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# Vehicle choices and urban transport externalities. Are Norwegian policy makers getting it right?

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## Abstract

Norway has the world's highest share of electric vehicles in its vehicle stock – in particular battery electric vehicles (BEVs). BEVs have reached a 20% share of the new car sales in Norway, thanks to a set of policies that include high purchase taxes for fossil fueled cars, and for BEVs, free parking, no tolls, and the right to drive on the bus lanes. This paper uses a stylized model of the transport market in the greater Oslo area (1.2 million inhabitants) to analyze transport policies. First, we explore the medium-term effects of the current BEV friendly policies. Second, the model is used to explore the potential of better pricing of car and public transport use, and of better car purchase taxes. We find that the current policies lead to massive penetration of BEVs and therefore to a strong reduction of $CO_2$ emissions. However, they also lead to much more congestion and a decrease in the use of public transport. Better policies require efficient pricing of road congestion, a better use of public transport, and provide incentives for consumers to choose the most efficient combinations of cars. Such policies lead to a less extreme penetration of BEVs, and lower $CO_2$ emissions reductions than the current transport policies. However, they do achieve a better transport equilibrium and substantial resource cost savings, leading to higher welfare levels.

**Keywords:** electric vehicles, climate policy, urban transport policy, transport modeling

**JEL classification:** H23, H71, Q54, Q58, R41, R48

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# 1 Introduction

The transport sector is among the world's biggest polluters. It accounts for approximately one quarter of global energy-related greenhouse gas emissions (International Energy Agency, 2017). Road transport alone accounts for about 20% of the European Union's (EU's) overall greenhouse gas emissions, and according to the European Environmental Agency (2017), emissions from this sector increased for the second year in a row in 2015.

Enforced in 2016, the Paris agreement responds to the pressing threat of climate change, aiming to limit the global temperature increase this century to well below 1.5°C above pre-industrial levels. Being one of the top polluters, the transport sector is required to deliver major emissions reductions to achieve these targets. The electrification of transport is considered to play an important role in reducing greenhouse gas emissions (International Energy Agency, 2017; WWF, 2012). In June 2017, the Clean Energy Ministerial launched its EV30@30 campaign that aims for a 30% sales share for Electric Vehicles (EVs) by 2030. The UK and France have both announced plans to end sales of new conventional petrol and diesel cars by 2040.

Norway has the highest penetration of EVs worldwide, making it much like a social experiment to examine the results of EV-friendly policies. Currently, there are about 140 000 battery electric vehicles (BEVs) and 67 000 plug-in hybrids (PHEVs) in Norway, a small country with only 5.3 million inhabitants. BEVs and PHEVs have reached a fleet share of 5.1% and 2.5% respectively. In 2017, BEVs accounted for 20% of all new personal car purchases nationally, while PHEVs accounted for 17% (Figenbaum, 2018). As BEVs still have a limited range, one finds the highest market share in the big cities. In Oslo, the share of BEVs was 5.9% in 2016 (ibid), and close to 30% of all new personal vehicles were BEVs.

The EV literature has focused on enhancing the speed of integration of EVs into the car stock. In this paper we take a broader look at the EV question by considering multiple market failures in urban transport and their policy implications. The key research questions we address are the following: Which policies will be the most welfare-enhancing in the urban transport system with multiple market failures: congestion, accidents, local air pollution and $CO_2$ emissions, and what role can BEVs play in achieving these policies? What characterizes the potential conflicts between welfare maximization and targets for reducing $CO_2$ emissions – where the promotion of BEVs is a key instrument – and car transport in cities? Furthermore, what trade-offs do we see between efficiency and acceptability? To answer these questions, we develop a stylized transport model for passenger transport in the Oslo metropolitan area, an urban area with approximately 1.2 million inhabitants.

While the modeling approach draws on Börjesson, Fung, and Proost (2017), our paper provides several novel extensions to the framework, most notably multiple heterogeneous representative agents and a car choice module. This model gives a simplified but complete description of the urban transport market equilibrium. This allows us to analyze how different types of agents respond to different transport policies, and how costs and benefits of polices are distributed among agents. This distribution is key to understand political feasibility.

Our results indicate that the key question policy makers must ask themselves in this context is what balance they want to strike between welfare maximization and $CO_2$ emissions reductions, or in other words; how much welfare are you willing to sacrifice to reduce emissions? Welfare-maximizing policies, at the recommended social cost of carbon, lead to very small $CO_2$ emissions reductions. Policies for achieving the ambitious goals of halving the emissions from personal transport will inevitably bring about substantial welfare costs. These costs accrue mainly through the higher resource costs of BEVs and PHEVs, which play a crucial role in reaching ambitious emissions reductions.

Section 2 presents the current objectives and policies for the transport sector in Norway. Section 3 discusses briefly the literature on EVs and reviews their potential role in policies for curbing $CO_2$ emissions and externalities from urban transport. Section 4 presents the model. Section 5 and 6 present, analyze and discuss the model results. Section 7 concludes.

# 2 Current objectives and policies for transport sector in Norway

The development of the market share for EVs in Norway is in accordance with the Norwegian government's National Transport Plan. The overall goal of the national transport policy is to develop *a transport system that is safe, which promotes economic growth, and which contributes to the transition into a low-emission society*. Following the Paris agreement, Norway is committed to reducing its greenhouse gas emissions by 40% compared to their 1990-level, by 2030. Moreover, it aims to become a low-emissions society by 2050. Sectors that are not included in the EU's Emissions Trading System (ETS) face an emission reduction target of 30% compared to the 2005-level by 2030. The transport sector accounts for about 60% of all non-ETS emissions and will consequently be responsible for an important share of the emission cuts of the non-ETS sectors.

The National Transport Plan proposes a climate strategy to halve the transport sector's greenhouse gas emissions. Three areas are particularly emphasized; i) the promotion of low and zero emissions vehicles and the use of biofuels, ii) walking, cycling, and public transport in cities, and iii) a modal shift to maritime and rail in freight transportation. The Plan recommends that all new light vehicles, city buses and light commercial vans are zero emissions vehicles by 2025, and that all new heavy commercial vans, 75% of new long-distance buses, and 50% of new trucks are zero emissions vehicles by 2030. The zero-growth objective states that the growth in passenger transport should be facilitated by means of walking, cycling, and public transport. The objective applies to urban areas that are eligible for an Urban Environment Agreement,[2] which is a mutually binding agreement between the national and local governments that commits the central government to invest in public transportation while local governments are committed to land use development that accommodates walking, cycling, and public transport.

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[2] The Oslo metropolitan Urban Environment Agreement became binding in 2017 and lasts until 2023.

To achieve its target to promote low and zero emissions vehicles, the National Transport Plan outlines the following principles:

i. *The purchase costs of low and zero emissions vehicles should be competitive to conventional vehicles.*
ii. *The user costs of low and zero emissions vehicles should be less than conventional cars.*
iii. *When there is lack of road capacity (queuing) or space (parking), zero emissions vehicles should be prioritized.*
iv. *Power charging facilities or fuel supply for zero-emissions vehicles should be easily available to facilitate long-distance trips and to avoid unacceptable waiting times.*

The above principles are already well embedded in national transport policies. Initiatives to promote zero emissions vehicles – especially BEVs – were first introduced in the 1990s. A wide range of BEV-friendly policies have been introduced in the subsequent years. Table 1, which is adopted from Figenbaum, Assum, and Kolbenstvedt (2015), summarizes the policy instruments put in place to promote electromobility in Norway.

**Table 1**: *Policy instruments to promote BEVs*

| Year of introduction | Policy instrument |
|---|---|
| *Fiscal incentives* | |
| 1990 | Registration tax exemption. The government has pledged to uphold the exemption until at least 2020. |
| 2001 | VAT exemption. The government has pledged to uphold the exemption until at least 2018. |
| 1996/2004 | Reduced annual vehicle license fee |
| 2000 | Reduced company car tax for BEVs |
| *Direct subsidies* | |
| 1997 | Toll roads exemption. In 2018, a small toll fare for BEVs will be introduced in Oslo |
| 2009 | Reduced rates on ferries |
| 2009 | Financial support for charging stations |
| 2011 | Financial support for fast charging stations |
| *Accessibility* | |
| 2003/2005 | Access to bus lanes. On certain links in Oslo, there is a requirement to have at least one passenger to be granted access to bus lanes during peak hours |
| 1999 | Free parking. In 2017, local governments were given discretion in deciding whether to uphold this user benefit |

*Source: Figenbaum et al. (2015)*

In addition to the national ambitions for reducing $CO_2$ emissions, there are local ambitions. The city of Oslo and the county of Akershus, who together broadly make up the Oslo metropolitan area, have ambitions that surpass the national target. Oslo aims to reduce $CO_2$ emissions by 50% by 2020 (Oslo Municipality, 2016). The corresponding goal in Akershus is a 50% reduction by 2030 (Akershus County Council, 2016).

# 3 Literature

## 3.1 Electric vehicles and policy

The large-scale introduction of EVs to the transport system, and the current policies intended to promote EVs raise many interesting transport and energy economic issues. We put them in three categories.

First, there is the choice of low carbon technology for cars. BEVs are one of the options, next to PHEVs as well as biofuels and hydrogen. This raises questions on the cost development of different competing technologies, as there are interactions with the other uses of electricity via storage options for electric cars. This question is best addressed in a technology model like TIMES (see Diaz Rincon, 2015). There are also important R&D policy implications, where the effects of learning by doing and the effects of pure R&D development should be included in the model (Fischer & Newell, 2008).

Second, there is the analysis of the car purchase decisions. As EVs offer a different combination of car characteristics (range, refueling issues, prices), one needs to study the consumer preferences with respect to these characteristics. For an early study one can consult Brownstone, Bunch, and Train (2000) and research done on Norwegian data can be found in Østli, Fridstrøm, Johansen, and Tseng (2017). As the car market is a monopolistic equilibrium market, there is also a need to study the price and development strategies of the different car producers that take consumer preferences into account (Verboven, 2002).

Most studies investigating how incentives lead to adoption of EVs are concerned with hybrid-electric vehicles (HEVs), (Bjerkan, Nørbech, & Nordtømme, 2016). Several studies – including Beresteanu and Li (2011) Gallagher and Muehlegger (2011) – identify a positive impact of tax incentives on HEV sales. Gallagher and Muehlegger conclude that the type of tax incentive is important for the adoption of HEVs as vehicle sales tax waivers are found to lead to more than a ten-fold increase in hybrid sales relative to income tax credits. These papers also point to the importance of gasoline prices in promoting the competitiveness of HEVs.

In a recent study, Bjerkan et al. (2016) investigate the role of 7 different incentives to promote BEVs based on a membership survey by the Norwegian Electric Vehicle Association. They find that purchase tax exemption is the strongest incentive to purchase an BEV. However, to some BEV owners, access to bus lanes or toll road exemptions are the only decisive variables. Access to bus lanes is found to be an important incentive for commuters living in municipalities close to Oslo.

Third, there is the role of EVs in the urban transport market. The urban transport market is characterized by many externalities that need attention. Perhaps most costly in the urban setting is road congestion during peak hours (Thune-Larsen, Veisten, Rødseth, & Klæboe, 2014). However, there are also externalities like accidents, local and regional air pollution, noise, $CO_2$ and crowding on public transport. This balancing requires a model that represents explicitly the functioning of the urban transport market (Proost & Van Dender, 2001). As finding this balance is the overarching subject of our research questions, transport externalities and the urban transport market will be the main emphasis of this paper.

## 3.2 Instruments addressing $CO_2$ emissions

The most obvious instrument to address $CO_2$ emissions is of course a carbon tax. This instrument is already in place; it is called gasoline (or diesel) tax. In many European countries gasoline and diesel for car use is taxed at 200 to 300 Euro/ton of $CO_2$ (OECD, 2016). This could be complemented by a carbon tax on alternative fuels (natural gas, biofuels, fossil generated electricity, hydrogen) in function of their carbon emissions. In theory, this instrument will make sure that we have the right mix of the four levers of reducing carbon emissions in transportation: more fuel efficient driving, reduced car use, more fuel efficient vehicles, and alternative technologies. The carbon tax can be complemented by an instrument to correct knowledge spillovers of new technologies that take the form of subsidies for learning by doing and pure R&D knowledge spillovers (Fischer & Newell, 2008).

The EU and Norway pursue this option: there are high excise taxes in place on automotive fuels and there are tax exemptions/subsidies for the purchase and use of BEVs and for R&D.

When we consider this first-best set of instruments focusing on carbon emissions, we see that the potential use of these instruments is handicapped by several constraints. First, if one region or nation has more ambitious climate targets than its neighbors, its scope for varying gasoline taxes regionally or nationally is limited as this would induce tankering and tax competition (Mandell & Proost, 2016). The choice set is therefore largely limited to (given climate goals, too low) fuel taxes, complemented by discriminating taxes on car ownership and purchases according to emission standards, and specific R&D subsidies. Second, the use of instruments to correct knowledge spillovers has only limited effects as the market for new engine technologies is a world market. Third, very fuel-efficient vehicles lead to more congestion. This could be considered a rebound effect that arises because improved energy efficiency reduces the generalized transport costs.

If we still assume that the market for the other modes is priced correctly, the most efficient discriminating vehicle taxes are annual registration taxes. They are more efficient than discriminating purchase taxes as the latter tend to prolong the life of fuel inefficient vehicles. Subsidies for the use of low carbon vehicles can take the form of less taxed or subsidized fuels (electricity, natural gas etc.), but also other user costs can be subsidized. Examples are parking and driving rights in the bus lane in the peak period.

Surprisingly, in many countries, there is a much larger emphasis on the promotion of EVs than on the road congestion issue. This reflects the explicit or implicit values policy makers place on $CO_2$. In Norway, the current taxes on fossil fuels (excluding VAT) imply a carbon cost of about 240 Euros[3] per ton of $CO_2$. In this tax there is a pure $CO_2$-component that is supposed to reflect a carbon cost of about 50 Euros, which is close to the recommended social cost of carbon in Norway (NOU 2015:15, 2016). However, even with such a high value on carbon, the external carbon cost may be dwarfed by the external congestion cost of a km driven in a dense city during peak hours. In large and dense cities, the external carbon cost could also be matched by the costs per km of local pollutants such as nitrogen oxides and particulates (Thune-Larsen et al., 2014). These issues reflect our first research question.

## 3.3 How does the promotion of BEVs affect congestion and other urban transport externalities?

BEVs are promoted by lowering their purchase tax and user costs. Many Norwegian municipalities also offer free parking and allow BEVs to drive in the bus lane. This can give rise to policy goal conflicts.

Before we introduce the urban transport model in Section 4, we illustrate some of these conflicts that arise from different policy instruments using a highly stylized textbook case. Consider Figure 1, where a fixed number of commuting trips are made to the city center and the population has the choice between using a car or public transport. The average generalized cost of car use is upward sloping as the time cost increases with the number of cars on the road. Here we see that the *average* social costs are lower than the *marginal* social costs. We model the cost of public transport (PT) by a constant average cost per passenger[4]

In the optimum, we would see equal marginal social costs of private transport and public transport (illustrated in the figure by "Optimal equilibrium"). In the absence of any policy measures we end up in the user equilibrium A. In the absence of specific congestion tolls, the government often resorts to subsidies for public transport (PT). Subsidizing PT lowers the user cost of PT and leads to equilibrium B where congestion is mitigated and PT ridership has increased.

Now introduce a BEV promotion policy. As this is a promotion policy for one type of car, the composite cost of car use can only be reduced. Indeed, the population will only opt for BEVs in so far as they are a lower cost option than a conventional fossil car, so the composite cost can only decrease. This results in a new equilibrium C where car use has increased again and where part of the effects of second best PT pricing have been destroyed. Finally, we add a policy like allowing BEVs to drive in the bus lanes. This causes higher congestion levels in the bus lanes which increases the user cost for PT users. This leads to an equilibrium of type D, where the market

[3] Weighted average for gasoline and diesel, where the former counts for 59 % of the car fleet's fuel use, and the latter 41 %.

[4] We assume that the crowding externalities in public transport are addressed using increases in frequency so that the average generalized cost of PT is more or less constant.

share of BEVs has increased, but at the expense of PT users, and where the urban congestion levels have gotten worse.

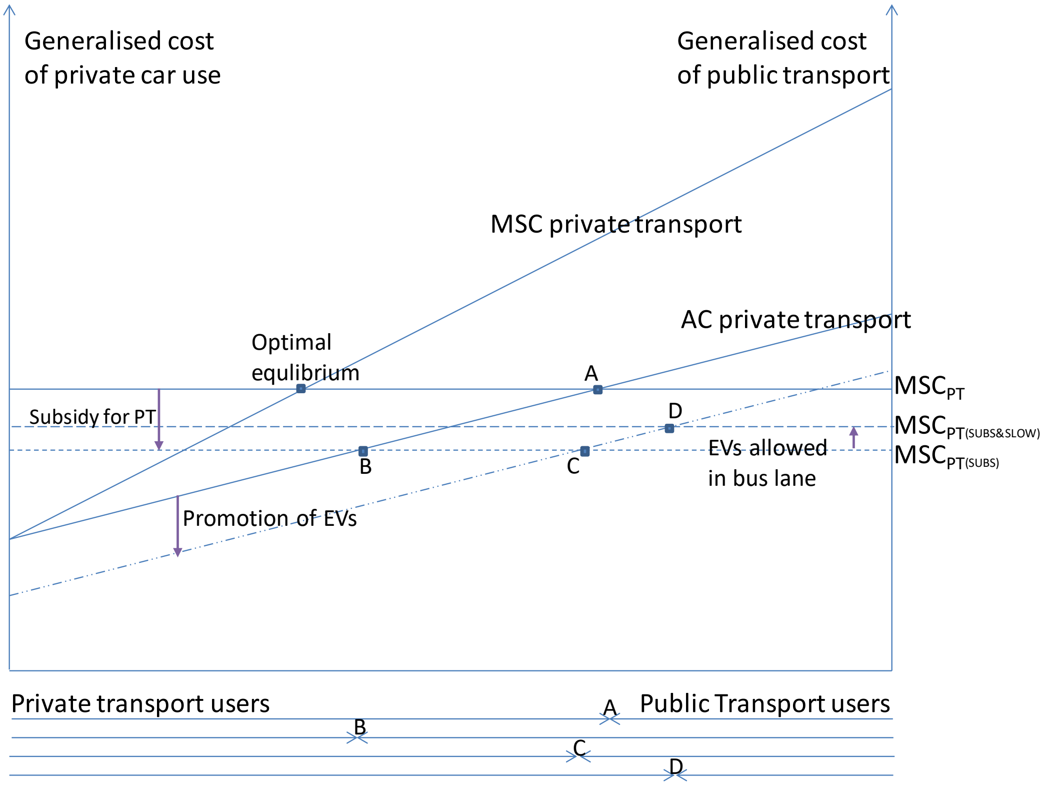


*Figure 1: Promotion of BEVs and urban transport equilibria*

There is a second subtle way in which the present BEV promotion leads to more congestion: the progressive $CO_2$ taxation of fossil cars. Confronted with the introduction of a progressive $CO_2$ tax on fossil cars, a car driver can react in four ways. She can abandon car use, she can opt for an EV, she can also choose a very fuel-efficient ICEV, and fourth, she can postpone buying a new car.

The second and the third choice reduce the variable cost of car use, which then stimulates higher transport demand, and consequently congestion. The conflict between fuel efficiency promotion and urban road congestion is well known (Parry, Evans, & Oates, 2014).

The fourth option, postponing buying a new car, does not lead to more BEVs and less carbon emissions. However, it does not lead to more congestion either, as long as fuel prices remain high.

In conclusion, if policy makers want to promote BEVs and address the urban road congestion issue, there is a need for other policies that complement the promotion of BEVs. We ask: What is a better mix of policies?

## 3.4 How to address urban congestion and continue to promote the use of BEVs

To address urban congestion, there is no other way than to build either more road capacity, to incentivize shifting the time of travel from peak to off-peak (e.g., through pricing) and/or to incentivize a shift from car to public transport, biking or walking (e.g., through improved public transport pricing and quality). We consider each of these alternatives in turn.

Additional road building is not really considered as an alternative in a country where one wants to limit overall car use in urban areas (see Section 2).

Pricing of all car use in the peak period is the most obvious instrument to be used. Just recently, in October 2017, Oslo began differentiating (slightly) between peak and off-peak car use.[5] However, BEVs will not pay the toll for another year.

The third alternative is to promote the use of public transport. This policy has already been pursued and current PT users pay some 50% of operation costs (Ruter, 2016). The effectiveness of this policy depends on the diversion ratio, i.e. the proportion of the new PT users incentivized by reduced generalized prices of PT, that are former car users. When the diversion ratio is close to 50%, this measure can still be effective (Parry & Small, 2009). If it is closer to 20%, the measure becomes very costly. The reason is that a price reduction for PT attracts many additional public transport users that do not pay the supply cost (i.e. the fare is subsidized), but still need to be accommodated by providing costly extra PT capacity. A study by Flügel, Fearnley, and Toner (2018) finds that the average diversion ratio for the Oslo area from car to PT varies from 29% to 44%, depending on the mode of PT.

# 4 Model set-up

The model is a stylized representation of the behavior of different groups of agents in the greater Oslo area, that is combined with supply costs. We use it to study how agents demand daily short trips by car transport and public transport, either in the peak or the off-peak period, and how some of the agents demand a number long trips by car throughout the year.

This is a very aggregated model that considers the transport of all inhabitants in the greater Oslo-area over the age of 18, where the overall population is represented by three representative agents.

## 4.1 Model components

The main components of this stylized model are; the gross utility derived from transport, the user costs of transport, the costs of public transport supply and the external costs of transport. These components are used to compute alternative urban

[5] https://www.fjellinjen.no/private/prices/ [last accessed April 9th 2018]

transport equilibria and their welfare effects. The model is inspired by Börjesson et al. (2017) but adds a vehicle selection stage.

### 4.1.1 Gross utility derived from transport

The preferences of the modeled agents are represented by a quasi-linear utility function *U*. Here utility is derived from consumption of other (non-transport) goods and services (normalized to money *m*), and from consumption of kilometers travelled for short daily trips (by car, by PT at peak, at off-peak) and the number of long car trips per year. The utility from transport consumption is represented by a sub-utility function B, which is assumed to be quadratic. *U* and *B,* for a given representative individual, are represented by the following equations:

$$U(m, q_c^p, q_c^o, q_b^p, q_b^o, q_c^l) = m + B(q_c^p, q_c^p, q_b^p, q_b^o, q_{lc}) \qquad (1)$$

where

$$\begin{aligned} B(q_c^p, q_c^p, q_b^p, q_b^o, q_c^l) &= [\alpha_c^p q_c^p - 0.5\beta_c^p (q_c^p)^2] + [\alpha_c^o q_c^o - 0.5\beta_c^o (q_c^o)^2] \\ &+ [\alpha_b^p q_b^p - 0.5\beta_b^p (q_b^p)^2] + [\alpha_b^o q_b^o - 0.5\beta_b^o (q_b^o)^2] + [\alpha_{lc} q_{lc} - 0.5\beta_{lc} (q_{lc})^2] \\ &- i_c^{po} q_c^p q_c^o - i_b^{po} q_b^p q_b^o - i_{cb}^p q_c^p q_b^p - i_{cb}^o q_c^o q_b^o - i_{cb}^{po} q_c^p q_b^o - i_{bc}^{po} q_b^p q_c^o \end{aligned} \qquad (2)$$

$q_j^t$ stands for the number of daily kilometers travelled, as demanded by the representative agent in period *t* using mode *j*. The peak and off-peak periods are represented by the superscripts *p* and *o*, respectively. The subscripts *c* and *b* represent the car and PT mode, respectively, while the subscript *lc* represent long car trip. Similarly, $\alpha_j^t$ and $\beta_j^t$ are parameters of the sub-utility function for period *t* and mode *j*. The terms $i_{jj}^{tt}$ are the interaction terms between modes and/or periods, for instance $i_{cb}^{po}$ represents the interaction between car mode in the peak period and the PT mode in the off-peak period. These terms are symmetric, in accordance with consumer theory, i.e. the symmetry of the Slutsky matrix. This formulation of the utility function allows us to derive the willingness to pay (WTP), i.e. the inverse demand functions, for the five types of transport.

$$\begin{aligned} \frac{\partial U}{\partial q_c^p} &= \alpha_c^p - \beta_c^p q_c^p - i_c^{po} q_c^o - i_{cb}^p q_b^p - i_{cb}^{po} q_b^o \\ \frac{\partial U}{\partial q_c^o} &= \alpha_c^o - \beta_c^o q_c^o - i_c^{po} q_c^p - i_{cb}^o q_b^o - i_{bc}^{po} q_b^p \\ \frac{\partial U}{\partial q_b^p} &= \alpha_b^p - \beta_b^p q_b^p - i_b^{po} q_b^o - i_{cb}^p q_c^p - i_{bc}^{po} q_c^o \\ \frac{\partial U}{\partial q_b^o} &= \alpha_b^o - \beta_b^o q_b^o - i_b^{po} q_b^p - i_{cb}^o q_c^o - i_{cb}^{po} q_b^o \\ \frac{\partial U}{\partial q_{lc}} &= \alpha_{lc} - \beta_{lc} q_{lc} \end{aligned} \qquad (3)$$

### 4.1.2 User costs of transport

We have standardized the consumer good daily short-trip transport to one kilometer, so the user costs are also on a per km basis. The user costs for daily car travel are given by:

$$uc_c^i = dc_c^i + \rho c_c + \tau_c^i + \left[\delta_c + \gamma\left(Nq_c^i\right)\right]VOT_c^{in} \tag{4}$$

The user costs comprise of the monetary distance-related costs $dc_c^i$ (fuel, repairs, lubricants etc.), toll costs $\tau_c^i$, parking costs $\rho c_c$ and time costs $\left[\delta_c + \gamma\left(Nq_c^i\right)\right]VOT_c^{in}$, where $\delta_c$ is free-flow travel time and $\gamma\left(Nq_c^i\right)$ is the added time as a result of congestion caused by other road users.

The user costs for daily PT travel is given by:

$$uc_b^i = ac_b^i + \tau_b^i + \delta_b VOT_b^{in}\left[\varphi\left(Nq_b^i\right)\right] + VOT_b^{w}\frac{60}{2f_b^i} \tag{5}$$

The user costs comprise access time costs $ac_b^i$, fare costs $\tau_b^i$ and time costs $\delta_b VOT_b^{in}\left[\varphi\left(Nq_b^i\right)\right]$, where $\delta_b$ is PT travel time and $\varphi\left(Nq_c^i\right)$ is a crowding factor that works as a weight on the agents' value of in-vehicle travel time. The crowding factor increases with the number of other agents riding in the PT system.[6]

The user costs for the occasional long car trip is given by:

$$uc_{lc} = dc_{lc}^i + \tau_{lc}^i + \delta_{lc} VOT_c^{in} \tag{6}$$

If the long car trip is done by a BEV, and the trip back and forth is longer than the range of the car, the agent is assumed to need to charge enough to cover the remainder of the round trip. This adds a disutility cost as a function of the charging time:

$$disU_{ch} = \omega_{ch} VOT_{lc}\left[\left(2lcL - r_{EV}\right)eff_{EV}/chCap\right] \tag{7}$$

The charging time is thus determined by the range of the BEV and the length of the trip $\left(2lcL - r_{EV}\right)$, the energy efficiency of the BEV $eff_{EV}$, and the charging capacity $chCap$.[7] The disutility cost of charging time is assumed to be the value of travel time times a disutility weight for waiting $\omega_{ch} VOT_{lc}$.

### 4.1.3 Cost of public transport supply

Since we are looking at a larger city area where PT is currently provided by metro, tram, city buses, commuter buses and ferries, we have constructed a cost function for the aggregate PT system. The cost function is assumed to be a linear function of

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[6] The crowding factor has a lower bound of 1. The crowding factor does not start to increase before all seats on the PT ride are occupied.

[7] For example, with a semi-fast charger with a capacity of 22 kW, and the EV has a battery utilization rate of 0.2 kWh/km, it would take 1 hour to get 110 km of driving distance charged.

annual frequency $f_b$ (which seems to fit the aggregate data from the PT company Ruter's annual report quite well (Ruter, 2016)).

$$C_b = FI_b + \kappa f_b \tag{8}$$

Any change in the annual frequency of PT can then be interpreted as a change in a "composite" PT-mode with shares of bus, metro, tram and ferry.

### 4.1.4 External costs of transport

Section 4.1.2 has already covered the external cost of congestion. The other important external costs are local pollution, greenhouse gas emissions, noise and accident risk. They are assumed to be constant per km per vehicle, depending on where the agents drive (Thune-Larsen et al., 2014). All the short daily trips are assumed to be in the city area, where population is relatively dense, thus having relatively high per-km external costs. The long car trips are assumed to be mostly on highways, and rarely drive through densely populated areas, thus having a fairly low per-km external cost (in addition to that we assume no congestion problems on the long trips). The external costs will also differ by the type of car. How the marginal external costs vary by car type and by area can be seen in Table 3. The simple relationship for total external costs $E$ is modelled in the following way:

$$E = \sum_{j=1}^{n} e_j q_j \tag{9}$$

The marginal external cost per km driven is given by $e_j$ for mode *j*.

## 4.2 Finding welfare optimum

The aggregate welfare function consists of several components, as described by Eq. 10. The first component is net consumption of other goods and the gross user surplus. The net consumption of other goods can be described as generalized disposable income after fixed and variable transport costs, the latter being the user costs described above. The second component is the net transport related deficit for the public sector (assuming the PT provider belongs to the public sector), i.e. the total revenue from the agents' transport consumption (tolls, fares, gasoline and diesel tax, and purchasing tax and VAT on vehicles (annuity)) minus the total cost of providing PT. The third component consists of the revenue to the parking company $P_{price}$ (a transfer), while the fourth component consists of the opportunity cost of occupying parking space $P_{\text{cost}}$. The fifth component consists of external non-congestion costs. This way we account for all costs and transfers for the involved agents.

$$\begin{aligned}\Omega = \sum_{k=1}^{n} &\begin{bmatrix} m_k + B_k(q_{ck}^p, q_{ck}^o, q_{bk}^p, q_{bk}^o, q_{lck}) \\ -uc_{ck}^p q_{ck}^p - uc_{ck}^o q_{ck}^o - uc_{bk}^p q_{bk}^p - uc_{bk}^o q_{bk}^o - uc_{lck} q_{lck} \end{bmatrix} \\ &- \left( C_b - \tau_c^p q_c^p - \tau_c^o q_c^o - \tau_b^p q_b^p - \tau_b^o q_b^o - \tau_g g_c q_c - \sum_k \tau_c^{ann} k \right) + P_{price} - P_{\text{cost}} - E\end{aligned} \tag{10}$$

Here, $\tau_g g_c q_c$ is the fuel tax revenue, where $\tau_g$ is the tax rate, and $g_c$ is the average fuel efficiency. We also have $\sum_k \tau_c^{ann} k$ , which is the annuity of the purchase and VAT tax revenues, summed for all agents that own cars.

For simplicity, we assume lump-sum taxes to finance any public sector deficits. Hence, we ignore labor market distortions. This implies that the marginal cost of public funds (MCF) equals 1, which we will discuss later in the paper.

We assume that in user equilibrium each agent adjusts her behavior so that her willingness to pay (marginal benefit) $\frac{\partial B}{\partial q_j^i}$ equals the generalized cost (marginal cost) $uc_j^i + \tau_j^i$ for the use of a given mode in a given period.

To derive optimal tolls and fares, we maximize the social welfare function w.r.t., the quantities of the different goods subject to constraints of user equilibrium in each mode and period.

$$\begin{aligned}\Omega = &\sum_{k=1}^{n} \begin{bmatrix} m_k + B_k(q_{ck}^p, q_{ck}^o, q_{bk}^p, q_{bk}^o, q_{lck}) \\ -uc_{ck}^p q_{ck}^p - uc_{ck}^o q_{ck}^o - uc_{bk}^p q_{bk}^p - uc_{bk}^o q_{bk}^o - uc_{lck} q_{lck} \end{bmatrix} \\ &- \left( C_b - \tau_c^p q_c^p - \tau_c^o q_c^o - \tau_b^p q_b^p - \tau_b^o q_b^o - \tau_g g_c q_c - \sum_k \tau_c^{ann} k \right) - P_{price} - P_{\text{cost}} - E \\ &+ \sum_{k=1}^{n} \begin{bmatrix} \lambda_{ck}^p \left( uc_{ck}^p + \tau_{ck}^p - \frac{\partial B}{\partial q_{ck}^p} \right) + \lambda_{ck}^o \left( uc_{ck}^o + \tau_{ck}^o - \frac{\partial B}{\partial q_{ck}^o} \right) + \lambda_{bk}^p \left( uc_{bk}^p + \tau_{bk}^p - \frac{\partial B}{\partial q_{bk}^p} \right) \\ + \lambda_{bk}^o \left( uc_{bk}^o + \tau_{bk}^o - \frac{\partial B}{\partial q_{bk}^o} \right) + \lambda_{lck} \left( uc_{lck} + \tau_{lck} - \frac{\partial B}{\partial q_{lck}} \right) \end{bmatrix}\end{aligned} \tag{11}$$

We differentiate $\Omega$ with respect to the transport quantities and set the expressions to zero and rearrange. We then get expressions for optimal tolls and fares:

$$\begin{aligned}\tau_c^p &= q_c^p \frac{\partial uc_c^p}{\partial q_c^p} + e_c \\ \tau_c^o &= q_c^o \frac{\partial uc_c^o}{\partial q_c^p} + e_c \\ \tau_{lc} &= q_{lc}^o \frac{\partial uc_{lc}^o}{\partial q_{lc}^p} + e_{lc} \\ \tau_b^p &= q_b^p \frac{\partial uc_b^p}{\partial q_b^p} \\ \tau_b^o &= q_b^o \frac{\partial uc_b^o}{\partial q_b^p}\end{aligned} \tag{12}$$

The resulting equations show that the optimal tolls for cars equal the marginal external congestion costs that they impose on other road users, plus the marginal external non-congestion-costs of road use. The optimal fares for PT equal the marginal external crowding cost (which depends on frequency).

## 4.3 Constructing and calibrating the numerical model

To calibrate the numerical model, we need three elements. First, we need a representation of the population by a limited number of representative user groups. For each of these user groups we observe their choices: type of car, use of different modes in peak and off-peak and on long trips, and the associated user costs. This generates one observation for calibrating the utility function of each user group. Second, we need price and cross-price elasticities for each representative user. The first two elements allow the description of the utility function of each user to be completed. The third element is the supply functions for road space (speed-flow relations) and public transport.

An important first element is the Norwegian travel survey from 2013/2014. Documentation of the travel survey is found in Hjorthol, Engebretsen, and Uteng (2014). Of the approximately 60 000 respondents in this survey, about 10 400 (18 years or older) lived in the greater Oslo area. These respondents represent about 1.2 million inhabitants in the greater Oslo area (0.95 million over 18). The travel survey experts at The Institute of Transport Economics have constructed frequency weights for each respondent based on geography, sex, season and time of week. Applying these weights gives us a synthetic adult population of the greater Oslo area represented by the travel survey respondents.

Based on this synthetic population, we construct and calibrate a numerical model in MATLAB using the steps described in Table 1.

*Table 1: Model calibration, step by step*

| Step | Description |
|---|---|
| 1 | Aggregate the National Travel Survey data for the counties Oslo and Akershus (that approximate "the greater Oslo area") into 3 aggregate agents in terms of<br>Baseline travel pattern (PT and car).<br>Employment and incomes (which determine value of time).<br>Car ownership, access to parking at home, etc. |
| 2 | Compute generalized transport costs of each agent for each mode and for each car type, for short and long trips |
| 3 | Select own-price and cross-price elasticities for each type of agent for the "travel products" person-km per day by car and by PT, peak and off-peak, and long car trips per year (see the Appendix for more information). |
| 4 | Calibrate the utility function using the data from steps 1, 2 and 3. |
| 5 | Check the calibration of the utility function by simulating the choice of each agent (number of trips per mode) and cross-checking them with observed choices. This step completes the calibration of the agents' utility functions. |
| 6 | Construct the speed-flow function for peak car trips based on a linear approximation of peak and off-peak speeds. |
| 7 | Construct the cost functions for public transport in peak and off peak using a linear function with intercept (fixed costs), and an automatic frequency "rule-of-thumb" optimization rule for peak and off-peak. A similar approach was used by Parry and Small (2009) and Kilani, Proost, and van der Loo (2014). |
| 8 | Construct the crowding cost functions of public transport (see the Appendix for more information). |
| 9 | Construct linear cost functions for the non-congestion external costs; air pollution, noise & accidents. Values are given in Table 3, based on Thune-Larsen et al. (2014). |
| 10 | Construct a welfare function to represent equation (11), that consists of the sum of utility for each agent – user costs for agents (including taxes, tolls, fares and parking charges) – transfers to government and parking company – external costs other than congestion – the operational costs of PT – the opportunity cost of parking spaces. |

In this model, we have created the 3 representative agents X, Y and Z. The agents are classified according to whether they have taken any long car trips (+ 100 km) in the past month (whether the travel pattern includes occasional long trips may be important for the choice of car type), and whether they are employed or not. The key agent characteristics are shown in Table 2.

*Table 2: Key agent characteristics*

| Characteristic | Agent X | Agent Y | Agent Z |
|---|---|---|---|
| Estimated number of people | 267 955 | 468 187 | 210 187 |
| Working/ Not working | Working | Working | Not working |
| Annual gross income (NOK) | 591 183 | 500 972 | 320 821 |
| Any long trips by car per month | Yes | No | Yes |
| Number of short car trips per day | 1.9 | 1.38 | 1.0 |
| Number of short car trip km per day | 20.9 | 15.6 | 9.8 |
| Average length of long car trip | 191 | N/A | 175 |
| Number of long car trips per year | 19.5 | N/A | 11.8 |
| Number of PT trips per day | 0.4 | 0.7 | 0.4 |
| PT km per day | 7.6 | 10.8 | 6.9 |
| Peak trips car per day | 0.9 | 0.7 | 0.3 |
| Peak km car per day | 10.5 | 7.7 | 2.8 |
| Off Peak trips car per day | 1.0 | 0.7 | 0.7 |
| Off Peak km car per day | 10.4 | 7.8 | 7.0 |
| Peak PT trips per day | 0.29 | 0.43 | 0.14 |
| Peak PT km per day | 4.5 | 6.9 | 2.3 |
| Off Peak PT trips per day | 0.15 | 0.32 | 0.26 |
| Off Peak PT km per day | 3.1 | 4.0 | 4.6 |
| Disutility markup from owning a small car, relative to price difference between small and large ICEV (see Table 3) | N/A | N/A | 10% |

Other important parameters for the calibration include generalized prices for car and PT travel, and own-price and cross-price elasticities. Description of and sources for these parameters are given in the Appendix, along with further details on the calibration procedure.

In addition to the user costs of travel, we must include the costs of ownership.[8] We have found the average purchase prices (including VAT and purchase taxes) of new cars sold in Norway in 2015-2016 for the broad categories "conventional car" (diesel and gasoline), "hybrid", "EV short-range" (range of 190 km) and "EV high range" (range of 528 km). The prices have been transformed to annuities over cars' average lifetime with a real interest rate of 2%[9] to make annual comparisons. We summarize the key car-specific parameters for technology, user costs, and externalities in Table 3.

[8] We have used data from The Norwegian Road Federation (OVF)

[9] Risk-free component in real discount rate applied in CBA (NOU 2012:16, 2012). In addition, car loans are usually given at 4%-5% and Norwegian inflation target is 2.5%.

*Table 3: Car specific parameters for technology, user costs, and externalities, baseline*

| | **ICEV small** | **ICEV large** | **PHEV** | **EV short** | **EV long** |
|---|---|---|---|---|---|
| Purchase price | 273 058 | 503 614 | 456 036 | 263 049 | 720 468 |
| VPT cost | 59 977 | 158 219 | 44 143 | | |
| VAT cost | 42 616 | 69 079 | 82 379 | | |
| Producer price | 170 464 | 276 316 | 329 514 | | |
| | | | | | |
| Annual tax | 2 820 | 2 820 | 2 820 | 455 | 455 |
| Range (km on full battery) | | | 47.8 | 190 | 528 |
| Fuel usage (liters per 100 km) | 7.99 | 9.50 | 6.15 | | |
| Share of city trips in e-mode[10] | 0 | 0 | 27.3% | 100% | 100% |
| kWh-usage per km, summer | | | | 0.15 | 0.17 |
| kWh-usage per km, winter | | | | 0.20 | 0.22 |
| kWh-usage per km, average | | | 0.28 | 0.17 | 0.20 |
| Non-fuel costs per km (including taxes, not tolls) | 2.05 | 2.05 | 2.05 | 1.98 | 1.98 |
| Non-congestion external cost per km in city (NOK) | 0.70 | 0.70 | 0.36 | 0.36 | 0.36 |
| Non-congestion external cost per km far from densely populated areas (NOK) | 0.16 | 0.16 | 0.16 | 0.15 | 0.15 |

## 4.4 The model procedure for analyzing policies

The model is ready for running policy scenarios when all the agents' utility functions are calibrated to fit the observed data, as explained in section 4.3. Solving the model for an alternative policy requires to find a new user equilibrium *first* for given type of car ownership and *second* when all agents have chosen their preferred type of car. As the type of car determines car user costs, this requires an iterative process. The exact steps in the solution process are given in Table 4.

[10] For PHEVs we assume that they run on electricity 27% of the time on short trips in the city area, and on fossil fuels when going on long trips.

*Table 4: Steps in the model procedure for analyzing transport policies*

| Step | Description |
|---|---|
| 1 | Change one or more exogenous policy variable (tolls, fares, parking charges) |
| 2 | Simulate a new equilibrium by<br>a. Solving for new individual utility optimum for agent X<br>Generating new utility-maximizing quantities for agent X (for each possible car option)<br>Agent makes discrete car choice (large ICEV, small ICEV, PHEV, short-range EV, long-range EV, or no car) – the choice that gives the highest net utility for the user, i.e. utility from transport and net consumption of other goods (net income minus fixed costs, e.g. annuity for car purchase)<br>Inserting the new quantities into the congestion and PT cost functions<br>b. Solve for new individual utility optimum generating new quantities (and possible car choice) for agent Y, using the new congestion and crowding levels that are generated in step a<br>c. Solve for new individual utility optimum generating new quantities (and possible car choice) for agent Z, using the new congestion and crowding levels that are generated in step b<br>d. Iterate: Redo step a using the updated congestion and crowding functions of step c<br>e. Iterate: Redo step b and c using the updated congestion and crowding functions of the previous step<br>f. Stop updating congestion levels and car choice after 3 iterations to avoid convergence problems |
| 3 | Based on quantities in new equilibrium, calculate the total new social welfare levels and its components associated with the changed policy variable values |

For model runs where the discrete choices of vehicles have been fixed for a specific combination, the optimization procedure becomes simpler and policy variables can be adjusted simultaneously to maximize welfare subject to behavioral constraints. The optimized policies are later run through the three steps described above to check for incentive compatibility, i.e. whether the model agents will make the choice of vehicle combination the optimal policies are designed for.

# 5 Policy analysis and results

We now present the results from the numerical modeling, designed to answer the three stated research questions.

We first explore the medium-term effects of the current policies. What is the welfare status of the current situation for the greater Oslo area? To what equilibrium are we heading if 2014 policies are continued, i.e., the business-as-usual (BAU) scenario? What equilibrium would we end up in if BEVs were treated the same as ICEVs with regards to tolls, parking and VAT (EV-SAME-scenario)?

In a second round we explicitly optimize policies to maximize welfare under constraints. We do this again in two rounds. First, we calculate welfare-maximizing policies (adjusting tolls for both BEVs and ICEVs and PHEVs and PT-fares) for all the possible car combinations. The best combination is then checked for incentive compatibility, here meaning that agents choose the optimal car combinations under optimal policies (i.e., tolls and fares), when given the full choice set. If they're not incentive compatible, vehicle taxes[11] are adjusted to make each user group choose its optimal car combination. This leads to the welfare-maximizing, incentive compatible policy mix.

Finally, we check whether the optimal car purchase and use policy achieves the political goals in terms of $CO_2$ emissions reductions; cf. section 2. If necessary, we adjust the set of policies to reach the $CO_2$-reduction target with the lowest social cost.

**What is the welfare status of the current situation for the greater Oslo area?**

The reference situation for the greater Oslo area is 2014, where "everybody" (98%) is driving an ICEV. PT fares and tolls are uniform across peak and off-peak. Only ICEVs pay for tolls and parking. The policies for the reference-scenario are given in Table 6, along with policies from the other important scenarios. The main results from the reference scenario are also given together with results from the other scenarios in Table 7. Such results include total welfare, calculated at 644.12 bn NOK per year in the reference scenario. They also include total $CO_2$-emissions from personal transport and kilometers driven in the city, which in the reference scenario is calculated to 1.19 mill tons and 3.73 bn km, respectively.

**To what equilibrium are we heading if 2014-policies are continued, i.e., the BAU-scenario?**

In our stylized model, we view the reference scenario as a result of historical choices *before* BEVs and PHEVs were widely available. In our BAU-scenario, we assess the choices of the agents when all five car types are widely available at current prices, and current polices remain constant.

When all agents have adapted to the policies and found a new equilibrium, we have that Agent X has switched to PHEVs, Agent Y has switched to a short-range EV, while Agent Z is sticking to small ICEVs. The result is a 64 % drop in emissions, well within the policy goals of a 50% reduction in metropolitan Oslo. However, due to lower user costs of both PHEVs and BEVs, the Oslo area becomes more congested with a 2.1 % increase in transport volume (for a constant population), thus

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[11] For the general case, vehicle taxes are adjusted to ensure incentive compatibility, as these taxes are only considered transfers between agents and government. For difficult cases, policies are re-optimized subject to incentive compatibility constraints where tolls, fares, parking charges and purchase taxes are instruments in the welfare maximization.

failing to reach the zero-growth goals. Welfare is also reduced due to higher resource costs per car and more congestion.

**What equilibrium would we end up in if BEVs were treated the same as ICEVs with regards to tolls, parking and VAT (EV-SAME-scenario)?**

Compared to the reference situation, Agent X switches to PHEV, while the two other agents stick to their small ICEVs. Agent X's shift leads to $CO_2$-emission reductions of about 30 %, as most of the city driving is assumed to be done in electric mode. While a large reduction, it is still not large enough to meet the stated policy goals. In addition, the lower user costs also lead to increases in total distance driven with 0.4 % in the city. Compared to the reference situation, welfare is reduced due to higher resource costs per car and more congestion, though not as much as in the BAU-scenario.

**Can we do better?**

For the three agents in this stylized model, there are 20 relevant combinations of vehicle ownership. This gives us 20 scenarios, for which the model maximizes welfare (see description above) by eliciting optimal tolls, fares and parking charges under fixed vehicle combinations.

Welfare maximizing policies imply drastic changes from the reference situation. In all scenarios, welfare is enhanced with higher tolls than in the reference situation, especially in the peak period. This goes for BEVs and ICEVs alike. In addition, we find that higher fares in the peak period and lower fares in the off-peak period increase welfare. Finally, welfare-maximizing policies involve all cars paying the opportunity cost of parking space, so BEVs and ICEVs would pay the same price.

The ranking of all these scenarios is given in Table 5. The vehicle combination that achieves the highest welfare level when tolls, fares, and parking charges are optimized is the same as in the reference situation, with Agent X driving the large ICEV and the other agents driving small ICEVs. The changes in tolls and fares lead to a 0.7% decrease in city driving, a 1% increase in rural driving and a 0.2% decrease in $CO_2$-emissions. The results indicate a 218 mill NOK increase in annual welfare from the reference situation, achievement of the zero-growth goals, but failure to reach the $CO_2$ emission reductions target. This implies that the recommended social cost of carbon of 420 NOK does not entail sufficiently large reductions in $CO_2$ from the transport sector. In fact, this external cost is already more than internalized by the fuel tax. The goal of reducing $CO_2$-emissions by 50% implies a shadow price of $CO_2$ that is far higher than the recommended social cost of carbon.

With the optimal transport user policies in place, and the agents given the free choice of vehicles, some additional adjustments are needed to make the optimal vehicle combination incentive compatible. These adjustments are made to make sure that Agent X does not choose the PHEV and Agent Y does not choose the short-range EV. To avoid PHEVs, the purchase tax for PHEVs needs to be increased by at least 150% (which still implies a 50 000 NOK lower purchase tax than the large ICEV). To avoid any short range EVs, tolls for EVs need to be imposed, at least amounting to 33% of the toll for ICEVs at peak, and EVs and ICEVs need to pay the same parking charge.

We conduct sensitivity tests for optimal policies in all the 20 scenarios with fixed vehicle combinations. We test assumptions that are highly uncertain and may affect the welfare-ranking of vehicle combinations. We test:

- What if PHEVs could drive in e-mode for *all* of their city driving? (relevant for 4 scenarios)
- What if Agent X's disutility markup (see Section 4.3) on driving small cars was only 1% and not 10%? (relevant for 8 scenarios)
- What if the resource costs of BEVs was reduced by 25%?[12] (relevant for 17 scenarios)

The alternative assumptions lead to higher welfare levels in the scenarios where they are relevant. In the four scenarios where Agent X drives a PHEV, allowing for 100% driving in e-mode on short trips, adds 154-155 mill NOK extra in welfare. The emissions reductions also become larger as more than 62 000 additional tons of $CO_2$ is abated. We see from Table 5 that one of the tested scenarios climbs in the welfare ranking, from 8th to 9th place.

In the eight scenarios where Agent X drives a small car, but his disutility markup from driving a small car is a lot smaller than initially assumed, welfare becomes about 389 mill NOK higher per year. We see from Table 5 that six of the tested scenarios climb in the welfare ranking. The highest ranked scenario of the affected ones climbs from 5th to 4th place.

The change in assumptions that causes the most extreme changes in welfare results is the 25% reduction in resource costs of BEVs. This change increases welfare by between 967 mill NOK and 6 498 mill NOK per year in the affected scenarios. This causes several changes to the internal welfare ranking of scenarios. The highest ranked scenario of the affected ones climbs from 7th to 5th place.

It is worth noting that the scenario where policies are optimized under the same car combination as in the reference situation, still generates the highest welfare in all of the sensitivity tests. This indicates that the welfare-maximizing vehicle combination finding is robust.

**How do we reach the $CO_2$-reduction targets at least cost?**

In 9 of the 20 scenarios with fixed vehicle combinations, the 50% $CO_2$ emissions reductions target is not reached, and the welfare-maximizing scenario does not even come close to the target. We impose the target as a constraint on the welfare maximization in these scenarios. As noted in Section 3.2, the most efficient instrument for reducing $CO_2$ emissions would be the fuel tax, but the use of this tax is limited due to tankering and tax competition from neighboring regions/countries. Our approach then is to set the $CO_2$ emissions reduction target as a constraint, and let the tolls, fares and parking charges be the instruments for maximizing welfare under this constraint. The $CO_2$-cap is binding in all of the 9 scenarios that in the original optimization did not reach the target, and welfare is consequently reduced in

[12] This is roughly in line with assumptions by The Norwegian Environment Agency (2016), where they assume a 4% annual decrease in costs of EVs, and a 2% annual cost decrease for ICEVs, giving the EV a 25% cost decrease relative to ICEVs by 2030.

all of these scenarios. The scenarios that were furthest away from achieving the emissions reductions target incur the greatest cost. The vehicle combination from the reference situation, which yielded the highest welfare level in both the original optimization and the sensitivity tests, results in the lowest welfare levels under the $CO_2$ constraint. This is because the policies necessary to achieve the target drastically decrease mobility, since the agents are stuck with their ICEVs. For instance, the necessary peak tolls would be 16 times their optimal levels, and off-peak tolls would be 33 times larger.

The highest achievable welfare levels under the binding $CO_2$-cap is with the combination of Agent X driving PHEVs, Agent Y driving small ICEVs and Agent Z driving a short-range EV. This scenario was initially ranked at fifth place in terms of welfare, but gets the highest rank under the $CO_2$-cap since the emissions reductions target can be achieved at a welfare cost of 78 mill NOK per year, compared to the initial optimization. Compared to the highest-ranking scenario in the initial optimization, the welfare reduction is of about 4 bn NOK per year. The average welfare cost per ton of $CO_2$ for achieving the emissions reductions target is 6 671 NOK. This comes in addition to the recommended social cost of carbon of 420 NOK per ton, that was already internalized in the initial optimization.

The tolls, fares, and parking charges that achieve the emissions reductions target at least cost when car combinations are fixed, are not incentive compatible. Without further interventions, Agent Y would choose the short-range EV and not the small ICEV and Agent Z would choose the small ICEV and not the short-range EV. Policies need to be adjusted so that one car becomes more attractive for one type of agent, but less attractive for the other, which of course is a bit tricky. This requires another model run with an incentive compatibility constraint. To ensure incentive compatibility at least cost, both tolls and purchase taxes need to be adjusted. The purchase tax for small ICEVs needs to increase by 210%, and the BEV would get a full VAT of 25%. At the same time, city tolls for ICEVs are reduced, but tolls for driving in rural areas are increased. Tolls for BEVs driving in the city are increased, but tolls for BEVs driving in rural areas are eliminated. Agent Y and Z then end up choosing the welfare maximizing car combination. These policies add a welfare cost of 7 mill NOK per year, which implies that the average welfare cost for achieving the $CO_2$ target increases up to 6 690 NOK. However, these adjustments to ensure incentive compatibility do not change the ranking of car combinations. Hence, we see that the policies for achieving incentive compatibility would add new complexity to the policy regime for achieving the emissions reduction goal at least cost.

The second-ranking car combination has a more intuitive policy package. It achieves the $CO_2$-goal when Agent X drives a PHEV, Agent Y drives a short-range EV, and Agent Z drives a small ICEV under optimized policies. This is the same vehicle combination as in the BAU-scenario, which achieves a 64% $CO_2$-reduction compared to the reference case. Ensuring incentive compatibility is more intuitive here. Before adjusting any purchase taxes, optimal policies would make both Agent Y and Agent Z choose the small ICEV. Getting Agent Y to switch to a short-range EV under optimal transport user policies would require increasing the price difference between the small ICEV and the short-range EV. This increase in price difference has to be at least as large as a 21% subsidy of the short-range EV. This achieves a welfare level that is 5.9 bn NOK lower than in the highest ranked scenario in the initial optimization, resulting in an average welfare cost of 7 661 NOK per ton of $CO_2$ reduced.

The ranking of all the 20 fixed car combinations (and the BAU and EV-SAME-scenarios) in the original optimization, the sensitivity tests, and under the $CO_2$-cap,[13] are given in Table 5:

*Table 5: Welfare ranking of all car combinations for agents X, Y and Z under different scenarios. ICl=Large conventional car, ICs=Small conventional car, Hy=Plug-in Hybrid, EVl=Long-range EV, EVs=Short-range EV*

| Welfare rank | Original optimization | Sensitivity: PHEV e-share | Sensitivity: Agent X disutility of small cars | Sensitivity: Cost of EVs | $CO_2$-cap |
|---|---|---|---|---|---|
| 1 | **X:ICl Y:ICs Z:ICs** | **X:ICl Y:ICs Z:ICs** | **X:ICl Y:ICs Z:ICs** | **X:ICl Y:ICs Z:ICs** | X:Hy Y:ICs Z:EVs |
| 2 | X:Hy Y:ICs Z:ICs | X:Hy Y:ICs Z:ICs | X:Hy Y:ICs Z:ICs | X:Hy Y:ICs Z:ICs | X:Hy Y:EVs Z:ICs |
| 3 | EV-SAME | EV-SAME | EV-SAME | EV-SAME | X:Hy Y:ICs Z:ICs |
| 4 | X:IC Y:lICs Z:EVs | X:ICl Y:ICs Z:EVs | X:ICs Y:ICs Z:ICs | X:ICl Y:ICs Z:EVs | X:ICl Y:EVs Z:EVs |
| 5 | X:ICs Y:ICs Z:ICs | X:ICs Y:ICs Z:ICs | X:ICl Y:ICs Z:EVs | X:ICl Y:EVs Z:ICs | X:EVl Y:ICs Z:ICs |
| 6 | X:Hy Y:ICs Z:EVs | X:Hy Y:ICs Z:EVs | X:Hy Y:ICs Z:EVs | X:Hy Y:ICs Z:EVs | X:EVs Y:ICs Z:ICs |
| 7 | X:ICl Y:EVs Z:ICs | X:ICl Y:EVs Z:ICs | X:ICl Y:EVs Z:ICs | X:ICs Y:ICs Z:ICs | X:ICl Y:EVs Z:ICs |
| 8 | X:ICs Y:ICs Z:EVs | X:Hy Y:EVs Z:ICs | X:ICs Y:ICs Z:EVs | X:Hy Y:EVs Z:ICs | X:Hy Y:EVs Z:EVs |
| 9 | X:Hy Y:EVs Z:ICs | X:ICs Y:ICs Z:EVs | X:Hy Y:EVs Z:ICs | X:ICl Y:EVs Z:EVs | X:ICs Y:EVs Z:ICs |
| 10 | BAU | BAU | BAU | X:EVl Y:ICs Z:ICs | X:ICs Y:EVs Z:EVs |
| 11 | X:ICl Y:EVs Z:EVs | X:ICl Y:EVs Z:EVs | X:ICs Y:EVs Z:ICs | X:ICs Y:ICs Z:EVs | X:EVl Y:ICs Z:EVs |
| 12 | X:ICs Y:EVs Z:ICs | X:ICs Y:EVs Z:ICs | X:ICl Y:EVs Z:EVs | X:Hy Y:EVs Z:EVs | X:EVs Y:ICs Z:EVs |
| 13 | X:EVl Y:ICs Z:ICs | X:EVl Y:ICs Z:ICs | X:EVs Y:ICs Z:ICs | X:ICs Y:EVs Z:ICs | X:EVl Y:EVs Z:ICs |
| 14 | X:EVs Y:ICs Z:ICs | X:EVs Y:ICs Z:ICs | X:EVl Y:ICs Z:ICs | X:EVl Y:ICs Z:EVs | X:EVs Y:EVs Z:ICs |
| 15 | X:Hy Y:EVs Z:EVs | X:Hy Y:EVs Z:EVs | X:Hy Y:EVs Z:EVs | X:EVs Y:ICs Z:ICs | X:ICs Y:ICs Z:EVs |
| 16 | X:ICs Y:EVs Z:EVs | X:ICs Y:EVs Z:EVs | X:ICs Y:EVs Z:EVs | X:EVl Y:EVs Z:ICs | X:EVl Y:EVs Z:EVs |
| 17 | X:EVl Y:ICs Z:EVs | X:EVl Y:ICs Z:EVs | X:EVs Y:ICs Z:EVs | X:ICs Y:EVs Z:EVs | X:ICl Y:ICs Z:EVs |
| 18 | X:EVs Y:ICs Z:EVs | X:EVs Y:ICs Z:EVs | X:EVl Y:ICs Z:EVs | X:EVs Y:ICs Z:EVs | X:EVs Y:EVs Z:EVs |
| 19 | X:EVl Y:EVs Z:ICs | X:EVl Y:EVs Z:ICs | X:EVs Y:EVs Z:ICs | X:EVl Y:EVs Z:EVs | X:ICs Y:ICs Z:ICs |
| 20 | X:EVs Y:EVs Z:ICs | X:EVs Y:EVs Z:ICs | X:EVl Y:EVs Z:ICs | BAU | **X:ICl Y:ICs Z:ICs** |
| 21 | X:EVl Y:EVs Z:EVs | X:EVl Y:EVs Z:EVs | X:EVs Y:EVs Z:EVs | X:EVs Y:EVs Z:ICs | |
| 22 | X:EVs Y:EVs Z:EVs | X:EVs Y:EVs Z:EVs | X:EVl Y:EVs Z:EVs | X:EVs Y:EVs Z:EVs | |

In Table 6 and Table 7 we show the policies and results from the following scenarios: the reference situation, the business-as-usual scenario, the EV-SAME-favoritism scenario, and the best and the worst scenario from the initial optimization and the optimization under the $CO_2$-constraint:

[13] The BAU and EV-SAME scenarios are not evaluated under the $CO_2$-cap as policies would be endogenous.

*Table 6: Policy combinations under different scenarios. ICl=Large conventional car, ICs=Small conventional car, Hy=Plug-in Hybrid, EVl=Long-range EV, EVs=Short-range EV, N/A=Not applicable to this scenario*

| Scenarios | Peak toll ICEV, NOK per km | Off-peak toll ICEV, NOK per km | Toll on long trips ICEV, NOK per km | Peak toll EV, NOK per km | Off-peak toll EV, NOK per km | Toll on long trips EV, NOK per km | Peak fare, NOK per average trip | Off-peak fare, NOK per average trip | Average parking cost ICEV, NOK per average roundtrip | Average parking cost EV, NOK per average roundtrip | EV VAT, % | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference/BAU | 0.31 | 0.31 | 0.16 | 0.00 | 0.00 | 0.00 | 33.00 | 33.00 | 17.50 | 0.00 | 0 % | | |
| EV-SAME | 0.31 | 0.31 | 0.16 | 0.31 | 0.31 | 0.16 | 33.00 | 33.00 | 17.50 | 17.50 | 25 % | | |
| Maximizing welfare, no $CO_2$-constraint | | | | | | | | | | | EV VAT for incentive compatibility | Change in PHEV purchase tax for incentive compatibility | Change in ICEV purchase tax for incentive compatibility |
| Best: X:ICl Y:ICs Z:ICs | 1.47 | 0.68 | 0.00 | 0.48 | 0.48 | 0.09 | 52.36 | 22.98 | 17.50 | 17.50 | 0 % | Add 150% | Unchanged |
| Worst: X:EVs Y:EVs Z:EVs | N/A | N/A | N/A | 1.72 | 0.92 | 0.09 | 51.84 | 23.50 | 17.50 | 17.50 | N/A | N/A | N/A |
| Maximizing welfare, with $CO_2$-constraint | | | | | | | | | | | | | |
| Best: X:Hy Y:ICs Z:EVs | 2.23 | 1.52 | 1.05 | 3.37 | 1.73 | 0.00 | 51.69 | 21.35 | 17.50 | 17.50 | 25 % | Unchanged | Add 210% |
| 2nd Best, but simpler: X:Hy Y:EVs Z:ICs | 1.44 | 0.63 | 0.00 | 1.80 | 1.02 | 0.09 | 52.08 | 23.76 | 17.50 | 17.50 | -21 % | Unchanged | Unchanged |
| Worst: X:ICl Y:ICs Z:ICs | 23.02 | 22.46 | 14.83 | N/A | N/A | N/A | 77.47 | 18.41 | 17.50 | N/A | N/A | N/A | N/A |

*Table 7: Transport, environmental and welfare related results under different scenarios. ICl=Large conventional car, ICs=Small conventional car, EVl=Long-range EV, EVs=Short-range EV*

| Scenarios | City road use (mill vkm) | PT use (mill pkm) | $CO_2$ emissions (1000 tons) | Transport utility + general disposable income, Agent X (bn NOK) | Transport utility + general disposable income, Agent Y (bn NOK) | Transport utility + general disposable income, Agent Z (bn NOK) | Transport externality costs (bn NOK) | Net govern-ment surplus (bn NOK) | Welfare (bn NOK) |
|---|---|---|---|---|---|---|---|---|---|
| Reference | 3 729 | 2 147 | 1 198 | 223 | 324 | 88 | 3.3 | 12.8 | 644.1 |
| BAU | 3 808 | 2 034 | 433 | 224 | 326 | 88 | 1.9 | 3.9 | 638.2 |
| EV-SAME | 3 744 | 2 131 | 820 | 224 | 324 | 88 | 2.7 | 9.9 | 643.0 |
| Maximizing welfare, no $CO_2$-constraint | | | | | | | | | |
| Best: X:ICl Y:ICs Z:Ics | 3 705 | 2 146 | 1 196 | 222 | 322 | 88 | 3.3 | 15.8 | 644.3 |
| Worst: X:EVs Y:EVs Z:Evs | 3 749 | 2 088 | 0 | 219 | 322 | 87 | 1.5 | 2.1 | 628.8 |
| Maximizing welfare, with $CO_2$-constraint | | | | | | | | | |
| Best: X:Hy Y:ICs Z:EVs | 3 677 | 2 196 | 599 | 221 | 317 | 85 | 2.4 | 19.5 | 640.3 |
| 2nd Best, but simpler: X:Hy Y:EVs Z:ICs | 3 693 | 2 124 | 434 | 223 | 324 | 88 | 1.9 | 6.2 | 638.5 |
| Worst: X:ICl Y:ICs Z:Ics | 2 523 | 3 634 | 599 | 187 | 290 | 75 | 2.0 | 70.0 | 620.6 |

We see there are substantial welfare differences between car combinations, even when policies are set to maximize welfare within each combination. Under the initial optimization, the difference between the lowest-achieving combination and the highest-achieving combination is an annual welfare difference of almost 16 bn NOK. The discrepancy gets even larger under optimization with the $CO_2$-cap, where it is almost 20 bn NOK.

# 6 Discussion

We start this section by going through the research questions and how they have been answered.

*What policies will be most welfare-enhancing in the urban transport system with multiple market failures, including $CO_2$ emissions, and what role can BEVs play in these policies?*

The model shows that highest welfare is found when policies induce optimal travel demand, and optimal choice of car. Optimal travel demand is achieved by setting tolls and fares so that the best balance between peak and off-peak travel for both PT and cars is found. For cars this means pricing of congestion and other external costs. For PT, this implies peak load pricing. These tolls and fares will vary with the car combination in any given scenario because volumes of car and PT use will be different, as indicated by Table 6. In the desired scenario, we find that tolls, and particularly peak tolls, and peak fares are increased, while off-peak fares and tolls are decreased, compared to the reference scenario. Parking charges are to be set equal to the marginal opportunity cost of parking space, and tolls on rural driving should be set equal to the marginal external cost, after adjusting for current fuel and electricity taxes.

The highest welfare levels are found when optimal policies are put in place for the agents when they use the same car types as they do in the reference situation; agent X drives a large ICEV and agents X and Y drive small ICEVs. This means that utility-maximizing agents would not choose BEVs, and there are no welfare gains from policies supporting BEVs. This implies that the agents have made the socially optimal car choice already. Welfare is maximized by polices that optimize the use of these vehicles. However, this car combination is socially optimal under a social cost of carbon of 420 NOK, which is already internalized in the fuel tax. Optimal polices will then not lead to any significant $CO_2$ reductions.

*What characterizes the potential conflicts between welfare maximization and the political goals of reducing $CO_2$ emissions and stopping the growth of car transport in cities?*

We learn from the BAU-scenario that if BEVs do not face any tolls or parking charges, along with an BEV-favorable purchase tax system, we end up in an equilibrium with high BEV-penetration. This substantially reduces $CO_2$ emissions, but leads to more city driving (as users of BEVs face lower user costs than in the reference situation), and consequently more congestion. If BEV-driving remains unregulated, there is a clear goal conflict between reducing $CO_2$ emissions and stopping the growth of passenger car transport in the city. We also see that in nine of the twenty fixed-vehicle-combination scenarios, congestion increases because of the lower user costs of BEVs.

As explained in Section 5, optimal policies under the welfare maximizing vehicle combination do not lead to significant emissions reductions. It is clear that an ambitious target of reducing transport emissions from agents living in the greater Oslo area is in conflict with welfare maximization at the recommended social cost of carbon.

As noted in Section 3.2, the most efficient instrument for reducing $CO_2$ emissions would be the fuel tax, but changing this tax was considered off-limits in our modeling. Instead, we set the $CO_2$ emissions reduction target as a constraint, and let the tolls, fares and parking charges be the instruments for maximizing welfare under this constraint.

Once the $CO_2$-cap becomes a binding constraint, the best car combination from the initial optimization becomes the worst. The best vehicle combination is a PHEV to Agent X, a small ICEV to agent Y and a short-range EV to agent Z. It is clear here that BEVs (or other low- or zero emissions vehicles) play a role in reaching ambitious $CO_2$-reduction targets at least cost. With this vehicle combination and optimized policies, we also see a decline in car transport in the city, so those goals do not conflict in this scenario.

However, there is a conflict between ambitious climate and city transport goals on one hand, and welfare maximization on the other. The policies that achieve the emissions reductions target at least cost cause large reductions in welfare compared to the unconstrained ($CO_2$-wise) welfare maximization. The average cost per ton of $CO_2$ reduced, compared to the welfare maximizing policies, is about 16 times higher than the recommended social cost of carbon.

*What trade-offs do we see between efficiency and acceptability?*

It is likely that the optimized policies ($CO_2$-cap or not) are going to be unpopular, as all agents get decreased transport utility because they have to pay high peak tolls and higher fares in the PT peak. However, in the best scenario without a $CO_2$-cap, the net increase in government revenue allows for redistribution to make all agents better off, without a need to raise taxes elsewhere. In the best scenario under the $CO_2$-cap however, there is no such opportunity. Compensation of all the agents would be larger than the net increase in government revenue, so it would require raising taxes elsewhere. Hence, reaching ambitious $CO_2$ emissions reduction targets will require fairly large sacrifices from transport-consuming agents and/or taxpayers. Politicians that are serious about reaching these emissions reductions goals would need a strong mandate from voters in order to achieve those goals. Because it is not going to be painless.

*Putting findings in context*

To find that optimal policies entail increasing peak tolls and fares, and reducing off-peak tolls and fares, is fairly common in the transport economics literature. This was also a finding in Börjesson et al. (2017). Extending their model with car choice, heterogeneous agents and occasional long trips have proven to be valuable, as it gives new insights. The agents' combination of cars matters for what the optimal policies are, and for the welfare levels achieved in any scenario. Implementing optimal polices means both providing the right incentives for transport demand, and for car choice. We find that optimal car choice often will differ for agents with different travel patterns. In particular, agents that demand occasional long trips, e.g., to their cabins, would often be better off with a different car than agents who do not have long trips in their transport consumption basket.

We find that purchase taxes are powerful instruments for obtaining policy goals, whether it is welfare maximization or greenhouse gas reductions. This confirms the finding from Fridstrøm and Østli (2017) that vehicle purchase taxes and feebates have a large potential for $CO_2$ abatement by inducing the uptake of BEVs and PHEVs. In our model, optimal transport use is ensured through tolls, fares and parking charges, while adjustments in purchase taxes are made to ensure that agents actually select the car combination the optimal policies are designed for, i.e., they are instruments for incentive compatibility.

*Caveats*

This analysis has some caveats: For starters, the model we use is very stylized. Although it adds some layers of complexity to previous models, it contains many major simplifications. An important simplification is that we only have five stylized car types that have average prices. We thus ignore the ranges of car prices, and the possibilities of even cheaper options. This relates to the simplification that agents only care about the quantity and mode of transport, and thus care only about the generalized cost of transport for a given mode. We have a small exception, with high-income Agent X who has a disutility cost of driving a small car. The other attributes of the car, e.g., comfort or brand, do not enter into the agents' utility function. We also limit the agents to one car each. And finally, having three representative agents add more insights then only one, but the model still overlooks many relevant issues of heterogeneity. This could be issues related to income, travel patterns, age, employment, family situation, etc.

It is worth noting that we assume no budget constraint for the government, and that the MCF equals 1. Relaxing these assumptions will change the optimization problem and most likely find other optimal policies. Later analysis using this model could test the implications of a MCF above 1, perhaps as a part of a "moral sensitivity analysis" (see e.g., Mouter, 2016).

Finally, many of the parameter values applied in this modelling framework could be considered fairly uncertain. For example, some elasticity values have been obtained from different Norwegian transport models, and others have been obtained from Börjesson et al. (2017), which cover transport users in Stockholm. The elasticity values have also been assumed to be the same for both types of agents. We have addressed some of the parameter uncertainty through sensitivity testing.

The exact numbers reported in the results must therefore be interpreted with some caution. However, we believe the results provide insights into the different mechanisms at play, and what balances policies need to strike in order to be welfare enhancing.

# 7 Conclusions and way forward

Our analysis shows that understanding both car ownership choices and transport patterns of different population groups is important in the search for welfare enhancing transport policies. The distribution of people taking occasional long trips and people who do not is an important aspect of this.

The key question policy makers must ask themselves in this context is: what balance do they want to strike between welfare maximization and $CO_2$-reductions; or in other words, how much welfare are you willing to sacrifice in order to reduce $CO_2$-emissions? Welfare-maximizing policies, at the recommended social cost of carbon, lead to very small emissions reductions. Policies for achieving the ambitious goals of halving the emissions from personal transport will inevitably bring about substantial welfare costs. These costs accrue mainly through the higher resource costs of BEVs and PHEVs, which play a crucial role in reaching ambitious emissions reductions.

The model finds that current policies will bring us to such an equilibrium with large $CO_2$-reductions, but at high welfare costs. In addition, the current "uncritical" promotion of BEVs for the sake of $CO_2$ emissions reductions comes in conflict with the goal of curbing growth in passenger car transport and limiting congestion.

There are many market failures and policy parameters to adjust in an urban transport market. There are reasons to believe that none of the current polices in Norway are optimally assigned. Although the exact numbers from the reported results must be interpreted with caution, they provide some policy lessons.

First, efficiency can be gained through differentiating tolls in peak and off-peak periods. Oslo started with a cordon peak toll system in October 2017, but it would probably be more efficient if the difference between peak and off-peak tolls was larger. Currently there are no tolls for BEVs, even in peak-hours, although this is expected from 2019. The differentiation is an important step, but widening the gap between peak and off-peak would probably be beneficial.

Second, widening the gap between peak and off-peak fares in public transport would also probably produce efficiency gains. The model finds that large increases in peak fares would be welfare enhancing, but reducing the consumer price for riding off-peak seems like a promising first step. It could perhaps be framed as an "off-peak-discount" to give positive connotations to efficient policy. Increasing the general fare price could come in later steps. Oslo's PT company Ruter proposed increasing fares in the peak back in 2012. The proposal was hit by a wave of unpopularity in the media,[14] and the debate died. Framing the proposal in a different way could perhaps avoid this.

Third, purchase taxes are powerful instruments for achieving policy goals. As noted in Section 3.2 it is not the most efficient instrument to correct market failures in the transport market, but it can serve a valuable purpose in a second-best world. A useful way of viewing the problem is in terms of market correction and incentive

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[14] https://www.nrk.no/ostlandssendingen/kan-bli-rushtidsavgift-pa-bussen-1.8079403 [last accessed April 9th 2018]

compatibility. Tolls, fares and parking charges can incentivize optimal transport use, and thereby provide corrections in the transport market. Purchase taxes (and possibly their exemptions) on the other hand, can ensure incentive compatibility in the corrected transport market. It can ensure that agents actually select the car combination the optimal policies are designed for. This can serve as an argument for maintaining a purchase tax structure that discriminates according to $CO_2$ emissions, if ambitious $CO_2$ reduction targets are to be achieved. However, there is no way around the fact that ambitious climate goals will come at relatively high welfare costs in the medium-run. Honest policy makers should communicate this to voters.

The model could be extended in many ways, e.g., with a richer set of cars and a richer set of heterogeneous agents. Analyzing the implication of marginal cost of public funds above 1 and/or binding governmental budget constraints would also be an interesting new application. Another promising extension of the model, would be related to the issues of EV-charging. Higher EV density could impose costs on other electricity users, as it would require enhancements of the local grid. On the other hand, strengthening the EV charging infrastructure could work as a positive network externality, as it would reduce user costs (e.g., searching and waiting) for all EV-users. More knowledge on these issues of charging could improve policy-making for a transport sector with a sizable and growing share of EVs, and thus makes a promising venue for further research.

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# Appendix A: Details for calibration of the model

For calibration we need quantities for each agent, generalized prices, and elasticities. The quantities used are kilometers travelled on short trips per day, in peak and off-peak, by car and public transportation (PT), and long trips (100 km+) by car per year. For short trips agents can substitute between PT and car, and peak and off-peak. For long trips, the agents can only choose the number of long trips per year.

A way to visualize this stylized world is a greater Oslo where agents travel by car and PT every day, and a couple of times a month/year, some of them take a longer drive to their cabin, relatives etc.

Generalized prices are described in Section 4.3. The own-price elasticities for short car trips are taken from the newest version of the regional transport model RTM23 (documented in Rekdal and Larsen (2008)). Own-price elasticities for PT and the cross-price elasticities between car transport and PT are taken from the transport model for the greater Oslo area MPMM23 (documented in Flügel and Jordbakke (2017)). The cross-price elasticities for shifting between peak and off-peak, and cross-price elasticities for shifting between both modes and travel time, are the same as those applied in Börjesson et al. (2017). We apply the aggregate elasticity from the National Transport Model (documented in Rekdal et al. (2014)) for long car trips. The elasticity values are given in Table 8.

*Table 8: Elasticity values*

| **Elasticity Parameter** | **Value** |
|---|---|
| Own money price elasticity, peak car trips | -0.152 |
| Own money price elasticity, off-peak car trips | -0.152 |
| Own money price elasticity, peak PT trips | -0.255 |
| Own money price elasticity, off-peak PT trips | -0.284 |
| Cross money price elasticity between peak and off-peak car trips | 0.100 |
| Cross money price elasticity between peak car trips and peak PT trips | 0.100 |
| Cross money price elasticity between off-peak car trips and off-peak PT trips | 0.086 |
| Cross money price elasticity between off-peak car trips and peak PT trips | 0.096 |
| Cross money price elasticity between off-peak car trips and off-peak PT trips | 0.050 |
| Cross money price elasticity between peak and off-peak PT trips | 0.050 |
| Own money price elasticity, long car trips | -0.172 |

With all these values, MATLAB solves a system of 16 equations with 16 unknowns to complete the calibration of the utility function for each agent. This means we obtain the various parameter values of $\alpha$, $\beta$ and $i$ (cf. Eq. 2) for the various agents.

The generalized prices for short car trips are the distance-based costs (fuel, repair, lubricants etc.), toll and time costs. Distance-based costs are the same as those applied in the National Public Road Administration's (NPRA) tool for Cost-Benefit Analysis, documented in Cowi (2014). Toll costs are based on reporting from the toll companies to NPRA. The value of time is based on the Norwegian valuation study, documented in Samstad et al. (2010). For long car trips, the generalized prices are distance and time costs for the average long car trip, for a given agent. For BEVs there is an added cost to the trip related to charging the car to fill the gap between the range and the length of the average trip times two (assuming back and forth). The time cost of charging is assumed to be VOT for long leisure trips, weighted by the same disutility weights as applied for waiting time for PT on long trips (0.6).

The generalized prices for PT is given by ticket costs and time costs (on board time, access time and waiting time). Samstad et al. (2010) also provide the basis for VOT for PT trips, waiting time and access time. In the presence of a large share of PT users having either 30-day tickets or 12-month tickets, and different price zones, we apply the method for calculating average ridership payment used in Dovre Group and Institute of Transport Economics (2016).

Additional costs: If agents were to buy EVs, a fixed cost is also added for charging equipment, and for renting parking close to home for the share of agents who do not have easy access to parking at or close to their home. Charging cost equipment is assumed to have an up-front cost 10 000 NOK (Norwegian Environment Agency, 2016). Parking rental is assumed to cost 1 400 NOK per month (median rent for parking space in Oslo in October 2017 on website finn.no).

With regards to the rest of the transport system, we have cost functions for PT and speed-flow functions for car transport. The cost function for PT is simply the annual aggregated operating costs for Ruter, the public transport company for Oslo and Akershus, as a linear function of annual frequency. In addition, there is a crowding cost function, where the travel time cost is weighted by a crowding factor. The crowding factor has been calibrated to be a piecewise linear function where the current peak ridership per hour gives a crowding factor of 1.3, same as in Minken (2017), and current average off-peak ridership gives a crowding factor of 1. The crowding factor will not get smaller if ridership falls below this level, so 1 serves as a lower bound for the crowding factor.

The speed-flow functions are based on model simulations from RTM23 on aggregate car travel and travel speed in Oslo and Akershus for a range of scenarios, but with constant road capacity. The result is an aggregate linear speed-flow function. The linearity simplifies the model calculation, but as shown in Arnott, De Palma, and Lindsey (1993), it also serves as a good approximation for a traffic bottleneck model.