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Published in
TRANSPORTATION RESEARCH PART D: TRANSPORT AND ENVIRONMENT

DOI
10.1016/j.trd.2018.08.011

Transportation Research Part D 65 (2018) 101–115

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Anxiety vs reality – Sufficiency of battery electric vehicle range in Switzerland and Finland

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A R T I C L E I N F O

Keywords:
Electric vehicles
Range anxiety
Travel surveys
Charging stations
Transport policy

A B S T R A C T

Limitations of battery capacity in battery electric vehicles (BEVs) contribute to what is known as range anxiety, and therefore poses an obstacle to their mass-market adoption. While high-range BEVs have been recently introduced, it is not clear whether they will be able to cover all possible trips without long recharging detours, and what the infrastructure needs of those vehicles are. To understand the impact of range limitations in Switzerland and Finland, we constructed a simulation model that is based on representative national travel surveys. We use it to calculate the potential of BEVs to cover any trips and investigate options to increase this coverage. The options discussed in this paper are ways to facilitate easy recharging, such as infrastructure development policies. We complement our results with insights from three focus groups. The results suggest that 85–90% of all national trips could have already been covered with BEVs prevalent in 2016. If the charging station infrastructure is developed appropriately and high-range BEVs are adopted, it is possible to reach a potential coverage of 99% or more in both countries. Deploying charging stations at users' homes and in residential areas does contribute significantly to this improvement and is desirable from a car user's perspective. Providing fast-charging stations in other locations is necessary to maximise the potential. We recommend to focus policy efforts on the development of residential charging options and to increase the visibility of electro-mobility using fast-charging stations.

1. Introduction

The fossil fuel-dominated transport sector contributes to some of today's major problems. Road transport is responsible for approximately 17% of total greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change, 2013) and exhaust gases are major drivers of local air pollution. Despite government initiatives to reduce such emissions and more and more stringent emission thresholds, internal combustion engine vehicles (ICEVs) are reaching natural limits in terms of their potential to limit both carbon dioxide and pollutant emissions. A prominent option to tackle these challenges is to increase the adoption of battery electric vehicles (BEVs) in passenger transport. Provided that the electricity mix originates from low-carbon sources, their total GHG emissions can be considerably lower compared to ICEVs (van Vliet et al., 2011; Zah and de Haan, 2012).

However, there are barriers to the mass adoption of BEVs, and we will focus on one of these: range anxiety in potential electric car

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https://doi.org/10.1016/j.trd.2018.08.011

Acronyms			
AFI	Alternative Fuels Infrastructure Directive	**HEV**	hybrid electric vehicle
BEV	battery electric vehicle	**ICEV**	internal combustion engine vehicle
EPA	Environmental Protection Agency	**MC**	Monte Carlo
EV	electric vehicle	**MZMV**	Mikrozensus Mobilität und Verkehr
FEDRO	Federal Roads Office	**NEDC**	New European Driving Cycle
FNTS	Henkilöliikennetutkimus	**PP**	policy package
GHG	greenhouse gas	**PHEV**	plugin hybrid electric vehicle
GIS	geographic information system	**SD**	standard deviation
		TUT	Tampere University of Technology

buyers. One important (but not sole) cause for range anxiety is the smaller range of BEVs compared to conventional cars. A smaller range can force a driver to change his driving patterns. If buyers are unwilling to adapt, they will prefer conventional cars. Since 2017, media coverage about more affordable BEVs with comparably high battery capacities and ranges of more than 300 km gained momentum, suggesting that this barrier could soon be a problem of the past. For example, Tesla, Opel, Nissan and other manufacturers all released new models with greater range, and other manufacturers announced they would introduce new BEVs in the future. Notably, Volvo stated their intention to only sell BEVs and hybrid electric vehicles (HEVs) from 2019 onwards. Moreover, the United Kingdom, France and China all announced to ban or phase out ICEVs in the near future (Ryan and Shankleman, 2017; The Economist, 2017). Despite progress on the vehicle side, it is not clear if current and future BEVs can cover all possible trips, and thereby mitigate range anxiety, given the current charging station network.

We examine and compare this coverage for Finland and Switzerland. We chose these two countries because they are opposites in many ways: Switzerland is small, densely populated except for the mountain areas, and people do not often travel long distances, whereas Finland is much larger and sparsely populated, with a tradition of spending weekends and holidays in countryside cottages.

Governmental policies could provide the means to overcome infrastructural barriers and facilitate the diffusion of BEVs into mass markets. Even though several hundred public charging stations already exist in both countries, and their number is increasing, a universal charging station network analogous to the network of filling stations seems to be a long way from realisation. To this end, the Swiss Federal Roads Office (FEDRO) recommends cantons and service area maintainers to install a network of fast-chargers at all main motorway service areas (Federal Roads Office, 2016). In the case of Finland and the EU, *Directive 2014/94/EU on the deployment of alternative fuels recharging and refuelling infrastructure* (known as Alternateive Fuels Infrastructure Directive (AFI)) directly addresses infrastructure development, i.e. it requires the EU member states to provide an appropriate number of publicly accessible charging points. The implementation draft of Finland proposes a market-based mechanism to build up this infrastructure (Ministry of Transport and Communications, 2016). But despite current policy efforts, a previous meta study states that further research is needed to better understand the infrastructure needs of future BEV models with higher ranges (Hardman et al., 2018).

This paper examines the aforementioned issues and explores whether the currently available and future BEV models and the charging stations network enables car users to cover all of their desired trips. Existing literature includes comprehensive studies about range needs and the effect of infrastructure deployment on BEV trips (see below), but nobody has, to our knowledge, extensively investigated the influence of policies on the share of successful BEV trips on a nation-wide level. Additionally, we do not know of any studies investigating and comparing these issues for the cases of Finland and Switzerland, apart from one study about plugin hybrid electric vehicles (PHEVs) in Finland (Rautiainen, 2015). Moreover, findings from other countries or powertrains are not easily transferable. We address these research gaps with the following three research questions:

1. What are car users' range needs?
2. What share of car trips can be successfully covered with the currently available (2016/17) BEVs and the current charging infrastructure?
3. How much can improved BEV range and an improved charging infrastructure increase the share of successful BEV trips?

We explore the first question using a combination of focus groups and modelling. As a means to quantify the share of successful BEV trips in question 2 and 3, we introduce and model the *BEV-potential* and define it as a share of trips that can be covered solely by BEVs given the availability of charging possibilities: i.e. we assume that not all households have the possibility to charge BEVs at their homes. Focus groups investigate the desirability of those charging possibilities.

Reaching a high BEV-potential does not guarantee that range anxiety in car buyers and users vanishes. As the following literature shows, psychological factors also play a role. The latter is not our focus and we leave these analyses to other scientists. We do however argue, that a high BEV-potential, i.e. the ability of BEVs to cover most or all trips is an important factor to mitigate range anxiety.

1.1. Range needs

In order to support the adoption of BEVs in the consumer mass-market, it is essential that policy makers understand factors and barriers influencing a car user's behaviour. Studies have shown that the limited range of BEVs, long charging times and public infrastructure availability constitute significant obstacles which can cause what is known as range anxiety (Rezvani et al., 2015; She et al., 2017; Lim et al., 2015; Banks, 2015; Egbue and Long, 2012). Still, research suggests that current BEVs, both low- and high-range, satisfy the range needs of most car users (Needell et al., 2016; Pearre et al., 2011). There is also evidence that range anxiety changes with increasing BEV experience but whether that anxiety decreases (Franke and Krems, 2013) or increases (Jensen et al., 2014) is contested.

Needell et al. (2016) have compared the capabilities of current and upcoming BEVs to the range needs of the population. They applied extensive physical modelling, and simulated car trips over a US national travel survey. The study finds that 87% of the trips could already have been covered by low-range, affordable BEVs in 2016 without the need for recharging. The corresponding figure for current high-range vehicles is even higher, reaching 98%. However, the study by Needell et al. (2016) also argues that alternative transportation modes, car-sharing and rental cars will continue to be necessary despite better batteries and an improved charging infrastructure, primarily to cover the most energy demanding trips and reach 100%. Furthermore, Khan and Kockelman (2012) and Jakobsson et al. (2016) find that one-vehicle households and multiple-vehicle households differ with respect to BEV use. Khan and Kockelman (2012) suggest that in a multiple-vehicle household, an average BEV in 2012 was able to satisfy notably more range needs. In contrast to evaluating national travel surveys, their study analysed detailed GPS data gathered during one year. Similarly, Jakobsson et al. (2016) found that the BEV range requirements to cover 70% of all driving needs is smaller in multi-car households, namely 220 km compared to 390 km.

Another GPS-based study examined the influence of recharging during the day and delaying parts of the travel (Pearre et al., 2011). The study found that one vehicle in ten never covered more than 160 km in one day, which means those vehicles could be substituted by BEVs without further adaptations. If users were willing to make behavioural adaptations six times a year, the results of the study suggest that 32% of car users could switch to low-range BEVs. However, behavioural adaptation may also evoke resistance in car users (Caperello and Kurani, 2011; Lane and Potter, 2007).

1.2. Charging infrastructure policies

Charging infrastructure policies have been proposed and discussed in many scientific studies. For instance, focus groups conducted with experts from five European countries evaluated the feasibility, efficiency and effectiveness of charging infrastructure support schemes (Bakker and Trip, 2013). These experts recognised that infrastructure development is necessary, has high political feasibility and should be considered near streets, 'shopping centres, railway stations and public parking facilities, […] [as well as] points close to EV owners' homes in case they do not have their own off-street parking space' (Bakker and Trip, 2013). An international survey conducted by Lieven (2015) reveals that the availability of charging stations along freeways is perceived to be an absolute necessity. And, Nie and Ghamami (2013) find that fast-charging stations are necessary to achieve a reasonable degree of service to users.

US car users considered an appropriate public charging infrastructure to be desirable but having charging stations at home to be even more important (Krupa et al., 2014). In fact, evidence suggests that most BEV users charge their cars at home: in some of the investigated projects, public charging stations contributed less than 10% to the total energy supply of a BEV (Gnann et al., 2013; U.S. Department of Energy, 2014). Therefore, several studies question government funding of public charging stations (Bakker and Trip, 2013; Gnann et al., 2013; Wietschel et al., 2013) and advocate for simple charging options. On the other hand, Gnann et al. (2013) argue that public charging stations might increase psychological acceptance of BEVs. Furthermore, it may be that the small share of charging at public stations enables some trips that would have otherwise been impossible due to range limitations; Jensen et al. (2013) showed that the general location of public charging stations and the possibility to charge at work are crucial for the demand of BEVs in Denmark. Other studies add that charging stations at public or semi-public sites could lead to an increase in users if the specific locations are optimised by GPS-analyses (Dong et al., 2014) and their costs are covered (Wietschel et al., 2013). Station owners can decrease their costs in the long-term by increasing the number of cars per time that use their fast charging stations; Gnann et al. (2018) found that stations of higher power (100 kW or more) improve the occupancy if BEVs' battery power increase.

Not only the location of chargers has to be considered but also their type and power. Lin and Greene (2011) investigated the effect of policies seeking to deploy and improve chargers at home, at the workplace and in public. They find that upgrading all home chargers to the level 2 standard ($>$ 7.4 kW) would have a larger impact on BEV sales than upgrading public or workplace charging infrastructures to fast-charging stations ($>$ 50 kW) (Lin and Greene, 2011). In contrast, Wietschel et al. (2013) find that already 3.7 kW are sufficient for most of the time. It is still unclear, if that finding holds true for current and future BEVs.

2. Methodology

This chapter first introduces options to develop the charging infrastructure and two BEV market share scenarios. We refer to these options as policy packages (PPs) and use them in combination with the scenarios to derive the BEV-potential of Switzerland and Finland. The model is described in the following section. Specifics about the used data sources are available in the supplementary material. Furthermore, we conducted three focus group discussions that are outlined in the last section of this chapter.

We describe the journey of one car over one single day with the terms *trip*, *day trip* or *car trip*. We use the term *day trip* in the context of the travel survey and *car trip* in the context of the model. The components of trips are single legs. We mostly use the term *leg* in the context of the travel survey and model. Finally, we use the term *route* in combination with geo-routing; it puts an emphasis on the spatial and geographical dimension of a trip.

2.1. Scenarios and policy packages

The two BEV market share scenarios are labelled *baseline* and *high-range*. The baseline scenario represents the market share of vehicles in 2016 and early 2017, as well as the charging station distribution at homes, workplaces and leisure activities. The high-range scenario represents a future with a significant increase in affordable high-range BEVs, i.e. BEVs with more than 300 km range.

Our definition of infrastructure policy packages (PPs) is inspired by policy options found throughout the literature. These options include the improvement of charging stations at BEV users' homes, support for on-street parkers, installation of charging stations at the workplace or in public spaces or the adoption of a fast-charging station network.

The policy packages, as we define them, are cumulative, depend on the implementation order and cannot be analysed separately. This means that the higher numbered packages also include the lower ones (e.g. the effect of pp3 only manifests if pp1 and pp2 are also implemented). The reason for this are the interaction effects between policy packages in a policy mix.[1] We assumed that a mix of policies is desirable, and set the implementation order according to general findings from the literature.

pp1, improvements to home charging: financial support for the installation of high power home charging stations. This means that instead of simple 1.8 kW power outlets, charging stations with a nominal power of 7.4 kW are installed at most of the homes and cottages.

pp2, public charging near homes: support for on-street parkers, i.e. users without own garages or parking spaces close to their homes, by installing public chargers of 7.4 kW at parking lots near residences. This policy package enables all households to charge a BEV.

pp3, workplace charging: support of a simple charging network at work. Simple in the sense that only low- to medium-power charging stations of 7.4–22 kW are installed at three-quarters of all workplaces. This policy package does not consider charging stations with higher output due to their high costs, potential electricity grid limitations and the lack of high power AC charging connection in cars.

pp4, increase public availability: installation of a charging network at private and public parking-houses by means of a public-private partnership. Because no direct representation of parking houses is available to the model, medium-power charging stations of 7.4–22 kW are installed at 60% of all shopping, service and leisure activities. This policy package does not consider charging stations with higher output for the reasons mentioned in pp3.

pp5, fast-charging at service areas: development of a charging station network at motorway service areas. The power of the fast-charging stations is 50 kW and enables BEVs to cover large distances and charge in a short time.

pp5a: variant of pp5 that includes pp1, pp2 and fast-charging at service areas, but not the charging stations at work places in pp3 and other public spaces in pp4.

2.2. Data sources

We relied on several data sources to model the BEV-potential of Switzerland and Finland. The main data sources are two travel surveys: the Swiss Mikrozensus Mobilität und Verkehr (MZMV) and the Finnish Henkilöliikennetutkimus (FNTS). The Swiss travel survey MZMV, which was conducted in 2010, is based on a representative survey of 62,868 Swiss inhabitants about their travel behaviour (Federal Statistical Office and Federal Office for Spatial Development, 2011). The Finnish travel survey FNTS, which was conducted in the same year, is based on a representative survey of 12,318 Finnish inhabitants (Finnish Transport Agency and WSP Finland, 2011). Parts of the surveys are structured in the form of a travel log book of the participants' day trips. The basic elements of each day trip are a series of single legs travelled by members of a household. For this paper, we extracted only legs covered by cars and data about time, distance, purpose, parking situation and addresses. To avoid exposing privacy-sensitive information, we aggregated any address data in the two surveys to postal codes. This reduced level of detail is still sufficient for the purpose of introducing fast-charging stations at motorway service areas. The charging stations and vehicle models inputs are based on publicly available information, mostly found in online sources.

2.3. Model implementation

Analysing the BEV-potential of a country or region is more complex than querying travel surveys for the longest driven distances and comparing them to the potential range of BEVs. Often the combination of legs can contribute to failed trips. The availability of public charging stations might also have a considerable influence. We therefore developed an object-oriented Java program[2] which we refer to as BEVPO to model the BEV POtential. The aim of the BEVPO model is to process and evaluate day trips and to be sufficiently flexible to handle datasets from different countries. In addition, it allows flexible integration of scenarios for the choice of car models and PPs for the availability of charging stations.

The BEVPO model performs several steps in which (1) the data is prepared, (2) the legs are geo-routed to insert fast-charging

[1] An example illustrating this interaction effect: On top of the baseline, policy package A adds 10% more home charging, B adds 8% more fast-charging stations and C first adds 10% more home charging stations and then 8% more fast-charging stations. The effects of A + B are different from C because the home charging in C reduces the need for some of the fast-charging stations and vice versa.

[2] The program (without the data) is available at https://github.com/MMWeb87/BEVPO.

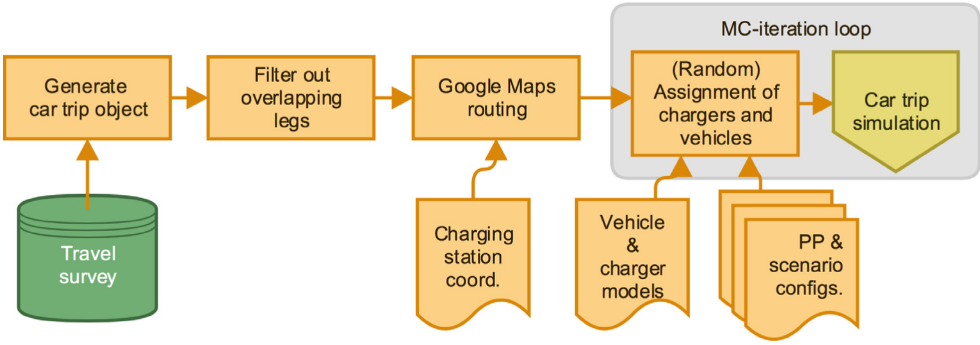

Fig. 1. Overview of the inputs and steps taken by the BEVPO model.

stations, (3) multiple charging stations and a vehicle model are randomly assigned to the car trip and (4) the car representation is passed through all the legs and charges at charging stations. This procedure simulates the situation that a user randomly selects a BEV model, makes a trip according to the travel survey and charges at home, work, service areas or other locations. Steps 1–4 are schematically shown in Fig. 1. The inputs include the travel survey, coordinates of fast-charging stations, lists of charging station and vehicle models, as well as the market share scenarios and PPs. The Monte Carlo approach (MC-iteration loop) aims at capturing variations that result from the random assignment of charging stations and vehicles.

In the first step, the travel survey input which consists of all single day legs that have been covered by individual car users, is processed. Based on the manually preprocessed travel survey input, the BEVPO model generates object representations of car trips. To accomplish this, individual legs that are covered by the same vehicle are combined into the same car trip object. Legs of different drivers or co-drivers are also combined into one object as long as they used the same car. In a further step, the model performs some data filtering tasks to avoid any double counting of legs (compare the supplementary material).

In the second step, the geo-routing is performed and fast-charging stations are introduced. The BEVPO model provides the possibility to insert charging stations at any point along a leg. In this paper, the inputs include coordinates of the current network of fast-charging stations as well as potential fast-charging stations at motorway service areas. To assess if such charging stations are located near a car trip's leg, the legs had to be spatially routed and intersected with the stations. Based on a trial and error approach, we found that an intersection circle with a radius of 100 meters around the Swiss and 300 meters around the Finnish stations picked out most motorway fast-charging stations (compare also to the supplementary material). For the spatial routing of the legs, we relied on the Google Maps Directions webservice.[3]

In the third step, the BEVPO model randomly assigns charging stations in-between the legs. This occurs at the beginning of each Monte Carlo (MC)-iteration and is based on random distributions that differ between scenarios, PPs and the leg's purposes. BEVPO also allows to represent a state where not all households have charging spaces with nearby power outlets available. Data from the travel surveys serve as proxy to estimate the availability of charging spaces at households (compare the supplementary material).

2.4. Simulation of a car trip

The fourth step, the simulation of a car trip, consists of a sequence of charging and uncharging events. The trip is considered to be successful if neither of two failure types occurs. The first type is referred to as a zero-charge failure and results from a situation where no charging station was assigned in the beginning of a trip and therefore no legs could have been covered. The second type is a run-out failure and simply denotes a trip that cannot be covered due to insufficient remaining charge.

Internally, the model passes a reference of the vehicle through a sequence of activity, leg and fast-charging station representations. Activities are based on the purposes of the preceding legs (e.g. work, business, home or leisure), may host a charging station and are characterised by their duration. Legs are characterised by their covered distance. If the vehicle reference is passed to a charging station, a recharging event is simulated. The energy uptake is calculated according to

$$\Delta E_{charging} = P_{charger} \cdot \Delta T \Leftarrow E_{battery} \qquad (1)$$

where $\Delta E_{charging}$ is the energy uptake in kWh during the charging duration ΔT in hours and the power of the charger $P_{charger}$ in kW. Any losses during the recharging event are already accounted for in the figures for battery capacity, energy consumption and range. We assume that a vehicle can be charged to $E_{battery}$, i.e. to 100% of the battery capacity. If the vehicle object is passed to a leg representation, a driving and therefore uncharging event is simulated. The energy loss of a vehicle is calculated according to

$$\Delta E_{uncharging} = EC \cdot \Delta D \qquad (2)$$

where $\Delta E_{uncharging}$ is the energy loss in kWh during the distance ΔD in km covered by a vehicle with a energy consumption EC in kWh/km. If $E_{uncharging,i} > E_i$ a run-out failure happens and the car trip fails because the energy needed for such a leg is larger than the

[3] https://developers.google.com/maps/documentation/directions/.

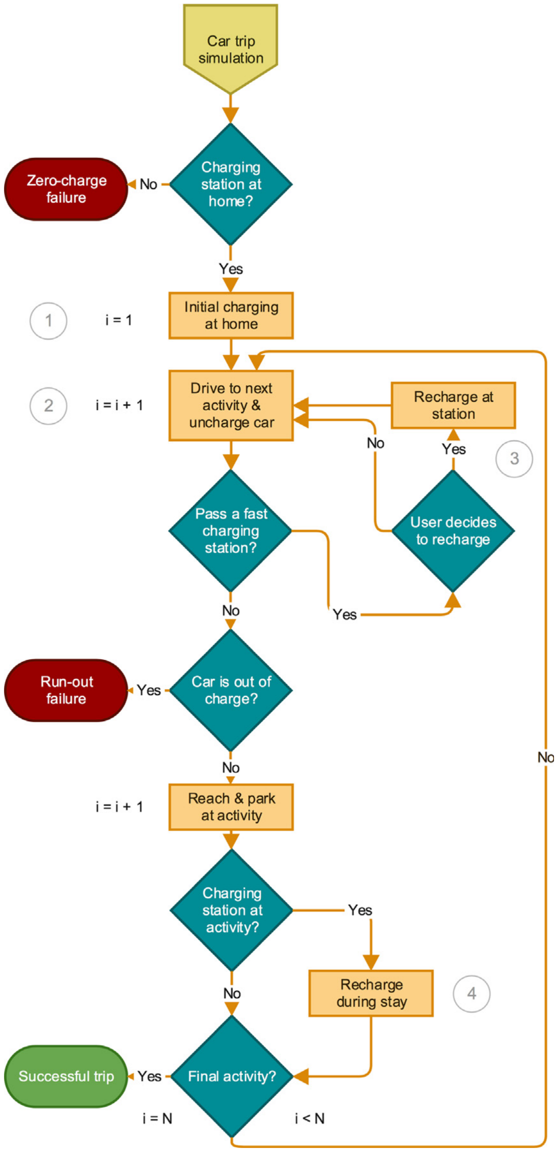

Fig. 2. Steps and decisions during the simulation of a car trip. In this example, the car starts from home and passes N representations of activities and legs. i indicates the current representation. Numbers in circles correspond to the list of steps in this section.

remaining charge E_i of the car. In such a case, the covered distance is calculated according to Eq. (2) and stored for later analysis. The steps and decisions in the BEVPO model are depicted in Fig. 2 and described below.

1. Provided that there is a charging station assigned to the initial activity (mostly home purposes), the car is charged starting from 00:00 to the start of the first leg. To compensate for the situation that the legs in our travel surveys only range from midnight to midnight, an additional *before midnight* charge is given to each car. The duration of this extra charge is calculated by subtracting 24:00 from the arrival time of the final leg in a trip and randomised to account for any uncertainties.
2. The leg is covered by the vehicle and an uncharging event happens.
3. If the trip route intersects a fast-charging station, an algorithms decides whether the car should deviate from the route and park at the charging station. The algorithm evaluates the following three conditions sequentially to trigger a charge event:
   (a) Only 30 km range is left.
   (b) Less than a quarter of maximal capacity is left.
   (c) The charge is insufficient for the expected trip.
   For condition c, we set a maximum number of times a day that a car can charge at a fast-charging station. The other two conditions have no such limit, as we assume that car users would want to charge if their cars approach a very low charging state. The length of each stop is either based on the time it takes to recharge the car to 100% or a maximum of 40 min.

4. Provided a charging station is assigned, a recharging event happens.

Steps 2–4 are repeated until the last activity is passed.

2.5. Adaptation to the refuelling behaviour

The travel surveys that we used are mainly based on trips covered by ICEVs. If the simulated car users cover these trips with BEVs and charge at fast-charging stations, they need to change their original schedule. Even though the users that covered the original ICEV trips certainly visited filling stations, we assume that these stays were comparably short and small in number.

The scenarios and policy packages differ in the degree that they require the user to change his schedule. The baseline and high-range scenario without PPs, as well as policy package pp5 all add fast-charging stations to the simulations. They are therefore a combination of infrastructure policy and behavioural adaptation: first the infrastructure needs to be built, and second, users need to take the time for recharging. In contrast, the actions proposed in policy packages pp1-pp4 do not lead to changes of schedule because they mostly rely on charging during parking.

In reality, car users would presumably take extended detours to reach a charging station rather than running out of charge. In remote areas, such detours could easily be in the order of several dozen kilometres, which would lead to entirely different trips than the ones recorded in the original travel surveys. Moreover, adhering to the original schedule (e.g. stopping at a leisure centre) might not be what real car users do after a long and unplanned detour. Therefore, we avoided an ineffectual solution to model such detours. It follows that in reality, a higher BEV-potential can be reached than what we show in our simplified BEVPO model. We nevertheless model the small detours required to leave the road and reach the nearby service stations because we assume that most car users will not regard these small detours as actual detours.

2.6. Focus groups

To get insights into the perception of some members of the public, we conducted focus groups. Focus groups are semi-structured group discussions involving a group of participants and a moderator guiding the discussion. They are especially suited to investigate complex interactions in social groups (Morgan, 1996) and have the potential to be a rich source of data. The focus group method is not standardised and can thus be carried out in a multitude of fashions; McLafferty (2004) determined that factors such as the number of groups, sample size, homogeneity of participants and the involvement of the moderator vary considerably among different studies. Even though most researchers state a reasoning for their choice, McLafferty (2004) summarises that there is no consensus on what is best.

In total, we conducted two focus groups in Switzerland and one in Finland. The focus groups in Switzerland consisted of three and five participants of Swiss nationality and diverse backgrounds. The group in Finland consisted of three participants of Finnish nationality (compare Table 1). The participants were BEV users and non-BEV users alike. We started the focus groups by giving information about the study, followed by an introduction and some initial questions to establish a discussion. These questions were about range in electric cars and preferences for infrastructure.

3. Results

The BEV-potentials represent our main results. In the simulations, we used 75 MC-iterations to capture the variation due to the random assignment of vehicle models and charging stations as well as the vehicle's probabilistic energy consumption (compare the

Table 1
Demographic data of three focus groups. The numbers represent the number of corresponding participants.

	CH	FIN	Total
Gender			
Female	2		2
Male	6	3	9
Age category			
20–29	1		1
30–44	1	2	3
45–59	2	1	3
60–80	4		4
Education			
Upper secondary School		1	1
Vocational School	2		2
University of applied sciences	1		1
University	5	2	8
Total	8	3	11

supplementary material). Thanks to this procedure, most of the comparably small variations in the resulting BEV potentials are covered.

3.1. BEV-potential

In this section, the BEV-potentials, which represent the share of successful trips, and the effects of the different policy packages (PPs) are presented for each of the two scenarios in both countries. As noted in Section 2.1, the policy packages are cumulative, so the effects of a PP should be compared in the context of the lower-numbered policy packages (that it includes).

3.1.1. Switzerland

Out of the 105,407 car legs in the MZMV, 5789 were made by co-passengers and filtered out because they overlap with legs made by the car drivers. In total, BEVPO generated 34,272 car trips for Switzerland. The number of successful trips is dependent on the PPs and the scenario. The results suggest that the BEV-potential of the baseline scenario amounts up to 87.4% in the absence of any policy action. The high-range scenario yields a slightly larger potential of 89.2% as shown in Fig. 3.

Fig. 3 further depicts the effect of the PPs for the baseline and the high-range scenario. The home charging PPs have the largest effect on the BEV-potential in both the baseline and the high-range scenario. First, pp1 increases the chances of a full recharge overnight. This results in a 3% and 4.1% increase of BEV-potential for the baseline and high-range scenario, respectively. Second, pp2 enables all households to drive a BEV by installing a public charging station for on-street-parkers which results in a considerable increase of around 5% for baseline and high-range. Both PPs highlight the importance of developing charging opportunities in residential areas; an aspect that was also identified as critical by our focus groups (compare Section 3.4). In contrast, the combined effect of further installing charging stations at workplaces (pp3) and other public sites (pp4) yields only a minor change below 1%. Finally, the additional effect of also installing a charging network at service areas is moderate, ranging from 0.9% for the high-range scenario to 2.2% for the baseline scenario. In total, a BEV-potential can be achieved of 98.5% for the baseline and 99.8% for the high-range scenario.

Due to the low contributions of pp3 and pp4, we simulated the BEV-potential in their absence. The simulation results of pp5a reveal that the BEV-potential decreases by around 0.3%. As the combined effect of pp3 and pp4 is roughly 1%, more than 0.7% of the BEV-potential can thus be covered by charging stations at motorway service areas. In total, pp5a yields a BEV-potential of 98.1% and 99.6%, respectively.

3.1.2. Finland

Out of the 21,566 car legs in the FNTS, 873 were made by co-passengers and filtered out because they overlap with legs made by the car drivers. In total, BEVPO generated 6809 car trips for Finland. The number of successful trips is dependent on the PP and the scenario. The results suggest that the BEV-potential of the baseline scenario amounts up to 85.2% in the absence of any policy action. The high-range scenario yields a slightly larger potential of 86.9% as shown in Fig. 4.

Fig. 4 further depicts the effect of the PPs for the baseline and the high-range scenario. Similarly to the Swiss simulation results, the Finnish results suggest that the home charging PPs have the largest effect on the BEV-potentials in both the baseline and the high-range scenarios. First, pp1 increases the chances of a full recharge overnight. This results in a 5% and 6% increase of BEV-potential in baseline and high-range scenarios, respectively. Second, pp2 enables all households to drive a BEV by installing public charging stations or upgrading available heat poles (as found in Finland) for on-street parkers. This results in a considerable increase of around 4% for both scenarios, which is similar to the results for Switzerland. In contrast, the increase by further installing charging stations at workplaces (pp3) and other public sites (pp4) is only around 1%. Finally, the additional effect of also installing a charging network at service areas is moderate, ranging from 1.3% for the high-range scenario to 1.7% for the baseline scenario. In total, a BEV-potential of

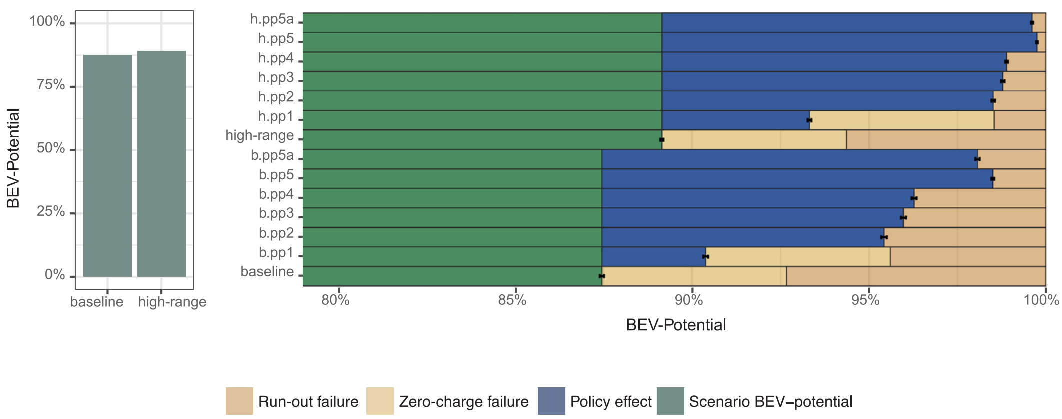

Fig. 3. Simulation results for Switzerland. Left: BEV-potential for the baseline and high-range scenarios. Right: comparison of the policy package effects. pp1–pp5 are cumulative. pp5a is without pp3 and pp4. Error margins indicate variance of the MC-runs.

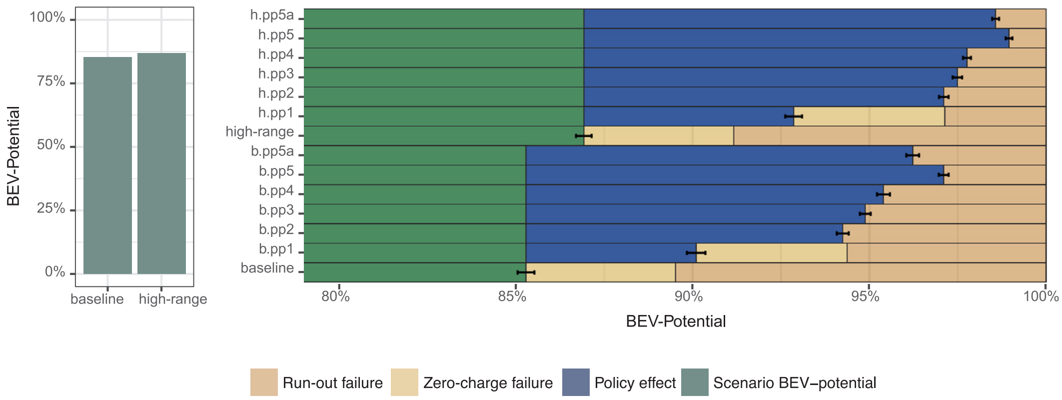

Fig. 4. Simulation results for Finland. Left: BEV-potential for the baseline and high-range scenarios. Right: comparison of the policy package effects. pp1–pp5 are cumulative. pp5a is without pp3 and pp4. Error margins indicate variance of the MC-runs.

97.1% and 99% can be achieved.

The Finnish simulation results for b.pp5a reveal that the BEV-potential decreases by 0.9% in the baseline. For h.pp5a the decrease is only 0.4%. In both cases, 0.3% of the BEV-potential can be covered by charging stations at motorway service areas. In total, pp5a yields a BEV-potential of 96.2% and 98.6%, respectively.

3.2. Comparison with households

The demonstrated BEV-potentials directly relate to the share of cars that successfully cover their trips. Because households could potentially have access to more than one car, the BEV-potential does not represent the share of households that manage to successfully cover their trips. However, this measure would be informative for policy makers and car dealers to estimate the share of households that would consider buying BEVs. We therefore filtered out car trips made by the same households.

Table 2 depicts the share of Swiss households which were able to cover all of their trips on a specific day, as well as the failed trips. For the failed trips, we distinguished between households with only one car and those with multiple cars, as the latter may be able to use another of their cars if that is not also a BEV. Comparing these shares to the BEV-potentials reveals that they are in the same order of magnitude, with only minor differences of 1–2%. For instance, the baseline scenario has a BEV-potential of 87.4%. This figure corresponds to 86% households that managed to do their travels without problems and that are therefore potential BEV buyers. The remainder are households in which at least one of the trips failed. In that scenario, 11.3% of those households have only one car and 2.7% have two or more cars. The latter are also potential BEV buyers, provided they are willing to substitute only one car and cover longer distances with the second conventional car.

By design, the Finnish travel survey is not based on single households but on individual trips. Therefore, we cannot make a statement about the share of affected households. Since there are slightly fewer households with 2 or more cars in Finland than in Switzerland (Tilastokeskus, 2012; BFS and ARE, 2017), we assume that the difference between the BEV-potential and the share of households with successful trips is smaller than in Switzerland.

3.3. Sensitivity analysis for charging station visits and higher energy consumption

We took assumptions that relate to stops at charging stations such as the maximally allowed charging time, the maximal number of visits per trip as well as thresholds indicating which charging level causes a recharging event. These assumptions are relevant for the outcome of the simulation results. Table 3 depicts the influence of the maximally allowed charging time at a fast-charging station

Table 2
Share of households (hh) with successful, failed trips and 1 or multiple cars. For Switzerland with 29,992 total households and 75 MC iterations as means. On average SD below 0.1%. Potential BEV buyers are in bold typeface.

	Successful hh	Failed hh			Successful hh	Failed hh	
		1 car	Multi-car			1 car	Multi-car
Baseline	**86.0%**	11.3%	**2.7%**	High range	**87.9%**	9.9%	**2.2%**
b.pp1	**89.3%**	8.7%	**2.0%**	h.pp1	**92.5%**	6.2%	**1.3%**
b.pp2	**94.8%**	4.1%	**1.1%**	h.pp2	**98.3%**	1.3%	**0.4%**
b.pp3	**95.4%**	3.7%	**0.9%**	h.pp3	**98.6%**	1.1%	**0.3%**
b.pp4	**95.8%**	3.4%	**0.8%**	h.pp4	**98.7%**	1.0%	**0.3%**
b.pp5	**98.3%**	1.4%	**0.3%**	h.pp5	**99.7%**	0.2%	**0.1%**

Table 3
Sensitivity analysis for the maximally allowed charging time and the maximally allowed number of charging station visits in the Swiss simulation with 34,200 total car trips and 75 MC iterations. The sensitivity analyses are based on b.pp5, as pp5 fosters the largest amount of fast-charging. Used values are in a bold typeface. Ranges in parentheses.

Max. charge time (min)	Successful	Max nr. visits	Successful
5	97.3% (0.1%)	0	97.4% (0.1%)
10	98.3% (0%)	1	97.9% (0.1%)
20	98.5% (0.1%)	2	98.3% (0.1%)
28	98.5% (0%)	**4**	**98.5% (0%)**
40	**98.5% (0.1%)**	6	98.6% (0%)
52	98.5% (0%)	10	98.6% (0%)
60	98.5% (0%)	20	98.6% (0%)

and the maximally allowed number of times that charging stations can be visited per trip (compare Step 3 in Section 2.4). It is evident that only a charging time of 10 min or less affects the number of trips that can be covered. Furthermore, the sensitivity analysis suggests that more than 4 visits per trip make no difference. The assumed simulation values of 40 min and 4 visits provide robust thresholds that do not restrict the simulation. In fact, the sensitivity analysis shows that 10 min and 2 visits are sufficient to reach almost the same BEV-potential. This is equivalent in practice to stopping for a cup of coffee every two or three hours of driving.

However, our model does not consider that all charging spaces in a location could be occupied upon arrival, and therefore the required charging time might be higher in reality. This limitation raises the issue of redundancy in the supply of charging. There should be more than one charging station per location and more than one connector per station in order to provide a good quality of service. However, our focus groups perceived that such redundancy is currently lacking (compare Section 3.4).

We also assumed that on average, differences in the energy consumption of many cars level out. However, due to the high heating demands in Finland during the winter months and the more than average altitude changes in Switzerland, a systematic deviation from the energy consumption figure we used in Section 2.4 seems plausible. To estimate this effect of the BEV potential without elaborate physical models, we present here a sensitivity analysis based on a simplified model. First, we apply a linear interpolation between the BEV-potentials of the baseline and high-range scenarios to estimate what change in range causes which BEV-potential. Second, we calculate the adjusted BEV-potential of the adjusted ranges. We base the adjusted ranges on a report about EVs in Nordic countries (Haakana et al., 2013).

For instance, the results using an increased energy consumption of 50%, simulating the influence of heating in the Finnish winter, indicates that the BEV-potential in the Finnish high-range scenario (without policy packages) decreases from 86.9% to 86.0%. Using an increased energy consumption of 30%, the adjusted BEV-potential is 86.3% (for detailed calculations compare the supplementary material).

3.4. Focus group results

This section presents the main points and issues raised by the three focus groups. First, we asked the participants about the desired range of electric cars. In response, they provided either different figures or stated that the needs depend heavily on the specific driver and use-case. One BEV user identified that people's expectations are probably a problem: 'I think that the electric car would require a new kind of thinking because it is often not necessary to have a capacity of 1000 km in one recharge and be able to fulfil every use case with it'. In that sense, two participants argued that the range is not so relevant because most trips are below 100 km, and BEV users would find solutions for the longer trips, as they already do now. Such solutions include knowing where to find charging stations or relying on alternative means of transport. In that context, another BEV user mentioned several existing problems such as the density of the current charging station network in Switzerland and the existence of several connection standards.

We further asked the participants, where public charging stations should be installed. The responses differed; mentioned locations were city centres, motorway service areas, filling stations, train stations, remote shopping centres, homes, residential areas as well as work and industry centres. Although, having a charging station or at least an outlet at home was favoured in several groups, it was also highlighted that not all BEV users have access to a charging station at home, like households in inner-city centres or large housing cooperatives. Affected participants mostly use public charging stations or stations at work but also noted that lack of a charging possibility at home is sometimes annoying, especially if longer trips are planned. One Swiss participant proposed to equip street lanterns with charging outlets as they are omnipresent and might have sufficient power supply. To conclude, the groups considered the availability of public charging stations in residential areas to be critical. This matches what other empirical studies have found (Krupa et al., 2014; Gnann et al., 2013).

Regarding charging at work, different opinions were raised. Even though it seemed desirable in general, one participant argued that it would be inefficient. The reason is that electric car users would often leave their cars parked at these stations, even if they are full. This issue goes beyond charging at work; participants reported of non-electric cars using dedicated charging spaces to park their cars. A related problem is that some charging stations are unreliable, according to one participant: 'I have already run into a charger that did not work, which is a problem because they are still so far apart'. This raises the need for bigger redundancy, i.e. installing more than only one charging station per location and more than one connector per station.

4. Discussion

Electric cars or battery electric vehicles (BEVs) constitute a means to reduce the climate impact of the transport sector. However, several barriers exist that impede their mass-market adoption. Foremost, car users' range needs have to be met to mitigate range anxiety. As the focus groups have shown, these needs differ between car users; some users require an equal range as in gasoline cars, others rely on alternative means to cover insufficient ranges. To enable mass-market adoption, we suggest that a large share of the population's range needs must be addressed. In this paper, we introduce the BEV-potential as a measure to estimate if those needs are met. It follows that a BEV-friendly infrastructure policy should aspire to increase the BEV-potential to 100%. Although our focus groups have shown that current electric car users might find other solutions to handle limited ranges, they require the user to adapt his behaviour. In this paper, however, we analyse the potential without the need for major behavioural change.

Even though the electric vehicle market has gained a lot of momentum in the past years, Switzerland and Finland have not yet reached that 100% goal. Still, they are very close. Our simulations suggest that Switzerland and Finland already have a BEV-potential of around 90% and 85%, respectively. In other words, the moderately developed infrastructure enables the low-range cars of our baseline scenario to cover most of their trips. Other studies that have also investigated the range needs of different countries have come to similar results (Needell et al., 2016; Pearre et al., 2011). Although the results cannot be directly compared due to different methods and assumptions, their qualitative insight is very similar to ours.

One issue in our analysis is the uncertainty in the number of charging spaces available to the current population. This has a considerable influence on the BEV-potentials below pp2. For the Swiss simulations, we use the number of households with access to parking spaces from the Mikrozensus. We do not have such data for the Finnish case, so we conservatively assumed that 30% of the households in the inner cities do not have access to regular parking spaces and their charging facilities. The 90% and 85% BEV-potentials depend on these assumptions, with higher availability leading to more home charging and fewer failed trips, whereas lower availability leads to more visits to fast-charging stations and, to a lesser degree, more overall failed trips.

4.1. Effect of policy packages

Against our initial expectations, the policy packages increase the BEV-potential in both countries to a similar level. In the presence of all our proposed policy packages, the results of the BEVPO model are very encouraging. We find a BEV-potential of 99% or more if high-range vehicles are adopted. In fact, the current developments in the vehicle market suggest that now is a turning point towards these vehicles. If the simulations are run with the low-range vehicles common in 2016 and 2017, the BEV-potentials are around 2–3% smaller.

The effects of improving home charging (pp1) and public charging near homes (pp2) are very pronounced for both countries. This emphasises one of our key insights: it is essential to ensure that households have access to an appropriate charging infrastructure because of two reasons. First, sufficiently powerful charging stations allow the users to recharge their BEVs overnight. Second, public charging stations near residential areas enable the on-street parkers to adopt BEVs. This second point address the issue that BEV adoption is less attractive for on-street parkers, as identified in the literature (Wietschel et al., 2013). Residential charging stations near homes do improve this situation. This finding also reflects our focus group discussions; The groups stated that public charging stations are critical at or near homes. Even though some of the groups' on-street parkers suggested the possibility to charge at remote public charging stations, with the implication that the effects of pp2 would be smaller, they consider this situation to be unsatisfactory. We, therefore, recommend exploring several options to improve this situation. Upgrading street lanterns or heating poles (in Finland) could be one possibility to use the currently available infrastructure. However, further research is required to assess the implications of additional power draw on the local electricity network.

The simulations further showed that the relative effect of PPs that introduce more powerful charging stations at home is larger for the high-range BEVs (i.e. the additional BEV-potential caused by h.pp1 is larger than that of b.pp1). It is evident that this effect is due to the larger battery capacities that would not reach a full charge with low-power chargers. Therefore, the benefits of powerful charging stations at homes are especially significant for these high-range BEVs. 3.7 kW outlets are therefore not ideal for current or future BEVs and high-power outlets might lead to more BEV users.

We further assessed the installation of charging stations at work and other public sites and again found similar results for both countries. They tend to be relatively inefficient compared to the other PPs, at least regarding the BEV-potential. Still, such stations are not entirely unnecessary since they manage to raise the BEV-potential slightly and have relatively low costs per unit compared to fast-charging stations at service areas. Given the many potential locations for such charging stations, we suggest that locations be carefully assessed with methods that are suitable for individual cases, e.g. GPS-analyses of traffic flows (compare Dong et al., 2014).

Despite considerable costs, we found that deploying fast-charging stations at service areas leads to a moderate BEV-increase and constitutes an important measure to reach a high BEV-potential. Our simulation results suggest that their advantages are particularly distinct for the lower-range vehicles, as they are required to charge more often. With higher range vehicles, the relative effect of the *fast-charging at service areas* (pp5) decreases. This result makes intuitive sense and has also been found by Gnann et al. (2018). They conclude that service area owners should increase the charging station power if more and more BEVs with high ranges are deployed. Furthermore, the increase in BEV-potential with a charging network at service areas is greater in Finland than in Switzerland for the high-range scenario, reflecting the fact that there are more very long journeys in Finland due to its geography. There are also fewer alternative means of transport due to the less extensive railroad network in Finland. This indicates that developing a fast charging network is even more important in Finland than in Switzerland in order to mitigate range anxiety, even though range needs differ between car users, as highlighted by the focus groups.

Participants in our focus groups further mentioned that charging stations are required at service areas. However, other locations, such as train station or shopping centres, could also improve coverage and availability. We suggest further research to determine the public's preference for charging stations and their locations.

4.2. Relevance for households

One limitation of the BEV-potential is that it is based on the trips made by individual cars. However, a household-centred view provides two advantages to policy makers. First, Khan and Kockelman (2012) and Jakobsson et al. (2016) emphasise that multiple-vehicle households with BEVs can satisfy a greater share of their trips than single-vehicle households. Our analysis of households revealed that some have access to more than one car. Now and in the near future, such households could become BEV buyers by substituting only one of their cars for BEVs. In this way, they still have the option to cover long trips with their conventional second cars. Further into the future, longer-range BEVs and improved charging station network will make this option obsolete.

Second, the share of (potentially) range-anxiety affected households indicates whether policy measures provide a benefit for a significant part of the population. We have shown for the Swiss simulations that this is the case; the number of range anxiety affected households lies in the same order of magnitudes as the BEV-potentials. We assert that the same holds true of Finland.

4.3. Requirements to reach a high BEV-potential

By implementing the suggested policy packages, BEV users can cover 99% or more of all trips. Reaching this potential requires the governments to develop a supportive legislation, building owners to provide charging points at households, service station operators to invest into fast chargers and BEV users to make adaptations to their recharging behaviour. Policy makers need now to know on which areas they should focus. To this end, we analyse our results in the context of current policy and population's needs.

One of the core questions is whether support should be directed more towards home charging or public infrastructure. Our results point towards a possible answer. We showed that the relative effect of *fast-charging at service areas* (pp5) is smaller for high-range BEVs than for low-range BEVs. Contrary, the relative effects of *home charging* (pp1) and *public charging near homes* (pp2) is larger in high-range cars. In other words, the more high-range electric cars there are, all the more users will charge them primarily at home; thereby reducing the need for a dense public fast-charging station network. We, therefore, recommend that policy focus should lie on home charging rather than public fast-charging. In this context, the proposed amendment to the directive on the energy performance of buildings (COM/2016/0765) is important to consider. It states that new non-residential buildings and those undergoing major renovation must equip one parking space per ten for commercial charging as of 2025. Moreover, new residential buildings and those undergoing major renovations will have to put in place the pre-cabling to enable installation of recharging points.[4]

In the light of our findings, we recommend that this infrastructure should be made mandatory before 2025. Given that major renovations typically happen once per several decades, it will take many years before the entire EU building stock is ready for electric vehicles. Furthermore, the one-per-ten in non-residential buildings and pre-cabling in residential buildings are very meagre requirements in light of the pending ban on ICEVs in several countries and cities. Based on our analysis, possible (financial) support should primarily be directed at home charging rather than public fast-charging. Of particular interest are larger block houses in which the shareholders need to establish guidelines on how to divide the costs of charging points and cabling. In such situations, a household probably cannot build charging points if the majority of households are not willing to carry the cost of recabling. Legally requiring and/or subsidising charging infrastructure in block houses may be necessary. Finally, forward-looking legislation becomes increasingly important as we suggest that home charging should provide more power for high-range vehicles, and therefore require more elaborate and costly recabling.

The same need for a robust home charging network holds true for Switzerland. However, to our knowledge, no legislation similar to the proposed EU directive exists in Switzerland. Given the currently higher share of electric cars in Switzerland, our recommendations are all the more relevant for that country.

Despite our argumentation in favour of home charging, some reasons justify the support of public fast-charging stations. First, governments in both countries have already directed their attention toward public fast-charging. In Switzerland, a recommendation to deploy fast-charging stations at motorway service areas has been issued by the Federal Roads Office (FEDRO), and Finland faces an EU directive seeking to increase the number of public charging stations, of which fast-charging stations could have a considerable share. The implementation of the latter, *Finland's national plan for alternative transport fuels infrastructure*, sets the national target at 2000 public charging stations of which 200 should be fast-charging points (Ministry of Transport and Communications, 2017). While we do not suggest that such targets should be considerably increased, the visibility and reliability of fast-charging stations are linked to user acceptance, as indicated by previous literature and our focus groups. Fast-charging stations must hence be made accessible to any electric cars. Membership requirements and non-uniform plugs are restrictive and should be abandoned to reach the BEV-potentials that we presented. Such interoperability may need to be promoted by regulators much like micro-USB plugs and a progressive reduction of roaming charges were for mobile telephony. Furthermore, having a redundant number of chargers per location is a necessity to increase the overall reliability. Our focus group participants did not perceive that such redundancy is already a reality.

The BEV-potential results make only sense if car users make adaptations to their recharging behaviour. Such adaptations mainly

[4] All this applies only to buildings with more than 10 parking spaces.

concern recharging at fast-charging stations, as users need to leave their planned routes and stay for some time at these stations. If the car users in our model drove the same routes as in the travel surveys, the fast-charging stations in the baseline and policy package 5 would be useless. Caperello and Kurani (2011) and Lane and Potter (2007) suggest that behavioural adaptations potentially lead to resistance in car users, and therefore, basing policies on such preconditions is critical, and we recommend to minimise the need for them. The critical variable in this context is the time that users are willing to stay at such charging stations. Even though we set a threshold of 40 min, our sensitivity analysis showed that 10 min suffice to reach a similar BEV-potential to the one presented above, if enough charging points are available. Finally, with increasing battery capacities, the issue of *charging time trauma* (Taub, 2017) becomes relevant. To further reduce the users' time losses and increase their general willingness, deploying charging systems of even higher power than we simulated (i.e. 50 kW) could be considered.

4.4. Limitations

The implementation of the BEVPO model and some of the assumptions we took, pose several limitations that have to be considered for the conclusions of this paper:

- The model does not simulate competition for charging stations, yet the unavailability of parking spaces already constitutes a problem. Therefore, we cannot draw any conclusion about the number of charging points required at one station.
- The model simulations do not cover the aspect of differing connection types and incompatible charging networks. Instead, we assume that every BEV can charge at any charging station.
- The decision algorithm (compare Step 3 in Section 2.4) for charging at a fast-charging station is modelled in a very simple way and will probably be much more complex in the real world.
- The model assumes that the lack of charging stations at households leads to zero-charge failures. Yet, car users could charge at public charging stations and leave a spare charge when returning home. The focus group results in Section 3.4 describe such behaviour, but show that this can be annoying for longer trips. Still, the zero-charge failures are presumably overestimated in our model. Future model extensions could improve this assumption, e.g. by introducing an empirical found factor that describes the willingness of car buyers and users to do without home charging.
- We used simple assumptions to model the initial charge of a vehicle. On the one hand, assuming that all BEVs have a full charge at the beginning of a day might not always hold. One the other, our assumption that the initial charge can be derived from the last activity of the modelled day might not be realistic either; When longer trips are planned, drivers can anticipate and recharge their vehicles fully during the preceding day or night.
- We did not consider long detours to remote charging stations in this paper. In reality, car users have the option to take longer detours and reach remote charging stations before running out of charge. Hence, we assume that even higher BEV-potentials can be reached. Whether drivers are willing to accept such detours is out of our scope and should be addressed in future work.

We restricted the scope of this paper to single day trips, neglecting some of the available data about multi-day trips and trips across national borders because only the Swiss travel survey provided that kind of data. Also, the simulation of international multi-day trips could improve the conclusions about fast-charging stations. We would expect that for such trips fast-chargers are more important than for national travel, at least in a relatively small country such as Switzerland. Future extensions of the BEVPO model and data basis should therefore explicitly consider these trips.

Finally, the size of our focus groups was comparably small. However, since we base our findings primarily on model results, supplemented by the focus group opinions, we consider the group sizes to be sufficient for our purpose.

5. Conclusion and outlook

By modelling BEV-potentials using real-world data, we showed that a vast majority of trips can already be covered by BEVs, even without any further policy. If policy packages to support the charging infrastructure are adopted, and users somewhat adapt their driving, almost all trips are possible, especially using upcoming high-range vehicles. First, improving infrastructure at homes increases the number of successful car trips considerably, especially in a future with high-range vehicles. Public policy, in the form of legal requirements and subsidies can help to increase the number of charging stations available to households, particularly to overcome barriers present in block houses. Second, the deployment of stations at service areas constitutes one of the last measures to reach a very high BEV-potential. Even though we suggest to focus policy effort on home charging, public fast-charging stations can promote the visibility of electro-mobility in the population. Finally, it is essential to provide sufficient redundancy, eliminate membership requirements and establish uniform plugs.

Although our analysis suggests that almost all trips are possible with these measures, small shares of problematic trips can impede a transition towards mass adoption of BEVs. On a scale of several million potential BEVs in the two countries, a share of 0.2% equals thousands of failed trips and should not be neglected. Apart from tackling the limitations of our model, further research should continue with that premise and investigate means to cover these failed trips. Because the uptake of BEVs is all about user acceptance, users' opinions towards electro-mobility and actions to tackle the remaining problematic trips should be profiled. For instance, regarding the willingness of users to undertake longer detours. In addition, detailed costs of our proposed policy packages and an appropriate cost allocation between the public and private sector need to be assessed. Such cost assessments could focus on comparing the costs of installing additional charging stations compared to increasing battery capacities from both public and private perspectives.

A further knowledge gap that desires further attention is the availability of charging stations at users home. Even though we took reasonable assumptions in that respect, empirically assessing the number of available home chargers is not only beneficial for future modelling but also for monitoring the success of targets.

Acknowledgement and declarations of interest

First, we would like to express our gratitude to the participants of our focus groups. We would like to thank Riku Viri and Tuomas Palonen of the Verne group at TUT for their assistance in organising the focus groups. We would like to thank Peter Hasler for advertising and conveying focus groups participants. Finally, we thank Prof. Dr. Johan Lilliestam, the editor, and 2 anonymous reviewers for their insightful feedback, as well as Anita Melliger for proofreading an earlier version of this manuscript.

Marc Melliger was funded by the TRIPOD project of the European Research Council (Grant No. 715132). Oscar van Vliet was funded by a consolidator grant of the European Research Council (Grant No. 313553). Heikki Liimatainen was funded by the Kone Foundation (Grant No. b4b919). The authors declare no conflicts of interest.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.trd.2018.08.011.

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