is a disadvantage when analyzing more local effects. To that end, the CDM introduces a considerably higher level of geographical detail, which particularly contributes to the analysis of effects in urban regions.

As for the estimation of CO2-effects, the starting point in both models is the transport performance, for which data is expected to be rather certain. While the NFM then employs average CO2 emission factors per ton-km, the CDM takes into account estimations on the capacity utilization of single shipments. In addition to the higher level of geographical detail, this is expected to yield more precise estimates on CO2-emissions, and thus also more precise comparisons of impacts from different warehouse locations.

In addition to both models having their own characteristics, relevant differences also exist at the case level. Firstly, the sample of deliveries in the Oslo case is much larger, and is less likely to be influenced by a number of dominant firms potentially accounting for a large share of the observations. Secondly, we saw that the geographical location of Oslo and Trondheim and the locations of new warehouses is less likely to yield large effects in the Trondheim case, than in the Oslo case. Conclusions for the one case therefore don't necessarily also apply to the other.

An important limitation of our study is the implicit ceteris paribus assumption: except warehouse location, all else remains the same. In reality, however, the relocation of warehouses often will allow for larger warehouses, due to lower land prices, and the centralization of warehouses, for example by replacing several regional warehouses by one, larger warehouse for the entire country, when cost savings from centralization are higher than cost increases from longer transport distances. This aspect will therefore likely lead to more pronounced effects than the ones found in our analysis.

The relocation of warehouses also opens up for other urban developments, such as housing, workplaces, or shopping. Avenues for further research could therefore include analyses of traffic effects from different urban developments, to include total effects of changed land use.

6. Conclusions and final remarks

For achieving wide-spread Norwegian objectives of stopping traffic growth and reducing GHG-emissions, large societal transformations are required. Empirical studies during the last decades overwhelmingly conclude that more centrally located activities generate less traffic. For such reasons, it is understood that area-intensive activities, such as warehouses, should not be located in the more central parts of cities.

While locating people-intensive activities (such as housing or workplaces) in central part of cities has received much attention in the literature, the (re)location of warehouses has so far predominantly focused on logistics or supply chain effects, rather than on environmental or traffic effects.

This study contributes to the literature by investigating and documenting effects of land use and transport-system development on traffic volumes and GHG-emissions with respect to the relocation of warehouses (for freight transport) within the urban region. This is done by considering three mechanisms: 1) increased transport distances for city distribution as warehouses relocate to fringe-locations, 2) changed transport distances for long haul transports, and 3) modal changes, depending on geographical locations of rail terminals and ports, and the relative cost of intermodal transports given old and new warehouse locations and the delivery pattern for the firm.

After identifying relevant cases and scenarios, we used data from Statistics Norway's Commodity Flow Survey and Foreign Trade Statistics as input in both the Norwegian National Freight Model, and an own developed Excel-based City Distribution Model with somewhat different characteristics.

Results from running these models indicate that, for the case of Oslo, transport performance through domestic trade increases as a result of warehouse relocations. Although a decrease in transport performance from foreign trade somewhat compensates for this effect, transport performance in total is still indicated to rise. At the same time, modal changes for domestic trade are marginal, and for the foreign trade part indicate some shifts from sea to road and increased distribution distances from intermodal terminals. All in all, warehouse relocations also cause CO2-emissions to increase. The fact that a large part of this increase materializes in the urban region suggests that urban areas could see relevant increases in local emissions (e.g. NOx). Finally, for the Oslo case, also transport costs are indicated to increase. Logistics costs in total may nevertheless go down due to e.g. lower land prices outside the central areas or the centralization of stockholding.

For Trondheim, effects on transport performance are smaller (minor decreases for domestic trade, a small increase through foreign trade, for a combined effect of 0.33%). Also, modal shares and CO2-emissions (+0.56% in total) change less than in the Oslo case, while transport costs are indicated to decrease by 0.09-1.22% in total. An important reason for these less pronounced effects can be that the relocated warehouses are often placed close to main existing transport routes. This is an important observation to keep in mind when extending or extrapolating results to other cases.

All in all, our results stand in some contrast to findings by Koç et al. (2015), who concluded that in most scenarios, it is most cost and environmentally efficient to minimize the number of warehouses and to locate them at the outskirts. Although Koç et al. consider total logistics costs, our study shows that for Oslo, at least the transport part of costs in fact increases, while for Trondheim, transport costs decrease only marginally. Moreover, and contrary to Koç et al., we find that environmental emissions increase, rather than decrease, for both Oslo and Trondheim.

Compared with Nuzzolo et al. (2014a and 2014b), our study focuses on isolated effects from sprawl, rather than sprawl and centralization combined. While this makes direct comparisons with those authors impossible, our approach is in line with the "logistics sprawl" trend observed in both the literature (e.g. Allen et al, 2012 or Dablanc et al., 2014) and in this study itself.

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Article

Crossing Borders and Expanding Modal Shift Measures: Effects on Mode Choice and Emissions from Freight Transport in the Nordics

Daniel Ruben Pinchasik [1,*], Inger Beate Hovi [1], Christian Svendsen Mjøsund [1], Stein Erik Grønland [2], Erik Fridell [3] and Martin Jerksjö [3]

[1] Institute of Transport Economics, Department of Economics, N-0349 Oslo, Norway; ibh@toi.no (I.B.H.); csm@toi.no (C.S.M.)
[2] Sitma AS, N-0213 Oslo, Norway; seg@sitma.no
[3] IVL Swedish Environmental Research Institute, Department of Transport and Department of Mobility, 41133 Gothenburg, Sweden; erik.fridell@ivl.se (E.F.); martin.jerksjo@ivl.se (M.J.)
* Correspondence: drp@toi.no; Tel.: +47-463-473-20

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Abstract: Considering the underachievement on modal shift and environmental objectives for freight transport, scholars and policy makers recurrently ask how more road freight can be shifted to rail and waterborne transport. The current study simulates transport and modal distribution effects for several scenarios in which modal shift policy measures are strengthened, expanded, combined, and harmonized across borders in the Nordics. Found transport effects were then used in an environmental model to assess implications for energy use and emissions of $CO_{2,eq}$, NOx, and particulate matter, gaining insights into which policy measures are more effective or complement each other, and whether international harmonization might increase effectiveness, and modal shift. From our simulations, a Norwegian ecobonus scheme for rail yields larger modal shift away from road than a similar ecobonus for sea transport. Facilitating longer freight trains yields more modal shift but has high policy costs. Effects of harmonizing policies across Nordic countries vary but can be strengthened by combining different measures. However, even for scenarios with strong policy measures, reductions in $CO_{2,eq}$ emissions do not exceed 3.6% in 2030 while sometimes increasing local air pollution. Modal shift policy should therefore not exclusively be regarded as environmental strategy, although it may contribute to other policy objectives.

Keywords: modal shift; intermodal; freight transport; emissions; environment; truck; policy measures; harmonization

1. Introduction

Inducing modal shift from road to rail and waterborne freight is a political objective in many countries [1], often motivated by ambitious emission reduction, sustainability, and traffic safety targets. In most European countries, modal shift ambitions are particularly driven by the European Commission's Transport White Paper [2], while in Norway, modal shift has additionally been a transport-political objective in all National Transport Plans (NTPs) since 2002, state budgets since 2005, and several government agreements [3].

Despite this focus, modal shift objectives both in Norway and many European countries are far from being met in practice [4,5]. In fact, in most countries, road transport has been increasing (often strongly), while freight has been shifting away from rail to road. Since the 1970s, rail freight's market share has for example steadily decreased throughout Europe [6–8], and particularly in Eastern Europe [5].

Important explanations behind these developments include several megatrends strengthening the position of transport by road/truck. A first example is a decades-long trend of sectors starting to organize themselves differently; less nationally and more internationally, country-overspanning, or Pan-European. This trend has caused an increase in international transport, often favoring road transport, as many production and consumption centers can only be reached by road [9–11].

Alongside, debates and developments have been ongoing towards increasing vehicle weight and length allowances in a number of European countries [12]. While making road transport more cost and environmentally efficient, this development also improves road transport's competitiveness vis-à-vis other modes and makes shifts to other modes less attractive.

Thirdly, Eastern-European transport firms have taken over sizable shares of international road freight transport in Europe, being able to compete with driver wages below the minimum in many richer EU-countries [5]. Also this has strengthened road transports' competitive position.

For the Nordic region (in this article, focusing on Norway, Sweden, and Denmark), similar developments have been visible—transport-generating enterprises such as distribution centers and logistics warehouses are increasingly established at a Nordic level and located in, e.g., the South of Sweden, the share of transport with drivers from low-wage countries has been strongly increasing at the expense of the driver share from the Nordic countries, and vehicle dimension allowances have increased in terms of length, weight, and the use of European Modular Systems [8,13,14].

In light of the above developments and far too little progress in reducing CO_2 emissions from freight transport [8], a recurrent theme with both policy makers and scholars has been how more modal shift can be achieved than has so far been the case.

For Norway, a freight analysis prepared for the National Transport Plan 2018–2029 [15] highlighted that assessments of domestic modal shift might underestimate the full modal shift potential, arguing that if more of the imported freight enters Norway by rail or sea; this increases the likeliness of further domestic transports by these modes (rather than by road). As such, the question was posed whether measures implemented at the Nordic level can contribute to increasing the share of foreign freight to and from Norway by sea or rail.

The current study takes a comprehensive approach, assessing a number of scenarios where existing policy measures with modal shift relevance are strengthened or expanded. The policy scenarios studied cover both single, mode-specific policy instruments, as well as combinations of instruments, including cross-border harmonization in Norway, Sweden, and Denmark. As such, we gain important insights into which policy measures might be more effective than others, whether measures might complement each other, and whether international harmonization might increase effectiveness, and thereby modal shift. In addition to effects on transport and modal distribution, we calculate environmental effects through energy use, emissions of CO_2 and NO_x, and particulate matter. As environmental effects are mode-specific, the latter also has implications for policy making, depending on the trade-offs between for example local and global pollution.

Although this study looks at policy instrument usage in the Nordic region as a whole, it should be noted that analyses are primarily carried out from a Norwegian perspective. Quantitative estimates of changes in modal choices and freight flows are for example made using the National Freight Model for Norway (NFM) [16–18], and given its inputs, the analysis only covers effects for freight flows with origin and/or destination in Norway. In addition, future policy scenarios studied with the NFM were specified based on the mapping of policy measures in the Nordics, but also with focus on freight flow analyses with (particularly) Norwegian relevance.

However, introducing modal shift from road transport to sea or rail in Norway's foreign trade will also lead to less road transport in other Nordic countries, being important transit countries for Norwegian import and export by road. Even though differences in geographical conditions and availability of transport modes will affect how comparable scenarios would turn out in other countries or regions than the Nordics, results and particularly insights from the current study will therefore be highly relevant for researchers, policy makers, and other stakeholders.

2. Literature Background

2.1. Political Objectives and Framework

As introduced above, an important driver of modal shift ambitions in Europe is the European Commission's White Paper or transport policy roadmap [2]. This document sets targets of transferring 30% of road freight on distances over 300 km to other modes like rail and inland waterways by 2030, and more than 50% by 2050. Amongst others, this implies that cargo volumes handled by rail will have to three- to four-double [19]. In the Nordic countries, modal shift objectives are also to an important degree driven by this framework.

Generally, modal shift objectives tend to focus on freight transport over longer distances, as transport over short distances (particularly <100 km) is dominated by road [19]. This is because rail/water modes can rarely be used for first- and/or last-mile delivery, meaning that, in most cases, only parts of transport chains can be shifted away from road, and leaving a necessity for road transport at origin and/or destination [5]. In addition to adding detours to and from rail or sea terminals rather than driving an optimal route, reloading at terminals adds handling costs. Since such costs are independent of trip length, reloading adds relatively more time and costs for shorter trips and further adds a risk of damaging freight [5,19,20].

2.2. Desirability of Modal Shift

In light of the above discussion, modal shift is generally considered more feasible for longer-distance transport, and there are several reasons that modal shift can be considered desirable. Both rail and water modes are generally more energy-efficient than road transport, and usually yield lower negative external effects per tonne-km performed. Sea transport for example tends to give lower CO_2 emissions and less externalities such as congestion, noise, and accidents, but typically has higher SOx, NOx-, and PM emissions [21]. Rail transport too, generally causes less environmental emissions and other negative externalities than road transport [7]. As such, a shift of freight from road to rail and/or water is seen as one means for reducing CO_2 emissions and could be particularly relevant for the Nordics, where transport's share in energy-related CO_2 emissions is higher than in many other European countries [22].

At the same time, it should be emphasized that decarbonization cannot happen through modal shift alone [1,5,11,23]. Further, it should be noted that in addition to sustainability and transport and safety objectives, there might be other (political) reasons that modal shift is desired, e.g., to support transport modes, such as Norwegian rail freight, where operators are struggling and a growth in freight volumes might be crucial to prevent a decrease in rail freight services [14,24].

2.3. Modal Choices and Decision Factors

Important factors that decide how modal choices are made, are costs, access to modes, transit time, reliability, service frequency, and different shipment and commodity characteristics [5,25]. In this regard, different modes have different strengths and weaknesses. Compared to water and rail transport, road freight for example has low capital costs, is more flexible from a geographical and timing perspective, and is often faster. However, road transport often also yields a number of negative externalities such as congestion, infrastructure wear and tear, negatively affects traffic safety, and is less suitable for bulk transport [20]. Particularly on longer distances, an advantage of waterborne transport compared to road are economies of scale, while on shorter distances, transshipment costs and ship size are less favorable [21]. Rail transport is also considered to be potentially cost-effective due to economies of scale [7] but has a number of inherent weaknesses, such as road dependency at origin and/or destination and long lead times [6]. Compared to road freight and to be competitive, both waterborne and rail transport will further require sufficient freight flows, both in terms of volume and regularity.

2.4. Instruments and Measures for Inducing Modal Shift

For policy to incentivize modal shift, it must in some way change the balance of choice factors where these currently favor road transport. Policy measures for promoting modal shift can be categorized in different ways. For example, Kaack et al. [5] distinguish the following two approaches: targeting infrastructure and efficiency improvements of freight systems and using financial incentives. The combining of policy measures (particularly increasing road costs and reducing lead times for intermodal transport) has been suggested as valuable approach. At the same time, Kaack et al. [5] find that many countries lack such policies. Nocera et al. [26] use a different, but comparable taxonomy, dividing instruments that can (in)directly encourage modal shift into push measures (making road transport less attractive) and pull measures (making rail and waterborne transport more attractive). For freight transport, push measures may include taxation, charges and tolls, and regulatory measures (e.g., orders and bans), while pull measures may include positive financial incentives for sea and rail transport or measures that improve reliability or infrastructure or reduce shipping costs. Both McKinnon [27] and Meers and Macharis [28] find that, in many cases, modal shift policies include taxation, regulation, infrastructural measures, and financial incentives. However, they also point to the use of legislative powers regarding interoperability, e.g., through standardization and harmonization, and to approaches where policy makers attempt to convince shippers individually to consider intermodal transport.

On a European level, well-known examples of some of the measures described above include the EU's Marco-Polo, Ten-T, and Motorways of the Sea initiatives, as well as key elements in the EU's so-called railway packages [7,21]. Nevertheless, according to Paulsson et al. [29], modal shift targets require significant further infrastructural upgrades throughout Europe, amongst others due to the lack of dedicated rail freight infrastructure and existing infrastructure being based on long-outdated traffic demand, but such upgrades are both expensive and complicated.

Policy measures studied in the current paper (for which a scenario description follows in Section 3.3) cover several of the types discussed above, including combinations of measures and border-crossing implementation.

2.5. Methods for Studying Modal Shift

When it comes to assessments of modal shift potential and effects, different approaches can be taken, depending on objectives and information that may be available. Jonkeren et al. [30] divide existing studies into macro and micro studies, depending on the spatial level assessed. Based on a literature review, they further distinguish four main methods of analysis: choice models, life cycle analyses, decomposition analyses, and strategic transport network models.

Because CO_2 emissions amongst others depend on origin, destination, and geographical proximity to intermodal terminals, estimation of environmental effects is not straightforward [5], and not all of the above methods are suitable to study environmental effects of modal shift.

Indeed, Jonkeren et al. [30] find that CO_2 reduction effects from modal shift are most often studied using strategic transport network models, noting that these have the advantage of being highly adaptable when several inputs have first become available (e.g., origin-destination matrices, cost and choice information, etc.).

However, in many cases, sufficiently granular high-quality freight data is not available, as data collection is often limited or inconsistent or only available for country-specific freight activities [5]. This is also the reason that the current study is limited to (domestic and international) freight flows with origin and/or destination in Norway and which are covered in the NFM. This includes considerable transport activity in important transit countries such as particularly Sweden and Denmark. Although the exact effect of similar policy measures in other countries/regions will depend on local characteristics (e.g., geographical situation and available transport modes), insights and reasoning in the current study will also be useful in other countries, particularly where foreign trade and transit are significant.

3. Methodology

The analyses in this study are divided into two stages. First, we use a National Freight Model for Norway to simulate a set of policy measure scenarios outlined in Section 3.3 and their influence on modal choice. Second, these estimates on changes in modal choice are used to compute environmental effects, using data on the fleet for trucks, ships and trains, together with emission factors from updated sources.

3.1. The National Freight Model for Norway

The National Freight Model or NFM for Norway can be classified as strategic transport network model [30], consisting of the following elements:

1. Transport demand, represented by commodity flow matrices between Norwegian municipalities, and between Norwegian municipalities and geographical zones abroad, distributed over 39 commodity groups representing different requirements regarding transport quality and time. The commodity flow matrices represent the annual sum of commodity flows between suppliers (producers, importers, and wholesalers) and end-use sectors (exporters, wholesalers, retailers, and service industry) [18].
2. A network model, representing each mode's physical infrastructure (road, sea, rail, and air) by distance and transport time, including locations of terminals for consolidation and reloading between modes [16]. There is also one node file for each commodity group, describing the properties for each node and terminal in the model.
3. Cost functions representing time- and distance-dependent costs for different transport modes, including loading/unloading/reloading, ordering, storing, commodity time values, etc. [17].
4. Optimization routines for choice of shipment size, frequency, and mode, based on a minimization of yearly logistics costs [31].

Combining these elements, the model determines optimal transshipment locations (from a list of available terminals) for each pair of origin and destination zones, and then calculates shipment size and transport chains (number of legs, selection of modes and vehicle types). Based on this, the model selects the transport chain with the lowest logistics costs. Model programming is done using an object Pascal Delphi compiler, and due to the involvement of common developers, the NFM features large similarities to the Swedish freight model used by Vierth et al. [32].

Policy scenarios assessed in this study are operationalized through changes in parameters in the NFM (e.g., cost parameters, changes in available terminals, costs related to train length restrictions in the network model, etc.). These changes affect which transport chains are calculated to yield the lowest logistics costs, and thus are selected in the model. As such, the NFM yields estimates on the distribution of mode of transport (compared to a reference scenario or "status quo"), impacts on transport costs, and overall logistics costs.

The scenarios are run for the future year 2030, based on projections made for the Norwegian Ministry of Transport and Communications towards the National Transport Plan 2018–2029 [33]. These projections were based on Statistics Norway's population projections from 2016 and macroeconomic growth trajectories compiled by the Norwegian Ministry of Finance [34] with macroeconomic model DEMEC. Growth paths are regionalized using PINGO, a spatial computable general equilibrium model for Norway [35]. The changes made in the NFM to represent a given scenario compared with a reference situation, are implemented in either the cost functions and the input files generated from those, in the files representing the different nodes, or in the input files for the networks. Beyond the changes and assumptions mentioned in our descriptions, cost developments are assumed to remain the same between modes. Relative costs can change if e.g., the phase-in of new technologies follows a different path or policy changes in levies/duties (e.g., on fuel) are introduced. Such hypothetical situations were not assessed, in order to be able to distinguish the partial effects of modal shift measures.

3.2. Environmental Effects

NFM-output on transport performance (tonne-km) from domestic and foreign trade was combined with energy use and emission factors to estimate environmental effects in the different policy scenarios (changes in energy use, GHG- and NOx emissions, and exhaust particulate mass (PM)). Emissions and energy use factors (in g/tonne-km and MJ/tonne-km respectively) were derived from different sources, depending on transport mode.

For road transport, energy use and emissions were calculated using transport performance output, together with fuel consumption and emission factors from the HBEFA-model (v.3). Both the distribution of road transport over different-size trucks and maximum load capacity for transport of different commodity groups are output from the NFM. The NFM divides trucks into light lorries, heavy lorries, and large trucks, each with several sub-categories. These subcategories were matched with truck sizes in HBEFA. Based on a weighting of sub-categories (an output of the NFM), energy use for each main truck category was calculated. Average load factors were estimated using information from the NFM on load capacities for each commodity group, to take into account that different commodities have different volumes per tonne. When applying environmental emission factors, empty trips were assumed to constitute 30% of the total distance, derived as average for freight transport with trucks in statistics for 2016–2018 from Statistics Norway.

For emission assessments of Norwegian freight trains, we used the basic methodology from energy and emission calculation system EcoTransIT [36]. In EcoTransIT, calculations are based on train weight (gross and net), after which conversion factors are used to correct for the positioning of empty wagons and topography. This work describes rail transport with three main train types, respectively "wagonload," "other rail," "diesel trains," and their sub-categories from the NFM. To calculate typical train weights within each sub-category, maximum capacities (from the NFM) were combined with tare weights for freight wagons from EcoTransIT. Average energy use for each main train type was calculated by weighting sub-categories (from the NFM), after which emission factors were derived based on the Norwegian electricity mix employed in EcoTransIT [36]. This mix was validated against the most recent statistics available.

For sea transport, the NFM uses a set of ship types. Characteristics of these were developed using data for existing ships of the same type and similar size from SeaWeb [37]. Fuel consumption for each ship type was obtained using specific fuel consumption data from IMO [38] together with average speeds from SeaWeb. Emission factors for calculating air pollutants emissions were based on Cooper and Gustafsson [39].

The share of renewable diesel blend in 2030 is assumed to be 20%, both for road transport and diesel trains. This is a continuation of the mandatory blend in 2020, as shares in later years have not been decided yet. Further, we assumed that all trucks used in 2030 comply with Euro-VI emission standards, while the share of fully electric trucks or electric hybrids is expected to be negligible [following 40]. For ships, fuel is assumed to remain of 100% fossil origin in 2030, and energy-efficiency and emission standards are held at current levels. Finally, all emissions are presented as tailpipe emissions and do not include upstream emissions from e.g., production and transportation of fuel, and elements of uncertainty discussed in the discussion section.

3.3. Scenarios

Based on a mapping of existing policy measures for modal shift in the Nordic countries (an update of Pinchasik et al. [8], analyses of volume flows and developments in foreign trade with trucks [14], and feedback on modal shift potential from a survey among firms with own sea terminal [40,41], we constructed a set of future policy scenarios. The first four scenarios consider single policy measures, while the latter five scenarios consider combinations of the single measures and/or border-crossing implementation in the Nordic countries. Together, the scenarios cover both infrastructure/efficiency improvements and financial incentives (in line with [5]) and can be characterized as both push and pull measures [26]. Vierth et al. [32] carried out a related analysis as in the current paper for the case of

Sweden, using the Swedish national freight model to calculate modal shifts, environmental effects, and changes in logistics costs from several proposed policy measures. Policy measures were studied in isolation and combined to illustrate whether measures reinforce each other or require coordination.

Both the scenarios covering single policy measures and those covering combinations and border-crossing implementation are assessed against a reference scenario based on the latest NFM, with 2030 as year of comparison (i.e., with road network and program versions of March 2019 and PWC-matrices for 2030 freight flows). The reference scenario represents "business-as-usual" and does therefore not include eco-bonuses or changes to current road pricing regimes. For railway, it includes current length allowances of 480 m for combi-trains (containers) and wagon loads, except for some border-near rail stretches where length allowances vary around ca. 600 m.

3.4. Scenarios Covering Single Policy Measures

3.4.1. Scenario 1: Norwegian Ecobonus for Sea Transport

In 2017, Norway established a trial scheme for an "ecobonus" for sea transport. Subject to certain requirements, this scheme was designed to pay out support towards sea transport replacing road transport on Norwegian territory. In May 2019, Norwegian Government [24] proposed to replace the scheme by other measures, but later announced to make the scheme permanent with an annual budget of NOK 50 million [42].

Due to the frequent recent changes, the current policy scenario is assessed for an ecobonus scheme with hypothetical budget of NOK 150 million/year, equal to the rail ecobonus in Scenario 2.

To implement the sea ecobonus in the NFM, we assume that the entire annual budget is paid out to shippers. Based on experience from practice, we further set eligibility limitations, including all ships suitable for transport of general cargo, but excluding, e.g., bulk transport and comparable (which already goes by ship where possible).

Based on the 3.9 million tonnes of goods that, from the latest NFM version, are loaded/unloaded from container ships in Norway annually, and considering that freight is handled twice in terminals, the ecobonus was operationalized as reduction in terminal costs for loading/unloading in Norwegian ports. Because the NFM does not allow applying cost reductions exclusively to newly generated sea transport, and some modal shift could be expected from road to sea due to reduced terminal costs, exact terminal cost reductions were calculated in an iterative process. Cost reductions per tonne were set equal for eligible ship types. Further, if the calculated terminal cost reduction yielded total support payments above/below the program's budget, parameters were adjusted, and the model reiterated. Assumptions for this scenario were implemented as direct changes in the port costs in the nodes files.

3.4.2. Scenario 2: Norwegian Ecobonus for Rail Transport

Until recently, when Norway's revised State Budget for 2019 included a "rail ecobonus" proposal, Norway did not have an ecobonus program for rail transport, such as, e.g., Sweden, or previously Italy [43]. We therefore modeled a policy scenario with an annual "rail ecobonus" budget of NOK 150 million, i.e., equal to the sea ecobonus in Scenario 1. Again, support is assumed to be payable only for the parts of road transport on Norwegian territory that are shifted away. Support is further assumed to be limited to combi-transport (i.e., excluding bulk and timber transport).

The ecobonus for rail was implemented in the NFM in a similar way as for the sea scheme, here with a reduction in terminal costs of 15 NOK/tonne combi-freight handled in Norwegian rail terminals (at both ends of the transport chain). The assumptions for this scenario were implemented as changes in the terminal costs in the nodes files.

3.4.3. Scenario 3: Increases in Eurovignette Rates in Sweden and Denmark

With regard to costs for trucks driving in the Nordic countries, we started out using the costs of today's Eurovignette, which is used in Sweden and Denmark (in addition to Luxemburg, the Netherlands, and until recently, Belgium), and applies to heavy trucks (gross weight ≥12 tonnes). For this policy scenario, we assumed a five-doubling of today's (daily) Eurovignette price, i.e., 5 × 8 EUR. To reflect that the Eurovignette applies in Sweden and Denmark, but not Norway, this rate increase is operationalized through the modelling of a "toll charge" for driving into or out of Sweden or Denmark. In the model, the assumptions for toll charges were implemented in the network files.

Although the rate increase assessed here might seem large, Bouchery and Fransoo [23] find that while implementing taxes on road transport aligns costs and CO_2 emissions, cost increases for the road mode have to be substantial, often beyond what is considered feasible in practice, to have significant effect. For example, for truck transport between Oslo-Bergen or Oslo-Trondheim in Norway, toll expenses (one way) average around 360 NOK/36 EUR (for Euro VI trucks, outside of peak hours).

3.4.4. Scenario 4: Longer Freight Trains

In order to lower operational costs and freight rates for rail, particularly important factors are the ability to operate heavier, longer and wider trains, with higher speeds and better capacity utilization [19]. Such factors can improve rail's competitiveness versus road by reducing unit costs per tonne-km. However, the extent of cost reductions depends on whether longer trains require changes to locomotive set-ups, such as extra locomotives or by replacing four-axle locomotives (used by most operators on the Norwegian freight network) by more powerful six-axle versions.

For this scenario, we analyze effects of facilitating longer freight trains for transport to/from Norway at Kornsjø and Charlottenberg (see Figure 1). Train length allowances are set to 740 metres for combi-trains (the required allowed length on the Trans-European transport network, TEN-T, increasing from the current ca. 600 m). We further assume length allowances of 640 m on main freight relations in the Norwegian rail network, an increase from 480 m for combi-trains (containers) and wagon loads. Where most cost-effective, we assume operation of six-axled locomotives. Finally, we take into account that for longer trains to yield modal shift, freight flows in the market must be large enough to fill up the extra train capacity at the same level of service (frequency). All these changes were implemented as direct input into the NFM's cost model and thereby the generated cost input files.

Figure 1. Illustration of combi-terminals in the Norwegian freight railway network. Adapted from: https://www.cargonet.no/tjenester/kombinerte-transporter/.

3.5. Combinations of Measures and Border-Crossing Implementation

For the following scenarios, we ran combinations of different policy measures in conjunction, and with implementations not just in Norway, Sweden, or Denmark, but in multiple countries at once. This is done to assess whether measures might complement each other and whether international harmonization might increase their effectiveness and resulting modal shifts.

3.5.1. Scenario 5: Combination of Longer Freight Trains and Norwegian Ecobonus for Rail

This fifth policy scenario combines increased freight train lengths (with operationalization as in scenario 4) with a rail ecobonus in Norwegian terminals only (as in Scenario 2).

3.5.2. Scenario 6: Idem Scenario 5, but with Rail Ecobonus also Applying in Swedish and Danish Rail Terminals

This scenario follows the fifth scenario above but assumes that the same rail terminal cost reductions as in Scenarios 2 and 5 also apply to Swedish and Danish rail terminals in the model's network (implicitly assuming that these countries make available sufficient public funds to accommodate this). The reasoning behind this is that Norwegian and Swedish schemes respectively, provide ecobonus support based on parts of transport carried out on each country's own territory. If transport firms or customers could receive support for the entire distance that goods are transported by rail instead of by road, this would cover a larger part of total shipping costs and (theoretically) increase the probability for modal shift.

3.5.3. Scenario 7: Combination of Road Measures, with Rail and Sea Measures in Norway

In this scenario, several policy measures are combined. We simultaneously consider the ecobonuses for sea and rail transport from Scenarios 1 and 2 (thus applying in Norway only), and the Eurovignette rate increases in Sweden and Denmark, from Scenario 3.

3.5.4. Scenario 7b: Expansion of Scenario 7 with Terminal Cost Reductions in Sweden and Denmark

To better understand effects on modal choice, we ran an additional simulation of Scenario 7, but expanding cost reductions for sea and rail as in Scenarios 1 and 2 from Norwegian, to also apply in Swedish and Danish ports and terminals. For this scenario, environmental effects were not calculated.

3.5.5. Scenario 8: Combination of Road, Rail, and Sea Measures, Coordinated for the Nordics as a Whole

In this final scenario, several policy measures are combined and coordinated for the Nordics as a whole. We consider ecobonus-induced cost reductions in both Norwegian, Swedish and Danish ports and terminals in the model's network, together with cost increases for road freight. For the latter, we assume that increases in Eurovignette rates as in Scenario 3 (or similar cost increases) also apply within Norway. This is operationalized as increase in per-km costs for semitrailers and European Modular Systems (25.25 m vehicles) of 0.60 NOK/km in all three countries. Given an annual mileage of 100,000 km this is equal to a five-doubling of today's Eurovignette costs. The increase is also equal to rates in a Swedish road pricing proposal as Eurovignette replacement [44], as was recently rejected by Swedish Parliament and has also been analyzed in Vierth et al. [32].

3.6. Scenario Overview

To summarize, Table 1 provides an overview of the different policy scenarios and their main assumptions.

Table 1. Main assumptions used for the different scenarios calculated using the National Freight Model, presented as change compared to the "business-as-usual" reference.

Scen.	Short Description	Modes Influenced	Change
1	Norwegian ecobonus for sea	Sea	Reduction in freight levy up to NOK 7/tonne for general cargo and container ships in Norwegian ports.
2	Norwegian ecobonus for rail	Rail	Reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals.
3	Eurovignette rate increases SE, DK	Road	Increased costs of NOK 360 per truck for driving into/out of Norway.
4	Longer freight trains	Rail	740 m lengths for combi-trains into/out of Norway. 640 m on main relations in Norway. Opening of terminals in Sweden, Denmark and Western-Europe for rail transport to/from Norway.
5	Combination of longer freight trains and Norwegian ecobonus for rail	Rail	Idem to scenario 4. In addition, reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals as in scenario 2.
6	Combination of longer freight trains and rail ecobonus also applying in SE, DK	Rail	Idem to scenario 4. In addition, reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian, but now also in Swedish and Danish rail terminals.
7	Combination of road measures, with rail/sea measures in Norway	Sea	Idem to Scenario 1.
		Rail	Idem to Scenario 2.
		Road	Idem to Scenario 3.
7b	Expansion of scenario 7 with terminal cost reductions in Sweden and Denmark	Sea	Idem to scenario 1, but with equal reduction in freight levy also applying in Swedish and Danish ports.
		Rail	Idem to Scenario 2, but with equal reduction in terminal costs also applying in Swedish and Danish terminals
		Road	Idem to Scenario 3.
8	Combination of road, rail and sea measures (coordinated for Nordics as a whole)	Sea	Reduction in freight levy up to NOK 7/tonne for general cargo and container ships in Norwegian ports, but now also in Swedish and Danish ports.
		Rail	Reduction in terminal costs of NOK 15/tonne for combi-trains in Norwegian terminals, but now also in Swedish and Danish rail terminals.
		Road	Increased costs of NOK 0.60/km for semitrailers and European Modular Systems in all Nordic countries

4. Results

4.1. Introduction

This section presents effects on modal choices in the different policy measure scenarios, as well as environmental effects. Because modal shift effects of different policy measures are calculated compared to a reference scenario for 2030 (business as usual), and environmental effects in turn derived from changes in transport, we first present the distribution between transport modes in the reference scenario. For completeness, Table 2 shows this distribution both in weight (tonnes) and transport performance (tonne-km or tkm) in the reference scenario for Norwegian commodity flows, both on Norwegian and foreign territory. This is in contrast to Vierth et al. [32], who only investigated changes in the part of transport performance occurring on Swedish territory (for commodity flows with a Swedish perspective).

Table 2. Norwegian commodity flows, domestically and through foreign trade. Transport volume (in million tonnes) and transport performance (in million tonne-km), reference scenario for 2030.

	Transport Volume (Million Tonnes)					**Transport Performance (Million tonne km)**			
	Road	**Sea**	**Rail**	**Ferry**	**Total**	**Road**	**Sea**	**Rail**	**Total**
Domestic	366.9	52.1	12.6	0.0	**431.6**	27,725	27,757	4723	**60,205**
Export	6.7	160.9	2.8	0.5	**170.9**	5185	505,536	1612	**512,333**
Import	11.3	32.7	26.2	1.5	**71.7**	9074	134,863	6291	**150,228**
TOTAL	**384.9**	**245.7**	**41.6**	**2.0**	**674.2**	**41,984**	**668,156**	**12,626**	**722,766**

Changes in transport performance are often the best indicator for assessing modal shift but can in some cases also be affected by changes in transport routes yielding changes in transport distance. When looking at weight (tonnes), it is important to keep in mind that a tonne of freight that shifts from road to rail can result in a triple weight increase, since tonnes are counted for each mode of transport, resulting in an additional tonne on both rail and road, as distribution transports generally take place at both ends of the rail link using road transport. The same applies for shifts from road to sea, but since the model only counts tonnes on the Norwegian mainland, for import and export flows, tonnes might be counted double, rather than triple.

The table illustrates that for Norwegian commodity flows, transport performance in the reference scenario is dominated by sea transport. This is particularly due to large export flows of bulk goods within foreign trade (e.g., oil, gas, minerals and gravel) and, to a lesser degree, import flows. For domestic flows, transport performance for road and sea modes is calculated to be roughly equal in 2030. This is due to the smaller domestic transport volumes by sea compared to road, being transported over on average considerably larger distances. The table further illustrates that rail in general, but particularly domestically, plays a relatively small role. Large import volumes on rail are mainly related to Swedish transit flows of iron ore from Kiruna, to the Norwegian port of Narvik, which is ice-free year-round. The above implies that a relatively small modal shift for sea can, in absolute terms, be larger than a relatively large shift for e.g., rail.

Table 3, in turn, shows the distribution of energy use and emissions over transport modes in the reference scenario, for 2030.

Table 3. Energy use, $CO_{2,eq}$ emissions, NOx emissions, and PM from road, sea, and rail transport in reference scenario, for 2030, domestic and foreign trade for Norwegian commodity flows in total.

	Road	**Sea**	**Rail**	**Total**
Energy use (PJ) *	69	126	3	198
$CO_{2,eq}$ emissions (ktonnes) **	3969	5994	34	9998
NOx emissions (t)	5682	104,693	151	110,526
PM (t)	65	1801	6	1872

* One PJ (petajoule) is 1015 joules or 278 gigawatthours [45]. ** kt (kilotonne) equals 1000 metric tonnes.

It can be seen that energy use for freight transport is dominated by the sea mode. This is also reflected in $CO_{2,eq}$ emissions, where the relative contribution from rail transport is even lower because of its high share of electrification. For emissions of air pollutants, sea transport is even more dominating due to the less stringent emissions regulations here. At the same time, it should be noted that the sizable transport performance for ships means that the majority of emissions take place outside of Norway and therefore do not appear in Norway's "climate accounts". Further, although not shown here, sea transport generally also has particularly high SO2 emissions compared to road and rail [21], as the sulphur content in marine gasoil (ca. 1000 ppm) is much higher than in road diesel (around 6 ppm). For reasons of space, in the rest of this chapter, transport and environmental effects in the different policy scenarios are presented as percentage changes compared to the reference scenario.

4.2. Single-Measure Scenarios

Table 4 shows percentage changes in transport volume and transport performance for all transport modes, for the single-measure policy scenarios, compared to the reference for 2030. Table 5, in turn, shows resulting changes in energy use, $CO_{2,eq}$ emissions, NOx emissions, and particulate mass. Changes are presented and discussed for the entire transport chain of Norwegian commodity flows, i.e., it includes the parts of transport taking place both on Norwegian and on foreign territory.

Table 4. Single-measure policy scenarios: modal shift in percent, for transport volume and transport performance respectively, compared to reference for 2030.

		Change in Transport Volume			**Change in Transport Performance**		
Scen	**Short Description**	**Road**	**Sea**	**Rail**	**Road**	**Sea**	**Rail**
1	Norwegian ecobonus for sea	0.05%	0.1%	−0.1%	−0.3%	0.2%	−0.4%
2	Norwegian ecobonus for rail	0.3%	−0.1%	5.9%	−1.4%	0.0%	5.4%
3	Eurovignette rate increases SE, DK	−0.2%	0.1%	3.2%	−1.9%	0.1%	2.9%
4	Longer freight trains	0.1%	−0.6%	8.2%	−6.8%	-0.3%	38.2%

Table 5. Single-measure policy scenarios: percentage changes in energy use, $CO_{2,eq}$, NOx, and PM compared to reference for 2030.

		Change in Energy Use				**Change in $CO_{2,eq}$ Emissions**				**Change in NOx Emissions**				**Change in PM**			
Scen	**Short Description**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**
1	Norwegian ecobonus for sea	−0.3%	0.4%	−0.4%	**0.1%**	−0.3%	0.3%	−0.4%	**0.1%**	−0.3%	0.4%	−0.3%	**0.3%**	−0.3%	0.4%	−0.4%	**0.3%**
2	Norwegian ecobonus for rail	−1.4%	−0.1%	6.7%	**−0.4%**	−1.4%	−0.1%	14.5%	**−0.5%**	−1.3%	-0.1%	16.9%	**−0.1%**	−1.3%	−0.1%	8.0%	**−0.1%**
3	Eurovignette rate increases SE, DK	−1.9%	0.2%	2.7%	**−0.6%**	−1.9%	0.2%	1.9%	**−0.7%**	−2.0%	0.2%	1.6%	**0.1%**	−2.1%	0.2%	2.5%	**0.1%**
4	Longer freight trains	−6.7%	−0.5%	35.6%	**−2.6%**	−6.7%	−0.5%	12.6%	**−3.0%**	−7.1%	-0.5%	5.5%	**−0.9%**	−7.3%	−0.5%	31.8%	**−0.8%**

4.2.1. Scenario 1: Norwegian Ecobonus for Sea Transport

From the tables, it is seen that a Norwegian ecobonus for sea transport with annual budget of NOK 150 million, yields small effects. In volume terms, sea transport increases by 0.1% (i.e., a shift of ca. 0.3 million tonnes), of which most was originally transported by road. At the same time, volumes on rail decrease slightly (about 0.04 million tonnes), while road volumes increase slightly (by ca. 0.2 million tonnes). The latter is caused by additional road transport at one or both ends of the sea link.

In terms of transport performance, sea transport also increases slightly (0.2% or ca. 1 414 million tonne-km). The observation that changes are larger in tonne-km than in tonnes indicates shifts of freight flows on distances above the average for sea. Alongside, we find small decreases in the transport performance for both road and rail transport (equivalent to 143 and 50 million tonne-km respectively), of which most are related to Norwegian territory. Transport performance for sea transport increases nearly three times more than the decrease for land-based transports. This illustrates that some of the freight transferred has origins or destinations in South-Eastern Europe, where distances to Norway by sea are much longer than for land-based transports.

Given the way that the ecobonus is modeled, the largest part of the program's budget is found to benefit existing sea transport. If existing sea transport is held constant, and the ecobonus exclusively directed towards 'new' sea transport, which is the intention of the support scheme, the distribution effect would be larger.

When looking at environmental effects, we find that the sea ecobonus yields a small increase in energy use for sea transport and small decreases for road and rail, with similar percentage changes in emissions of $CO_{2,eq}$, NOx, and PM. In total, $CO_{2,eq}$ emissions increase by 0.1% (7 ktonnes), which is a consequence of increased transport distances when shifting to seaborne transport in this scenario. Total NOx emissions and PM both increase by 0.3% (367 tonnes and six tonnes, respectively), particularly due to absolute increases for sea transport, given higher specific emissions for most ships relative to modern trucks.

4.2.2. Scenario 2: Norwegian Ecobonus for Rail Transport

For the Norwegian rail ecobonus with the same budget as the sea program above, we find considerably stronger percentage modal shifts. These shifts are largest from road to rail, but the model also predicts a decrease in sea transport in favor of rail. In volume terms, rail transport increases by almost 6% (2.4 million tonnes), while sea transport decreases by 0.1% (0.3 million tonnes). Road volumes increase slightly (0.3% or 1.3 million tonnes) due to increased distribution transport required to/from rail terminals at both ends of the transport chain.

Considering transport performance, modal shift away from road is about four times larger than in the scenario with sea ecobonus. Simultaneously, rail transport increases by 5.4% (686 million tonne-km), i.e., slightly less than the increase in tonnes. This illustrates that the ecobonus scheme affects rail transport on distances slightly below the average. For sea transport, transport performance decreases marginally (less than 0.1%, or just under 300 tonne-km).

Regarding environmental effects, modal shifts in this scenario imply that total energy use decreases by 0.4%, as increases for rail are more than offset by decreases for road and sea. Despite rail increases partially occurring on non-electrified (diesel) tracks, total $CO_{2,eq}$ emissions, NOx emissions, and PM show small decreases, in contrast to increases found in the sea ecobonus scenario.

4.2.3. Scenario 3: Increases in Eurovignette Rates in Sweden and Denmark

Given a five-doubling in Eurovignette rates applying in Sweden and Denmark, model simulations indicate that road transport decreases slightly (by 0.2% or 0.7 million tonnes in volume terms; by 1.9% or 813 million tonne-km in transport performance). Modal shift occurs both to sea and rail modes, with sea transport increasing by 0.1% both in volume and transport performance (i.e., 0.4 million tonnes; 806 million tonne-km). Rail transport sees a larger volume increase (3.2% or 1.3 million tonnes) and transport performance increase (2.9%), although in absolute terms, transport performance increases less than for sea, at 362 million tonne-km. This is due to the lower base in the reference scenario.

A breakdown of transport performance effects regionally (i.e., a subset of total effects presented here and for which more background documents and references are available in [46]) indicates that Eurovignette rate increases in Sweden and Denmark mainly reduce road transport related to Norwegian transit through Sweden, illustrating that route choices between southern and northern parts of Norway will be affected.

Further, we find that the changes in transport yield slight decreases in total energy use (0.6%) and $CO_{2,eq}$ emissions (0.7%), alongside a slight increase of NOx emissions and PM due to the increase of sea transport.

4.2.4. Scenario 4: Longer Freight Trains

In the scenario with longer freight trains, we find the largest shift to rail of the single-measure scenarios (8.2% volume increase, or 3.4 million tonnes; 38.2% transport performance increase, or 4823 million tonne-km). Larger percentage increases in tonne-km than in tonnes illustrate that particularly goods on longer distances are transferred to rail. Transports are shifted to rail both from road and from sea, with transport performance by road transport decreasing by 6.8% (2 864 million tonne-km) and for sea by 0.3% (1978 million tonne-km).

These modal shifts imply a decrease in total energy use of 2.6% relative to the reference scenario. Decreases are also found in terms of $CO_{2,eq}$ (293 ktonnes), NOx (967 tonnes) and PM (13 tonnes).

4.3. Impacts of Policy Packages and Border-Crossing Measures

Similar to the discussion above, Table 6 shows changes in transport compared to the 2030 reference, but now for the scenarios with policy packages/border-crossing measures, to assess whether this yields stronger effects. Table 7 shows resulting changes in energy use and environmental emissions.

Table 6. Combined-measure policy scenarios: modal shift in percent, for transport volume and transport performance respectively, compared to reference for 2030.

Scen.	Short description	Change in Transport Volume (in Percent), Compared to Reference			Change in Transport Performance (in Percent) in Total, Compared to Reference		
		Road	Sea	Rail	Road	Sea	Rail
5	Combination of longer freight trains and Norwegian ecobonus for rail	0.4%	−0.8%	12.2%	−8.2%	−0.4%	47.4%
6	Combination of longer freight trains and rail ecobonus also applying in SE, DK	0.4%	−0.8%	12.2%	−8.3%	−0.4%	47.2%
7	Combination of road measures, with rail/sea measures in Norway	0.2%	0.2%	6.8%	−3.6%	0.3%	7.2%
7b	Expansion of Scenario 7 with terminal cost reductions in Sweden and Denmark	0.4%	−0.4%	7.6%	−5.0%	−0.2%	12.5%
8	Combination of road, rail and sea measures (coordinated for Nordics as a whole)	0.5%	−0.3%	9.1%	−6.5%	−0.2%	16.6%

Table 7. Combined-measure policy scenarios: percentage changes in Energy use, $CO_{2,eq}$, NOx, and PM, compared to reference for 2030.

		Change in Energy Use				**Change in $CO_{2,eq}$ Emissions**				**Change in NOx Emissions**				**Change in PM**			
Scen	**Short Description**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**	**Road**	**Sea**	**Rail**	**Total**
5	Combination of longer freight trains and Norwegian ecobonus for rail	−8.1%	−0.6%	45.5%	**−3.1%**	−8.1%	−0.6%	21.8%	**−3.5%**	−8.4%	−0.7%	14.5%	**−1.1%**	−8.7%	−0.7%	41.6%	**−0.9%**
6	Combination of longer freight trains and rail ecobonus also applying in SE, DK	−8.2%	−0.6%	45.3%	**−3.1%**	−8.2%	−0.6%	21.5%	**−3.6%**	−8.5%	−0.7%	14.2%	**−1.1%**	−8.7%	−0.7%	41.4%	**−0.9%**
7	Combination of road measures, with rail/sea measures in Norway	−3.6%	0.5%	8.2%	**−0.8%**	−3.6%	0.4%	14.8%	**−1.1%**	−3.6%	0.5%	16.8%	**0.3%**	−3.7%	0.5%	9.3%	**0.4%**
8	Combination of road, rail and sea measures (coordinated for Nordics as a whole)	−6.4%	0.0%	16.6%	**−2.1%**	−6.4%	0.0%	13.8%	**−2.5%**	−6.4%	0.0%	12.9%	**−0.3%**	−6.6%	0.0%	16.2%	**−0.2%**

4.3.1. Scenario 5: Combination of Longer Freight Trains and Norwegian Ecobonus for Rail

When combining longer freight trains with a rail ecobonus in Norwegian terminals, model simulations predict a large increase in rail transport (12.2% or 5.1 million tonnes in volume terms; over 47% or almost 6000 million tonne-km in transport performance). This increase is caused by shifts away from both road and sea transport. Road transport is calculated to decrease by 8.2% (3457 million tonne-km), while sea transport decreases by 0.4% (2429 million tonne-km). Compared to the partial effects of each of these policy measures in sum (i.e., the sum of Scenarios 2 and 4), combining them yields a larger modal shift in total: although modal shift away from road is nearly the same, combining the measures yields some additional modal shift from sea to rail.

Considering energy use, modal shift in this combination scenario results in about a 3.1% decrease, because a large increase in energy use for rail is more than offset by decreases, particularly for the less energy efficient road mode. Further, total $CO_{2,eq}$ emissions decrease by around 3.6% (353 ktonnes), and NOx emissions and PM by about 1% (1160 and 15 tonnes respectively).

4.3.2. Scenario 6: Idem Scenario 5, but the Norwegian Rail Ecobonus also Applying in Swedish and Danish Rail Terminals

When expanding the previous scenario with rail terminal cost reductions applied not only in Norwegian, but also in Swedish and Danish terminals, we find only a marginally larger reduction in road transport (of 8.3% or 3485 million tonne-km), while also transport volumes and performance for the rail and sea modes remain nearly the same. As a result, environmental effects in the fifth and sixth scenario are almost equal as well. It should be noted that in this scenario it is assumed that in addition to the Norwegian Government, also the Swedish and Danish Governments make public funds available to reduce terminal costs in their countries, but that the effect, at least through Norwegian commodity flows, seems marginal.

4.3.3. Scenario 7: Combination of Road Measures, with Rail and Sea Measures in Norway

When combining both sea and rail ecobonuses in Norwegian ports/terminals with Eurovignette rate increase in Sweden and Denmark (corresponding to Scenarios 1, 2, and 3 in total), we find small increases in road and sea volumes (both 0.2% or 0.7 and 0.5 million tonnes respectively), and an increase for rail (6.8%; 2.8 million tonnes). In transport performance terms, road transport decreases by 3.6% (1524 million tonne-km), while both sea (0.3%; 1975 million tonne-km) and rail transport (7.2%; 904 million tonne-km) increase. Because of changes in where transport takes place geographically, increases in transport performance for rail and sea in sum are larger than the reduction for road transport. Compared to the sum of partial effects of each measure, combining them yields a marginally smaller modal shift in total, with a slightly larger increase in transport performance by sea, and a slightly smaller increase for rail. This illustrates that the Norwegian ecobonuses for rail and sea, respectively, only to a minor degree attract some of the same freight flows. When both bonuses appear as possibility, the sea ecobonus seems to be marginally more attractive than the rail ecobonus. These results suggest an effective design of the three policy measures, as they each mostly affect different transport flows.

Environmentally, modal shifts in this scenario yield a reduction in total energy use of 0.8%, reducing $CO_{2,eq}$ emissions by 1.1% (111 ktonnes). NOx emissions and PM, however, both increase slightly, particularly driven by the increases in sea transport with higher specific emissions. In isolation (sum of scenario 1, 2 and 3), the policy measures yield a slightly larger decrease in energy use and $CO_{2,eq}$ emissions, and slightly smaller increases in NOx emissions and PM, than when the policy measures are combined.

4.3.4. Scenario 7b: Expansion of Scenario 7 with Terminal Cost Reductions in Sweden and Denmark

When expanding ecobonus-induced terminal cost reductions from a national level (scenario 7) to the Nordic level (this additional simulation), we find a slightly larger increase in road volumes (0.4%

or 1.4 million tonnes) and rail volumes (7.6% or 3.2 million tonnes), while sea volumes decrease (0.4% or 0.9 million tonnes). In terms of transport performance, however, we find stronger decreases for road transport (5% or 2117 million tonne-km) and stronger increases for rail transport (12.5% or 1580 million tonne-km). We further find (not shown here) that the additional transport performance decrease for road, and increase for rail transport, almost exclusively take place outside of Norway. For sea transport, however, almost half of the decrease in transport performance takes place on Norwegian territory.

These results indicate that a harmonization of ecobonuses for rail and sea to the three Nordic countries yields additional modal shift away from road, particularly to rail. Simultaneously, increasing the ecobonus for both rail and sea transport seems to increase the competitiveness for rail compared to sea transport, resulting in transfers from sea to rail. This is in contrast to the result we found in Scenarios 5 and 6, where harmonization of the rail ecobonus yielded only marginal additional effects. Therefore, it seems that increasing train lengths will further increase the competitiveness of rail and make the impact of the ecobonus stronger. The cause for this is that increased train lengths result in decreased costs for rail, which means that the ecobonus now adds a more significant cost reduction in relative terms. This further illustrates that in order to achieve such a significant effect, alternatively to increase train lengths, ecobonus rates may be increased.

4.3.5. Scenario 8: Combination of Road, Rail and Sea Measures, Coordinated for the Nordics as a Whole

Finally, we look at the combination of rail terminal and port cost reductions applying in Norway, Sweden and Denmark, and road cost increases no longer applying only in Sweden and Denmark, but also in Norway. This policy scenario is found to yield a strong decrease in road transport (of 6.5% or 2712 million tonne-km) and further a decrease for sea transport (of 0.2%; 1311 million tonne-km), while the rail mode increases by 16.6% (2095 million tonne-km). As a result, total energy use is calculated to decrease by 2.1%, and $CO_{2,eq}$ emissions by 2.5% (252 ktonnes). Alongside, NOx emissions decrease slightly (by 0.3%, 327 tonnes), as does PM (by 0.2%, 3 tonnes).

Compared to scenarios 7 and 7b, policy measures in this scenario are considerably stronger. Not surprisingly, the road cost increases result in a considerably larger shift away from road. Further, the increase for rail more than doubles, while sea transport decreases further compared to scenario 7b. A factor contributing to the latter is that distribution transports using road at the start/end of transport chains become more expensive per km, and that distribution transports for a part of freight flows, particularly abroad in Continental Europe, have longer distances to/from ports than for rail terminals.

Regarding environmental effects, reductions in energy use and $CO_{2,eq}$ emissions are around 2.5 times larger than in Scenario 7, following shifts to overall more efficient modes. NOx emissions and PM also decrease. Reasons for this are particularly the decrease in transport performance for ships.

5. Discussions and Conclusions

5.1. Induced Modal Shift Through Combinations of Policy Measures

In light of underachievement on modal shift objectives and too little progress in reducing CO_2 emissions from freight transport given climate commitments [8], a recurrent theme with both policy-makers and scholars has been how more modal shift can be achieved than has so far been the case. In this article, we analyzed the effects of strengthening existing policy instruments for transferring freight transport from road to sea and rail, and of harmonizing policy-instruments across borders between Norway, Sweden and Denmark, for potentially more effect.

From our simulation of policy scenarios, we find that a Norwegian ecobonus scheme for rail yields much larger modal shifts away from road transport than a similar ecobonus for sea transport. The rail ecobonus also yields positive environmental effects, with small reductions in emissions of $CO_{2,eq}$, NOx and PM, rather than minor increases under the sea ecobonus scheme. This is due to the high degree of electrification of the rail mode, and because with the sea ecobonus, more transport performance is added on sea than reduced on road, due to longer distances stemming from the location of the transferred goods. Further, most ships have higher specific NOx and PM emissions relative to modern trucks.

Significant increases in Eurovignette rates in Sweden and Denmark also result in reduced road transport, mostly through shifts from road to rail and particularly by affecting road route choices between southern and northern Norway, shifting from transit through Sweden to transport within Norway. As a whole, however, modal choice and environmental effects are limited. Allowing longer freight trains, in turn, has a larger impact on modal choice than the ecobonus schemes and road cost increases, and also yields larger decreases of environmental emissions. However, the infrastructure investments required are expected to entail much higher policy costs for government [29].

Combining a Norwegian rail ecobonus with policy measures facilitating longer trains yields slightly stronger effects than the sum of effects when the measures are studied in isolation, by causing some additional shifts from sea to rail. However, further expansions, by applying ecobonus-induced cost reductions also in Swedish and Danish rail terminals, only result in a marginally larger reduction in road transport. This suggests that harmonizing the rail ecobonus across the Nordic countries yields little additional effects, despite requiring the use of more public funds. Most likely, this is due to distances between the Nordic countries being too short to exploit rail transport's main benefits and to overcome inherent weaknesses, such as (expensive) road dependency at origin and/or destination and long lead times [6].

Combining both sea and rail ecobonuses in Norwegian ports and terminals with Eurovignette rate increases in Sweden and Denmark gives strong modal shifts from road to rail, and smaller shifts to sea transport. Because of different distances for different modes on different relations, tonne-km increases for rail and sea transport in sum are larger than the reduction in tonne-km by road, as a result of the relations with changes in mode choice. While the increased use of rail results in reduced $CO_{2,eq}$ emissions, emissions of air pollutants increase due to increased use of ships. In many cases, however, sea transport will have shorter distances than land-based transport between Norway and the European Continent, suggesting that effects of measures might be case-specific, and that emissions in many situations could decrease.

When additionally expanding sea and rail ecobonuses to apply also in Swedish and Danish terminals, results suggest that such harmonization yields additional modal shift away from road, particularly to rail. Simultaneously, such expansions of both rail and sea ecobonuses seem to increase rail's competitiveness versus sea transport, resulting in transfers from sea to rail. This contrasts findings from Scenarios 5 and 6, where harmonization of the rail ecobonus yielded only marginal additional effects.

Finally, a harmonization of ecobonuses for both sea and rail, combined with a per km-charge for road transport in all three Nordic countries, results in minor additional modal shifts compared to the previous scenarios. This is followed by a decrease in $CO_{2,eq}$ emissions and somewhat larger decreases in emissions of air pollutants.

Our results suggest that in some, but not all cases, harmonization of policy measures such as ecobonuses may strengthen effects of modal shift policy, depending on transit traffic and border-crossing effects.

5.2. Environmental and Other Considerations

Altogether, most scenarios show reduced environmental emissions, particularly when policy measures are combined and/or include the facilitation of longer freight trains. However, even in scenarios with rather strong policy measures, reductions in $CO_{2,eq}$ emissions do not exceed 3.6% in 2030. This indicates that modal shift can only be a moderate contributor to the decarbonization of freight transport, and is in line with observations by e.g., Tao et al. [1], Kaack et al. [5], Pinchasik et al. [8], and McKinnon [11].

Moreover, in several scenarios, we find increased air pollution. This is due to increases in sea transport, which has higher specific emissions of NOx and PM. Policy makers aiming at modal shift should therefore also consider other environmental impacts than CO_2. Further, in line with Bouchery and Fransoo [23], maximizing modal shift is not necessarily optimal for reducing CO_2 emissions. As intermodal transport in some cases increases transport distances compared to direct truck transport, environmental effects of modal shift depend on a trade-off between efficiency gains and losses due to longer transport distances (as well as mode-specific changes).

However, it should be noted that even when modal shift measures do not yield large effects for society as a whole, governments may find them desirable for other reasons. An example from Norway includes a fear that without measures, even more rail freight routes might be cancelled. Moreover, modal shift may be considerable in specific transport corridors where rail or sea is desirable. Further, even when emissions and mode choice for the whole of transport chains do not change much, countries might have an interest in what happens on their own domestic territory.

5.3. Policy Design, Developments, Assumptions, and Uncertainty

Lessons learned from the analysis are that support schemes such as the ecobonuses for rail and sea must be designed such, that they are only paid out if the support results in a (new) modal shift away from road transport. Based on Norwegian freight flows, we find that harmonizing over the borders of the Nordic countries would do this in some, but not all cases, when it comes to Norwegian freight flows. However, what is not analyzed here is the impact of the assessed policy measures on Swedish and Danish freight flows, which can make it possible to establish new shipping or rail routes that can attract goods from the Nordics as a whole. In this regard, implemented policy measures should be evaluated and findings shared between the Nordic countries, as this may improve the design of new policies.

Given this study's conclusions, it is appropriate to remember that model simulations do not capture all societal trends. There are at least three megatrends that strengthen the competitive position of road transport and trucks [14]: Establishment and use of Nordic distribution centers, increased use of transport firms from lower-wage countries for border-crossing transports, and increases in vehicle dimensions in terms of weight and length [8]. These developments have improved the competitive position of road transport and are particularly relevant because wage expenses constitute a larger share of total transport costs for trucks than for rail or sea transport. Policy makers should therefore take into account that, while measures such as larger allowances for vehicle dimensions might improve the efficiency of road transport, they also make road transport more competitive versus rail and sea.

As all projections about the future, developments in important drivers and assumptions are subject to uncertainty. In our analysis, important factors are particularly the employed emission factors, commodity flows and projections of these toward 2030, and an assumption of equal developments in future costs for the different transport modes.

With regard to emission factors, we for example assumed that electric trains use a Norwegian electricity mix, which, due to its renewables share, implies relatively large environmental benefits (both CO_2 and air pollutants) when shifting from sea/road to rail transport. Different electricity mixes, e.g., based on electricity production using natural gas, would yield smaller, albeit still positive environmental benefits from modal shifts to rail. Similarly, we assumed that the share of electric trucks is still small by 2030 [40]. A large-scale introduction of electric or significantly more efficient vehicles (e.g., resulting from recently adopted emission standards for heavy-duty vehicles [47]), or a higher blend-in requirement of biofuels, would make the environmental benefits of modal shifts away from road, smaller.

Regarding cost development, deviations from our assumptions can affect the competitive position of different modes, and where this competitiveness change is large enough, result in a mode change. Examples could include cost increases (decreases) from a different technology uptake track, further increases in vehicle dimensions, regulation disproportionally affecting one mode (e.g., emission requirements), fuel requirements, levy increases on fossil fuels, etc.

Finally, commodity flows may develop differently than projected, both in volume terms as well as with regard to origins/destinations and relative changes between commodities. This may have implications for how much transport takes place, where, and by which mode. Depending on the deviation from projections, this may imply both increases and decreases in transport performance overall, and for different modes. The same applies to environmental effects. Altogether, uncertainty may therefore have an impact on results. For many factors, this impact will likely not be very large.

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Can active follow-ups and carrots make eco-driving stick? Findings from a controlled experiment among truck drivers in Norway

Daniel Ruben Pinchasik [a,*], Inger Beate Hovi [a], Eirill Bø [b], Christian S. Mjøsund [a]

[a] *Institute of Transport Economics, Department of Economics, Gaustadalléen 21, N-0349 Oslo, Norway*
[b] *BI Norwegian Business School, Department of Accounting, Auditing and Business Analytics, Nydalsveien 37, N-0484 Oslo, Norway*

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ABSTRACT

This article presents results from a randomized controlled eco-driving experiment with differential treatment between two groups of truck drivers in Norway. Using data from in-vehicle devices, we investigate whether eco-driving interventions (a course, active monthly follow-ups, and non-monetary incentives) reduce fuel consumption by inducing more efficient driving behavior for drivers in a treatment group, compared to a control group. Hereby, we consider persistence of effects over time and the relative importance of eco-driving factors, while controlling for fixed vehicles, routes, drivers, and weather.

We find significant fuel consumption reductions, persisting over a longer period of time than in most previous studies (where effects fade or disappear), that weather conditions are important, and evidence of an 'eco-driving learning curve'. This might result from monthly follow-ups and driver rewards. Further, we find spill-over effects through significant fuel savings for drivers in the control group (undergoing no interventions). These are likely the result of them becoming aware that 'something eco-driving related' is going on.

Our analysis suggests that improvements on engine and gear management contribute most to fuel savings. We estimate the potential for fuel savings to lie between 5.2 and 7.5% (lower bound, control group) and 9% (upper bound, treatment group). This implies a potential for significant cost savings and emission reductions, which might to some extent be scalable and transferable to other settings. As such, eco-driving may play one part in reducing emissions from road freight, for which much-needed emission reductions are challenging to achieve, especially in the shorter run.

1. Introduction

Climate change is one of the major issues of our time, and tackling it requires large efforts across different economic sectors. A key and common feature for pathways in which global warming is limited to 1.5 °C, is that sizable emission cuts from transport are indispensable [1]. In addition, and following from the notion of a global carbon budget, emission cuts from transport have to take place urgently, because delaying them, even just a few years, has detrimental effects (see e.g. [1,2,3,4]).

Within transport, a segment identified as particularly challenging is freight transport by road [3,5]. Already, road freight stands for about 50% of all global diesel consumption and is a major driver of emissions [6]. More importantly, however, both diesel consumption and CO_2 emissions are projected to keep increasing strongly over the coming decades, with road freight surpassing passenger cars as the world's largest oil consuming sector [4,6]. Besides its climate impact, fuel consumption within road freight is also an important consideration from a cost perspective: depending on the size of the freight vehicle and the transport segment (e.g. distribution or long-haul), fuel expenses can easily make up 30% of per-km costs, wages excluded [7]. The above illustrates that reductions in fuel consumption are desirable both for freight operators and society as a whole.

Reducing fuel consumption from road freight, however, is not straightforward. This is due to the sector's high expected demand growth and fossil fuel dependency [5], alongside a lagging uptake of low and zero emission technologies relative to the passenger car, van and bus segments; particularly when it comes to electric propulsion [7]. This lagging uptake is attributed to the demanding requirements set by freight transport (e.g. regarding driving range, engine power, and tradeoffs between vehicle weight, payload and charging needs), and which have thus far yielded high investment costs. Also the market

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* Corresponding author.
E-mail addresses: drp@toi.no (D.R. Pinchasik), ibh@toi.no (I.B. Hovi), eirill.bo@bi.no (E. Bø), csm@toi.no (C.S. Mjøsund).

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availability of electric propulsion trucks, particularly in heavier classes, has so far been very limited and largely consisted of converted diesel trucks rather than series-produced vehicles [3,5,6]. Whilst these barriers are expected to be resolved in the medium- to longer term, they imply that for road freight, the achievement of emissions reductions at scale will take time [8]. The same goes for other promising developments (such as e-highways, platooning and connected and automated vehicles (e.g. [3,6,9]). Also many other determinants of fuel consumption are largely given in the short- to medium term and/or beyond the control of transport operators and their drivers, with main examples including vehicle characteristics, road infrastructure, traffic and driving conditions, and load rates [10,11].

One of the main remaining determinants of fuel consumption is driving behavior [12]. Compared to other determinants of fuel consumption, driving behavior can be influenced more immediately, through the concept of eco-driving. Stimulating eco-driving is further regarded as low-cost and scalable approach [12,13,14,15,16,17], and in the present research studied in the context of trucks and truck drivers, through an eco-driving experiment carried out in Norway (see 'Present research').

Besides the particular challenge of reducing emissions from road freight, focusing on eco-driving for truck drivers is also warranted for other reasons. Although a number of studies have been performed on effects of eco-driving interventions for drivers of passenger cars (and buses), the number of studies regarding eco-driving within freight transport and for heavy-duty vehicles (HDVs) has been more limited [18,19,20,21]. Relative to drivers of passenger cars, professional truck drivers further spend much more time and kilometres behind the wheel, and fuel consumption per kilometre is also considerably higher both per km and in total for HDVs [22]. This implies that the same relative improvement in fuel efficiency yields larger absolute savings for truck drivers in terms of diesel, costs, and emissions [18]. Hence, a euro spent on eco-driving training is potentially (much) more cost effective for truck drivers than for passenger car drivers.

2. Literature review and theoretical background

2.1. Eco-driving: Concept and strategies

Definitions of eco-driving vary in scope, and the broadest definitions encompass factors that affect fuel consumption and which can be addressed either prior to, during, or post trips [8,13]. Most eco-driving studies and initiatives, however, focus on factors which can be addressed while driving, and which can be controlled directly through driving behavior [17,23].

In its core, driving can be divided into acceleration, cruising, and braking. During each of these stages, fuel consumption is affected by how the driver operates the vehicle [10]. Simply put, eco-driving theory recognizes that most drivers operate vehicles in a way that is suboptimal for fuel efficiency [10] and provides insights into how driving behavior can be improved to minimize tank-to-wheel energy losses, fuel consumption, and emissions [19,24]. In general terms, eco-driving is often described as the adoption of a less aggressive or smoother driving style (e.g. [13,14,16,18,19,25]), and the main eco-driving strategies include driving at a moderate, constant speed, anticipating traffic, gentle acceleration and deceleration, optimizing gear changes, minimizing unnecessary braking and stops, and avoiding unnecessary idling [8,10,13,17,18,19,20,22,25,26,27,28,29,30]. Because these definitions are not standardized and strategies are interrelated, overlap, and may have somewhat different optimums under different road conditions [16,31], eco-driving strategies should be viewed somewhat generically.

Looking at the different strategies, limiting unnecessary idling is one of the most intuitive, as idling uses fuel without contributing to vehicle movement (e.g. [17,19,29]). With regard to speed choice, the eco-driving rationale is that vehicles have an optimal speed or speed range in which they are most fuel efficient. This optimum varies between vehicles and is also dependent on topography and driving conditions, but tends to lie at around 70–80 km/h for trucks [17,19]. In most cases, it is therefore advisable to drive at a moderate pace and to avoid overspeeding [10]. Fuel consumption is further lower when maintaining steady speeds, which can be achieved either manually or through the use of cruise control [17,18,19,25].

Better anticipation, or 'planning ahead' is pointed out as eco-driving strategy because it helps avoid unnecessary braking and stopping, and thereby reduces the amount of energy that is lost [10,26,28,30]. Looking further ahead also allows the accelerator pedal to be released earlier, meaning that the vehicle can roll on using its existing momentum, rather than through additional fuel consumption that is later wasted in braking [10]. Better anticipation can also be seen as a way to reduce fuel inefficient 'stop-and-go'-driving [13].

The rationale behind optimal gear use, and particularly shifting up early, is that fuel consumption is lower when appropriate speeds are achieved at low RPM (revolutions per minute) (e.g. [16,18,22,25,26,27,29]). Similarly, eco-driving theory recognizes that hard acceleration and braking result in higher energy losses than mild or smoother operation, making the latter preferable from a fuel efficiency perspective (e.g. [8,14,16,19,27,28,30]).

For many of the above eco-driving strategies, connected and automated vehicles could in the medium- to long term reduce much of today's suboptimal human performance, both by excelling at situational awareness and by more accurately following the most energy-efficient driving trajectory in any situation [24, p.558]. Until this is technologically and financially feasible, and implemented at scale, however, eco-driving may contribute to reduce the gap to optimal vehicle operation, albeit within human limitations.

2.2. Eco-driving analysis and interventions

Eco-driving has been researched in several settings. To date, the main approaches for stimulating eco-driving have been training programs and driver support systems [10,17,28,32,33]. Training programs usually consist of knowledge-based training, but can also include practical training or combine both elements [17]. Driver support systems usually revolve around providing drivers with eco-driving feedback, either as part of stand-alone interventions or as follow-ups to training sessions. Feedback can be given in real-time, through in-vehicle devices, shortly after trips (e.g. through online portals), or with a longer time lag between trip and feedback [10,20,33]. Other related and partially overlapping approaches to eco-driving stimulation include information campaigns and gamification initiatives [12,13]. Research methods evaluating the effects of eco-driving interventions, in turn, have predominantly consisted of laboratory or simulator studies, field trials (on-road driving on test tracks or real-world routes), and numerical modelling [14,17].

2.3. Effects of eco-driving on fuel consumption

Both eco-driving training and in-vehicle devices have shown to result in rapid and significant improvements in driving behavior, with estimates on fuel efficiency improvements varying between 1 and 40%, depending on the study [14,16,17,18,34]. While most of these estimates stem from studies involving drivers of passenger cars and buses, the fewer studies on freight vehicles suggest that results are similar for truck drivers (e.g. [11]). In a review, Boriboonsomsin [19] finds that for larger truck studies, eco-driving interventions usually yield fuel efficiency improvements of between 5 and 15%.

Although effects of eco-driving interventions thus tend to be significant and often considerable in the short term after an intervention, effects are found to fade markedly or even disappear in a longer run as a result of drivers returning towards previous behavior [8,12,13,14,16,17,26,35,32,36,37]. This decline is seen both after eco-driving training and in studies using in-vehicle devices [17], although its extent is dependent on the quality and nature of interventions, and whether or not interventions are followed up with reinforcements [13]. Thus, with some exceptions (e.g. [22]), the challenge seems to be to make behavioral changes from eco-driving interventions more permanent.

At the same time, it should be noted that both effects and persistence vary considerably between individuals [18,26,29]. In some cases, driving behavior has for example been seen not only to improve immediately after an eco-driving intervention, but to follow a progressive trend or 'learning curve'. This has been observed both for individual drivers and driver groups, although in the latter case, effects wore off in the longer term [18,29]. Other reasons for exercising caution when comparing results across studies are the often considerable differences in methodology, vehicles, type of eco-driving interventions, evaluation settings (e.g. closed course vs real routes), drivers, baseline driving behavior, and other sample characteristics [19,20]. Fuel efficiency improvements found in field trials are for example typically smaller than what modelling and laboratory tests would suggest [14,16,17]. This implies either an untapped potential [17] or suggests that achieving major results is difficult in practice. Several studies point out that the simplified and artificial setting of laboratory and modelling studies may not adequately reflect real-world driving, and thereby overestimate the fuel saving potential (e.g. [17,18,22]). Examples of oversimplification include inadequate representation of real-world traffic conditions and road state, noting that different driving behavior is optimal under different conditions [31], and the dependency of laboratory and modelling results on congestion assumptions [14]. Also stress levels and safety risks may be significantly higher in real traffic and limit a driver's focus on driving fuel efficiently [17,31]. More generally, it is noted that modelling results tend to be less accurate and reliable, and may lack external validity [17,27].

2.4. Fuel savings contributions of different eco-driving strategies

In terms of contributions of different eco-driving strategies to fuel savings, results too, are difficult to compare directly, amongst others due to the lack of consistent definitions of eco-driving strategies between studies, as well as the overlap and interrelations between strategies [16].

Nevertheless, some overarching insights can be inferred. Boriboonsomsin [19] points to fuel 'waste' for typical trucks being 33% due to speeding, 25% due to hard acceleration, 20% due to idling, 16% due to hard turns, and 6% due to hard braking. Based on a summary of multiple studies, Huang et al. [17, p. 600] conclude that 'acceleration and deceleration' is the most important eco-driving factor, with improvements yielding a fuel savings potential of between 3.5 and 40%. Driving speed, in turn, could reduce fuel consumption by 2–29%, while reductions in idling could contribute between 6 and 20%. In another summary, Sivak and Schoettle [25] find that effects from reducing idling vary, that overspeeding can increase fuel consumption by 30%, not using cruise control by 7% (under highway conditions), and aggressive driving styles by 20–30%.

Schall and Mohnen [29, p. 292] conclude that both optimal speed choices and less aggressive driving styles (through acceleration and deceleration behavior) can improve fuel efficiency by 10%, while holding speeds constant and anticipating stops can give an 8% improvement and reductions in idling an improvement of between 4 and 10%. As such, the authors point out speed and driving aggressiveness as the most important factors, but note that effects may vary, depending on specific circumstances.

Finally, from a truck field study by Walnum and Simonsen [11], it can be derived that among different eco-driving factors, driving with high engine loads is most detrimental for fuel efficiency, while driving in the highest gear has the largest positive influence. This is followed by idling and high speeds (negative effects) and coasting (positive effects). Increased use of cruise control and automatic gear shift have relatively smaller, but positive effects on fuel efficiency. From the above, improvements in speed choice and acceleration/deceleration behavior seem to be the main contributors to fuel reduction, followed by avoiding unnecessary idling.

2.5. Reinforcing and maintaining effects of eco-driving interventions

Existing studies suggest that eco-driving interventions limited to training are not sufficient to sustain long-term effects, and that the main challenge seems to be to make behavioral changes from eco-driving interventions both more permanent and large enough [13,16,26]. Indeed, several studies point out that the repetitive and habitual nature of driving implies that purely information-based approaches are likely to have a limited impact and that some form of reinforcement or long-term driver support is required after completion of eco-driving training (e.g. [8,12,19,27]). Several approaches have therefore been proposed aimed at incentivizing and/or reinforcing eco-driving behavior. These include different forms of feedback and driver support after training, as well as different types of reward incentives [8,19,27,32].

With regard to feedback, a number of approaches have been tried, spanning from real-time feedback using in-vehicle devices or online feedback directly after trips, to regular feedback at varying intervals [12,16,34]. Both regular feedback and different types of in-vehicle feedback have been shown to be effective tools for reinforcing eco-driving behavior, and evidence suggests that instantaneous feedback might be somewhat more effective to maintain eco-driving behavior [16,34,38]. However, instantaneous feedback is also associated with driver distraction [16].

Reward incentives, in turn, have been proposed to address the behavioral aspect of driving [32], and it is recognized that monetary and non-monetary rewards may have different effects, because they tend to impact motivation and behavior in different ways [27]. Using reward incentives as a reinforcement for energy conservation behavior has demonstrated mixed results [27]. For eco-driving specifically, non-monetary rewards have been shown to give stronger effects than monetary rewards, but still with attenuation of effects over time [29].

2.6. Moderating factors

When evaluating effects of eco-driving interventions, one moderating factor that should be considered is weather. Fuel consumption is affected by weather conditions such as ambient temperature, precipitation, air pressure, etc. Generally, precipitation increases fuel consumption, amongst others by increasing friction, while fuel consumption is lower at higher ambient temperatures, up to a certain optimum [11,27,28,39]. An illustration of the importance of weather is provided by Allison and Stanton [16], who discuss a study which found significant fuel consumption reductions both in the short and a longer term after an eco-driving intervention, but when data were reanalyzed controlling for temperature, evidence for a long-term effect was no longer significant.

The strength and effects of eco-driving initiatives and strategies are further thought to be influenced by a range of driver and situational characteristics, such as gender, age, driving experience, pressure experienced under driving, knowledge, and attitudes [33,39]. Eco-driving incentives and motivation may for example be stronger in private settings than when driving for an employer [33,40]. Positive attitudes to the environment, as well as attitudes towards, knowledge about, and perceived usefulness and satisfaction from eco-driving, may also positively affect results [33,40]. With regard to driving experience, theoretical eco-driving training has been found to be more effective for inexperienced drivers than for experienced drivers, whose ingrained habits are thought to be more difficult to change through training [37]. In another study, it was found that new drivers with eco-driving as part of their mandatory license training had a better understanding of eco-driving techniques than experienced drivers who lacked this training, and also converted this understanding to more efficient driving in practice [40]. As addressed later, most of the latter factors fall beyond the scope of the present article.

2.7. *Limitations of existing studies*

While interesting and relevant, most existing eco-driving studies exhibit one or more limitations. As pointed out above, most eco-driving studies have focused on drivers of passenger cars and buses, while studies on eco-driving within freight transport and HDVs have been more scarce [18,19,20,21]. Generally, most eco-driving evaluations have been based on comparisons of fuel efficiency pre- and post- an eco-driving intervention [26]. Few studies, however, have employed a control group [18,26,35], a gap that is especially apparent among the limited research on truck drivers [22]. Further, most studies are based on small-scale samples [22,26] and have been limited to evaluations of short-term benefits, while research on effects after more than a few months has been scarce [22,26,27,35]. Additionally, many studies have been based on artificial driving conditions [22], and many fewer on natural experiments [27]. This may reduce the external validity of results if factors independent of the driver, but with a considerable impact on fuel consumption, are not adequately controlled for, e.g. road geometry, vehicle type, traffic conditions, and loading factors [12].

2.8. *Potential side-effects of eco-driving*

In addition to fuel consumption, emissions, and costs reductions, eco-driving is associated with side-effects related to traffic safety, vehicle maintenance, and driver fatigue (e.g. [31,41]). Many of the main eco-driving strategies overlap with strategies for safe driving [13,19,28]. Anticipation, driving at consistent and appropriate speeds [13], smoother acceleration and deceleration, fewer gear changes, and less braking, for example, tend to be beneficial both from a fuel efficiency and safety perspective [17,18]. Smoother driving may additionally reduce wear, and thereby expenses on maintenance and repair, and is associated with less stress and driver fatigue, which might be a traffic safety benefit in itself [18]. However, driving behavior involving less braking and use of high gears may also have opposite effects by reducing headway and vehicle control [28]. It has further been pointed out that while beneficial at the individual level, eco-driving behavior could yield opposite effects at a network level through changes in headway, speed and congestion [14]. Some eco-driving approaches, particularly those involving active in-vehicle feedback, have further raised safety concerns as a consequence of driver distraction (e.g. [14,16,39,42]). These potential side-effects have not been a focus area in the present research, but are mentioned in light of some feedback which we report as part of our discussions.

3. Present research

The present research builds on a randomized controlled eco-driving experiment with differential treatment between two groups of truck drivers, working within freight distribution in the South-Eastern part of Norway. In short, the experiment subjected drivers in a treatment group to an eco-driving course, monthly eco-driving evaluations, and 'carrots' in the form of non-monetary rewards, while drivers in a control group were left alone. Details on the experimental design and specifics are described extensively in the next chapter.

Objectives behind the experiment were to shed light on the following overarching research questions:

- Do eco-driving interventions have the potential to reduce fuel consumption by inducing more efficient driving behavior among truck drivers, and if so, to what extent?
- Are changes in driving behavior temporary, or do they persist when an eco-driving course is reinforced with additional interventions?
- Which eco-driving strategies contribute most to reductions in fuel consumption?
- How are results affected by weather conditions?

From the literature, we expect to find significant short-term improvements in driving behavior and fuel efficiency following an eco-driving course (with fuel and emissions savings likely in the 5–15% range). We further expect to observe considerable variation between individual drivers, and possibly a 'learning curve' with a progressive trend in effect strength, up to a certain peak (cfr. [18,29]). Without follow-ups, however, effects of the eco-driving course would be expected to attenuate or disappear in the longer run, likely in the course of several months. Both regular and non-monetary rewards could potentially strengthen the persistence of effects, but most likely only delay the fading of effects, rather than completely avoiding it (e.g. [16,29,34]). Due to the many ways and extents in which feedback and rewards can be implemented, the latter expectation is particularly uncertain.

Of different eco-driving strategies, we expect improvements in behavior related to driving speed and acceleration/deceleration to yield the largest potential for fuel savings, followed by reduced idling. Finally, we expect to find significant effects of weather conditions on fuel efficiency through ambient temperatures (positive relationship) and precipitation (negative relationship).

4. Methodology

4.1. *Study design*

As mentioned, the current study, performed in 2019, was designed as a randomized controlled eco-driving experiment with differential treatment between two groups of seven truck drivers: a treatment and a control group. All fourteen drivers work for the same firm (a large Norwegian freight forwarder operating about 130 trucks), and take shifts driving the same regional freight distribution rounds in the South-Eastern part of Norway. As part of their employment, all drivers had previously been informed about and consented to the potential use of data from their employer's fleet management system (FMS) for analytical objectives. This made it possible to use such data in the current experiment, and in other parts of an overarching 'LIMCO' research project, for which data utilization additionally was cleared with the Norwegian Centre for Research Data.

Because of the arrangement of driving into work shifts (e.g. two weeks on, two weeks off), the fourteen drivers were first divided into 'complementary pairs', driving the same routes and vehicle types. Thereafter, one driver from each pair was assigned to a control group and the other to a treatment group by means of random draws.

Although the above leaves a relatively small sample size, the strength of this design compared to many previous studies, is that it allows an assessment of eco-driving in a real-world setting, while to a large extent controlling for the same vehicles (see also data collection), fixed routes (regular and predictable distribution routes, predominantly fulfilling the same order types for the same clients every week), and fixed drivers (the experimental participants). As such, the design attempts to control for effects of driver-independent factors which may have a considerable effect on fuel consumption and might otherwise lead to unfair comparisons between drivers [12].

4.1.1. *Participants*

The participants in our experiment were all male, professional truck drivers. From information provided by the freight forwarder, we know that within their driver pool of ca. 225 drivers, around half is aged between 30 and 39 and another quarter between 40 and 49, while 16% of drivers are 50 + and 10% are aged under 30. Regarding driving experience, we were provided with a rough split-up of tenure (45% between 0 and 3 years, 13% between 3 and 6 years and 42% with tenure of 6+ years). However, these numbers indicate tenure only at the current freight forwarder, disregarding truck driving experience at previous employers which most drivers were said to have. The freight forwarder further provided information indicating an average annual mileage per driver of ca. 45.000 km. Because we have not had access to more detailed information for drivers in the experimental sample specifically, the above factors fall beyond the scope of the present research, as is also mentioned in our discussions. However, it can be noted that the freight forwarder has indicated that the base sample of fourteen drivers was intended to have a very homogeneous composition (attempting to avoid e.g. socio-economic differences).

4.1.2. Experimental baseline and eco-driving course

During the first three months of the experiment, none of the drivers knew that they participated in an experiment. This was done to have them continue their work as usual, so that driving behavior and fuel consumption baselines could be established both for drivers in the control and treatment group, and unaffected by any intervention. Three months into the experiment, in early April 2019, an intervention was arranged for the treatment group. Drivers in this group were given a course in eco-driving, while the control group was not. The eco-driving course was held by Cognia, a Norwegian supplier of the FMS-solution used in our experiment (details in next section). During a one evening session, drivers were taught eco-driving theory closely linked to the eco-driving strategies discussed earlier, and how they could improve their performance.

4.1.3. Monthly follow-ups for the treatment group

After the course, drivers in the treatment group started receiving monthly performance reports, covering a total eco-driving score, scores on 'anticipation', 'engine and gear use', 'speed adaption' and 'idling', and their respective sub-components (also explained in detail in the next section). Performance reports were actively followed up through individual monthly evaluation sessions between driver and manager, and with focus on (further) improvement of driving behavior.

4.1.4. Non-monetary rewards for the treatment group

Around 2.5 months after the eco-driving course, non-monetary awards were introduced to give drivers in the treatment group an additional performance incentive: Drivers who achieved a minimum monthly (total) score of 85 (out of a possible 100; see data collection) could earn a t-shirt or fleece jacket with respective texts 'Certified Eco-driver' and 'Perfect Eco-driving skills', depending on their performance. The use of non-monetary rewards was inspired by the eco-driving experiment carried out by Schall and Mohnen [27], and for which results suggested that non-monetary rewards might be a more effective follow-up than monetary rewards.

4.1.5. Potential spill-overs to the control group

While the experiment was intended to have a pure treatment group (with eco-driving interventions) and a pure control group (no interventions), the experiment's implementation gave rise to two potential sources for spill-over effects. Firstly, the non-monetary rewards for drivers in the treatment group may have revealed to the control group that some eco-driving activity was ongoing. Secondly, we were informed in retrospect that between August-December 2019, drivers in the control group were also sent an eco-driving performance report, together with their monthly pay check. Both these potential sources of spill-over effects are addressed in our analysis and discussion. While unintended and unfortunate, it is important to clarify that at no point did drivers in the control group receive any active follow-ups, evaluations, reviews or explanations of performance report contents, nor were they taught or given information on eco-driving, eco-driving strategies, or how to improve their driving behavior and scores. Because of the latter, changes or improvements to driving behavior are most likely associated with driver's own belief of what would constitute good eco-driving behavior.

4.2. On data collection

Modern trucks are increasingly equipped with different sensors, which log data on a number of driving performance indicators. Although many of these indicators vary between vehicle manufacturers and models, examples include (comparable) data on various trip characteristics and driving behavior (e.g. speed, distance, fuel consumption, eco-driving indicators, etc.), as well as other factors, such as geographical conditions [43].

Depending on ownership arrangements, owners or operators of trucks may have access to a variety of valuable indicators, which allow for the follow-up of daily, weekly and monthly behavior through scores on different driving performance indicators in FMS systems. In practice, however, relatively few organizations have so far actively started utilizing logged data more than superficially, and in fact, experience in the overarching LIMCO project indicates that many lack active subscriptions to such data (which form an expense). Further, even when active subscriptions are in place and information could be valuable for research on transport and driving behavior, a challenge remains that data from FMS systems are normally kept in-house. In the current experiment, however, cooperation with both the freight forwarder and FMS provider ensured access to such data.

Overall, data collected in our study cover driving with 15 Volvo trucks (all 3-axled distribution trucks with closed chapel and max. allowed total gross weight of 27 t). Nearly all driving was done with seven of these trucks (all basically identical Volvo FH trucks from 2014 with 460 HP engine and the same dimensions and characteristics), while the remaining eight trucks (including more near identical models from the same year) were only driven over very short total distances by participants in our experiment. Since our sample consists entirely of Volvo trucks, data for most indicators of interest could have been extracted through Volvo's own FMS system (Dynafleet). However, for generalizability, repeatability, and as source for the monthly follow-ups with drivers from the treatment group, we chose to extract data through Cognia's FMS solution, 'Linx'. This solution is developed to be universal across vehicle brands, based on the least common multiple information from different manufacturers' factory-fitted FMS-API, making it possible to capture data from a huge number of trucks and enterprises (as is currently done in the LIMCO project).

In addition to direct engine performance indicators, Linx reports scores on four eco-driving performance indicators mentioned earlier (anticipation, engine and gear, speed adaption and idling), as well as a total score (all with possible range from 0 to 100, where 100 is best). Sub-components used by Linx to calculate these scores are indicated in Table 1.

Data was collected for the period between January 1st and December 31st, 2019. Data on driving behavior performance is available at the daily level, while GPS-tracking usually is available at a (much) higher time frequency. However, the frequency of GPS data from Volvo trucks can easily be set by the driver and therefore varies more in frequency than for other brands: this is for example seen for Scania trucks tracked in the LIMCO project. Unfortunately, GPS-data for the vehicles in the current sample are scarce and therefore not actively utilized in this study.

4.3. Data compilation and quality

After data collection, data quality was checked and certain outlier observations removed (3.2% of observations). For example, all observations where drivers had a daily driving distance below 10 km were excluded, because rather than covering distribution routes, such observations are typically related to the moving and rearranging of vehicles. This comes with high average fuel consumption, predominantly influenced by starts and stops, rather than driving performance. Since each daily observation has the same weight in our analysis, regardless of the daily fuel consumption or mileage, these observations were

Table 1
Descriptives for selected variables included in the data set.

Variable	Description	Descriptives
Average fuel consumption while driving	In liters per 100 km. Only fuel consumption while driving.	Avg: 36.1 L/100 km; Min: 19.1 L/100 km; Max: 59.3 L/100 km.
Distance	Distance driven in km on day of observation	Avg: 313 km; Min: 13 km; Max: 673 km.
Anticipation score (0–100 range)	Derived by Linx from coasting and braking parameters.	Avg: 80.3; Min: 40; Max: 100Calculated based on percentage of distance spent coasting (Avg: 16%; Min: 0%; Max: 46%) and braking score (Avg: 92.2; Min: 42; Max: 100)
Engine & gear score (0–100 range)	Derived by Linx from parameters on use of automatic gear and power	Avg: 98.8; Min: 56; Max: 100Calculated based on percentage of distance using automatic gear (Avg: 99.4%; Min: 83%; Max: 100%) and power take-off (data on this individual component was missing in the data set).
Speed adaptation score (0–100 range)	Derived by Linx from parameters on (over)-speeding and use of cruise control	Avg: 73.9; Min: 0; Max: 100Calculated based on percentage of distance spent speeding (Avg: 16.4%; Min: 0%; Max: 81%) and using cruise control (Avg: 40.5%; Min: 0%; Max: 91%)
Idling score (0–100 range)	Derived by Linx from parameter on idle running	Avg: 49.3; Min: 0; Max: 100Calculated based percentage of time with idle running (Avg: 23%; Min: 1%; Max: 97%).
Total score (0–100 range)	Calculated by Linx as weighted average of scores on the above four eco-driving parameters.	Avg: 80.3; Min: 40; Max: 100

removed. Further, all observations with a total score of 0 were also removed, because a score of 0 as a monthly weighted average across four different driving performance indicators is most likely a result of an error.

As complement to data collected from the vehicles, the data set was expanded with a number of (dummy) variables. These variables were constructed to indicate whether drivers were part of the treatment group (1) or control group (0), and whether observations were from a date after the eco-driving course (1) or during the baseline period (0), in addition to an interaction dummy (treatment group, after treatment). Further, we added dummy variables representing time passed after the eco-driving course in 6-week intervals (0–6 weeks, 6–12 weeks, etc.). This approach was chosen for a combination of reasons. Firstly, two independent providers of eco-driving tracking solutions provided feedback that meaningful eco-driving performance changes should be considered at time scales of 1–2 months (citing e.g. random variations in traffic, such as traffic jams, road closures, etc., and weather (see below) as reasons). Secondly, while we expect changes in eco-driving scores and fuel consumption over time, these changes may have different strength, direction, persistence and timing (cfr. our discussion of [18,26,29]). This makes it difficult to specify suitable functional forms for regression analyses with time as metric variable (see Section 4.4). Using time period dummies additionally allows us to test differences in effects at different intervals after treatment.

Further, we added variables on average daily temperature, as well as precipitation (in mm) on the observation day. These data were collected from the Norwegian Meteorological Institute, for a measurement location in Oslo (i.e. centrally located relative to the trucks' distribution routes), and were intended to control for effects of weather conditions on fuel consumption (cfr. e.g. [16]).

The resulting data set yielded 1,523 daily observations in total, for all drivers, covering the whole of 2019, and for a total driving distance of over 475,000 km and fuel consumption over 178,000 L of diesel. Drivers in the treatment group stood for 58% of both the observations and total mileage. Further, at 314 and 312 km, average distances driven per day were almost equal between the treatment and control group. This suggests that distribution routes driven in practice were indeed similar between the two groups, as was intended and expected in the study design.

Table 1 provides a summary of the most important variables in the data set. It should be noted that the four Linx-scores on eco-driving parameters are not stand-alone scores, but are derived (by Linx) from 1 or 2 sub-parameters per score, as indicated in the table, while the total score in turn is derived from the four eco-driving parameters. In addition to parameters in the table, the data set includes amongst others anonymized IDs to distinguish vehicle and driver, date, week number, parameters on weather conditions, a number of vehicle characteristics such as age and weight, as well as the dummy variables discussed above.

4.4. *Analysis and modeling of effects*

To analyze effects of the eco-driving intervention and follow-ups for the treatment group, we constructed two multivariate regression models with daily average fuel consumption (per 100 km) as the dependent variable. The reason for constructing two models is A) to measure how performance on different eco-driving aspects affects fuel consumption (the driving performance score model), and B) to investigate whether there is a difference between the treatment and control group before and after the eco-driving course takes place (the dummy model) - as outlined through our research questions.

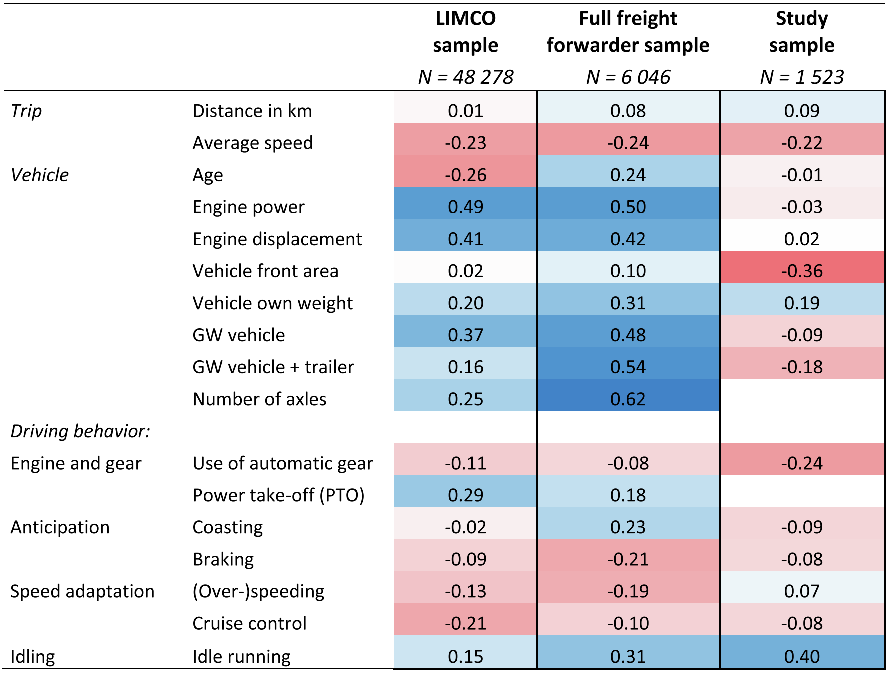
Both models were tested using different sub-specifications through inclusion of different independent variables. Before presenting these models and specifications, Table 2 illustrates correlations between fuel consumption, and trip-specific, vehicle-specific and driving behavior parameters. Correlation coefficients were calculated according to Spearman's rank-order approach, as this methodology provides better robustness to outliers than Pearson correlations, and because underlying assumptions for Pearson correlations might not be met across all pairs of variables and all samples. The table reports correlations within three different sub-sets, for all observations in 2019 related to 'driver and vehicle days'. The three sub-sets consist of 1) all vehicles for which the LIMCO project has data capture through Linx ('the LIMCO sample'; this includes both vehicles of the freight forwarder in the study and vehicles of a range of other firms); 2) a sub-set of 'the LIMCO sample', limited to those vehicles that are owned by the freight forwarder ('the full freight forwarder sample'); and 3) only those vehicles driven by drivers in either the treatment or control group ('the study sample', i.e. a subset of both 'the LIMCO sample' and 'the full freight forwarder sample'). The purpose of this approach is to compare observations in the study sample with larger samples with more variability both for vehicles and driving behavior, and thereby to validate the representativeness of the study sample. In the table, positively correlated parameters are shaded blue, and negatively correlated variables are shaded in red, with shading intensity representing the degree of correlation.

For trip-specific parameters, the table indicates negative correlations between average fuel consumption and trip average speed, which is as expected from eco-driving theory, as average fuel consumption usually decreases up to an optimal speed. Fuel consumption and distance have a positive correlation, albeit very weak. Here, we had expected a negative correlation, because fuel consumption tends to be lower for long-haul transport than e.g. urban distribution (e.g. [3]). For the full freight forwarder sample and the study sample, this is likely a result of less variation in routes driven, with longer trips more likely taking place in areas with harsher driving conditions (elevation and/or winding roads, see also [11]).

Of vehicle-specific parameters, several are positively correlated with fuel consumption for both the LIMCO sample and the full forwarder

Table 2

Spearman's correlations between average fuel consumption and different trip-specific, vehicle-specific, and driver behavior parameters, for three different sub-groups of vehicles and drivers. Rounded to two decimals. GW = Max. allowed vehicle gross weight. N represents number of observations in 2019 related to driver and vehicle days.



		LIMCO sample *N = 48 278*	**Full freight forwarder sample** *N = 6 046*	**Study sample** *N = 1 523*
Trip	Distance in km	0.01	0.08	0.09
	Average speed	-0.23	-0.24	-0.22
Vehicle	Age	-0.26	0.24	-0.01
	Engine power	0.49	0.50	-0.03
	Engine displacement	0.41	0.42	0.02
	Vehicle front area	0.02	0.10	-0.36
	Vehicle own weight	0.20	0.31	0.19
	GW vehicle	0.37	0.48	-0.09
	GW vehicle + trailer	0.16	0.54	-0.18
	Number of axles	0.25	0.62	
Driving behavior:				
Engine and gear	Use of automatic gear	-0.11	-0.08	-0.24
	Power take-off (PTO)	0.29	0.18	
Anticipation	Coasting	-0.02	0.23	-0.09
	Braking	-0.09	-0.21	-0.08
Speed adaptation	(Over-)speeding	-0.13	-0.19	0.07
	Cruise control	-0.21	-0.10	-0.08
Idling	Idle running	0.15	0.31	0.40

sample: engine power, engine displacement, vehicle front area (vehicle width times height in m^2), the vehicle's own weight, allowed maximum vehicle weight and maximum allowed gross weight for vehicle and trailer, and the number of axles. This is as expected, as larger and heavier vehicles usually consume more fuel (see e.g. [11]). However, for observations within this study's sample, many of the vehicle-specific parameters have the opposite sign. This is most likely caused by the trucks in the study being very similar, resulting in too little variation to give plausible correlation coefficients. Vehicle age has a negative sign also for the LIMCO sample, opposite of what can be expected from e.g. engine inefficiencies increasing with age. Only for observations in the full freight forwarder sample do we find the expected positive correlation between age and fuel consumption.

The four eco-driving behavior indicators from Linx consist of different sub-parameters. From the table, we find negative correlations between average fuel consumption and use of automatic gear, coasting, braking score, and use of cruise control. This is as expected from our discussion on eco-driving strategies in Section 2.1. Surprisingly, we also find a negative correlation between (over-)speeding and fuel consumption for the LIMCO sample, while for the study sample, we do find the expected positive correlation between (over-)speeding and fuel consumption. Further, we find positive correlations between power take-off (PTO or engine load) and idling, with fuel consumption. This too, is as expected from the literature. For drivers in the study sample, we only have 'engine and gear scores', but lack separate underlying data on the use of PTO. In all, the correlation matrix illustrates that we can expect that improved driver behavior will reduce fuel consumption through increased focus on the use of automatic gear, cruising, braking, and cruise control, and less use of PTO, (over-)speeding and idling.

4.4.1. *The dummy model*

As pointed out, the main objective of the dummy model is to identify differences in fuel consumption between the treatment and control group, as well as differences before and after the eco-driving course. The number of independent variables in the model is increased stepwise to analyze partial effects of various exogenous variation and how co-efficients are affected by controlling for additional variables, as well as to analyze the longer-term effects of the eco-driving course and follow-ups.

In its base specification (Model I), the dummy model is constructed as follows:

$$FC_{i,t} = \beta_0 + \sum\nolimits_{n=1}^{3} \beta_n {}^* D_{n,(i),(t)} + \varepsilon_{i,t} \qquad [I]$$

where $FC_{i,t}$ is driver i's average fuel consumption on day t in liters per 100 km, $D_{1,i}$ is a dummy variable equal to 1 when a driver i is part of the treatment group and 0 otherwise, $D_{2,t}$ is a dummy variable equal to 1 for observations occurring (t) after the eco-driving course has taken place and 0 otherwise, and $D_{3;i,t}$ is an interaction dummy equal to 1 for cases when both the driver i is part of the treatment group and the observation is for a day (t) after the eco-driving course has taken place, and 0 otherwise. Finally, $\varepsilon_{i,t}$ is the random error term, while β_n represent parameters that we seek to estimate.

In its second specification (Model II), dummies for eco-driving course completion and the interaction dummy are replaced by dummies for 6-week intervals after course completion, while the third specification (Model III) adds to this two control parameters: average temperature and precipitation on the day of observation:

$$FC_{i,t} = \beta_0 + \sum\nolimits_{n=1}^{7} \beta_n {}^* D_{n,(i),(t)} + \varepsilon_{i,t} \qquad [II]$$

$$FC_{i,t} = \beta_0 + \sum\nolimits_{n=1}^{7} \beta_n{}^{*}D_{n,(i),(t)} + \sum\nolimits_{n=1}^{2} \gamma_n{}^{*}\chi_{n,t} + \varepsilon_{i,t} \qquad \text{[III]}$$

where $FC_{i,t}$, and dummy $D_{1,i}$ have the same meaning as before, while $D_{2\ldots7,t}$ are different dummies equal to 1 for respective 6-week intervals after the eco-driving course (0–6; 6-12…30 + weeks) and 0 before this course has taken place. The variables χ_1 and χ_2 in Model III indicate average temperature and precipitation on day t, respectively. As before, β_n (and in Model III also γ_n) represent the parameters we seek to estimate.

The fourth specification (Model IV) is similar to Model III, but while using observations from both groups for the period before the eco-driving course, the six-week interval dummies after the eco-driving course are only included for the treatment group, while for the control group, a new dummy variable is introduced for the full period after the eco-driving course (D_8).

$$FC_{i,t} = \beta_0 + \sum\nolimits_{n=1}^{8} \beta_n{}^{*}D_{n,(i),(t)} + \sum\nolimits_{n=1}^{2} \gamma_n{}^{*}\chi_{n,t} + \varepsilon_{i,t} \qquad \text{[IV]}$$

4.4.2. *The driving performance score model*

The purpose of the driving performance score model is to investigate how changes in driving performance influence fuel consumption. Driving performance is measured by the four eco-driving score indicators or strategies discussed in Section 4.3, and variables are transformed to a logarithmic scale. This has the advantage that elasticities constant of scale can be deduced, and yields the following base specification:

$$ln(FC_{i,t}) = \beta_0 + \sum\nolimits_{n=1}^{4} \beta_n{}^{*}ln(\chi_{n,i,t}) + \varepsilon_{i,t} \qquad \text{[A]}$$

where $FC_{i,t}$ is the driver i's average fuel consumption on day t in liters per 100 km, χ_1 through χ_4 are a driver i's respective Linx-scores on anticipation, engine and gear, speed adaptation, and idling, on day t, and $\varepsilon_{i,t}$ is a random error term. β_n represent the parameters we seek to estimate.

In its second specification (Model B), the base specification is expanded with control parameters for average temperature ($\chi_{5;t}$) and precipitation ($\chi_{6;t}$) on the day (t) of observation. To enable a logarithmic scale, temperature (which can include negative values) is converted from Celsius to Kelvin. In the third specification (Model C), a further parameter is added for distance, ($\chi_{7,i,t,}$ again in logarithmic transformation, for driver i on day t). This can be summarized as follows:

$$\ln(FC_{i,t}) = \beta_0 + \sum\nolimits_{n=1}^{6} \beta_n{}^{*}ln(\chi_{i,t}) + \varepsilon_{i,t} \qquad \text{[B]}$$

$$\ln(FC_{i,t}) = \beta_0 + \sum\nolimits_{n=1}^{7} \beta_n{}^{*}ln(\chi_{i,t}) + \varepsilon_{i,t} \qquad \text{[C]}$$

5. Results

5.1. *Developments in eco-driving and fuel consumption*

Before moving results from our regression, we first look at developments in eco-driving and fuel consumption throughout 2019. Fig. 1 illustrates developments in the average monthly total driving performance score (0–100) for both the treatment group and control group, i.e. the weighted average of the four score sub-indicators from Linx. The dotted curve represents drivers in the control group who participated throughout the entire period, i.e. excluding the drivers that quitted their positions and for whom data is missing towards the end of the period.

From the figure, it can be seen that drivers in the treatment group on average started out from lower total scores than the control group. A significant increase started immediately after the eco-driving course in the beginning of April, for both groups of drivers, but this increase leveled out in May. While this increase is not unexpected for the treatment group, observations for the control group are less intuitive. We expect the latter to be a result partially of the transition from winter to spring, and partially of score variation internally in the control group (combined with the sensitivity of group averages to relatively small group sizes). While we discussed potential sources of spill-overs from treatment to control group, these are likely first relevant after the introduction of rewards in June or performance reports unintentionally being sent out also to control group drivers, from August onwards.

For the treatment group, a new increase is visible from May to June, and further on to July, while the control group had a stable score level until June, with a sharp increase from June to July. This distinctive increase can partially be explained by the fact that three of the drivers, whereof two with the lowest scores in the control group, quitted their positions from the start of July. However, the dotted line also illustrates that the rest of the control group had an increase in score from June to July, most likely a result of the differential treatment becoming visible because of the introduction of non-monetary awards at this time. From July onwards, the treatment group maintained a relatively stable average total score level, while scores for the control group exhibited

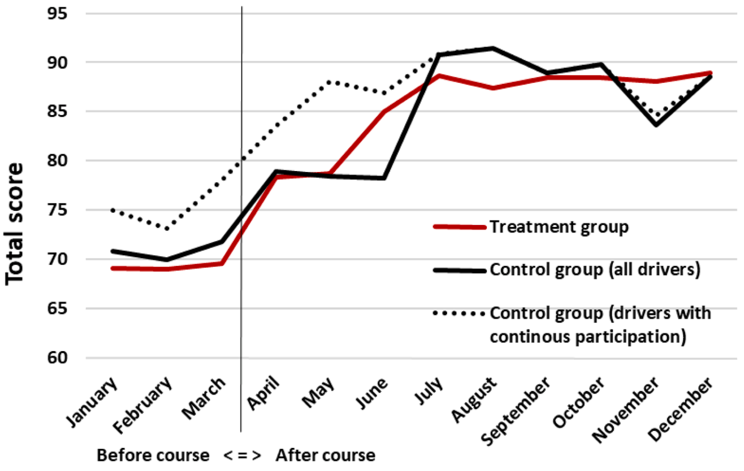


Fig. 1. Development in average monthly total driving performance score for the treatment and control groups, before and after the eco-driving course in early April 2019.

more variation. The control group reached its maximum average total score level in August and later exhibited a seemingly temporary decrease in November.

Fig. 2 presents average driving performance scores before and after the eco-driving course, and well as corresponding percentage changes, for individual drivers in both groups.

From the figure, it is seen that all drivers in the treatment group increased their average total scores by 10% or more after the eco-driving treatment. The figure further shows that most drivers in the control group also increased their scores; only one driver exhibited a score reduction, while another maintained nearly the same average level.

On the other hand, two of the three drivers with the highest percentage improvements are in the control group. While one of the drivers in the treatment group increased his score to nearly the maximum of 100, this increase is from a high initial level, yielding a percentage change of less than 15%. The driver with the largest relative improvement showed an increase in average score of nearly 40%. In line with several previous studies (e.g. [18,26,29]), the figure further confirms considerable variation between individual drivers.

A similar illustration is given in Fig. 3, but now for average fuel consumption before and after the eco-driving course.

This figure shows that two of the drivers in the treatment group had a slight increase in average fuel consumption in the period after treatment, and one of these is the driver who achieved a nearly perfect average total driving score after treatment. This is a case in point, illustrating that fuel consumption is affected by more than eco-driving parameters (e.g. weather), and one reason for studying partial effects in more detail. All other drivers show a reduction in average fuel consumption after treatment. With a reduction of nearly 15%, the largest reduction in average fuel consumption after treatment is found for a driver in the treatment group.

5.2. *Differences in fuel consumption between treatment and control group*

Table 3 summarizes regression results for different specifications of the dummy model, with coefficients being the β- and γ-values in the respective sub-specifications according to equations I, II, III and IV given above.

Using these results, we further carried out a series of Wald tests comparing coefficients between all pairs of time period dummies, with the null hypothesis that coefficients are not significantly different. Results of these comparisons are presented in Table 4, for Models II, III and IV respectively, and indicate whether effects (change in average fuel consumption) are significantly different between time periods, e.g. indicating a learning curve, progressive increases, or effect fading (cfr. [18,29]).

From Table 3, Model I has an adjusted R-squared of 0.078, i.e. around 8% of variation in average fuel consumption can be explained by the independent variables in the regression model. While this value is low, it is not unexpected given that fuel consumption is affected by many variables not included here (cfr. [10]). The positive and statistically significant coefficient on the treatment group dummy indicates that before the eco-driving course, the fuel consumption for drivers in the treatment group was on average 2.3 L/100 km higher than for drivers in the control group, who had an average fuel consumption of 37.1 L/100 km.

Further, fuel consumption after the eco-driving course is significantly lower (on average 2.9 L/100 km) than before the course. Although the coefficient on the interaction dummy for treatment group and completion of the eco-driving course is negative (suggesting that the post-course reduction in fuel consumption is larger for drivers in the treatment group than in the control group), this difference is not found to be significantly different from zero.

In Model II, we take a closer look at changes in fuel consumption in a short and a longer term. As seen from Table 3, coefficients on all variables are significant at the 99% level, and the share of variation explained by the model is slightly higher. In the reference (all timing dummies equal to zero, i.e. before the eco-driving course), fuel consumption for drivers in the treatment group was on average 1.9 L/100 km higher than for drivers in the control group. The largest reductions in fuel consumption are found from weeks 12 to 24 after the treatment, but also in the last period for which we have data (i.e. up to a whole 9 months after the eco-driving course), we find that fuel consumption is lower than before the course (99% significance). Results from Wald tests comparing coefficients between pairs of dummies in Table 4 further suggest that drivers may experience a learning curve: effects between 12 and 30 weeks after the course are namely significantly stronger than in the first 12 weeks (98–99% confidence). In the last time period, fuel consumption is still significantly lower than before the eco-driving course, but the effect is significantly smaller than in the peak time intervals 12–24 weeks after the course (99% confidence) and 24–30 weeks after the course (95% significance).

In model III, average daily temperature and precipitation (in mm) are included as control variables. The negative coefficient on temperature indicates that higher average temperatures might reduce fuel consumption (but not significantly), while the positive and significant coefficient on precipitation indicates that increases in precipitation on average increase fuel consumption. The latter is as expected due to

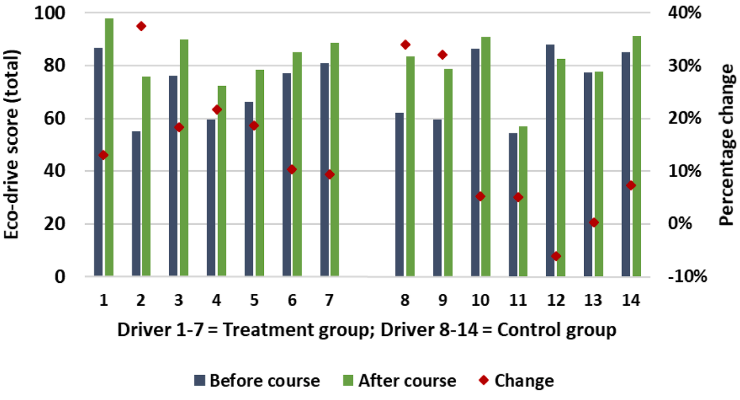


Fig. 2. Average driving performance score before and after the eco-driving course, for each driver in the treatment group (driver 1–7) and the control group (driver 8–14), and corresponding percentage changes (right axis).

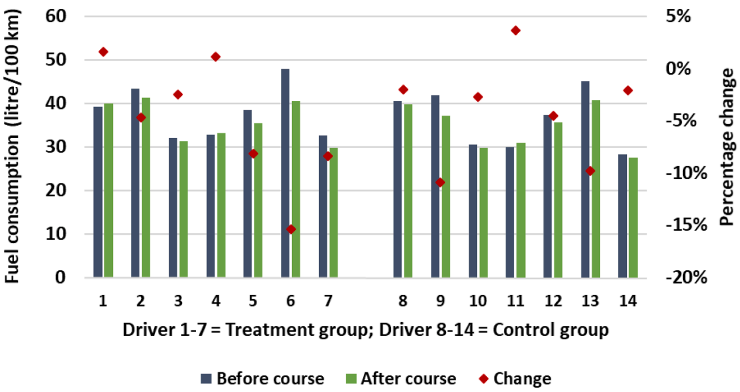


Fig. 3. Average fuel consumption before and after the eco-driving course, for each driver in the treatment group (driver 1–7) and the control group (driver 8–14), and corresponding percentage changes (right axis).

Table 3
Results from four different specifications of the dummy model for avg. fuel consumption (liters per 100 kms) for the treatment group and the control group, before and after the course, the short and long-term effects, and how weather conditions influence fuel consumption.

		Model I		Model II		Model III		Model IV	
β_0	Intercept	37.09	***	37.17	***	37.03	***	36.88	***
β_1	Dummy treatment group	2.34	***	1.91	***	1.92	***	2.26	***
β_2 (in I)	Dummy eco-driving course	-2.91	***						
β_3 (in I)	Interaction dummy treatment group & eco-driving course	-0.82							
β_2	0-6 weeks after treatment			-1.78	***	-1.40	**	-1.50	**
β_3	6-12 weeks after treatment			-2.43	***	-2.01	**	-1.45	*
β_4	12-18 weeks after treatment			-4.36	***	-3.57	***	-3.73	***
β_5	18-24 weeks after treatment			-5.11	***	-4.48	***	-3.96	***
β_6	24-30 weeks after treatment			-3.99	***	-3.84	***	-3.95	***
β_7	30+ weeks after treatment			-2.34	***	-2.39	***	-2.85	***
β_8	Dummy control group after eco-driving course							-2.12	***
γ_1	Average temperature					-0.04		-0.07	**
γ_2	Precipitation (in mm)					0.06	**	0.06	**
	Adjusted R-squared	0.078		0.095		0.097		0.092	

increased rolling resistance from rain. Remarkable is that controlling for weather conditions reduces the coefficient values of the short and longer-term changes in fuel consumption, except for the last time interval, which is in winter time. Results in Table 4 show that effects are stronger between 12 and 30 weeks after the course than during the first 12 weeks (95–99% significance), again suggesting a learning curve. After controlling for weather conditions, we further find fewer indications of effects fading over time. Fuel consumption in the last time interval for which we have data is still found to be significantly lower than before the eco-driving course, and the fuel reduction effect is no longer significantly different from the effect in the time interval 12–18 weeks after the course (β_4), while differences compared to peak reductions in the intervals 18–30 weeks after treatment (β_5 and β_6) become less statistically significant (at 95% and 90% level vs. 99% and 95% in Model II).

Model IV is similar to model III, but uses only observations from the treatment group for the estimation of differences in effects in the long term, while for the control group, a new dummy variable is introduced for the period after the eco-driving course. The dummy for the treatment group still indicates that drivers in this group have a significantly higher initial fuel consumption than the control group. All coefficients are significant at the 95–99% level, except for the period 6–12 weeks after treatment, where fuel consumption is significantly different at the 90% level (for later intervals, statistically significant reductions found lie between 2.8 and 4.0 L/100 km). Further, both temperature and precipitation coefficients are statistically significant (95%), and have the same signs as in Model III. The last series of Wald test results in Table 4 shows that for the treatment group, effects early on (0–6 weeks after the course, β_2) are significantly different from effects in the intervals 12–30 weeks after the treatment (95–99% confidence). Further, effects from 6 to 12 weeks after the eco-drive course are found to be different from effects between 12 and 30 weeks after the course (99% significance). This suggests a learning curve effect specifically for drivers in the treatment group. However, unlike for Model II and III (including long-term observations for the control group) we find no statistically significant differences between effects after 12–18 weeks and later intervals, and hence, no evidence of fading effects for drivers in the treatment group.

Table 4
Results from Wald tests comparing coefficients between all pairs of time periods, with null hypotheses that coefficients are not significantly different, for each individual pair. Table reports test statistics (F) with corresponding degrees of freedom and p-values indicating statistical (in)significance.

	Model II			**Model III**			**Model IV**		
	$F_{1,1515}$	p-value		$F_{1,1513}$	p-value		$F_{1,1512}$	p-value	
β_2 vs β_3	1,3	0,258		0,9	0,343		0,0	1,00	
β_2 vs β_4	18,1	0,000	***	8,1	0,004	***	6,5	0,01	**
β_2 vs β_5	27,4	0,000	***	18,2	0,000	***	7,5	0,01	***
β_2 vs β_6	12,7	0,000	***	15,0	0,000	***	10,3	0,00	***
β_2 vs β_7	0,8	0,371		2,0	0,156		2,6	0,11	
β_3 vs β_4	9,8	0,002	***	5,8	0,017	**	7,3	0,01	***
β_3 vs β_5	17,2	0,000	***	14,3	0,000	***	8,0	0,00	***
β_3 vs β_6	6,1	0,014	**	7,1	0,008	***	9,0	0,00	***
β_3 vs β_7	0,0	0,888		0,2	0,663		2,0	0,15	
β_4 vs β_5	1,3	0,262		1,8	0,185		0,1	0,79	
β_4 vs β_6	0,3	0,572		0,1	0,740		0,1	0,81	
β_4 vs β_7	9,4	0,002	***	1,3	0,247		0,7	0,39	
β_5 vs β_6	2,7	0,101		0,7	0,400		0,0	1,00	
β_5 vs β_7	16,3	0,000	***	4,8	0,028	**	1,2	0,28	
β_6 vs β_7	6,1	0,014	**	3,7	0,054	*	1,6	0,20	

5.3. *Results from the driving performance score model*

Table 5 show results from three specifications of the driving performance score model, assessing how different eco-driving scores and weather conditions influence fuel consumption and corresponding elasticities. Coefficients represent the β-values in the respective sub-specifications according to equations A, B and C given above.

All parameter coefficients in the three model specifications are significant at the 99% level (except for the coefficient on rainfall in Models B and C, which is significant at the 90% and 95% level respectively), and differences stemming from introducing additional variables to the base specification are not large. Further, adjusted R-squared values indicate that between 14.5 and 17.2% of the variation in average fuel consumption can be explained by the independent variables. Of the four driving performance factors, it can be seen that improvements in ‘engine and gear score’ reduce fuel consumption most, followed by improvements in ‘speed adaptation score’ and ‘idling score’. These results seem consistent with eco-driving theory and conclusions in previous research (Section 2.4), although differences in definitions and score compositions make direct comparisons difficult. On the other hand, the coefficient for ‘anticipation score’ has a positive sign. This implies that higher scores lead to increased fuel consumption, and is the opposite of what was expected. An explanation could be that the anticipation score is composed of the two variables for coasting and braking, which are expected to be correlated with the topography of the area where the truck is driving. Higher coasting scores could be related to more opportunities for coasting due to downhill driving on a route, but when such routes also imply more uphill driving, this could result in a net fuel consumption increase.

Also in the driving performance score model, average temperature and precipitation significantly influence average fuel consumption, and have the expected signs (Model B and C). At the same time, temperature and precipitation do not influence coefficients or significance of coefficients on the score parameters particularly.

In the specification of Model C, the coefficient on the parameter for ‘distance’ has a positive sign, again contrary to what was expected. However, it is important to note that the study data contain a limited number of distribution routes. Increased fuel consumption for the longest routes can therefore be the result of these longer distribution routes to a larger extent taking place in areas with harsher topography and curvature than the shorter routes in the Central South-Eastern parts of Norway.

Total elasticities (i.e. the sum of elasticities for the score parameters) of between −0.322 and −0.350 indicate that an *increase* of 10% in total driving performance score leads to a *decrease* in average fuel consumption of between 3.2 and 3.5%. As was shown in Fig. 1, drivers in the treatment group on average increased their (rounded) total driving performance scores from 69 in January to March, to 89 in October to

Table 5
Results from three regression specifications of how performance on different eco-driving indicators and weather conditions influence fuel consumption, and corresponding elasticities.

		Model A		**Model B**		**Model C**	
β_0	Intercept	5.121	***	8.868	***	8.268	***
β_1	LN(anticipation score)	0.050	***	0.060	***	0.069	***
β_2	LN(engine and gear score)	-0.328	***	-0.344	***	-0.321	***
β_3	LN(speed adaptation score)	-0.036	***	-0.036	***	-0.038	***
β_4	LN(idling score)	-0.033	***	-0.030	***	-0.032	***
β_5	LN(average temperature)			-0.662	***	-0.616	***
β_6	LN(rainfall in mm)			0.006	*	0.007	**
β_7	LN (distance)					0.037	***
	Adjusted R-squared	0.145		0.173		0.172	
	Sum elasticity	-0.348		-0.350		-0.322	

December, i.e. a score increase of 28% on average. Combining this information with the estimated elasticities indicates that the eco-driving intervention results in a decrease of 9.0% in average fuel consumption from January to December, taking into account differences in temperature and precipitation. This can be interpreted as 'upper bound potential' for savings from the eco-driving interventions in the current study.

Also the control group had an increase in total score, from (rounded) 71 in January to March, to 87 in October to December, or 23%. Correcting for the drivers that quitted their positions during the summer, this improvement is 16%. Combining this information with the estimated elasticities indicates that the reduction in average fuel consumption from January to December was between 5.2% and 7.5% for the control group. This is despite the control group not participating in the eco-driving course and not receiving follow-ups, and might be the result of spill-overs from the treatment group. The 5.2% reduction might be interpreted as 'lower bound potential', given that eco-driving is not actively addressed for these drivers and driving behavior improvements might be induced by an indication that 'something is going on'. Active follow-ups should be expected to strengthen this effect.

The freight forwarder reports a total annual fuel consumption of 3.4 million liters of diesel in 2018. This corresponds relatively well with the fuel consumption in our dataset for 2019 (2.9 million liters of which 179,000 L by drivers in our experiment). The average score level for all drivers of the freight forwarder was 78 in 2019. This is below the annual average for both the treatment group in 2019 (85) and the control group (83, not corrected for drivers quitting their position, or 86 for drivers in the control group with continuous participation in 2019).

As can be seen from Fig. 4, the monthly score level for drivers not participating in the study was more constant throughout the year than for the other two groups, with a peak in July. This indicates that also drivers at the company that weren't part of this study might have a potential for improved driving behavior. However, this improvement potential is smaller than for the treatment group, which started from a lower initial score level in January. The score level of other drivers at the forwarder is more in line with the initial level of the control group. This suggests a potential for increasing total scores by between 16% and 28%, corresponding to a reduction in fuel consumption of between 5.2% and 9.0%. For the freight forwarder as a whole, this would correspond to potential annual diesel savings of between 178 and 306 thousand liters, a reduction in CO_2 emissions of between 454 and 779 tonnes (based on the Norwegian biodiesel blend-in in 2019 [7], and savings on fuel expenses of between 2 and 3.5 million NOK (ca. 205–350 thousand EUR or 230–393 thousand USD at 2019 average exchange rates and Norwegian diesel prices (cfr. [7]).

6. Discussion

6.1. Summary of results

In summary, our results indicate that an eco-driving course, combined with active follow-ups and 'carrots' in the form of non-monetary rewards, might induce more efficient driving behavior among truck drivers, and thereby significantly reduce fuel consumption. Although considerable variation is observed between individual drivers, results indicate that driving behavior improves progressively up to a peak, suggesting an eco-driving 'learning curve'. Results further indicate that effects do not disappear or fade significantly over time, and suggest that follow-up evaluations and non-monetary rewards may reinforce or strengthen effects of a theoretical eco-driving course. Based on improvements in driving behavior found for the treatment group, and potential spill-overs of effects to the control group, we estimate a potential for fuel savings between a lower bound of 5.2% and an upper bound of 9.0% on a yearly basis (for driving in comparable settings).

Of four driving performance factors, representing eco-driving strategies, results indicate that improvements in 'engine and gear' management (consisting of automatic gear use and power take-off) may contribute most to reductions in fuel consumption, followed by improvements in 'speed and adaptation' (consisting of cruise control use and avoidance of speeding) and 'idling' behavior. Better 'anticipation' (consisting of coasting and braking behavior) is not found to contribute to fuel savings, a finding that might be the result of the topography of the routes driven. Weather conditions are found to be significant and largely as expected, with lower fuel consumption at higher ambient temperatures and higher fuel consumption with increased precipitation. Controlling for weather also makes our finding that effects do not fade significantly over time, more robust.

6.2. Implications

Reducing emissions from road freight transport is seen as highly necessary and urgent, but also very challenging due to large projected increases in demand and the high fossil fuel dependency of road freight. At the same time, it is expected that large-scale adoption of both low-

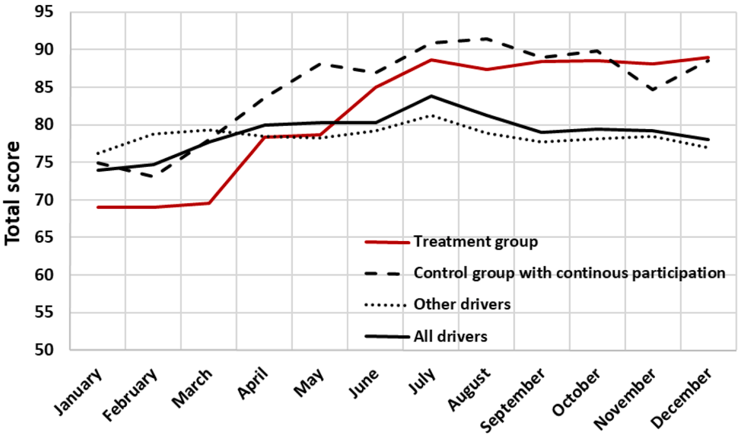


Fig. 4. Monthly averages in total score for treatment group, control group, other drivers of the freight forwarder, and on average for all drivers of the forwarder (treatment and control group, and others).

and zero-emission technologies and other solutions with considerable emission reduction potential (such as connected, automated vehicles, platooning, etc.) will take time. Also many other main determinants of road freight's fuel consumption are largely given in the short- to medium term, or beyond the control of transport operators and their drivers. Inducing more fuel efficient driving behavior, eco-driving, is therefore often seen as one of the few veins through which fuel consumption can be reduced both significantly and in a shorter term [3]. In addition, eco-driving is regarded as a low-cost and scalable approach [13,14,17]. However, the effect of eco-driving initiatives tends to fade over time, and the challenge seems to be to make improved driving behavior more permanent [13,16,26].

Through its approach and results, the present research has several implications for this latter challenge and future eco-driving initiatives and research. Although we acknowledge a number of limitations in the next section, our results are promising with regard to the effectiveness of combining eco-driving training with active follow-ups and rewards. While different settings might moderate results, it is not unlikely that significant fuel savings are achievable also at other firms and by other drivers, and at relatively low cost. Our research also implies that future interventions could benefit from designs where knowledge training is followed up with reinforcement mechanisms. Our research further provides insights into the importance of different eco-driving strategies, which may contribute to increased focus in eco-driving interventions and potentially lower the threshold for implementing such initiatives. In addition, if spill-overs indeed took place, this strengthens the view that eco-driving might be a rather low-hanging fruit.

Compared to previous literature, a number of findings and observations are confirmed or supported. Examples include the rapid materialization of effects (e.g. [17]), the size of effects (falling within the 5–15% fuel savings range compiled by [19]), the possibility of a 'learning curve' [18,29], considerable variation between drivers [18,26,29], the importance of including weather, and direction of effects [most notably 16], and possibly the materialization of spill-overs (related example in [35]). To a large extent, our results also seem consistent with findings on the relative importance of (improvements on) different eco-driving factors for fuel consumption [11,17,19,25,29]. Different from many previous studies is that effects are not found to fade significantly in the longer term. While both feedback and non-monetary rewards have been found to be effective in reinforcing effects after eco-driving training [16,34,38], effects are usually still expected to fade in the longer term (e.g. [29]).

In addition to contributing to the relatively limited body of literature on truck eco-driving, and particularly real-world studies on longer-term effects and reward incentives [12,26,27], our research added some new elements. For example, we combined real-world conditions with a design in which trucks, routes and drivers are relatively fixed. As opposed to some laboratory experiments or eco-driving evaluations on dedicated testing tracks, real-world examples are scarce, but needed, to increase external validity of results. Further, we utilize data from in-/vehicle FMS-devices. Such data are currently often underutilized, but have a large potential for detailed future data collection and utilization given that FMS-devices have become a 'standard' in new trucks and are increasing rapidly in number [43].

6.3. Limitations, strengths and suggestions for future research

Despite best efforts, our study revealed a number of challenges. One of these challenges was related to potential spill-overs of effects to the control group, once treatment group rewards became visible, or after control group drivers unintentionally started receiving feedback reports. This challenge implies that the control group might not fully reflect what would have happened without any eco-driving interventions, and indeed, developments in scores from drivers at other departments of the freight forwarder suggest that some spill-overs may have taken place. At the same time, spill-overs are unlikely to have affected effects for drivers actually undergoing eco-driving interventions. These effects could be regarded as 'upper bound potential' and provide an indication of what can be achieved through the interventions in our experiment.

Further, even though our experiment aims to control for fixed routes, drivers, and trucks, the sign of some estimated coefficients is not as expected. This is particularly true for improvements on coasting and braking, which are generally assumed to improve fuel efficiency. We believe this is rather the result of some critical factors not being included in the analysis because of data availability issues. Examples are the lack of information about dynamic on-board cargo weight and the topography and curvature of roads in areas where transports are carried out. Even though the selection of routine distribution routes and sample of trucks and drivers likely reduces these deficiencies, there will still be some day-to-day variations in payload, and occasional variations in routes. Our attempt to control for these factors as much as possible also put a natural limit to the sample size that could be included, which was exemplified by some attrition due to drivers in the control group quitting their position. Similarly, drivers could not be compared at the exact same time because distribution routes were driven in shifts. Any differences between shifts are particularly thought to relate to weather, which we controlled for in our analyses. In all, eco-driving experiments such as the one described here must balance between the representativeness of experiments for real-life driving, the ability to control for external factors, availability of and access to sufficiently comprehensive data covering sufficiently long periods, and sample size.

The above challenges also point out the critical moment for using FMS data for transport analyses, because factory-fitted FMS-APIs do not provide access to dynamic vehicle weight information. For information on actual payload, access is required also to order system data, but these are rarely available and not easily coupled to vehicle data. Ideally, information on driver behavior, fuel consumption, payload, and GPS data should be available at a high and similar frequency, i.e. usually every 2–3 min or preferably more frequently, or at least event-based. In the current study, controls for topography could not be included due to the very low (driver-set) frequency of GPS data logging, but this challenge could be addressed in future studies.

Another limitation of our research is that we were unable to consider several driver and situational characteristics, which are thought to potentially moderate effects. For example, we lacked access to sample-specific information on factors such as age, driving experience, average mileage, or eco-driving knowledge and attitudes. At the same time, the freight forwarder indicated that the study sample was intended to have a very homogeneous composition and that it was believed that differences between drivers would be small.

Although our experiment did not explicitly consider potential side-effects of eco-driving, e.g. on safety (other than giving feedback post-trip, rather than in-vehicle), a few points are worth noting. Both the supplier of Linx and an independent other supplier of FMS solutions claim that eco-driving improvements in practice also yield reductions on maintenance and damage costs for their clients. Anecdotic evidence from the freight forwarder also suggests that drivers with good eco-driving performance have had reduced maintenance expenses, damages and other deviations (e.g. vehicle/goods damages or administrative breaches). For future research and experiments, it could therefore both be interesting and relevant to more explicitly consider eco-driving and traffic safety in conjunction. Further, although not explored in detail, observations during our analyses suggest that real-world data on fuel consumption from in-vehicle FMS-systems may deviate considerably from factors or averages often used in research and transport policy analyses, and as such have a potential to contribute to better calibrated analyses in future. The increasing prevalence of such systems might contribute to future studies being able to study driving behavior over longer time periods than before, and at larger scale.

Finally, it is worth mentioning that right before the eco-driving course, drivers in the treatment group completed a survey asking them to characterize their own performance and prioritization of coasting, speed adaptation, idling, use of cruise control, engine and gear, and anticipating behavior. This was done in connection with a Master Thesis on short-term effects of the eco-driving course, within the same project [44]. Although the sample size was very small, survey results suggested that driver perception on some eco-driving factors was closer to performance scores than on other factors, but that overall, drivers overestimated their driving performance compared to objective score data (e.g. how much they used cruise control or their coasting performance). When the same survey was repeated towards the end of May, perceptions were more consistent with Linx score data, but overall still an overestimation of driving performance. This could suggest that some further effectiveness gains may be possible by further closing the gap between perceptions and reality (e.g. more frequent or real-time feedback).

6.4. Conclusions

Through the present research, we demonstrated that eco-driving training can give significant fuel savings for truck drivers, and that effects can be maintained longer than is often assumed, when training is combined with active monthly follow-ups and non-monetary rewards. We shed light on the importance of different eco-driving strategies, the progression of effects over time, and the importance of controlling for weather conditions. This is done through a real-world, or naturalistic, randomized controlled experiment, which contributes to the existing literature in several ways, including its design, controls, and use of reinforcement mechanisms after completion of an eco-driving course, but also through the way data are used. Our research points to eco-driving being a relatively low-hanging fruit for the road freight sector, for which emissions reductions are very challenging, especially in the short term. Until emission reduction solutions are technologically and economically feasible at a large enough scale, eco-driving can be a scalable, immediate, and not insignificant part of strategies towards (urgent) emissions reductions from the road freight sector. In addition, eco-driving interventions can yield beneficial results also from the financial perspective of freight operators, which contributes to eco-driving acceptance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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