



A Model for Projecting the Uptake of Electric Vehicles

for Ministry of Transport

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1. Introduction

To inform the Ministry of Transport on the expected levels of imports of new and used light passenger electric vehicles (EVs), this report summarises a review of literature and discusses two spreadsheet models that have been developed to project future EV purchases.

The literature review (Section 2) examines literature on:

- the factors that affect consumer demand for EVs, including any barriers relating to technical uncertainty;
- the differences in demand between early adopters and later purchasers;
- policy measures used in other countries that have affected EV sales; and
- parameters included in other demand modelling exercises.

From the literature review we draw some conclusions about the appropriate approach to modelling demand for EVs in New Zealand, namely that of the whole of life Total Operating Cost (TOC).

Sections 3 and 4 describe the models that have been developed to project the demand for EVs in New Zealand, and the operation of the models.

The models have been calibrated with a set of default values based on international research and various best guesses by us and Ministry of Transport staff. With these values we believe that the models produce plausible projections of EV uptake out to 2030. We do not, however, claim that these projections necessarily represent most likely outcomes. Indeed, while the two models have an identical core (TOC), different ways of using this concept to project EV demand lead to different results.

Each model represents a decision making process on the part of consumers, but it is too early to say which is the better representation. This just reflects a world in which vehicle technology and consumer attitudes and behaviour are changing rapidly; not a situation that is conducive to extrapolating past trends. Thus the models should be continually updated and re-run. Over the next few years one model may dominate the other, but in meantime their spread of results acts as an indicator of uncertainty. Nonetheless sensitivity testing with each model is also highly recommended.

We also stress that the models are demand models, not models of the entire vehicle market. While we have included some deterministic mechanisms to deal with instances where demand for a particular type of EV exceeds estimates of future supply, it may at some stage be useful to consider more sophisticated ways of simulating industry and consumer reaction to supply constraints.

2. Literature Review

A number of studies have analysed the factors contributing to demand for electric vehicles (EVs). The response is different between a small number of early adopters for whom demand is less dependent on relative price and the later adopters for whom relative price is of significant, if not paramount, importance.

Barriers to EV Adoption

Demand for EVs is restrained currently by some significant barriers that include (Amsterdam Roundtables in collaboration with McKinsey & Company, 2014; Element Energy et al, 2013; Joint Working Party on Trade and Environment, 2015; National Research Council, 2013):

- EVs have a high price premium over non-EVs;
- Supply of EVs model is limited, in terms of vehicle segments and brands;
- Consumers are concerned by EVs' short kilometre range (before recharge is required) and long charging times;
- Reliability and re-sell concerns – concerns that the technology is not sufficiently advanced, including reliability, safety and battery degradation issues, as well as uncertainty regarding residual values; and
- low awareness of the potential availability of EVs.

Even if there was a price advantage currently, eg as a result of government subsidy, some of these other factors would be expected to limit demand.

Policies to Encourage EV Sales

Countries and other sub-national jurisdictions have adopted policies to overcome these barriers and to encourage EVs. A summary is provided in Table 1. The OECD authors note that direct government support has been concentrated in three areas:

- improving the capacity and lowering the cost of storage batteries;
- increasing the scale of deployment of plug-in hybrid electric (PHEV) vehicles and battery-electric vehicles (BEVs); and
- developing the infrastructure for recharging electric vehicles.

Understanding demand for EVs needs to be in the context of this widespread use of policies that are having significant effects on demand in other jurisdictions.

Table 1 Deployment incentives for all-electric and plug-in hybrid-electric vehicles by country

Type of incentive	Locations
Income-tax credit or deduction for purchase of a BEV or PHEV	Austria, Belgium, Israel, Netherlands (BEV taxis or vans only), United States (federal, Colorado, Georgia, Montana, Oklahoma, South Carolina, Utah)
Grants or rebate on purchase or lease of a BEV or PHEV	Canada (Ontario, Quebec), China (paid to manufacturers), Spain (federal and several regions), Sweden, United Kingdom, United States (California, Hawaii, Illinois, Louisiana, Maryland, Tennessee, Texas)
“Fee-bate” scheme	Austria; Belgium (Wallonia); China; Estonia; France; Ireland; Japan; Luxembourg; Singapore, Spain; Sweden
Reduction in, or exemption from, vehicle purchase or registration tax	Belgium (Flanders), Costa Rica, Denmark, Finland, India, Ireland, Israel, Japan, Malaysia, Netherlands, Norway, Portugal, Romania, Singapore, Sweden, United Kingdom, United States (District of Columbia, Maryland, New Jersey, Washington State)
Exemption from, or reduction in, annual circulation, road, or tonnage taxes	Austria, Australia (Victoria), Czech Republic, Denmark, Finland, Germany, Greece, India, Ireland, Italy, Japan, Latvia, Netherlands, New Zealand, Norway, Portugal, Romania, Sweden, Switzerland (varies by canton), United Kingdom (London), United States (New Jersey)
Discounted or free battery charging	Netherlands, Norway, United States (California, local incentives)
Privileged access to bus or high occupancy vehicle (HOV) lanes	Korea, Netherlands, Norway, Portugal, Ontario (Canada), United States (Arizona, California, Florida, New Jersey)
Free or reduced charges for parking in public car parks	Denmark, France, Netherlands, Norway, Portugal, United Kingdom
Public procurement preferences	Belgium (Walloonia), Bulgaria, Estonia, France, Italy, Japan, Korea, Portugal, Sweden, United Kingdom, United States (federal and several states)
Government support for the deployment of battery-charging infrastructure	Austria, Canada (BC and Québec), China (in selected cities), Denmark, Estonia, France, Germany, Israel, Italy, Japan, Korea, Netherlands, Norway, Poland, Portugal, Spain, United Kingdom, United States
Income-tax credit, rebate, or grant for private installation of a charger	Belgium, Canada (BC), Denmark, United States (Arizona, Georgia, Maryland, Oregon)

Source: Joint Working Party on Trade and Environment (2015)

Early Adopters

Some individuals and companies purchase EVs despite the barriers noted above. This is likely to reflect a number of personal preferences. Amsterdam Round Tables with McKinsey (ART&M) notes that research in Shanghai, New York, Paris and Norway identified that early adopters were primarily high-income, well-educated consumers who are looking to save money, are concerned about the environment, or both (ART&M, 2014). They suggest three key motives for early EV adoption:

- **Carbon footprint reduction.** The desire to reduce their carbon footprint is a motivator for environmentally conscious consumers to buy EVs. Some are even willing to pay a premium for the zero- or low-emission alternatives to ICE. For example, 29% of Norwegian EV buyers cite “environment” as their primary reason for purchase.
- **Driving and usage benefits.** Additional benefits are afforded to drivers of EVs by many governments and cities in an effort to stimulate EV sales. These benefits may include preferential parking permits in dense urban areas (e.g., City of Amsterdam) or the ability to drive in bus and taxi lanes and save considerable time during rush hours (e.g., City of Oslo).
- **Cost savings.** Without subsidies, EVs are significantly more expensive than ICE cars. But in some specific cases, as a result of government subsidies, EV models are cheaper than their ICE counterparts. Consumers looking to benefit from these types of regulations are drawn to EV, because they provide a cheap mobility solution in the recent period of high fuel prices in Europe. For example, in Norway, EVs are more attractive than ICEs on a TCO basis as a result of subsidies that include exemption from purchase tax, VAT, toll road charges, registration tax, and annual circulation tax.

However, they go on to note that cost, either as total cost of ownership (TCO) or purchase price, is critical for large-scale EV adoption. Citing a study in Norway that found that for 41% of (early) EV buyers, the primary reason to buy an EV was “to save money”, they suggest cost is likely to be even higher as a demand factor in the general population compared to early EV adopters.

General Demand

To understand the factors driving demand for EVs beyond that of the initial early adopters, studies have examined the relationship between market penetration of EVs and the levels of incentives and/or relative price of EVs and internal combustion engine vehicles (ICEVs). In general, countries with the highest rates of EV penetration have introduced significant policy measures to reduce purchase costs relative to conventional vehicles and have addressed non-cost barriers including, vehicle supply and consumer receptiveness (Element Energy *et al*, 2013).

International Comparisons

Mock and Yang summarise the incentives in place and their effects in a number of countries, as of early 2014 (Mock & Yang, 2014). They examined the relationship between market share and incentive levels for three policy interventions:

- Direct subsidies (defined as a one-time bonus upon purchase of an EV);
 - Fiscal incentives (defined as a reduced purchase and/or annual tax for EVs);
- and

- Fuel cost savings (incentive due to electricity prices being lower than fuel prices as a result of lower taxation and/or lower energy costs, as well as higher efficiency of EVs).

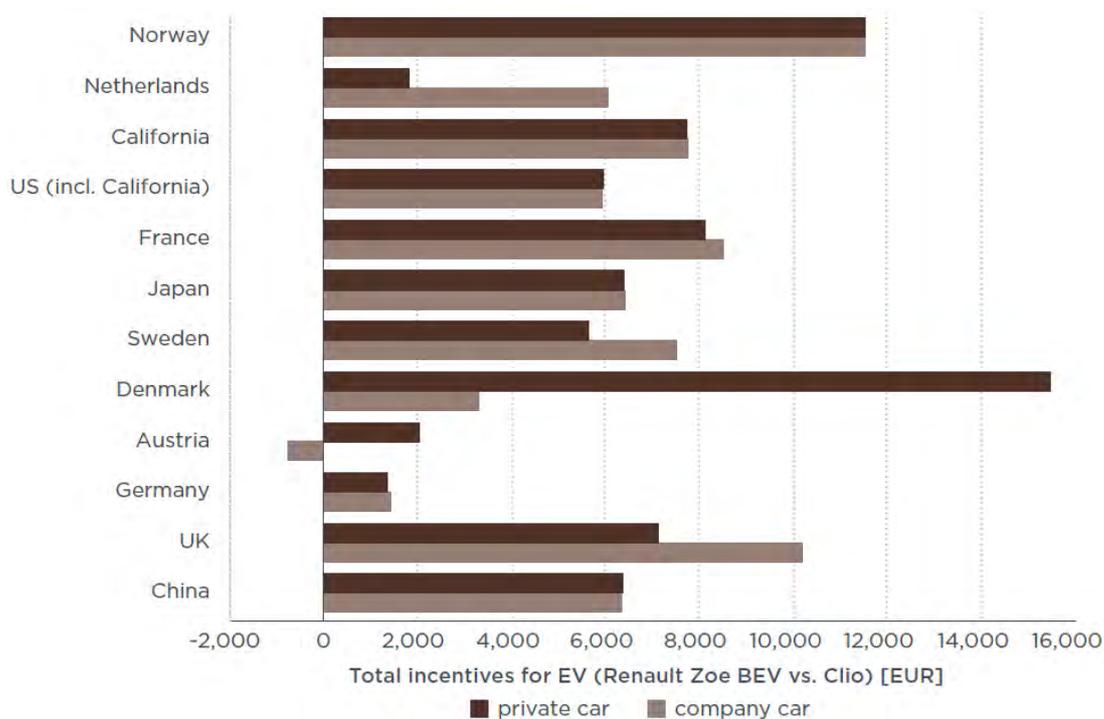
Analysis is limited to financial incentives because of the ease of quantification, but it might be ignoring some of the response to other policies.

Mock and Yang's analysis compared the impacts with respect to two vehicles:

- Renault Zoe as a representative battery electric vehicle (BEV), and accounting for about 13% of all EV sales in Europe in 2013. Its internal combustion engine (ICE) counterpart is the Renault Clio, Europe's fourth most popular passenger car.
- Volvo V60 as a representative plug-in hybrid EV (PHEV), accounting for about 11% of all EV sales in Europe in 2013. It is available in a conventional diesel version, as well as a diesel-PHEV version.

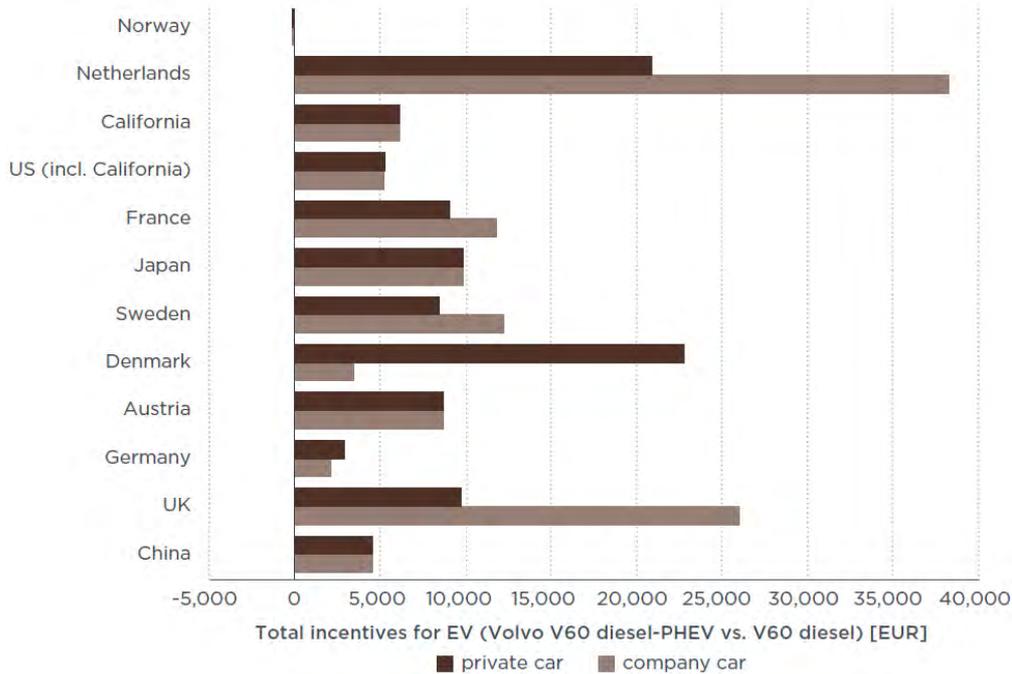
Figure 1 shows the levels of subsidy for BEV relative to a petrol ICE vehicle, including the difference in incentives between private and company cars. Figure 2 shows the same information for PHEVs.

Figure 1 Estimated level of total incentives for petrol vehicle: Renault Zoe (BEV) vs. Renault Clio



Source: Mock & Yang (2014)

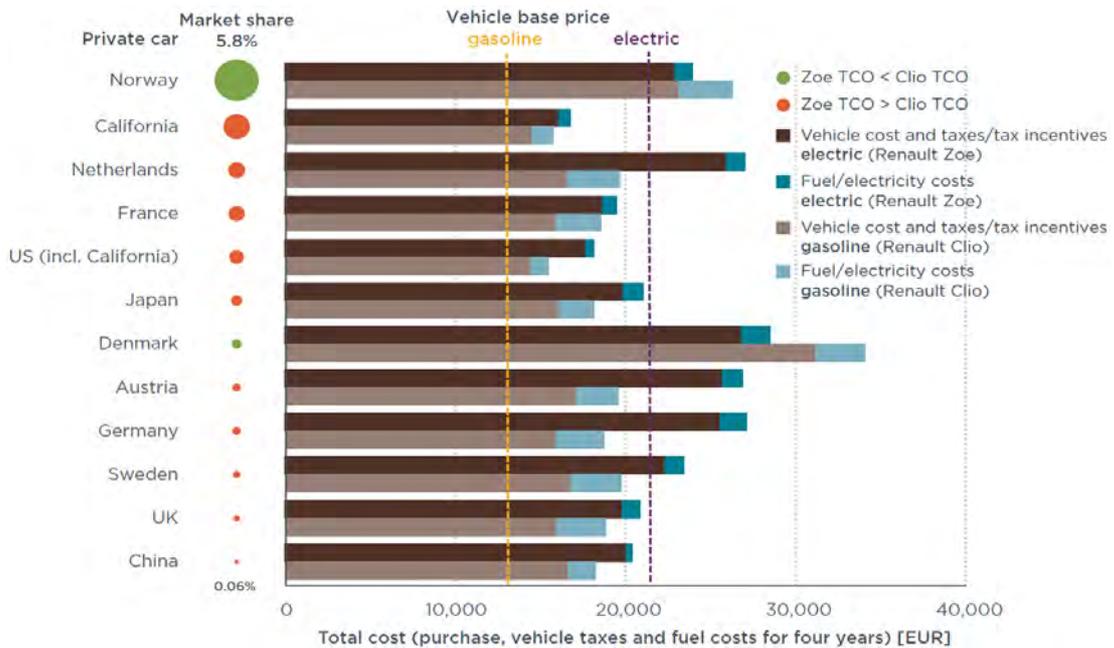
Figure 2 Estimated level of total incentives for diesel vehicle: Volvo V60 diesel-PHEV vs. Volvo V60 diesel



Source: Mock & Yang (2014)

Taking account of the difference in purchase and running costs, and the levels of subsidy, Figure 3 shows the estimated total cost of ownership (TCO) for a petrol vehicle over four years. TCO is lower for electric vehicles only in Norway and Denmark.

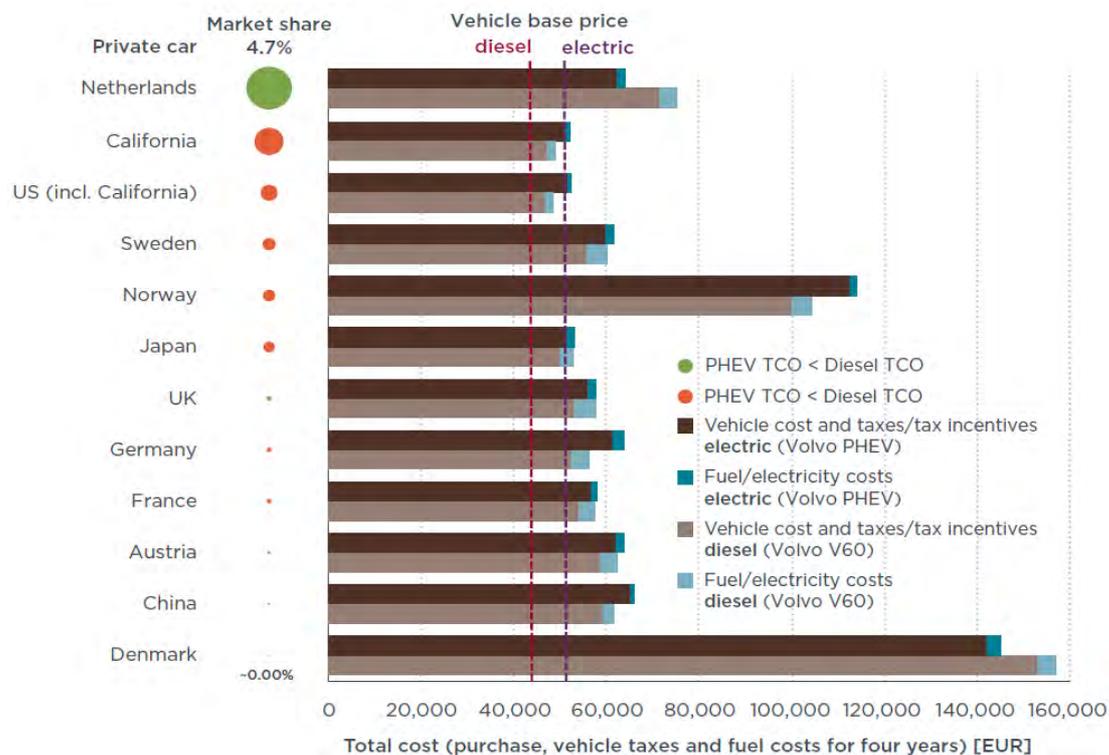
Figure 3 Summary of TCO calculations for Renault Clio vs. Renault Zoe (private car market)



Source: Mock & Yang (2014)

Figure 4 shows the same calculations for a diesel vehicle for which the vehicle base prices (pre-subsidy) are much closer.

Figure 4 Summary of TCO calculations for Volvo V60 diesel-PHEV vs. Volvo V60 diesel (private car market)



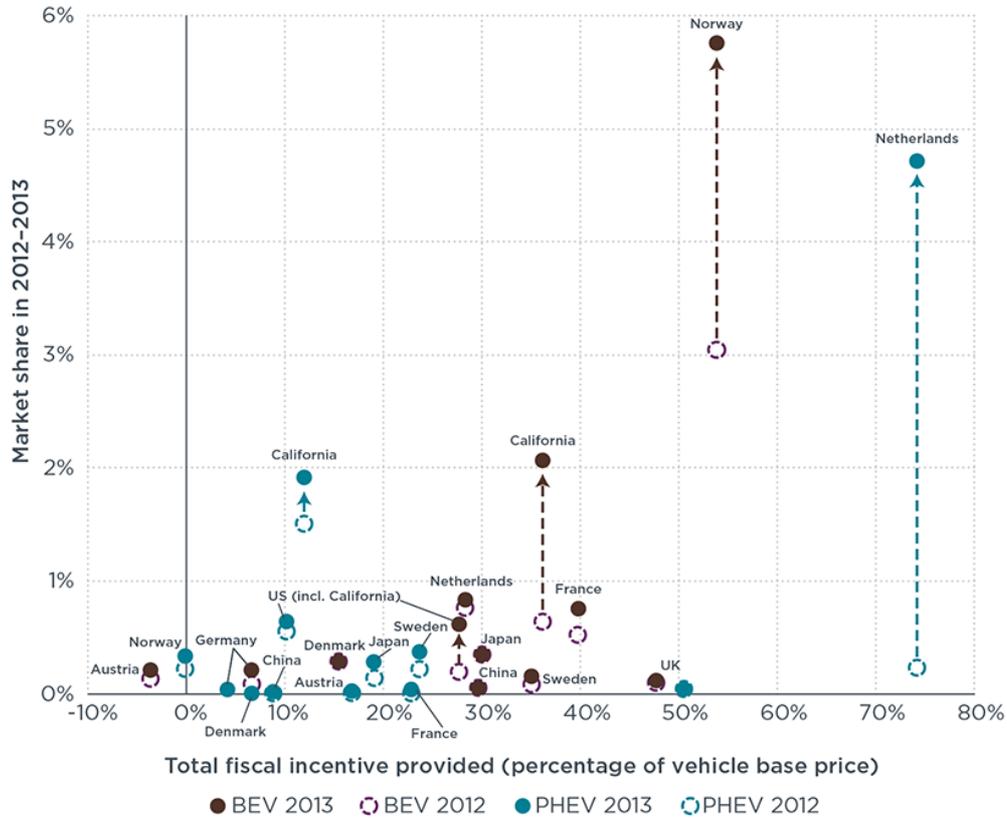
Source: Mock & Yang (2014)

These figures also show the percentage market share of the EVs in the different countries, and this is shown more clearly in Figure 5. This shows the incentive of relative price. Norway¹ and the Netherlands have the highest absolute market shares and growth in market share for BEVs and PHEVs respectively; they also have subsidy levels sufficient that these vehicles have a price advantage over ICEs. The anomaly is Denmark which a higher level of incentives for BEV if purchased as private cars, but with little absolute or growth of market share.

An analysis of the reasons for the low uptake in Denmark suggested that the four most significant barriers were: driving range, price, infrastructure, and consumer knowledge (Green *et al*, 2014).

¹ We note that Norway is reviewing the extent of the subsidies for electric vehicles because of the level of uptake and the fiscal cost: www.reuters.com/article/2015/04/20/us-norway-autos-idUSKBN0NB1T520150420

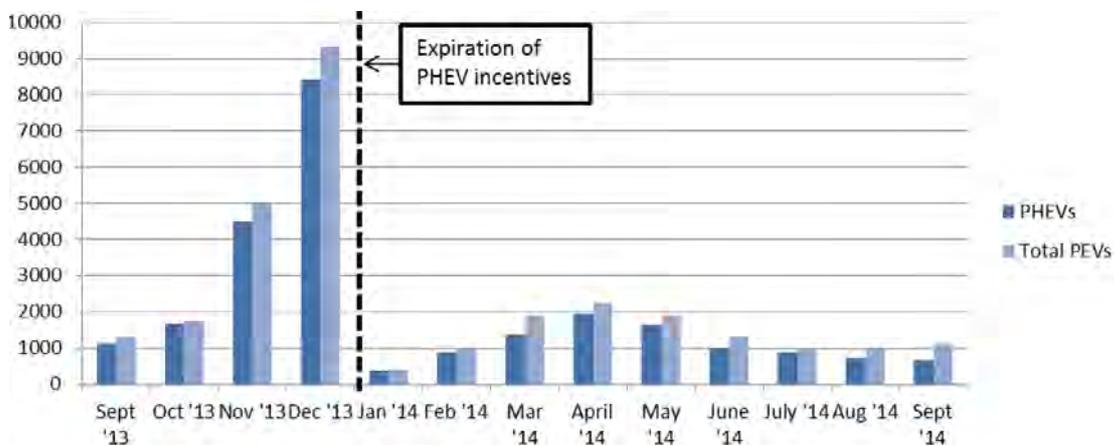
Figure 5 EV market share vs. per-vehicle incentive provided for BEV (Renault Zoe) and PHEV (Volvo V60) (where applicable, only company car market incentives shown here), 2012–2013



Source: Mock & Yang (2014)

The influence of financial incentives is made starkly clear in the Netherlands experience reported by Vergis et al that shows the impact of withdrawing PHEV financial incentives, including a tax reduction equivalent to approximately 10-12% of the cost of the vehicle, from January 2014 (Figure 6).

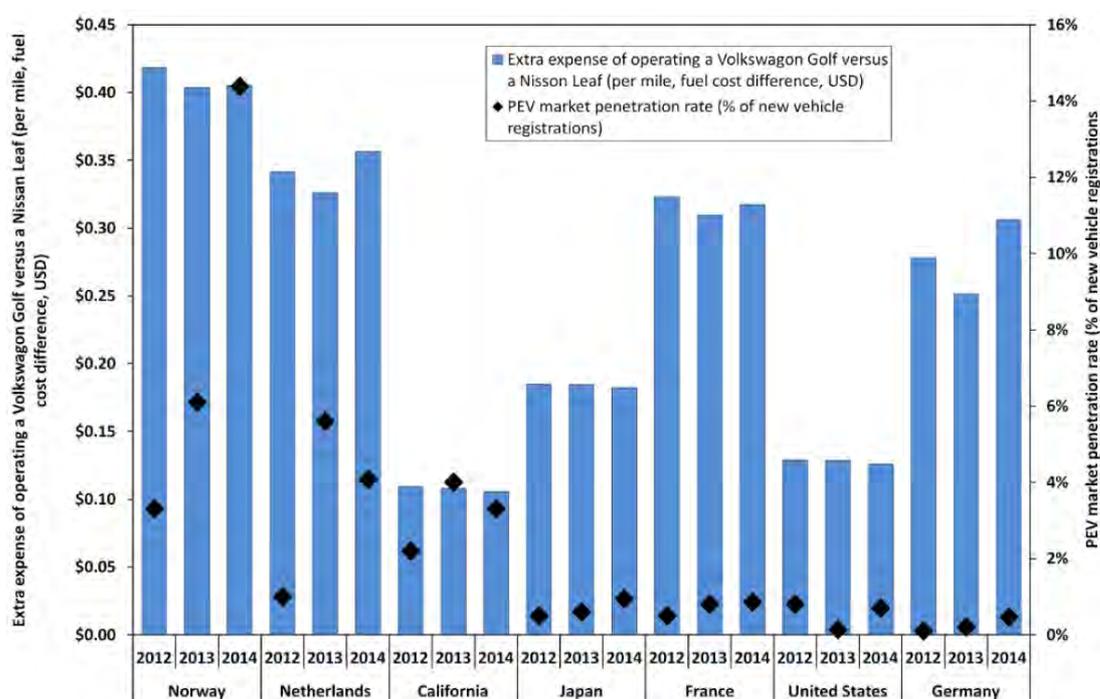
Figure 6 PHEV and PEV units sold, by month (Sept 2013- Sept 2014)



Source: Vergis et al (2014)

Vergis et al summarised the different levels of incentive in individual jurisdictions in terms of a difference in the per mile cost; they compared these with market penetration rates (Figure 7). They note that in Norway, the country with the highest PEV uptake rates, the operating cost differential is greatest: a Volkswagen Golf costs approximately an additional US\$0.40/ mile extra, as compared to a Nissan Leaf. However, they also note that more than just relative operating costs are affecting market penetration rates. For example, California has the third highest market penetration rate of PEVs amongst the jurisdictions they examined, but the lowest operating cost differential. We explore the response in US States further below. Vergis et al conclude that significant factors in EV penetration are financial incentives both at purchase and ongoing (market formation and positive externalities in their parlance) and actions that help to increase social acceptance of EVs (legitimation).

Figure 7 Per mile operating costs of a gasoline versus a BEV, as compared to PEV market penetration rates



Source: Vergis *et al* (2014)

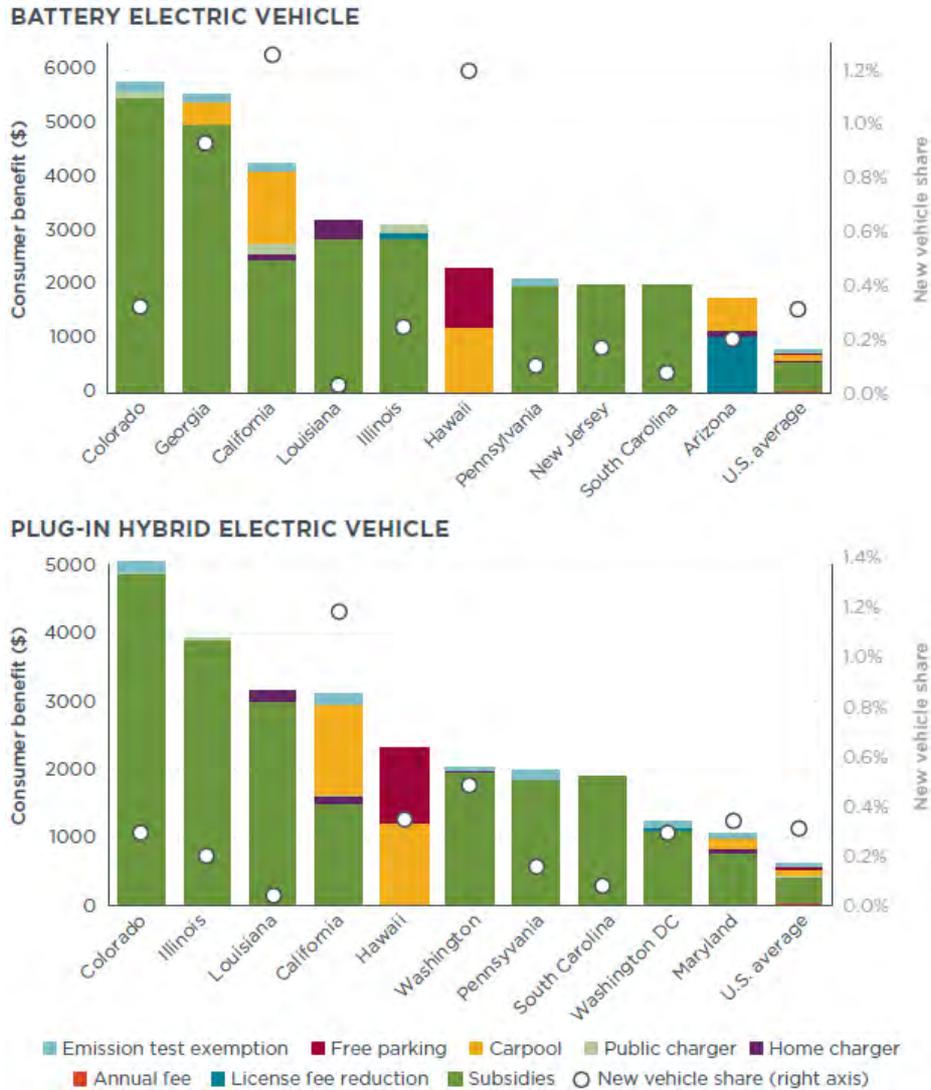
In an analysis of EV adoption across 30 countries in 2012, Sierzchula *et al* (2014) found that financial incentives, charging infrastructure, and local presence of production facilities to be significant and positively correlated to EV market share. Of those factors, charging infrastructure was most strongly related to EV adoption.

US States

Jin *et al* (2014) analysed the effects of a wider range of policies on EV market share in the US. Their analysis examined the impacts of policies that included emission test exemptions, free parking, carpool vehicle lane access, public chargers, subsidised home chargers, license fee reduction, in addition to subsidies; they also examined

fees for electric vehicles (disincentives). The effects for the States with the largest incentives are shown in Figure 8.

Figure 8 Incentives (consumer benefits) and new vehicle share for US States with largest incentives



Source: Jin et al (2014)

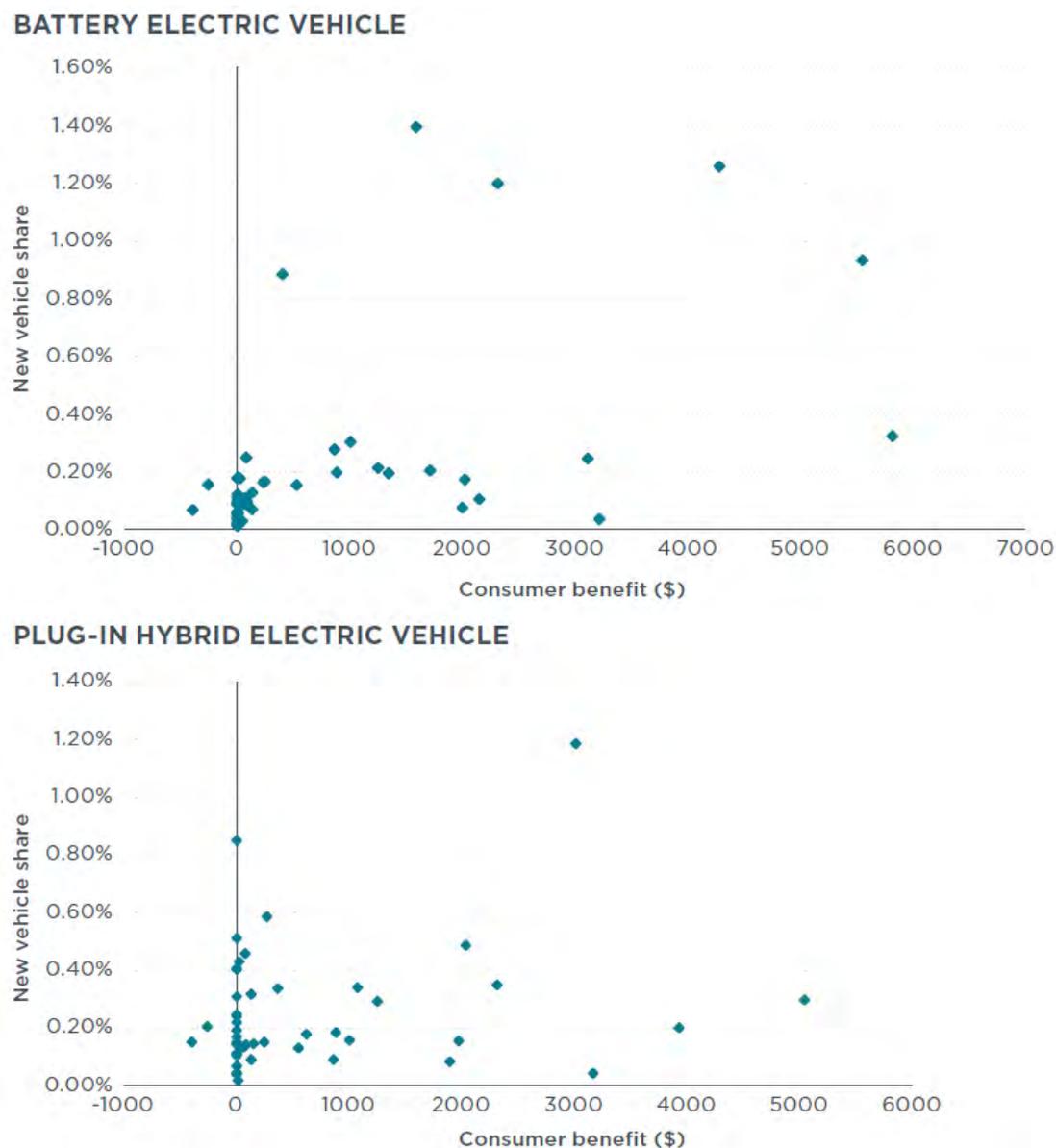
The States in which EVs represent the largest share of the new vehicle market (California and Hawaii) are not those with the highest incentives, and they rely significantly on policies other than direct subsidies: access to carpool lanes for EVs (both) and free parking (Hawaii).

Figure 9 shows the relationship between incentive levels and market share across all US States and DC, with negative benefits being an annual fee on EVs. There is little evidence of a relationship between incentive level and market share for PHEVs, but a possible trend for BEVs.

The authors used regression analysis to interpret the results, suggesting that "total monetary benefit available to BEV owners is significantly positively correlated to BEV sales, but that PHEV benefit is not correlated with PHEV sales." Jin et al also found that sales were significantly correlated with the percentage of people with income

greater than US\$100,000. The authors suggest that three of the policy variables have a significant positive impact on sales: subsidies, carpool lane access and emissions testing exemption.

Figure 9 Consumer benefit and new vehicle share for US States with largest total BEV and PHEV shares



Source: Jin *et al* (2014)

The US analysis examined levels of incentive (consumer benefit) rather than relative price as was done for the international studies (Mock & Yang, 2014), although the international studies included the US and California. The international analysis suggests that the price of EVs was higher than for the equivalent ICEV (see Figure 3 and Figure 4).

The US analysis might suggest that the State-level experience is still largely of early adopters rather than more generalised demand, or that the other policy interventions

are valued significantly highly such that the overall package of incentives is sufficient to encourage greater market share. However, the impact of the non-price incentives is likely to vary significantly with local circumstances, eg the value of carpool lane use will vary with congestion levels. Thus the authors conclude that "Further research is needed to more deeply analyse the impact of other factors on electric vehicle sales."

Demand Models

A number of researchers have developed demand models to explain and/or predict changes in market share for EVs. These have attempted to include variables beyond just the relative price of vehicles.

LAVE-Trans Model

In the US, the Light-duty Alternative Vehicle Energy Transitions (LAVE-Trans) model (Greene *et al*, 2012) has been developed to project market penetration rates for alternative vehicles. It incorporates market decision making and reflects the most significant economic barriers to the adoption of new vehicles and fuels (National Research Council, 2013). Penetration rates of different vehicle and fuel types are determined in this model in response to price, costs, and vehicle fuelling characteristics.

The LAVE-Trans model uses a nested, multinomial logit model of consumer demand. The probability of choosing among the set of available options is governed by representative parameters for a particular class of consumer. As a nested model it has multiple layers of choice: the first level of choice is whether or not to buy a light duty vehicle (LDV). If a consumer chooses to buy an LDV, the next level of choice is between purchasing a passenger car or a light truck. Then, within a particular class of vehicle there are multiple options, such as whether to purchase an ICEV or EV.

Nine variables determine the market shares of the alternative advanced technologies (Table 2).

Greene and Liu (2014) note that the LAVE-Trans model includes several feedback loops through which adoption of alternative vehicles and fuels generates network external benefits that drive down costs and increase the acceptability to consumers of the novel technologies and fuels. For example, consumers are divided into innovators/early-adopters and the majority. As vehicles are sold, the risk aversion of the majority is diminished while the preference for novelty of the innovators/early-adopters is likewise eroded. As more fuel cell vehicles are sold, more refuelling stations are built. As more stations are built, the attractiveness of hydrogen fuel cell vehicles to consumers increases. As more vehicles are sold, costs approach long-run, high volume levels through the benefits of scale economies and learning-by-doing. Because knowledge about many of these relationships is weak, LAVE-Trans uses best available data, informed by judgment, and seeks to narrow uncertainties over time as knowledge grows.

Income and Other Socio-economic Variables

The analysis of US State incentives by Jin *et al* derived a demand relationship for BEVs in which BEV sales are related to the value of total incentives, total vehicle sales (ie EVs plus conventional vehicles) and income (the percentage of residents with an

income over US\$100,000 per annum). They tested another model that found statistically significant explanatory variables included subsidies, access to high occupancy vehicle (HOV) lanes, and emissions testing exemption.

Table 2 Variables included in LAVE-Trans model

Variable	Approach
Retail price equivalent (RPE)	Purchase prices
Energy cost per kilometre	Present value of future fuel costs – discount rates are varied to take account of variety of consumer attitudes
Range (kilometres between refuel/recharge events)	Range anxiety is defined as the loss of utility due to a vehicle's inability to be used for more than a certain number of miles per day. Range anxiety declines exponentially. The values are taken from a study which calculated the number of days a vehicle with range R would be unable to accomplish the daily driving pattern of typical US drivers. The authors suggested a daily penalty of \$15 to \$30, which is typically less than the cost of renting a vehicle to accomplish the usual driving, because motorists have other options, especially if the household owns more than one vehicle.
Maintenance cost (annual)	Assumed to be incurred annually over the life of a vehicle
Fuel availability	The estimate used here starts with a measure of the extra time required to access fuel in a metropolitan area as a function of the ratio of the number of stations offering the alternative fuel to a reference number of gasoline stations.
Range limitation for BEVs	The value (or cost) of range is calculated as the discounted present value of time spent refuelling over the life of the vehicle. The range variable is defined as the time required per refuelling (in hours), multiplied by the value of time (in \$/hr), divided by km per tank of fuel or km per charge.
Public recharging availability	The value of the availability of public recharging to BEVs is a function of the present value of full availability of public recharging versus none. The value of public recharging is a function of the number of days in a year an EV would not be able to satisfy typical kms travelled and the cost of renting a vehicle with unlimited range for those days.
Risk aversion (innovator versus majority)	Represented in a manner analogous to learning by doing. Innovators have a preference for novel technologies (a utility premium) that decreases with cumulative sales. The majority of the market may have an aversion for novel technologies (a negative utility) that decreases with cumulative sales.
Diversity of make and model options available	Represented in the vehicle choice model as the log of the ratio of the actual number of makes and models available, n, to the "full diversity" number, N, represented by the number of makes and models of the conventional technology available in the base year.

Source: National Research Council (2013), Appendix H.2.3.2

Glerum *et al* (2011) conducted a survey to analyse the factors that could be used to explain demand for EVs. In addition to cost variables (purchase price, fuel prices, incentives etc), they tested variables relating to household composition, usage of public transportation, income, age and the number of cars in the respondent's

household. They found some significant relationships with these factors but not sufficiently to develop a demand model.

Adepetu *et al* (2014) developed a model in which someone's decision to purchase a vehicle is dependent on income, their "greenness", social network threshold (the fraction of someone's social network that must own EVs in order for them to buy an EV), and typical driving behaviour, as well as the prices and attributes of the vehicles on the market. Because greenness and social network threshold were unknown, they tuned these parameters to match observed practice in San Francisco. They classified agents based on their inclination towards EV adoption as: early adopters (16%), early majority (34%), and late majority (50%). They noted the importance of financial incentives in establishing the EV market but that the ability to estimate total costs of ownership (TCO) did not seem to be significant.

Research in Scotland (Morton *et al*, 2015) analysed whether the quantity of EVs registered in a local region (Unitary Authority, UA) area is statistically related to other characteristics of that area. Findings of the analysis indicate that the level of EV adoption across UAs is significantly positively related to the proportion of a UAs populace that: hold a university degree, consider climate change to be an immediate and urgent problem, commute to work by foot, and the presence of rapid charge points in a UA.

These analyses have identified factors that have had a positive impact on EV adoption rates. Some identify the characteristics of people for whom demand levels are higher (e.g. those with higher income or education); these may be relevant factors in New Zealand also, although they are more likely to affect early adoption rates than longer run demand levels. Other factors identified as influencing take-up rates include purchase prices (e.g. via subsidies), costs of use (e.g. exemption from emissions testing) and convenience (e.g. access to HOV lanes), relative to ICEVs. Not all are relevant to New Zealand, but the principle is that anything that provides some cost or other relative advantage to EVs has the potential to increase rates of purchase.

Conclusions and Implications for Projections in New Zealand

This brief literature review has discussed a number of studies that have identified barriers to adoption of EVs and the factors that determine rates of uptake. In general, the modelling suggests that, in the long-run, total operating costs (TOC) of EVs relative to ICEVs will determine levels of uptake, but that TOC includes factors such as range (and thus the frequency of recharging), the convenience of recharging plus a number of other factors that currently operate as barriers, that include perceived risks of EVs reflecting the newness of the technology. Substantial early adoption of EVs in other countries has been particularly associated with subsidies that have reduced initial purchase price to the extent that EVs have a price advantage over ICEVs.

Models of penetration rates have included parameters to take account of some of the drivers of demand that are additional to price. However, there is considerable uncertainty in these parameter values, particularly about how they will change with increased penetration rates that will feedback effects on barriers to adoption.

For modelling demand in New Zealand, the best approach would appear to be one that correlated rates of uptake to relative price. Rates of EV purchase would be

expected to increase particularly if prices fell below those of ICEVs, although this will be limited by the number of models available (and thus the extent to which they provide complete substitutes) and other constraining factors including technical limits (e.g. driving range).

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3. Demand Model

The demand model covers petrol and diesel powered internal combustion engine vehicles (ICEVs) and electric vehicles (EVs), including plug-in hybrids (PHEV-Ps and PHEV-Ds). There is also a split by these types of vehicles into New Zealand new vehicles and used imports.

For each type of vehicle the model first calculates total operating costs measured on a whole-of-life basis,² expressed in terms of \$/100km for different amounts of annual travel. The second part of the model uses this relative cost information to produce demand projections for each vehicle type.

Demand V_i may be expressed as:

$$V_j = f(X_{ij}, Z_{ij})$$

$$Z_{ij} = f(\text{distance travelled})$$

...where:

- V_j is the demand for vehicles of type j ; petrol ICEV, diesel ICEV, BEV & PHEV-P and PHEV-D.
- X_{ij} are explanatory variables with a unit cost (per 100km) that does not depend on distance travelled (such as fuel prices).
- Z_{ij} are explanatory variables with a unit cost (per 100km) that does depend on distance travelled – essentially variables such as the cost of the vehicle.

Table 3 sets out the explanatory variables in the model and how they are measured and converted to the desired \$/100km (denoted as \$/km for simplicity).

Table 3: Model Variables

Variable	Dimensions	Comment
Depreciation - fixed	\$/km = \$/t * t/km	t = time
- variable	\$/km	
Insurance, registration etc	\$/km = \$/vehicle * vehicle/km	
Fuel cost	\$/km = \$/litre * litre/km	Petrol
	\$/km = \$/kWh * kWh/km	Electricity
Road User Charges	\$/km	
Maintenance	\$/km	Include battery life
Range	}	Different values of \$/t for
Charging time	}	waiting v moving
Charging infrastructure	}	
Preferences, incentives & disincentives	\$/km directly or \$/vehicle * vehicle/km	Policy interventions or consumer tastes

² www.treasury.govt.nz/publications/guidance/planning/costbenefitanalysis/lifecosts-guidance.pdf

The capital cost of a vehicle is modelled as the purchase price, less the discounted value of the vehicle at sale, taking account of depreciation over a specified number of years. Depreciation has two components: a fixed component based purely on the age of the vehicle (dollars per year) and a variable component based on the distance travelled (dollars per km). The profile of the depreciation rate over time is different between ICEVs and EVs. For ICEVs depreciation rates are specified by the user. For EVs, the rate of depreciation is the rate for ICEVs plus an additional percentage to take account of the fall in price of new EVs.

Further details of the variables and how to use the model are given in Section 3.

Given calculation of X and Z, and thus total operating costs (TOC) per 100km, the next stage is to determine the demand for each vehicle type (V_i). Here we adopt the two different approaches, in essence two models:

1. Elasticity Model

Applies price elasticities of demand to relative TOCs to determine the demand for EVs, with the demand for ICEVs being a residual. The underlying assumption is that, in the very long run, EVs will totally dominate the vehicle fleet. The rate at which that occurs is a function of relative TOCs, including the perceived cost penalty (currently) associated with limited EV choice and consumer reluctance around new technology – discussed further below. Total demand for new vehicles and used imports is exogenous to the model, along with the petrol-diesel split.

2. Cost Minimisation Model

In contrast to the Elasticity Model in which a change in relative price leads to a change to the (existing) percentage of vehicles that are EVs, the Cost Minimisation Model does not limit the extent of shift, with vehicle purchasers always choosing the lowest TOC option. However, to constrain the tipping point effect (demand immediately shifting from one vehicle to another), the model assumes that the relative TOCs are actually point estimates around which there are distributions, giving rise to overlaps between the TOC distributions of the different types of vehicle. Demand for each vehicle type is shared within that overlap. As with the Elasticity Model, total demand for new vehicles and used imports is exogenous to the model, along with the petrol-diesel split.

Elasticity Model

A simple functional form is used to determine the shares of petrol vehicles that are BEV and PHEV-D, with ICEV-P as a residual. Similarly for PHEV-D and ICEV-D.

$$S_{it} = (S_{it-1} + S_{jt-1}) / (P_t^{t\eta} * \left(\frac{S_{jt-1}}{S_{it-1}}\right) + 1)$$

...where:

S_i is the share of BEV or PHEV-P and S_j is the share of ICEV-P in petrol vehicles. Similarly for PHEV-D and ICEV-D in diesel vehicles.

P is the TOC of BEV or PHEV-P divided by the TOC of ICEBV-P. Similarly for diesel

η is the relative price elasticity (default value is 1).

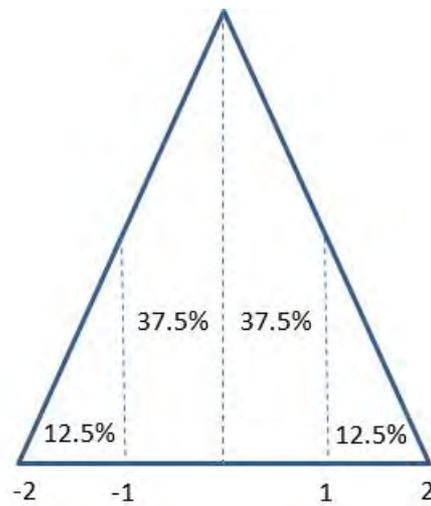
t is time starting with $t=1$ in 2015.

It will be seen that as long as $P < 1$ (EVs have a cost advantage over ICEVs), as t increases the ICEV shares becomes progressively smaller and thus the EV share approaches 100% of demand.

Cost Minimisation Model

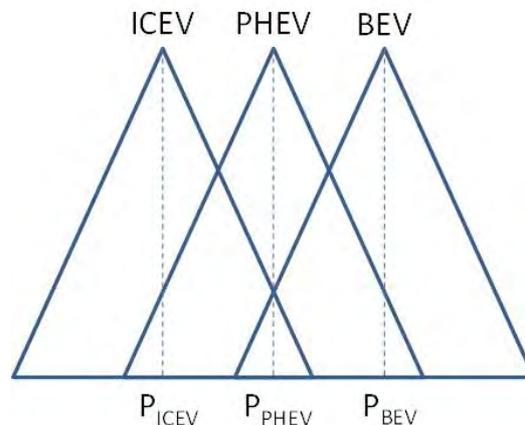
The model starts by assuming a distribution around the average TOC of each vehicle type. The distribution is represented by a triangular shape. It is assumed that 75% of the distribution is within 1 standard deviation of the mean and a further 25% within 2 SDs (Figure 10).

Figure 10 Distribution of prices around the mean



We estimate the overlap between TOC distributions as shown in Figure 11.

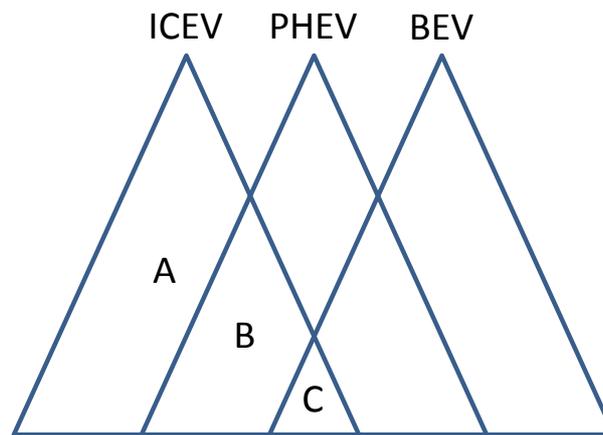
Figure 11 Overlapping TOC distributions



The distribution between the vehicles is estimated as follows, and as shown in Figure 12:

- ICEV: 100% of area A + 50% of area B + C
- PHEV: 50% of Area B + 25% of C
- BEV: 25% of area C

Figure 12 Sharing of distributions



The approach is explained mathematically in Box 1.

Box 1 Estimating the Size of the Overlap

Firstly the height of the triangle is estimated such that the area of the triangle is equal to 1. The height (H) is estimated as a function of the area (A) and the standard deviation (SD):

$$H = \frac{A}{2 \cdot SD} = \frac{1}{2 \cdot SD}$$

This is simplified, as shown, because we have defined the area as equal to 1. We estimate the change in height as we move from one corner of the triangle as:

$$dH = \frac{H}{2 \cdot SD}$$

Combining this with the equation above, this means the change in height (dH) can be defined as:

$$dH = \frac{1}{(2 \cdot SD)^2}$$

We then define the change in area (dA) as we move from one corner of the distribution, as follows:

$$dA = \frac{(dTOC \cdot dH) \cdot dTOC}{2} = \frac{dTOC^2 \cdot dH}{2}$$

To estimate the overlap, we first assume that one SD is equal to 25% of the mean TOC across the five vehicle categories. We then estimate the overlaps by defining the bottom axis of a right-angled triangle as half the difference in TOC (dTOC) between the lower TOC plus 2 SDs and the higher TOC minus 2 SDs. The area of this triangle is used to define the proportion of the distribution that is allocated to the lower-priced and higher-priced vehicles (50:50).

EV Penalty

Element Energy (op cit) estimates a model supply or variety 'penalty' ranging from £4,000 to £10,000 for EVs, corresponding to about 30% of the average ICEV price in 2013.

They argue that this vehicle model supply penalty (along with other barriers to EV uptake) needs to essentially disappear by 2030 if their high uptake scenario of 60% of new vehicles being EVs is to be realised – compared to 19% under 'Business as Usual'.

Element Energy use the same approach to deal with the gradual awareness and acceptance by consumers of EV technology. They note (p53) note:

The common expectation that rapid technological and infrastructural developments will make current models obsolete also acts as a further barrier to near-term uptake.

They estimate that this barrier is equivalent to about £2500 per PHEV and £4500-£5000 per BEV.

Combining the two penalties means that BEVs start with a penalty of about 50% of the purchase price, while the penalty for PHEV;s is about 25%. These decline over time – see Model Operation below.

4. Model Operation

The model consists of a number of worksheets as described below. The term EVs is used to refer to BEV, petrol PHEVs and diesel PHEVs unless a distinction is required

Inputs

The Inputs worksheet contains most of the assumptions and parameter values that users are likely to wish to change. The options include:

1. Starting year.
2. Discount rate (currently set at 10%).
3. Initial values for average prices of petrol ICEVs and diesel ICEVs, and changes in real price over time.
4. Price paths to 2030 for EVs, in terms of their margin over ICEV prices: low, medium or high. These relate to the range of values included in the Emission Impossible & Covec (EI/C) report.³
5. The option to override these price paths, described as 'Profile' by opting for 'Direct input', including the starting price differential, the year that EV prices converge to ICEV prices (for otherwise equivalent vehicle specifications) and the maximum degree to which EV prices can fall below ICEV prices.
6. Maximum driving range of EVs (120km, 160km or 240km).
7. Road User Charges and the date at which the exemption for EVs expires.
8. The percentage of RUC that would apply to PHEV-P vehicles, as a proxy for whatever charging mechanism may ultimately be introduced.
9. Replacement age for new vehicles, age of entry for used vehicles, and replacement age for used vehicles.
10. Vehicle depreciation linked purely to age. These represent rates of depreciation of real prices. Users can input the depreciation rates for ICEVs; depreciation rates for EVs are calculated to take account of the percentage fall in price of new EVs also.
11. Depreciation related to distance travelled, at an adjustable rate per km. Distance travelled reduces by 3.7% pa, but this is also changeable. The default value is estimated from MoT's Vehicle Fleet Model (VFM).

All of the depreciation calculations lead to an overall depreciation cost per 100km.

³ See Appendix 2 in Metcalfe J, Kuschel G and Denne T (2015) Research into the long-term trends for electric vehicle price and supply – understanding developments in the global market. Final Report prepared for the Ministry of Transport. Emission Impossible.

12. Other assumptions relating to fuel economy, insurance costs and maintenance costs, including the option to change the proportions of electricity-fossil fuel use with distance travelled,
13. Policy interventions by vehicle type consisting of either subsidies on the purchase price, a discount on the annual registration fee, or any other incentive (or barrier) expressed on a \$/100km basis. By default these are set to zero.
14. The rate at which the price penalty associated with model variety and consumer resistance abates.
15. The number of new and used vehicle imports to 2030.
16. Potential supply constraints on the number of new and used EV imports.
17. There is an option to turn off the possibility of BEVs being used for long trips, although it should be noted that not having any long trips when annual distance travelled is in the tens of thousands of kilometres is probably inconsistent.
18. Also in relation to long trips by BEVs, the user may set the length of long distance trips, the waiting (battery recharge) time and the value of waiting (\$/hour). Note that the number of long trips per year varies with initial annual kilometres. See Assumptions below.
19. The 'Run - all years' button will run the model for all years from 2015 to 2030. The results go into the Results worksheet and ultimately into the Projections worksheet.

This worksheet also contains a number of graphs showing results for EV penetration and Total Operating Costs.

Assumptions

This worksheet contains a number of assumptions which may be varied by the user, although some are technical factors which would not generally be changed.

1. Technical – fuel energy and CO₂ emissions coefficients.
2. Distribution of distance travelled by vehicles in first year of ownership – by New Zealand new versus Used imports and petrol versus diesel.
3. Distribution of the annual number of long distance trips for which an EV might be used, in relation to total distance travelled in first year of ownership.
4. A calculation that adjusts the amount of RUC incurred by owners of EVs as function of when the current RUC exemption is removed and the EV holding period. By default the removal of the exemption is beyond the end of the forecast period.

New

The new worksheet is really the core of the model, showing how whole of life Total Operating Costs are calculated and converted into a cost per 100km basis. In order

to demonstrate how the model works it is shown as an example for a benchmark vehicle that travels the mean number of kilometres in the first year of ownership, assuming that it is held for a stipulated period of time.

The lower part of the worksheet uses the model to calculate total operating costs per 100km for different values of the distance travelled in the first year of ownership. The output is summarised in the bar graph at the top of the worksheet.

Used

The Used worksheet essentially does the same as the New worksheet, but for used imports. Most parameter values are drawn from the New worksheet.

Fuel Prices

This worksheet calculates the price of petrol and diesel at the pump, given assumptions about the price of oil in US\$/bbl and the US\$/NZ\$ exchange rate. The relationship between the NZ\$ price per barrel and the price at the pump is econometrically estimated using historical data.

There is also the option to change other parameters:

1. The rate of petrol excise duty, and whether to apply it to diesel (should its price structure be changed).
2. The carbon price.
3. The wholesale price of electricity.
4. The retail electricity price for household, commercial and industrial consumers, and whether the marginal or average electricity price is used. Note that the model has not been calibrated (at this stage) to use the commercial or industrial prices.

Vehicle Prices

This worksheet contains the projections of relative EV-ICEV prices produced by Emission Impossible and Covec. Changes in vehicle prices due to subsidies are also recorded here.

Working

This worksheet is used for the macro. It should not be changed or renamed.

Results

If the 'Run - all years' macro is activated in the 'Inputs' worksheet the results appear in this worksheet. It has a panel for each of New and Used and for the five vehicle types, and each panel has the projection of total operating costs disaggregated by calendar year and distance travelled in the first year of ownership.

Shares-New and Shares-Used

The relative total operating costs are used to project the shares of new and used imported (light passenger) vehicles for each of the five vehicle types.

Projections

In this worksheet the shares are converted into vehicle numbers by applying them to the exogenous annual projections of the total numbers of New and Used vehicles.

If demand for any type of EV in any year exceeds the supply constraint the relevant cell will turn yellow.

If a supply constraint is exceeded for Used vehicles the following rules are adopted:

- Any excess demand for BEVs is shifted to petrol PHEVs provided the TOC for petrol PHEVs is more than 10% below the TOC for petrol ICEVs.
- If the demand for petrol PHEVs (including any demand reallocated from BEVs) exceeds supply, it is shifted to petrol ICEVs.
- Any residual excess demand for BEVs is also shifted to petrol ICEVs
- Excess demand for diesel PHEVs is reallocated to diesel ICEVs.

These rules are inevitably somewhat ad hoc. The model is a model of the composition of vehicle demand, not a model of the entire vehicle market. If a supply constraint is reached other market reactions could occur; for example prices may increase or buyers may defer purchase. While the model is not designed to directly simulate such market behaviour it could be used to investigate its effects.