

# Integrated mode choice and traffic assignment approach for petrol-based and electric vehicles<sup>\*</sup>

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## Abstract

The drastic increase in the emissions of CO<sub>2</sub> (carbon dioxide) is one of the major reasons for global warming. A large amount of the overall CO<sub>2</sub> emissions is caused by the transport sector. Depending on their speed, petrol-based vehicles produce more than 50 times more CO<sub>2</sub> than electric vehicles. The slower the speed is, the larger is this difference. Since daily commuting within larger cities often means travelling in congested road networks, an increase of electric vehicles could contribute to a reduction of CO<sub>2</sub>. For this reason, we consider different approaches to increase the general uptake of electric vehicles.

We present an integrated mode choice and traffic assignment approach for petrol based and electric vehicles and comment on existence and uniqueness of its solution. In a case study on the Auckland Northern Motorway, we consider different incentives for electric vehicles and compare the resulting traffic flow as well as overall travel time and emissions.

## 1. Introduction

The reduction of energy consumption is an important topic in New Zealand (NZ) and world-wide. A large amount of the overall required energy is used in transport. In NZ, transport consumed 37% of the overall consumer energy in 2015 (Ministry of Business, Innovation & Employment 2015, 2016), where 98% of the transport energy is based on oil (Ministry of Transport, 2013). Even though most cars are becoming more fuel-efficient, the total energy consumption of domestic transport in NZ increased its demand for petroleum by 4% in 2015 (Ministry of Business, Innovation & Employment 2015, 2016).

In this paper, we will focus on the emissions caused by private cars during the daily work commute. Besides the general decrease of the average fuel consumption per car, especially electric vehicles (EVs) could reduce the overall consumption of oil. Unfortunately, even though EVs cause, without a doubt, fewer emissions than petrol-based vehicles (PVs), only a small number of EVs is currently used in NZ.

Even though EVs are good for the environment, there is only a slow increase of EVs. First of all, motorists worry that the range of an EV is not large enough to reach the desired destination(s), a problem also known as range anxiety (Eberle and von Helmlt, 2010).

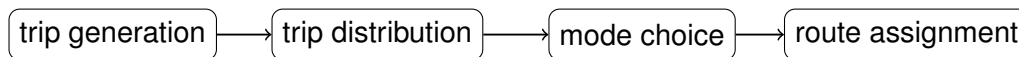
Besides the financial benefits, advantages that lead to faster travel times for EVs in daily traffic could help increase the number of EVs. As an initial test in Auckland, from 6th to 19th March 2017, EVs were allowed to use five on-ramp lanes, which are normally reserved for buses, trucks and high-occupancy vehicles (NZ Transport Agency, 2017). According to user feedback, the trial was a success. A next step could be to allow EVs to use bus lanes. The transport minister of NZ (2016) suggested that this would be the "single most effective non-financial

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incentive you can put in place to increase electric vehicle uptake” (Wade, 2016). In Norway, this idea was included in a raft of other incentives including generous tax exemptions. Since the number of EVs in Norway increased a lot, two years after EVs were permitted in transit lanes, they began to impact negatively on bus networks and EV access was removed.

Whether the implemented approach is a financial benefit or a travel time advantage in road traffic, the number of EVs would probably increase. Therefore, it is important to analyse effects of different implemented approaches on traffic and EV uptake. The influence of these interventions can be modelled with the help of the traffic assignment model (Patriksson, 2015). In traffic planning, the goal is to set up a model which reflects the behaviour of people as well as possible. The general model is based on a four-step approach (Ortúzar and Willumsen, 2002):



In most of the research on traffic assignment, the mode choice is done separately from the route assignment (e.g., Nagurney, 2000; Ortúzar and Willumsen, 2002). Some research is done for the mode choice between cars and public transport (Florian, 1977; Florian and Nguyen, 1978). In this, however, the public transport travel times are considered as independent of the flow of the cars. Brands et al. (2014) consider the iterative computation of the mode choice and traffic assignment. Ryu et al. (2017) consider the combined modal split and assignment problem by applying an elastic demand denoting the bus trips. The bus travel times are adapted iteratively to model the dependence on the traffic flow.

Due to the increasing uptake of EVs, the mode choice between PVs and EVs is considered in other research as well. In (Jiang and Xie, 2014) it is assumed that everyone owns both a PV and an EV and the mode choice is the decision which of the two vehicles to use. The fixed costs (e.g. purchase cost and depreciation) are not included in the running costs such that the running costs of EVs are lower than those of PVs. Thus, EVs are used for all trips shorter than the EV range. To solve the problem, the authors present a mathematical program for the combined mode-route choice behaviour.

As pointed out in (Hagman et al., 2016), the total cost of ownership is much higher than the purchasing value only. Depending on the considered source, EVs can be cheaper or more expensive to PVs depending on cost and time period assumptions. In our research, we will differentiate between running costs (per kilometre) and fixed costs. In our analysis, the overall running costs of EVs are higher than those of PVs such that incentives for EVs are necessary to promote their use. In the case study in Section 5.2, the distances between all origin-destination pairs (OD-pairs) are less than 100km such that the use of EVs is always possible without the need to charge en route. In New Zealand, the average daily travel by car is less than 29 km, and 90% of all journeys are under 90 km. Thus, it is reasonable to assume that charging is not necessary.

In this paper, we consider the integrated mode and route choice between EVs and PVs and the related traffic assignment. The decision to buy and use an EV depends on the costs and on the available advantages which an EV driver has. The mode choice should not be considered separately from the route assignment but as an integrated approach. For this reason, the presented approach will combine the mode choice and the traffic assignment of PVs and EVs in a single model.

## 2. Model

As stated in the introduction, we consider different approaches to increase the number of EVs in the daily traffic. In traffic assignment, it is assumed that the traffic flow consists of infinitesimally small users that act selfishly, i.e. try to decrease their travel time or costs as much as possible following Wardrop's first principle (Wardrop, 1952). In the following, we will sketch the idea of the model and state some results on the existence and uniqueness of a traffic equilibrium. For the complete mathematical description of the model as well as the proofs of the results, we refer to the journal paper related to this conference talk.

Route choice decisions are modelled based on the assumption that network users aim to minimise their travel costs and travel times, where travel times are converted into their monetary equivalent by means of the value of time (VOT). The combination of travel costs with the monetary value of the travel time will be denoted as generalised travelling costs.

The novelty of this paper is that we consider an integrated mode choice and traffic assignment model to understand the effect of network design modification such as special vehicle lanes that can only be used by EVs. Depending on the different scenarios, an EV can allow shorter travel times and thus reduce the overall costs.

We assume that we are given a road transport network where the travel time on each link is assumed to be a positive-valued, strictly increasing, continuous function of the flow. This dependence of the travel time on the flow is given through a volume-delay function (VDF). We will use the so-called BPR volume-delay function as proposed by Bureau of Public Roads (1964) and the volume-delay functions based on the Auckland Regional Transport model (ART3) (Sinclair Knight Merz, 2008). The ART3 model uses modified Akcelik volume-delay functions and includes intersection approach delays (Akcelik, 1991).

In order to visualize how the modified traffic assignment model is built, we consider a simple network with a single OD-pair as given in Figure 1. It should be noted that the corrugated arcs denote any connection/path, the solid arcs can be used by all vehicles and dashed arcs denote arcs which can only be used by EVs. We suppose that people want to travel from  $s$  to  $t$ . The basic idea is to build a separate graph for PVs and EVs with a new source  $S$  and sink  $T$  defining the modified OD-pair. For the graph given in Figure 1, the modified graph is given in Figure 2. It can be seen that the EV-only arc  $a_3$  has no copy in the PV subgraph in Figure 2.

Figure 1: Given graph  $G$

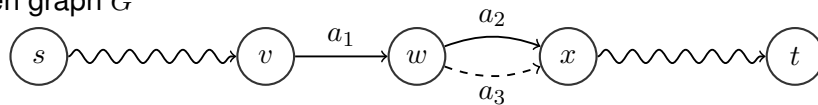
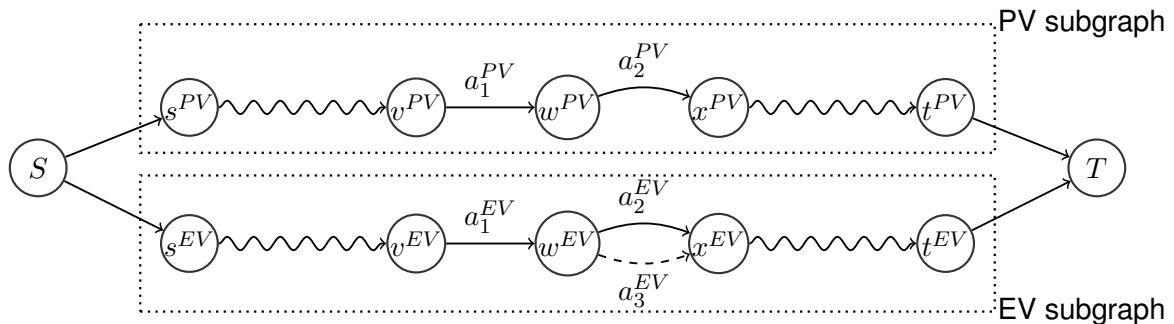


Figure 2: Modified graph with link interactions



The decision of using a PV or an EV is equivalent to the choice of travelling in the PV or the EV subgraph in the modified graph. The arcs  $a_1^{PV}$  and  $a_1^{EV}$  are used to model PVs and EVs

on the initial arc  $a_1$ . Thus, people travelling on arc  $a_1^{PV}$  influence people on arc  $a_1^{PV}$  as well. Due to this so called link interaction, existence and uniqueness of a traffic equilibrium cannot be guaranteed in general.

### 3. Existence and uniqueness

In this section, we show that the introduced model of the integrated mode choice and traffic assignment problem has an equilibrium (and that it is unique). In the computation of traffic equilibria, a relation between arcs can be enforced through link interactions. Since EVs and PVs influence each other exactly in the same way, these user interactions are symmetric. In Sheffi (1985, Chap. 8), it is shown that the traffic equilibrium with symmetric link interactions problem is equivalent to a minimization problem on a compact set. Since the total flow is bounded (by the total demand), the objective of the minimization problem is also bounded such that an equilibrium exists. If the arc costs are non-decreasing, the objective is convex, and if the costs are strictly increasing, the objective of the minimization problem is strictly convex. In  $\tilde{G}$ , all arc costs are non-decreasing and therefore the existence of a traffic equilibrium follows.

We saw that a requirement for existence was symmetric link interaction. If the interaction is not symmetric (e.g. cars and buses), the general existence of an equilibrium cannot be guaranteed any more. This is due to the fact that a user in a car influences the travel time of other users more than a user in a bus.

So far, we have shown that there always exists at least one equilibrium. In the following, we will show that the determined equilibrium is unique. For traffic equilibria with link interactions, the following conditions are needed for the existence of a unique equilibrium (Sheffi, 1985):

- the travel time on each link is a strictly increasing function of the flow, and
- the main dependence of a link's travel time is on its own flow.

Unfortunately, none of these conditions hold such that the known results (Sheffi, 1985) cannot be applied. Despite this, we are able to show that even if the number of EVs is not unique, that the travelled distance of EVs and the reduction of emissions is unique.

### 4. Data

In this section, we briefly consider and describe the data which we will use in the case study of the Northern Motorway. The mode choice decision between an EV and a PV depends on the retail price, maintenance costs and also on the running costs. We consider the cheapest PVs and EVs as given in NZ Automobile Association (2017). Since the considered trips in our examples differ a lot in length, we adapted the computation of the average costs to be dependent on the daily trip length. For each commuting trip, an PV fixed costs of \$3.71 with additional \$0.40 per driven kilometre. With \$6.37 plus \$0.60 per kilometre, an EV is more expensive.

In order to convert travel time into costs, we use the factor of Value Of Time (VOT) given in dollar (\$) per hour. For the model and case studies presented in this paper, we use a VOT of \$21.83 (Beca Ltd, 2014).

One of the main purposes of this paper is to investigate whether promoting EVs could decrease the overall greenhouse gas emissions. For the emissions of PVs, the NZ Transport Agency and the Auckland Council provide an vehicle emissions prediction model (*Vehicle emissions prediction model (VEPM 5.1) user guide Version*, 2013). The emissions of EVs are related to their energy consumption, which in turn depends on their speed and the emissions of the energy

generation. For the speed-dependent energy consumption, we use the analytical energy consumption for EVs given in (Wu et al., 2015). To estimate the emissions due to the generation of electricity, we consider the special case of NZ where 85% of the generated electricity comes from renewable sources. It follows that the generation involves an average of 128.62 g CO<sub>2</sub>-e per kWh.

## 5. Case scenarios

### 5.1. Introductory example

In Section 4, we saw that EVs have higher fixed and running costs. Thus, without additional incentives, no EVs are used in the models. One possibility is to transform PV lanes into EV lanes. In an example with two parallel links (one for EV only), the number of used EVs and thus also the emissions depend on the length of the arcs.

We assume that there is a demand of 2000 people and that each arc has a practical capacity of 1000 with the BPR volume-delay function given in Bureau of Public Roads (1964).

Figure 3: Percentage of EVs

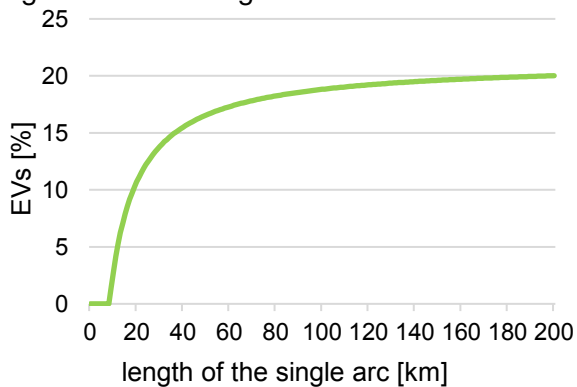
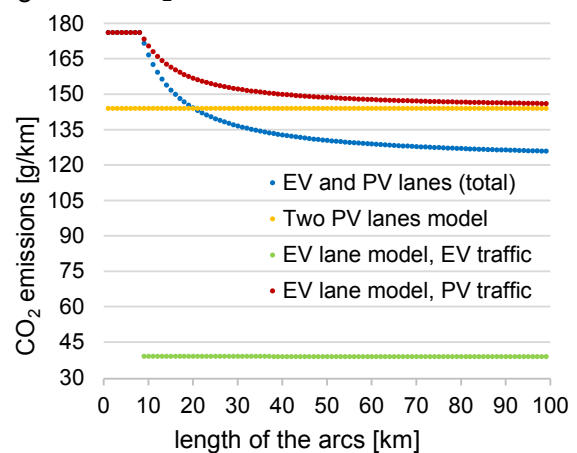


Figure 4: CO<sub>2</sub>-emissions



In Figure 3, we see that EVs are not economical for a length less than 8km. In Figure 4, the emissions (per km per car) of the initial case (two PV lanes) are given in yellow. If both arcs have a length less than 20km, the introduction of an EV lane creates higher overall emissions than the initial state (blue curve). This is due to the fact that only a few people use an EV such that the speed on the PV lane is small and thus the emissions are high (red curve). For an arc length of at least 20km, the average emissions could be reduced (blue curve compared to the yellow curve).

### 5.2. Northern Motorway

An application of the proposed integrated EV / PV model choice and assignment model is discussed in this section. The Northern Motorway model is based on the *Auckland Regional Transport* (ART3) model (Sinclair Knight Merz, 2008). The provided data contains all necessary network information, 564 zones, volume-delay functions with capacities as well as the travel demand for different peak hours. We consider the morning peak (7am-9am) of the Northern Motorway. The Northern Motorway region contains 16 nodes which will be used as origins and destinations.

We will consider the following scenarios:

- The do-nothing instance will be the current state, neither financial nor other incentives (DN) are granted for EVs.
- The Auckland Harbour Bridge and the motorway south of it have up to 4 and 5 lanes. (4L) On all segments with at least 4 lanes, we assume that one of these lanes is for EVs only.
- From the north of Auckland to Takapuna, there already exist special lanes reserved (BC) for buses parallel to the motorway. For this scenario, we assume that EVs are allowed to use these bus lanes. In order to not increase the model complexity, we neglect the time to and from the on/off ramps of the separated bus way.

Since we have seen that the fixed and the running costs of an EV are higher than the costs of a PV, it is clear that no EVs are used in the basic case (DN). The other presented scenarios will have different impacts on the costs and time of the commuters, but also on the emissions.

In Table 1, the resulting percentage of EVs, change of costs and time as well as the emissions are given. However, it should be noted that it is not fair to compare the different infrastructure incentives since removing a PV lane has a completely different impact than adding an EV lane.

Table 1: Overview of the impacts of the different scenarios

	(4L)		(BC)	
	PV	EV	PV	EV
percentage use	93%	7%	99%	1%
costs	+17%	+35%	-4%	-18%
time	+85%	-17%	-7%	-75%
CO <sub>2</sub>	+5.2%		-7%	

In the first column (4L), some of the PV lanes become EV-only lanes. In summary, 7.06% of the vehicles would be EVs and with these, 8.12% of the overall travel distance would be driven electrically. Since the number of PV lanes is reduced, the required time (and thus the costs) can only increase for people using PVs in the modified instance. The large increase of travel time is mainly caused by an additional loss of 5 minutes on the Harbour Bridge. People using an EV in the modified instance have an average time gain of 17.2% but still an average generalised costs increase of 34.7%. This higher increase of the generalised costs is due to the fact that people changing from PV to EV are exactly those people most impacted by the reduction of PV lanes and resulting increase in travel time. Concerning the emissions, this approach is not promising. From initially 198.68g CO<sub>2</sub> per kilometre, after the conversion of a PV lane to an EV lane, we have 209.05 g CO<sub>2</sub> per kilometre (an increase of 5.21%).

In the second column (BC), existing bus lanes, which are parallel to the motorway, will be available for EVs. This modification is modelled as extra lanes on the existing motorway. Thus, for this scenario, the travel time and the generalised costs of the considered vehicles (EV and PV) will not increase. The effect of the EVs on public transport will be investigated in further research and is omitted here. We assume that the buses do not influence the cars on the extra lanes, and vice versa. As an overall result, there are 318.7 EVs (1.05% of the total demand) and we have a CO<sub>2</sub>-reduction of 7%. People using an EV would have an average cost gain of 18.2% and a time gain of 74.7% (i.e. up to 21 minutes of time reduction). Even if the PVs do not have a special lane, they also experience a speed-up due to the additional EV lanes. Due to the reduction of traffic on the PV lanes, the costs of PVs are reduced by 4.2% and the travel time by 7.7%. The effect of a reduction of 7% on the emissions results in a reduction of 1169 tonnes of CO<sub>2</sub> per year (carbon cost savings of nearly \$20000 for the Northern Motorway only).

## 6. Conclusions and future research

In this paper, we presented a model to combine the mode choice and the traffic assignment of PVs and EVs. Even if the number of EVs is not necessarily unique, the total distance driven by EVs and the resulting emissions are unique.

From an economical point of view, buying an EV for commuting is not financially beneficial. In the first example, we considered an introductory example and saw that a transformation from a PV lane to an EV lane can increase the emissions. This happens if the monetary value of the loss of time due to the traffic congestion is not smaller than the additional costs for an EV. Different scenarios were compared in Section 5.2 to demonstrate how the integrated EV and PV mode choice and assignment approach models EV uptake for different types of incentives for EVs.

It would be possible to model the return trip by duplicating the modelled network for the morning and afternoon peak periods, however, this would significantly increase network size and computational complexity. In this paper, we only considered the additional lanes with the help of bus lanes but it would be interesting to consider high occupancy vehicle lanes as well. Besides the consideration of the complete region of Auckland, we also want to extend the integrated approach to public transport. The main difficulty for this extension will probably be the non-symmetric link interactions.

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