Accelerating the uptake of electric vehicles in New Zealand

How much fossil fuel use is avoided by Low Emission Vehicles?

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Executive Summary

Estimation of the fossil fuel savings by Low Emission Vehicles (LEVs) requires an estimate of the fuel consumption of 'equivalent' internal combustion engine vehicles (ICVs) that have been displaced. Therefore we first constructed a statistical model of standardised vehicle test 'driving cycle' measures of fuel consumption of 90 conventional (ICVs) for 'urban', 'ex-urban' and 'combined' driving conditions in New Zealand. The model showed highly significant associations between ICV fuel consumption (L/100 km) and seven parameters which collectively explained 84-86% of the variance in driving cycle results. Fuel consumption per kilometre was higher for models with larger volume and more seats, had more horse power, and used petrol (12.3% more petrol is required than for diesel). Fuel consumption was lower for models that had higher torque (for a given horse power) and were manufactured more recently. 'Sports Utility Vehicles' had higher fuel consumption than other vehicle types of similar size, power, torque and year-of-manufacture. 'Urban' driving cycles predicted 49.7% higher fuel consumption per km of travel than the 'Ex-urban' driving cycles. A 'correction factor' of 1.273 was applied to the driving cycle results to better approximate real-life driving performance in New Zealand.

We then substituted the size, power, torque and type specifications of each model of fully electric vehicle (EV), Plug-in Hybrid (PHEV) and Range-extended electric vehicle (REX) into the statistical model to predict the fuel consumption of their notional 'equivalent' ICVs. The predicted amount of fuel avoided varied around threefold between the smallest to the largest LEV models. For example, an ICV of similar size and power as a Mitsubishi iMiEV would use approximately 5.25 L of petrol per 100 km of urban travel, whereas the equivalent of a Tesla Model S would use approximately 16.88 L/100km. The most common EV in New Zealand is the Nissan Leaf. Its 'Generation 2' model is predicted to avoid 7.48 L of petrol per 100 km of urban travel, and 5.54 L/100 km when driven outside urban areas. If a Nissan Leaf owner had displaced a diesel rather than petrol powered ICV, it would avoid 6.09 and 4.87 L of diesel per 100 km in urban and ex-urban travel respectively.

These estimates of avoided fuel consumption assume that a PHEV and REX are being driven entirely in EV mode. Additional fuel is used to manufacture and distribute petrol and diesel before it is pumped into ICVs, PHEVs and REXs. Fossil fuels are used to generate around 20% of New Zealand's electricity, and some energy is then lost during distribution through the national grid. A fuller accounting of the fuel use avoided by LEVs will have to incorporate these additional consumptions and losses, and requires an estimate of the amount of electricity used to propel LEVs.

Our review of LEV driving cycle measures of energy consumption showed, like that for fuel use by ICVs, a threefold variation in kWh/100 km between the smallest and the largest models. However the correlation between fuel use avoided by equivalent ICVs and electrical energy consumption is weak. The Tesla has particularly high electrical energy efficiency. The PHEV models have comparatively high consumption of electricity per km of travel in 'EV mode'. National electricity demand from the entire LEV fleet will greatly depend on the relative energy efficiency of the different LEVs chosen by New Zealanders, whereas much of the national discourse so far centres of the comparative energy efficiency and cost of owning and operating LEVs compared to ICVs in general. We urge sharper focus on the comparative energy efficiency of the different LEV options, and in particular the relative benefits of PHEVs, REXs and pure EVs.

There is a paucity of information on the way EV driving efficiency varies between driving cycles and real-life driving conditions in New Zealand (and other countries); and between urban and ex-urban conditions. In the meantime we recommend use of uncorrected driving cycle results for estimating electricity demand of LEVs, and urgent research to better inform policy and fuel savings from LEVs in future. It is particularly important to measure the comparative fossil fuel use of PHEV compared to EV and REX models because the PHEVs are likely to be popular and come to predominate within the LEV in the short term at least. PHEVs suit New Zealanders' outdoor lifestyles and are less affected by the sparseness of our rapid charging network, yet they may not deliver the same environmental and financial benefits of fully EV models. Policy interventions, research and education could help encourage uptake of EVs rather than PHEVs in particular.

The estimates of avoided fuel use calculated by this preliminary study will now be incorporated into measures of financial, environmental and social benefits captured by participants in '*Flip The Fleet*', a citizen science project where LEV owners report their monthly vehicle use and performance. That collaboration will help fill some of the information gaps identified by our review, and use scientifically robust estimates of the benefits to advocate for faster uptake of LEVs in New Zealand.

Contents

Acknowledgements

We thank Mark Walkington and Dr Parry Guilford for advice on calculating the fuel consumption of Mitsubishi Outlander PHEV and provision of data to check our estimations. Jefferson Dew (Summer Intern, PowerCo), Dr Parry Guilford (EV owner, University of Otago), Jinquin Lo (Planning Engineer, PowerCo) and Dr Mark Nixon (EV owner, Christchurch EV Owners Group) provided helpful peer review of this report. Fiona Stirling proof-read and formatted the report. Preparation of this report was mainly funded by Ecosystems Consultants Ltd. and PowerStats Ltd. Completion and final publication was funded by a grant from Otago Museum's *Science into Action* programme www.scienceintoaction.nz for Curious Minds www.curiousminds.nz.

Introduction: the need for this research

Uptake of 'Low Emission Vehicles' (LEVs[1]) will provide local, national and international environmental, social and economic benefits. Quantification of these benefits is one way to encourage individuals, families, community groups and businesses to switch from using conventional vehicles ('Internal Combustion engines Vehicles', ICVs) to 'LEVs. *Flip the Fleet* (FtF) is a 'citizen science'[2] project that seeks to accelerate uptake of LEVs by collecting monthly travel, energy use and efficiency data from LEV owners throughout New Zealand[3]. Participants upload data from their vehicle's dashboard to enable software to instantly calculate and report distance travelled, energy used and the financial, environmental and social benefits.

Calculation of LEV benefits depends on predicting the fuel that would have been used by an 'equivalent' ICV model had it been driven over the same distance in the past month, since it was first registered in New Zealand, and since it was manufactured. This report primarily estimates the fuel consumption (L/100 km) of an ICV, but we also report the energy consumption of LEVs (kWh/100 km[4]) so that the amount and cost of electricity used can be offset against saving in fuel costs to predict the net financial benefit of operating a LEV compared to its ICV counterpart. Some fossil fuels are used to generate electricity, so an estimate of the LEV's electric motor energy consumption will be needed for a full 'Life cycle Assessment' of the amount of Greenhouse Gas (GHG) emissions avoided by LEVs.

Predicting benefits is more complicated for Plug-in Hybrid Electric Vehicles (PHEVs) which are propelled by both an internal combustion engine (ICE) and an electric motor: calculation of their benefits requires an estimate of travel efficiency for both propulsion systems, as well as of the proportion of a PHEV's travel that was driven by each mode. Our analysis also includes 'Range-extender' models (REXs)[5] i.e. these have a small on-board ICE and petrol tank to charge the EVs battery once it becomes depleted, even though most of the energy stored in the battery is uploaded by plugging into an external electricity supply between trips. We do not consider the conventional hybrid vehicles such as the Toyota Prius, even though others may consider them as legitimate examples of LEVs.

Here we report a statistical analysis of published estimates of fuel consumption of a full range of ICVs, and the predicted consumption of a notional 'equivalent' ICV for each of the

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[1] See Appendix 1 for definitions and abreviations used in this report. Throughout we use EECA's terminology for Low Emission Vehicles.

[2] Citizen science is the collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with professional scientists (https://daily.zooniverse.org/2014/09/16/citizen-science-in-dictionary/)

[3] See Ivanov & Moller (2017) or www.flipthefleet.org for a fuller description of the projects aims and methods.

[4] Consumption is measured as L/100 km and kWh/100 km; Efficiency is measured as km/L and kWh/100 km.

[5] These are sometimes called "Series Plug-in Hybrids", as opposed to "Parallell Plug-in Hybrids" where both the ICE and electrical motors propell the wheels. See Magnusson (2017) for an efective diagram of the differences

LEVs. In most cases these estimates of consumption are determined from the 'New European Driving Cycle' (NEDC)[6]. Equivalency is assessed by matching each LEV model with an ICV of similar size, power & torque, performance and year of manufacture. The energy consumption of the LEVs is then collated from manufacturers' websites and user manuals. Our report concludes with a discussion of the assumptions and limitations of using such published measures of fuel and energy consumption for predicting the benefits of operating LEVs compared to ICVs in New Zealand. A forthcoming report[7] will incorporate our estimated efficiencies into fully detailed equations that predict the dollars saved and 'Return on Investment', maximum vehicle range between battery recharges, Kgs of carbon dioxide-equivalent (CO_2e) tailpipe emissions avoided, and a variety of ensuing environmental and social benefits of operating LEVs.

Methods

Primary data for ICVs

The fuel consumption of 90 ICVs of varying size, type and performance was collated from online automotive databases which had already collated data from the manufacturers, and specific searches to fill gaps. This random selection of ICVs was supplemented by deliberate inclusion of four 'focal models' (latest models of Nissan Pulsar, Mazda 3, Ford Focus, Toyota Corolla) which were identified by experts in the 'NZ EV Owners' Facebook group[8] as being the most similar to a Nissan Leaf[9]. We mainly included models first manufactured from around 2010 onwards in the analysis so as to match the year of manufacture of the LEVs currently in use in New Zealand. Occasionally we also included earlier models upon which the manufacture of each LEV model was based. For example, the very popular Nissan leaf was based on their Tiide Model, which was first manufactured in 2004[10].

In all cases we primarily based the estimated fuel and energy efficiencies on standardised 'driving cycle' test regimes which are performed in the laboratory[11]. We used the NEDC which was designed in the 1980s, and is still used as the reference cycle for homologating cars in Europe under the EuroVI benchmark[12]. The cycle involves four repeats of an 'Urban' test aimed to imitate slower speed driving. This is followed by an 'Ex-Urban' test which is more similar to open road driving. The results from these tests are then used to find a

[6] More information on the NEDC and the methods used during the test can be found at www.gov.uk/government/uploads/system/uploads/attachment_data/file/4247/ppr-354.pdf

[7] Moller & Ivanov (2017)

[8] Discussion held 3 & 4 May 2016

[9] Nissan Leaf is currently the most popular EV in New Zealand (Magnusson 2016).

[10] https://en.wikipedia.org/wiki/Nissan_Leaf

[11] www.car-engineer.com/the-different-driving-cycles/

[12] The NEDC has been the preferred cycle for European standards since 2000, however it is expected to be foregone in favour of the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) with the eventual EuroVII standards - http://www.car-engineer.com/the-different-driving-cycles/

'Combined' statistic. While the NEDC does have its weaknesses[13], we prefer it other cycles because it has more readily available data and has a close relationship to the Australian Design Rules and the New Zealand Vehicle standards. Both countries are contracted parties to the World Forum for Harmonization of Vehicle Regulations[14].

A combined fuel consumption was not available for four vehicles in our sample, so we used a weighting of 68% for urban and 32% for ex-urban to estimate the combined consumption for the four cars where the latter was not reported[15].

We followed Arup (2015: 40): i.e. by applying an additional "real-world consumption scaling factor of 1.273 to increase the standard test values[16]… This was derived from NZ fleet statistics that compared real-world fleet fuel consumption to the average test-cycle consumption rates of the current NZ light vehicle fleet registrations. This real- world scaling factor is also consistent with international observations[17]".

Predictors of equivalence

We sought to predict the fuel consumption of equivalent ICV for each LEV model[18] present in New Zealand based on their fuel type (diesel or petrol), kerb weight (kg), size (M^3 calculated from Height x Width x Length), number of seats, number of doors, power and torque, acceleration (seconds to reach 100 km from a standing start), and year of first manufacture. We also used ANCAP[19] style categories, but further divided them into size (small, medium, large) and type (car, SUV, sports, utility/van) categories.

'Power' is a measurement of the rate at which an engine can do work, or the rate which it can use its available 'torque'. For cars this is measured in horsepower (HP) which is related to torque with the equation horsepower = (torque*rpm)/5252[20]. This relationship does not guarantee that higher horsepower means higher torque when comparing two vehicles

[13] www.transportenvironment.org/sites/te/files/publications/Dont_Breathe_Here_report_FINAL.pdf
[14] NZ: http://www.saferjourneys.govt.nz/action-plans/vehicle-standards-map/
AUS: https://infrastructure.gov.au/roads/motor/design/
[15] The 'Urban' (ECE) section consists of 4 identical cycles and is 780 seconds in duration with the 'Ex-Urban' (EUDC) section being 400 seconds long. See Table 3: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4247/ppr-354.pdf. The 'Combined' (NEDC) statistic comes from using the entire 1180 second test to measure fuel consumption, so the urban efficiency contributes 68% of the combined measure cf. 32% for the ex-urban portion.
[16] New Zealand fleet statistics (Ministry of Transport, 2013) show average test-cycle fuel consumption for petrol vehicles of 7.72L per 100km, compared to an average real- world fuel consumption for petrol vehicles of 9.83L per 100km. The ratio is 1.273:1.
[17] International Council on Clean Transportation
[18] The diversity of models available in New Zealand forces a need to present a large number of models in this analysis. Customisation of estimates of fuel savings for each FtF participants model is important to personalise the data reports and encourage ongoing participation in this citizen science project (Ivanov & Moller 2017).
[19] https://www.ancap.com.au/
[20] http://www.epi-eng.com/piston_engine_technology/power_and_torque.htm

because engine performance is also partly determined by the speed at which the engine is turning[21].

Torque is a measure of twisting force. It is a measurement of an engines potential to do work in the form of delivering force to twist the crankshaft in a car[22]. A car with higher torque is able to accelerate quicker than one with lower torque (assuming all other variables are equal) as it would be delivering more rotational force to the wheels. Generally cars with more torque will have a better ability to haul heavier loads[23]. If an engine has low torque but rotated very fast, it would have high horsepower; or it could also have high horsepower if the torque was large even when it was rotating very slowly. Generally cars with more horsepower can travel faster[24], but overall performance will be predicted better by incorporating both torque and power.

Statistical modelling

We built three General Linear Models[25] (GLMs) using *Genstat*[26] to predict Urban, ex-Urban, and Combined fuel consumption (L per 100 km). Full models with major interactions were fitted first and residuals inspected to check for homoscedasticity. Each model was successively reduced to ensure equal and normal distribution of residuals and parsimony by further eliminating variables indicated by Wald's Test to not explain a significant proportion of the variance.

Although models that used kerb weight as a predictor often supplanted volume estimates and explained 5-6% more of the variance, we eventually dropped kerb weight from the final model selection. This was a logical choice because LEVs are likely to have a different weight than an equivalent ICV model that delivers equivalent power or performance i.e. (a) electrical motors and their transmission are significantly lighter than ICEs and their transmission, (b) LEVs have the added weight of a battery, and (c) PHEVs and REXs have added weight of an ICE, fuel tank, electric motor(s) and a battery. These counteracting differences are unlikely to perfectly compensate for each other[27], so we cannot be certain that the weight of a LEV is generally lower or higher than that of an 'equivalent' ICV. Therefore we retreated to using volume as an imperfect substitute for kerb weight to indicate the overall size of the vehicles. Weight (mass) would have been a better predictor

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[21] http://www.autoexpress.co.uk/car-news/95110/what-is-torque-the-mystery-explained
[22] https://www.edmunds.com/car-technology/the-twist-on-torque.html
[23] http://rac-london.co.uk/what-is-bhp-ps-kw-and-torque/
[24] http://www.cheatsheet.com/automobiles/torque-vs-horsepower-the-science-behind-car-performance.html/?a=viewall
[25] General Linear Modeling is a statistical technique that estimates the relative importance of a set of "predictor" variables (e.g. power and torque) in determinging the "predicted variable" (here fuel consumption). It separates the effects of many variables at once (e.g. we estimate the effect of Torque once the effect of power has also been taken into consideration. No interaction terms have been used in our anlslysis, so we have assumed that the effect of each predictor variable is indpendent and additive.
[26] 17th Edition, VSNi, www.vsni.co.uk/
[27] We were unable to assertain the weights of the both ICE and LEV motors, transmissions and in the case of LEVs, the battery itself to attempt corrections for these systematic difference.

because the fuel consumption is in part determined by the work (mass x speed) as well as the friction caused by drag. Volume is an approximate substitute because it is a proxy measure for the weight and amount of air displaced by the vehicle as it travels[28].

Five and two outlying observations (nearly all very large SUV vehicles) with extreme residuals were eliminated from the ex-urban and combined consumption models to meet assumptions of homogenous variance.

Predicting the fuel consumption of a notional ICV of the same size, power etc. as each LEV in New Zealand requires some practical additional assumptions:

i. For REX models (Chevrolet Volt and BMW i3), we substituted the electrical torque and power estimates into the GLM to predict the fuel consumption of an ICV with equivalent performance and size i.e. the power and torque of the REX's ICE was excluded because it does not propel the vehicle directly.
ii. For PHEVs models (Mitsubishi Outlander, Audi e-tron), we added the torque and power of all the motors (ICE and electrical motors) on board. PHEVs are normally configured to drive using just the electrical motor while the battery charge lasts or until the speed and engine revolutions are low ('EV mode'). They then switch to the ICE and/or and combined ICE and EV mode ('Hybrid mode'). We substituted the combined power and torque of ICE and electrical motors for predicting the equivalent ICV fuel consumption i.e. assuming it was delivering maximum performance by being driven in the hybrid mode.
iii. Where two (Outlander) and four (Audi e-tron) electrical motors drive the car, we added their power and torque together to estimate the combined pushing power of the engines.

Primary data for LEV energy consumption

We estimated the electric motor's energy consumption only i.e. we ignored the contribution of the ICE in propelling a PHEV when being driven in hybrid mode. Where available we used the Wikipedia reviews of the LEV performance in order to maximise peer review and avoid manufacturer exaggerations. Similarly we used the EPA tests of LEV performance because more of these were available for LEVs[29].

[28] Drag is also an important determinant of fuel and energy consumption. It is partly related to the frontal surface area, partly to the aerodynamics of the vehicle's shape and partly its mass and resulting "rolling resistance" (friction with the road surface). On flat terrain, drag energy loss is the major contributor to fuel use at higher speeds. At lower speeds, rolling resistance dominates.

[29] We substituted the Japanese test cycle in the case of the iMiEV, even though it is considered considerably less taxing than the US EPA's test. This was necessary because the lithium titanate oxide SCiB battery technology used in iMiEVs manufactured in Japan is considered to be 1.7 times more efficient than the standard lithium ion batteries used in the US.

Results

Predicted fuel use

Acceleration, number of doors, ANCAP size class were all dropped from the final models because they failed to predict a significant proportion of the variance. The final models explained 84-86% of the overall variance. The same predictors were selected in all four models (Table 1).

Fig.1 shows the predicted fuel consumption per 100 km for each of the fuel and vehicle types, assuming that they have the average predictor values observed for the combined urban and ex-urban sample i.e. torque (305 Nm), power (173 HP), number of seats (5), volume (13.0 m^3) and were first produced in 2012. Overall 12.3% more litres of petrol is used per 100 km than diesel, especially in urban travel (Table1). This results from the increased energy density of diesel compared to petrol[30]. Urban travel requires 49.7% more fuel than ex-urban travel (averaged across all types and fuels). Predicted consumption of fuel increased with the overall power of the vehicle, but decreased with torque. This is expected because torque indirectly measures the amount of power transferred to propulsion of the vehicle. There was a strong negative relationship between first year of production of the model and its fuel consumption, showing excellent improved fuel efficiency of the more modern ICVs. Vehicle type had the least overall impact on fuel consumption and was mainly reflected in higher fuel consumption by SUVs. Fig.1 and Table 1 emphasize that the proportion of travel within urban compare to ex-urban conditions has a much greater effect on the fuel consumption than does the fuel and vehicle type itself.

Substitution of the size, power etc. predictors into the GLMs led to the predicted fuel consumption of each of the LEVs reported in Table 2 had they been an ICV of similar size and performance. We predict that the smallest LEV operating in New Zealand so far (iMiEV) would use just a third of the very largest (Tesla Model S), had each been an ICV. The Generation 2 Leaf[31] has lower predicted fuel consumption that the Generation 1 Leaf, even though the motor and battery did not change, and reduction in the kerb weight was small. The difference arises mainly because the Generation 2 was first produced in 2013, whereas the Generation 1 was released for mass production in 2011 and the efficiency of ICVs was improving over that period i.e. purchasers of a new Leaf in 2011 or 2012 would have avoided more fuel use than an equivalent choice after 2013.

[30] www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf

[31] The original Nissan Leaf was modified in 2013. This revised model is called 'generation 2' In New Zealand, but 'Generation 1.5' in some overseas juridictions.

Table 1. General Linear Model parameters that predicted fuel consumption (L/100 km) of cars driven in urban (<50 kph restricted) zones, outside urban zones, and combined urban and Ex-urban zone.

	Urban (86%[1])			**Ex-Urban** (85%[1])			**Combined** (84%[1])		
Predictor	estimate	s.e.	t pr.	estimate	s.e.	t pr.	estimate	s.e.	t pr.
Constant	738	102	<.001	292.5	57.2	<.001	549.9	79.4	<.001
Fuel Type[2]	1.301	0.554	0.021	0.511	0.282	0.074	1.072	0.427	0.014
Max Torque (Nm)	-0.0191	0.00364	<.001	-0.00756	0.00185	<.001	-0.01069	0.00284	<.001
Power (Hp)	0.04416	0.005	<.001	0.01729	0.00256	<.001	0.02551	0.0039	<.001
Seats	1.075	0.283	<.001	0.495	0.144	<.001	0.594	0.218	0.008
Type Sports[3]	1.355	0.847	0.114	0.995	0.432	0.024	0.852	0.66	0.201
Type SUV	1.189	0.56	0.037	0.615	0.293	0.039	1.246	0.422	0.004
Type Utility/Van	-0.92	1.1	0.404	-0.06	0.559	0.915	-0.376	0.848	0.658
Volume (M^3)	0.545	0.155	<.001	0.3934	0.0787	<.001	0.462	0.117	<.001
Production Year[4]	-0.3695	0.0507	<.001	-0.1464	0.0284	<.001	-0.2748	0.0394	<.001

[1] Percent variance explained by the overall model.

[2] Reference level for the model was diesel (i.e. add this coefficient for predicting petrol consumption.

[3] Reference level for the model was ‘car’ type.

[4] Year of first production of that model

The eNV200 van also has the equivalent motor and battery as a Nissan leaf Generation 2, but is predicted that it would have required 6.5% and 17.5% more fuel than a Leaf Generation 2 in urban and ex-urban driving conditions respectively, had both been ICVs. The difference presumably arises because of the increased volume of the van, and consequent added drag, especially at the higher speeds of the van in open road conditions.

Qualitative matching by LEV owners nominated the latest models of Nissan Pulsar, Mazda 3, Ford Focus 3 and Toyota Corolla as being the most similar to a Nissan Leaf in overall performance. Our statistical model predicted a notional fuel use of 6.47 L/100 km for combined (urban and ex-urban) driving of the Gen 2 Nissan Leaf. The observed efficiencies[32] for Nissan Pulsar (6.37 L/100 km), Mazda 3 (6.45) and Ford Focus (6.45) are very similar to our predicted ICV equivalent. However, the Toyota Corolla (7.62) fuel use is higher, probably partly because we used a drive cycle test from 2012 before recent fuel efficiency gains were captured by ICVs.

Observed and predicted performance of Outlander ICV and PHEV models corresponded in ways that give confidence in our modelling approach. The fuel consumption for the ex-urban travel by a 2015 Mitsubishi Outlander 2L petrol model is 7.26 L/100 km[33], after the real-life correction scalar has been applied. Our model predicted it would be 7.34 L/100 km. Two participants of FtF test panel report fuel consumption of their Outlander PHEVs on three long (predominantly ex-urban trips) after the battery was exhausted to have been 6.1 - 6.3 L/100 km[34]. This travel would have included some use of the electric motor as the ICE simultaneously jointly propelled the vehicle and partly charged the battery. As expected, these observed fuel consumptions are lower than our model's predicted consumption of 7.04 L/100 km for ex-urban motoring of the conventional (ICV) Outlander that does not have the assistance of the electrical motor or recovery of energy back into the battery as the vehicle slows and brakes.

Predicted electrical energy use

EV Driving energy consumption varied threefold between the different models of LEV being operated in New Zealand so far (Table 3). It is not clear whether the 'real-life driving' adjustment of 1.273 that is applied to driving cycles of ICV is also applicable to electric vehicles.

There is only a very loose correlation between the predicted ICV equivalent consumption (based on an ICV of similar size, power, torque and type) and the observed EV driving energy consumption (Fig. 2). The Tesla S stands out as having remarkably good EV driving efficiency considering that is comparatively such a large and powerful vehicle. The two PHEV models have high electrical energy use per 100km (Fig. 2), presumably because relatively small electrical motors are propelling reasonably heavy vehicles.

[32] Using the 2014 models for each around 2000cc ICE capacity.
[33] Measured in a drive cycle test.
[34] Mark Walkington and Parry Guilford, in litt.

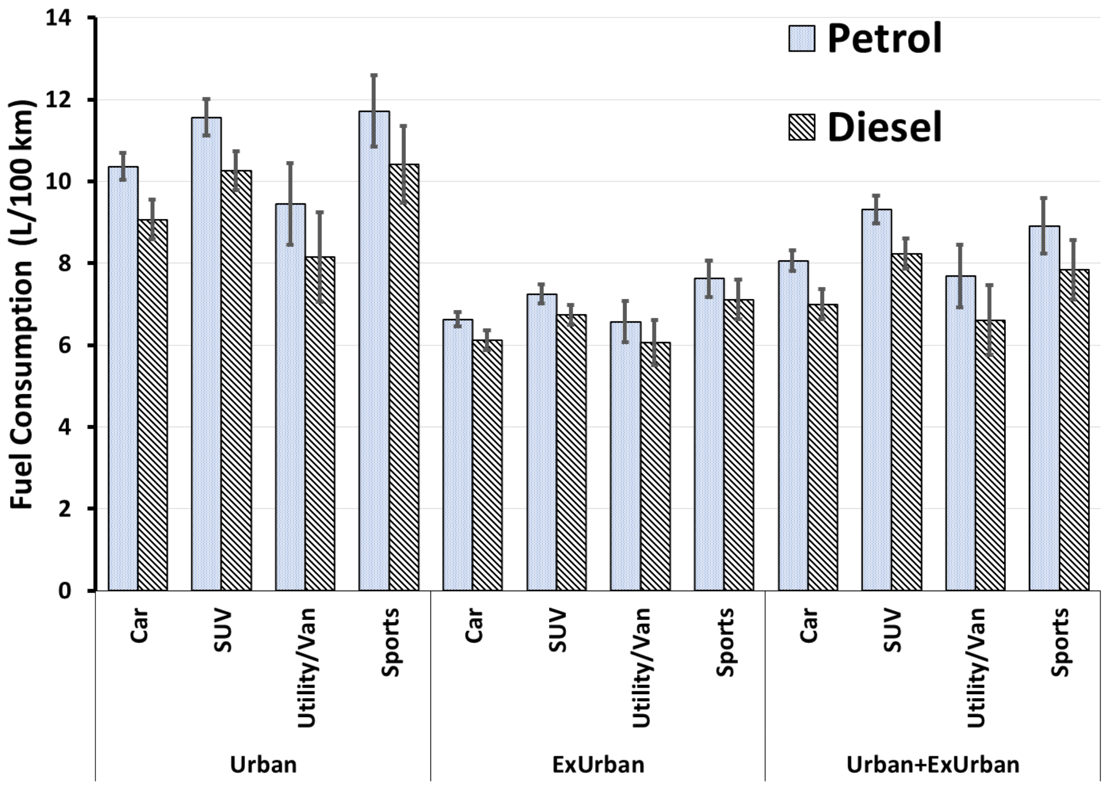

Figure 1: Fuel consumption (L/100km) predicted by our General Linear Models for each fuel and vehicle type being driven in urban (<50 kph restricted) zone, outside the urban zone and for combined zones.

Table 2. Fuel consumption (L/100 km) of an Internal Combustion Vehicle of equivalent style, size, power, torque and year of first manufacture as predicted by our General Linear Model for Low Emission Vehicles operating in New Zealand.

Model[1]	Petrol			Diesel		
	Urban	**Ex-Urban**	**Combined**	**Urban**	**Ex-Urban**	**Combined**
iMiEV	5.25	3.90	4.85	3.95	3.39	3.77
Renault Zoe	5.83	4.69	5.21	4.53	4.18	4.14
Leaf Gen 2	7.48	5.54	6.47	6.18	5.03	5.40
Chevrolet Volt Gen I[2]	7.39	5.38	6.48	6.09	4.87	5.41
Leaf Gen 1	8.22	5.84	7.02	6.92	5.33	5.95
Audi A3 e-tron[3]	8.80	5.83	7.02	7.50	5.32	5.95
eNV200	7.97	6.51	7.29	6.67	5.99	6.22
BMWi3[2]	9.71	6.24	7.61	8.41	5.73	6.54
Mitsubishi Outlander[3,4]	10.76	7.38	9.19	9.46	6.87	8.12
Tesla Model S	16.88	9.69	12.12	15.58	9.17	11.05

[1] Vehicle models are arranged in order of increasing combined fuel consumption.

[2] Range extender model, so power and torque estimated for electrical motor only

[3] Plug-in Hybrid model, so power and torque estimated for combined electrical motors and ICE

[4] Model given is for 2014 Outlander specifications

Table 3. Observed electric motor energy consumption of LEVs operating in New Zealand.

Model [1]	Usable Battery Capacity (kWh)	EV Range (km)	Driving cycle		Adjusted [2]	
			kWh/100 km	km/KWh	kWh/100 km	km/KWh
iMiEV[3]	16.0	160	10.0	10.0	12.7	7.9
Renault Zoe	22.0	210	10.5	9.5	13.3	7.5
BMWi3	18.8	130	14.5	6.9	18.4	5.4
Leaf Gen 2	24.0	135	17.8	5.6	22.6	4.4
Tesla Model S	70.0	390	17.9	5.6	22.8	4.4
Chevrolet Volt Gen I	10.3	56	18.4	5.4	23.4	4.3
Leaf Gen 1	24.0	121	19.8	5.0	25.2	4.0
eNV200	24.0	121	19.8	5.0	25.2	4.0
Mitsubishi Outlander	12.0	55	21.9	4.6	27.9	3.6
Audi A3 e-tron	8.8	27	32.1	3.1	40.9	2.4

[1] Vehicle models are arranged in order of increasing electrical energy consumption.

[2] Adjusted efficiencies have been multiplied by the same 'real-world consumption' factor (1.273) used to scale fuel consumption of ICVs from simulated driving cycles.

[3] Assumes Japanese manufacture inclusion of lithium titanate oxide SCiB battery technology.

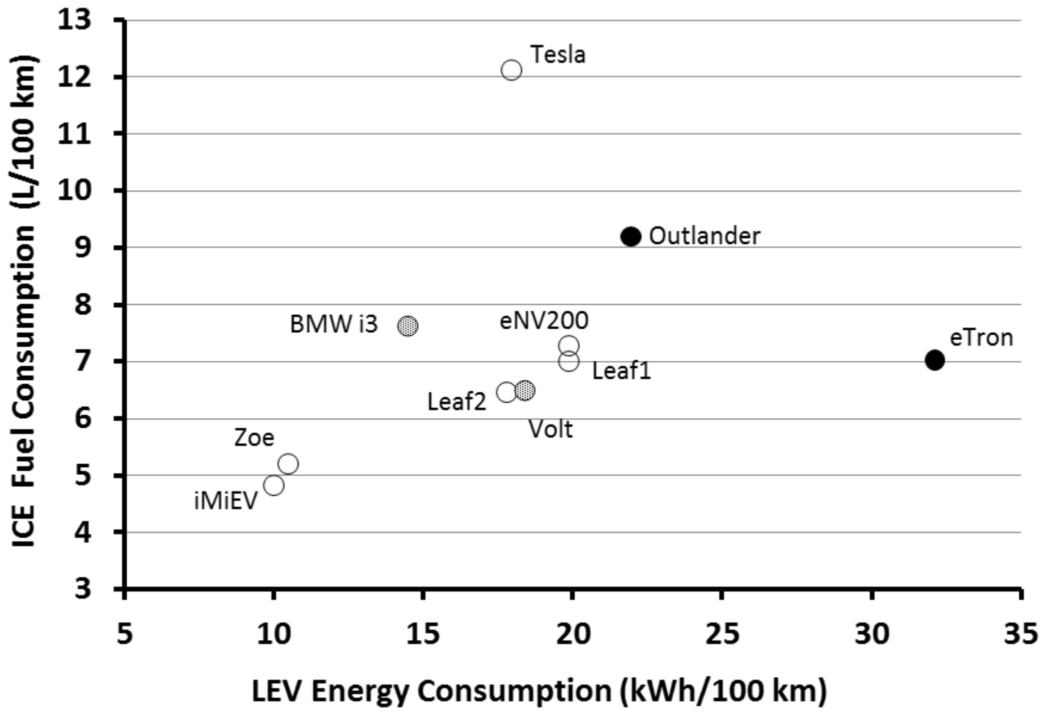

Figure 2. Predicted fuel consumption of equivalent ICVs versus predicted LEV energy consumption. Open circles = EVs; Stippled circles = Range Extender models; Filled-in circles = PHEVs. Energy consumption for PHEVs and REXs assume that they are travelling in full EV driving mode.

Discussion & Conclusions

Fuel consumption estimates

People purchase vehicles on varying emotional and practical criteria according to need, lifestyle, performance, cost, ethics and aesthetics. For some the contribution of LEVs to combatting climate change is paramount, for others cost saving, for others the high performance and smooth driving simply makes them fun to drive[35]. It is therefore a significant challenge to predict what a current LEV owner would be driving had they chosen an ICV. Building a statistical model where several potential vehicle selection criteria are all included helps find a median predicted fuel consumption for an approximate equivalent of each LEV model, but it does assume that each of those criteria are equally weighted. Our results should therefore be assumed as first approximations until research measures the relative importance of each of the predictors.

Fast acceleration is one factor that attracts some purchasers to buy LEVs[36]. Electric motors are different from the ICEs as they have access to maximum torque and power from 0 rpm, while ICEs depend on the engine rpm being at an optimal range to reach maximum torque or power[37]. This is one reason why electric vehicles might have lower HP values, yet be just as fast as an ICE with much more HP[38]. Our modelling of performance based on independent estimates of power and torque are therefore only approximate. In general we expect the overall performance of the LEVs to be higher at lower rpm when the vehicle is accelerating from a standing start than is reflected in the equivalent torque and power predictors.

Fuel use per km will vary greatly with terrain, load, use of car accessories (air-conditioning, lights, heaters, windscreen wipers) and individual driving style (acceleration, cruising speed, braking). The vehicle driving cycles do not vary load or accessory use, but in real life, larger vehicles and vans will at times carry more weight and therefore may be even less efficient than our model predicts for their smaller counterparts.

The ratio of urban to ex-urban driving has a particularly important influence on fuel consumption (Table 1 & 2, Fig. 1). It will therefore be ideal to build an individual driving 'correction factor' into predictions of the fuel use avoided when driving a LEV rather than simply using average consumption for a given model.

The observed fuel consumption of the four models judged by LEV experts to be most similar to the Nissan Leaf in performance and quality were close to those predicted by statistical model constructed from all 90 vehicles. Also, our model predictions corresponded closely with observed fuel consumption of ICV versions of the Outlander. These comparisons give us confidence that the model has successfully captured a lot of the variation in observed

[35] Moller & Ivanov (2016, 2017a,b).
[36] Moller & Ivanov (2016).
[37] www.carthrottle.com/post/how-do-electric-vehicles-produce-instant-torque/
[38] http://auto.howstuffworks.com/how-does-horsepower-figure-into-electric-cars.htm

fuel consumption to predict the notional consumption of an 'equivalent' ICE year and model. We believe that our model is more objective than qualitative matching of each LEV with a few similar ICV models. It is also flexible and generalizable, so it can reliably predict the fuel savings of new LEVs reaching the New Zealand market in the near future. However, the database of vehicle driving cycle performance and statistical modelling will need to be refreshed regularly to explore whether the recent improvements in ICV fuel efficiency are ongoing and occur at the same rate in future.

EV driving energy consumption

Estimates of EV driving energy consumption are needed to predict the electricity demand of New Zealand's LEV fleet as it grows. The FtF project also needs these estimates to calculate the cost of electricity when predicting savings and return on investment from switching to LEVs. Eventually full life cycle assessment measures will be incorporated into FtF's financial and environmental metrics. These will need to account for the GHGs used to manufacture the LEVs and to generate and distribute electricity[39] and fuel before it reaches a vehicles battery or fuel tank. In the meantime the predictions of avoided fuel use and electricity use presented in this report will be used simply to estimate immediate reductions in running costs and tail-pipe emission from LEVs.

EV driving energy consumption also provides a potential scaler that reflects individual driving performance and challenges. Every month, FtF participants will report their EV driving efficiency, and in the case of PHEVs, also their fuel consumption. An individual 'correction factor' can therefore be calculated for each driver simply by dividing their observed EV driving efficiency by the New Zealand average EV driving efficiency for a given LEV model. The estimates of average fuel use avoided in Table 2 should therefore be multiplied by this correction factor to customise the prediction for each FtF participant. While this correction will undoubtedly improve estimates of cost savings, GHG emissions avoided etc. for each FtF participant's own circumstances, the adjusted measures will still be approximate because the correction assumes that terrain, load, urban driving and individual driving style etc. all affect average EV and ICV driving efficiency to a similar relative degree. EV driving efficiency drops significantly during winter[40], so care will be needed to scale individual performance against a seasonally adjusted average.

Once enough representative measures of EV driving efficiency in New Zealand conditions are available, the average difference in electricity use between driving cycles in controlled conditions and real-life use can be used to calculate a scalar like that used for ICVs in Table 1 & 2 to make generalised predictions about electricity use from Table 3. In the meantime we do not know if the uncorrected driving cycle results (columns 4 and 5 of Table 3) are the best approximation to real-life EV transport efficiency, or whether the adjustment using the

[39] Around 20% of New Zealand's electricity is generated by fossil fuels.
[40] Nixon (2015) calculated that winter range is approximately 70% of that achievable in summer in Christchurch conditions.

ICV scaler of 1.273 (columns 6 & 7) is more appropriate. A small sample of 'test drivers' have been evaluating the FtF beta software by reporting monthly statistics, mostly since August 2016. The average EV driving energy consumption of 94 monthly estimates by 20 different Nissan Leaf (Gen 1 and 2 combined) test drivers so far is 15.29 kWh/100km (6.54 km/kWh). This consumption is lower than that of driving cycles (17.8 kWh/100 km; Table 3), whereas the experience with ICVs is that real-life consumption is 27% higher on average than predicted by the driving cycles (Arup 2015). A much larger sample of consumption measures, spread throughout the year are now needed, along with tests of whether the FtF participants provide a representative sample of LEV efficiencies, to confirm the higher than expected EV driving efficiency. However this preliminary result suggests that the ICV adjustment would make the predictions of electrical energy efficiency worse rather than better. It may also be that the driving cycles are more representative of real-life EV driving efficiency, so we await the international evidence for the relative correspondence between driving cycles and reality for LEVs. The LEV's delivery of immediate torque from a standing start may mean that the stop/start conditions of urban driving has less relative impact on LEVs than ICVs, so we are sceptical that LEVs will show the same degree of difference from within to outside urban areas.

Statistical modelling to determine the predictors of EV driving efficiency requires more local data from a greater variety of vehicles. However, the preliminary correlation analysis in Fig. 2 signals that the PHEVs (and perhaps also REXs) have relatively high energy consumption in EV driving mode. Relatively high EV driving energy consumption of the Outlander (and subsequent PHEVs) is important because the PHEVs are likely to be particularly popular in New Zealand where off-road use is part of many people's lifestyles and range anxiety is exacerbated by sparse rapid charging infrastructure. Relatively low EV driving efficiency has less impact on cost savings and return on investment than does low ICV efficiency because fuel is much more expensive than electricity when propelling vehicles. However, there is more embodied energy (and so more GHG emissions during manufacture) in PHEVs and REXs, so their initial cost is higher. Therefore their lower EV driving efficiency further erodes the relative financial and environmental net benefits of choosing PHEVs and REXs over EVs. A crucial and as yet unmeasured variable is the proportion of travel by a PHEV and REX that is in pure EV driving mode; and the proportion of battery energy used in a REX that is from a plug-in source rather than the ICE used to recharge the battery once the car has exhausted its original charge.

More information is needed to assess whether the BMW i3 has unusually high efficiency, or whether REXs in general are relatively less efficient (in part because of the weight of the ICE and fuel tank used to charge the battery). In general there is little Life Cycle Assessment and comparative information on the relative benefits of REXs compared to PHEVs, but each should be treated separately as very different modes of propulsion when compared with pure EVs.

The importance of improved efficiency measures

We have modelled travel efficiencies in this study primarily to estimate the fuel use avoided by a notional 'control group' of equivalent ICVs that would otherwise have been used by people operating LEVs. This is an indirect but much more cost-effective method than establishing a formal matched control group of ICVs to monitor every month alongside the FtF panel. Efficiency measures are key elements of most of the proposed FtF formulations currently under development (Moller & Ivanov in prep.): i.e. cost savings; return on investment; range between battery charges; impact of battery health degradation; GHG emissions and their equivalents; comparisons between models and types, seasonal and terrain impacts. Fine-grained and customised measures of efficiency and resulting benefits are an important part of FtF's way of operating and incentivising data reporting.

Apart from the use in FtF, efficiency measures are useful in their own right and for much broader and varied applications. They can help people choose the most appropriate LEV for their needs and budget, can rapidly assess new LEV models entering New Zealand into such choices, and can form the basis of learning and policy development to accelerate LEV uptake in New Zealand. Electricity demand planning and optimisation of electricity supply is one important national priority that will be informed by LEV efficiency measures. Unwanted impacts of transport can be avoided by reducing the overall kilometres travelled on New Zealand roads. Resource and pollution costs of vehicle manufacture can also be reduced by reducing the number of vehicles owned and operated in New Zealand. These are formidable challenges.

A complementary and more politically achievable way to reduce unwanted transport impacts is by improving transport efficiency i.e. reduced 'cost' per km, 'cost' per car and ultimately cost per person-kilometre travelled. This can primarily be achieved by reducing fuel and electricity use, environmental harm and social impacts per km travelled, by increased sharing of private and public transport, and by concentrating all necessary travel in fewer vehicles. Ultimately transport system sustainability and resilience is most likely to be improved by a combination of strategies that improve efficiency and reduce distances travelled. LEVs have enormous potential to increase the financial, environmental and social efficiency of New Zealand's transport system. This very preliminary study signals the importance of obtaining improved estimates of EV, REX and PHEV efficiency in New Zealand to capture these benefits.

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Appendix: Glossary and abbreviations used in this report

Abbreviation	Description
EPA	US Environmental Protection Agency
EV	Electric vehicle
FtF	The *Flip The Fleet* project
GLM	General Linear Model is an Analysis of Variance procedure in which the calculations are performed using a least squares regression approach to describe the statistical relationship between one or more predictors and a continuous response variable. Predictors can be factors and covariates
ICE	Internal combustion engine
ICV	A vehicle powered solely by an Internal combustion engine
LEV	Low Emission Vehicle. Battery Electric Vehicles or Plug-in Hybrid Vehicles, but excluding Conventional Hybrid Vehicles and Hydrogen cell vehicles.
NEDC	New European Driving Cycle
PHEV	Plug-in hybrid electric vehicle. An electric motor and an ICE directly propel the vehicle. These models are sometimes also referred to as a “Parallel PHEV”.
REX	A ‘Range Extender’ plug-in electric vehicle i.e. These vehicles are propelled entirely by an electric motor, but they have a small internal combustion engine and petrol tank on board that generates electricity to recharge the main battery serving the vehicles electric motor(s). These models are sometimes also referred to as a “Series PHEV”.