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# An Interdisciplinary Study to Explore Impacts from Policies for the Introduction of Low Carbon Vehicles

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# An Interdisciplinary Study to Explore Impacts from Policies for the Introduction of Low Carbon Vehicles

Driven by concerns of climate change, governments across the world are introducing a number of policies to accelerate the uptake of low carbon vehicles, with a specific focus on electric motors. However, there is uncertainty in the effectiveness of such policies and technology pathways, which are inherently interlinked. This paper considers the short-term situation to 2020 and focuses on the concern that these policies may bring about some disproportionate impacts in society due to changes in mobility. An ethical framework is established that seeks to balance obligations to reduce greenhouse gas emissions and rights to car ownership, then selected policies are modelled within this framework to assess acceptability of implementation. Although these policies are successful in introducing low carbon vehicles and reducing greenhouse gas emissions, findings also indicate uneven cost burdens and reduced affordability of car ownership. Following this, recommendations for policy amendments and model improvements are made.

Keywords: low carbon; electric vehicles; transport policy; ethics; system dynamic modelling

## Introduction

This research addresses concerns that transport greenhouse gas (GHG) emission reduction policies and the opportunity for car ownership may be in conflict. For over a century, car use has continued to grow in developed countries, to a point where car ownership is no longer viewed as a luxury by many, but as a necessary part of maintaining their current lifestyle. Car ownership is a means to mobility that gives many advantages over other modes, including flexibility, time-savings and independence. Moreover, with many political decisions regarding transport networks and infrastructure since the mid-20th century being biased towards car ownership, some journeys are almost impossible without a car.

However, over the last few decades there has been growing recognition and concern over the potential impacts of climate change caused by anthropogenic greenhouse gas (GHG) emissions, and one of the major sources is the transport sector, which accounts for approximately 15% of global GHG emissions (ITF 2010). As such, governments are introducing policies to facilitate a transition to low carbon vehicles (LCVs), which is further driven by other policies on local pollution and resource security. Although the automobile industry has been very much a free market up until now, these policies are being implemented to stimulate the market for LCVs , which consist of small ultra-efficient conventional (fossil-fuel powered) Internal Combustion Engine Vehicle (ICEV) in addition to alternative fuels and powertrains. The policies are particularly important as LCV uptake is currently stifled by comparatively high purchase prices and/or perceived inferior attributes to current technologies.

The concern which has driven this work is that although these technologies are necessary they, and the policies to promote them, may have a disproportionate negative impact on those in society who are already worst off, by reducing their opportunity to own a car and thus affect their mobility needs. This research considers the initial transition to a low carbon fleet in California, covering a short time period (to 2020) and using a unique interdisciplinary approach that seeks to incorporate an ethical framework for LCV policy within a System Dynamic model, in order to identify potential impacts on both societal inequities and carbon reduction targets. Only once impacts are recognised, can they be duly considered in policy appraisal. It should be noted however, that in this study we limit ourselves to considering a constant car fleet, and as such does not consider indirect effects of changes in car ownership or transport behaviour.

This paper is structured as follows. Firstly, an ethical framework is established which argues that governments have obligations to mitigate climate change, but also that these must be balanced against individuals' claims to car ownership, with a focus on those already worst off in society. This is followed by a brief overview of the two policies considered in this specific study, which are Californian regulations on automobile manufacturers and purchase rebates for customers. The third section describes the methodology applied to a case study model of these policies and then the model outputs and findings are presented. Finally, the conclusions from this work are presented, which link together the modelling findings and ethical framework, presenting recommendations for policy amendments and model improvements.

## The Ethical Framework: A Balancing Act

### *Climate Change*

It is widely accepted that humans are responsible for contributing towards climate change, and that it will harm a significant number of people across the world, both those alive now and future generations (IPPC 2007). The extent that humans can be held accountable and how to respond is the more disputed ethical debate. Climate change poses a number of philosophical challenges as it addresses responsibility, justice, rights and harms

The gathering catalogue of work on climate change ethics (see, for example, Gardiner et al. [2010]) generally agrees that Western governments are morally obliged to take action to prevent or restrict carbon emissions and work towards both climate change mitigation and adaptation. Alongside this there is a weak claim that individuals are obliged to reduce personal emissions (Butler 2010; Hourdequin 2010; Nolt 2011) but obligations lie more strongly towards ensuring that governments are successful in fulfilling their obligations to implementing climate change mitigation policies and, once in law, to follow legal policies (Cripps 2011; Sinnot-Armstrong 2005).

### *Car Ownership Claims*

The private automobile is seen as an essential part of everyday life for many citizens in the western world. To an extent, this is true regardless of class, income, location or family and work commitments. The accessibility it provides not only adds value to lives through enabling involvement in social activities, but also may be a vital instrument in pursuing deeply held convictions, assuring employment and security, and allowing a freedom of movement in many other areas important to us as individuals (Featherstone, Thrift, and Urry 2005; Lomasky 1997; Rajan 2007). In fact, it is most difficult for one to imagine what the world could be like if the car had not been invented.

Since the first cars and roads were introduced around a hundred years ago, infrastructure and culture have co-evolved, and while it is outside the scope of this work to go into this history, numerous political decisions have indirectly enabled it’s place in society, almost to the point of creating a ‘lock-in’ to car ownership (for example cuts to rail networks and the building of out-of-town shopping and leisure centres). It may be argued that some members of society rely so heavily on their access to a private car, that their standard of living may be unfairly reduced if that access is prevented or diminished in some way, especially if it contributes to concerns of social exclusion (Lucas 2012; SDS 2011).

As such, there are certain segments of society that may have special or stronger claims than others for the preservation of car ownership should policies to decarbonise transport impact on the opportunity to do so. This may depend upon personal mobility (related to any physical disabilities), current use (reliance on car ownership for maintaining social relationships, commitments to work, study, domestic tasks and hobbies, availability and cost of other modes of transport) or preference satisfaction (some people may simply enjoy driving their car). The short time scale of this work reflects the recognised need to move away from private car ownership in the long term. For now, the question of whether cars should be allowed at all is one that will be put aside, though it is acknowledged that there are many reasons why we may wish to remove cars from the roads, from environmental and safety concerns to social inequality (Sloman 2006).

### *Striking the Balance*

Assuming that harmful anthropogenic climate change is occurring, is wished to be avoided (or minimised) and that the automobile makes a significant contribution, then it follows that carbon emissions from automobiles must be reduced. As there is currently such heavy reliance on the automobile, climate change mitigation policies may therefore place unfair burdens on some people, even if in some cases it can be argued to be a luxury. This is particularly important for those who are already the most vulnerable in society and have strong claims for ownership.

To reconcile climate change obligations and car ownership claims, this paper assumes a long term aim to decarbonise transport, and a short term aim to minimise the negative impact on car ownership. This reflects an ethical framework that sees coercive LCV policies as permissible (due to the harms of climate change), but requires within this protection for those who are already amongst the worst off in terms of mobility (Harrison, forthcoming). There are already numerous examples of this type of public policy, such as council tax discounts and exemptions, disability access regulations and the semi-controlled free market.

In this research, a system dynamic model of certain policies for low carbon vehicle uptake is explored to understand what impacts the tested policies may have on this ethical framework, by realising carbon reduction targets and highlighting areas of concern regarding inequalities in the opportunity to own a car. The focus is on income segments and ownership costs as we have identified suitable proxy indicators for income groups in the model.

## Low Carbon Vehicle Uptake Policies

International LCV policies are driven by GHG reduction goals and managed by the UN Environment Programme (UNEP 2012) and the World Forum Harmonisation of Vehicle Regulations (UNECE 2012). Individual regions and countries then translate these into their own laws. Policies cover barriers to LCV uptake on both the demand and supply sides. Some may cover both or interact between them – for example building infrastructure assures both consumers and manufacturers of the government commitment to a low carbon fleet, whereas vehicle demonstrations are required to build consumer confidence in the technologies, which in turn assures manufacturers of a viable business case.

### *Policies Explored in this Research*

This study assesses the *Californian Advanced Clean Cars Program*, which combined previous vehicle regulations on pollutants with newer initiatives driven by climate change. Two policies within this programme are of interest in this paper, *Regulations* on the automobile manufacturer, and *Subsidies* (or rebates) on purchase prices for the car owner.

*The Low and Zero Emission Vehicle Regulations*[1] classifies ZEVs as Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PiHEV), and (to a lesser extent) conventional Hybrid Electric Vehicles (HEV). These Regulations place the onus on the manufacturer to reduce the average fleet[2] emissions of Green-House Gases (GHGs) through producing more LEVs, and sell increasing shares of ZEVs, by imposing civil penalties on the manufacturers for non-compliance. These penalties are calculated on GHG and ZEV "credits" earned over a period, valued at $5000 fine per negative credit (over 5 years for GHG and 3 years for ZEV) is incurred. Under the LEV component, GHG credits are calculated annually by the difference between the standard government target and actual sales weighted fleet emission average. The ZEV credit target for a company is a percentage quota of non-ZEV sales from the previous six years and credits are awarded to the company for ZEVs produced and sold.

Secondly we consider the *California Clean Vehicle Rebate Project*[3], This is funded by the California Air Resources Board and provides $42m for the period 2009-2013, and is expected to be extended until 2015, to give rebates of up to $2500 to customers who purchase or lease eligible zero emission or plug-in hybrid vehicles. These are very similar to the European Average Fleet Emission Regulations (EC 2012a), which enforce fiscal penalties on manufacturers for every extra g/km $CO_2$ over average fleet targets, and the UK Plug-in Car Grant (OLEV 2011), which currently gives government subsidies of up to £5000 at the point of purchase of eligible plug-in vehicles.

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1 Further information on these regulations can be found on the California Air Resources Board website: http://www.arb.ca.gov/msprog/levprog/levprog. htm. http://www.arb.ca.gov/msprog/zevprog/ zevprog.htm.

2 This is tailpipe only so includes all ICEV, HEV and PiHEV

3 Further information is available from the Centre for Sustainable Energy, California: http://energycenter.org/index.php/incentive-programs/clean-vehicle-rebate-project.

## Model Methodology

### *Previous Studies*

There have many academic studies on modelling the likely uptake of LCVs, and a selection of these are set out in Table 1. As can be seen, there is a wide range of localities, technologies, modelling approach and study objectives. Most are discrete choice models, whereas more complex system models are beginning to be more widely studied.

| Study | Location | Alternative Fuels and Technologies | Type of model | Study Objective(s) |
|---|---|---|---|---|
| **Ahn, Jeong, and Kim (2008)** | Korea | CNG, LPG, HEV | Choice | Forecast demand (ownership, use, fuel consumption, emissions). |
| **Batley, Toner, and Knight (2004)** | UK | AFV | Choice | Forecast demand, cost elasticities, impact of taste variation. |
| **Beggs, Cardell, and Hausman, (1981)** | UK | EV | Choice | Potential consumer demand, preference parameters. |
| **Brownstone et al. (1996)** | California | AFV | Choice | Forecast demand, usage and charging patterns, including vehicle transactions |
| **Cao and Mokhtarian (2004)** | U.S.A | BF, CNG, HEV | Diffusion | Future demand, evaluate influence of factors and policies. |
| **Dagsvike et al. (2002)** | Norway | LPG, EV | Choice | Potential demand, elasticities, willingness to pay. |
| **EST (2007)** | UK | BF, EV, HEV, HFCV, LPG | Choice | Model vehicle parc and policy mechanisms, project carbon emissions. |
| **Greene, Duleep, and McManus (2004)** | U.S.A | HEV | Choice | Market potential and impact on fuel economy. |
| **Janssen et al. (2006)** | Switzerland | NG | System Dynamic | Estimate market development and study reaction to policies. |
| **Leiby and Rubin (1997)** | USA | BF, CNG, EV LPG, | System Dynamic | Identify conditions and associated costs for successful market transition. |
| **Mabit and Fosgerau (2011)** | Denmark | BF, BEV, HEV, HCFV | Choice | Assess potential future demand. |
| **Potoglou and Kanaroglou (2007)** | Canada | AFV, HEV | Choice | Influences on choice and willingness to pay. |
| **Shepherd, Bonsall, and Harrison (2012)** | UK | BEV, PHEV | System Dynamic | Considers impacts on future demand and carbon emissions. |
| **Struben and Sterman (2008)** | California | AFV | System Dynamic | Feedbacks that affect consumer awareness of AFV and diffusion. |
| **Tran et al. (2013)** | Global | BEV, HEV, HFCV. PHEV | Energy System | Assess consumer heterogeneity for early and mass market adopters. |
| **Walther et al. (2010)** | California | BEV, HEV, PHEV | System Dynamic | Examines manufacturer strategies for compliance to emission regulations. |

Table 1: Selected LCV uptake model studies *(*CNG: Compressed Natural Gas, LPG: Liquefied Petroleum Gas, BF: Biofuel, HFCV: Hydrogen Fuel Cell Vehicle)

The focus of the studies varies between general AFV forecasting (Ahn, Jeong, and Kim 2008; Beggs, Cardell, and Hausman. 1981; Greene, Duleep, and McManus 2004) or willingness to pay (Batley, Toner, and Knight 2004; Dagsvik et al. 2002; Potoglou and Kanarogolou 2007) to more explicit considerations such as policy development and requirements (Cao and Mokhtarian 2004; EST 2007; Janssen et al. 2006; Mabit and Fosgerau 2011; Shepherd, Bonsall, and Harrison 2012; Struben and Sterman 2008), wider system impacts (such as environmental or energy demands) (Tran et al. 2013) and manufacturer strategies (Walther et al. 2010).

These studies generally suggest that ICEV will continue to dominate in the immediate future due to its current strong and widespread existence and infrastructure, combined with higher costs and deficient LCV attributes. Despite this, most studies agree that under the right conditions, a slow but successful introduction of LCVs is possible that will eventually lead to a decrease in emissions. These conditions vary, but include technology improvement without strong government commitment, appropriate timing and co-ordinated policy intervention (Cao and Mokhtarian 2004; Tran et al. 2013; Batley, Toner, and Knight 2004). HEV and PiHEV are positioned to be most favourable as they closely resemble ICEV and are a requirement in the success of LCVs as technology matures and consumer confidence is achieved (Ahn, Jeong, and Kim 2008; Dagsvik et al. 2002; Greene, Duleep, and McManus et al. 2004; Shepherd, Bonsall, and Harrison 2012; Whalter et al.; 2010). Due to this, BEV are thought by many to not expect to gain significant market shares until around 2030, even in the most supportive policy regimes (Dagsvik et al.; 2002, Leiby and Rubin 1997; Mabit and Fosgerau 2011; Shepherd, Bonsall, and Harrison 2012) and dedicated CNG, LPG or biofuel ICEV are unlikely to achieve anything more than a niche market position (Ahn, Jeong, and Kim 2008; Dagsvik et al. 2002; Janssen et al. 2006; Leiby and Rubin 1997). However, some studies suggest that there are some strong interactions between different types of LCVs, and their combined impact on emissions (EST 2007; Walther et al. 2010).

Disaggregated studies showed a large heterogeneity in preferences when socio-demographics are taken into account (Brownstone et al. 1996; Dagsvik et al. 2002; Potoglou and Kanaroglou 2007), but it is of note that none of these studies have explicit concerns of how the policies may impact across society. The concern that is addressed in this research is that because of this, many have recommended policies focused on achieving the objective for the study (i.e. emission reduction or market penetration), without assessing the costs they may impose on an individual level, taking an implicit utilititarian stance. We have already outlined our belief that policies should be adopted within an ethical framework that balances long term climate change concerns and short-term prevention of inequalities that may arise from changes in the opportunity for car ownership and use. This study seeks to establish if this can be accounted for within a system dynamic model.

### *Case Study Description*

The case study selected for this research is a recent example that considers the policy Regulation through a detailed and complex system dynamic model (Walther et al. 2010) of the Californian LEV and ZEV Regulations as described previously. The complexity of the model is partly due to the nature of the Regulations, in particular the ZEV classification and credit accounting system, which affects a multitude of feedbacks between the make-to-stock production supply chain and manufacturer adjustment behaviour to when motivated by incurred penalties[4]. Further to this, sixteen different vehicle models are offered through four powertrain options (ICEV, HEV, PiHEV and BEV) and four segments based on vehicle weight and size (extra small (XS), small (S), medium (M) and large (L)). On the demand side, the model links together a diffusion model with an interesting feature of consumer awareness and non-awareness through interaction with drivers of all 16 vehicle types (Struben and Sterman 2008) and discrete choice theory, utilising an established detailed customer choice model (Brownstone and Train 1999).

This level of detail within the vehicle market allows for identification of potential GHG emissions reductions and the deduction of impacts on segments of society desired in order to incorporate the proposed ethical framework. Walther et al., use the model to assess different manufacturer strategies in meeting these regulations at lowest cost, incorporating vehicle or fleet adjustments of ICEV emissions and conservative or aggressive introduction of ZEVs (BEV and PiHEV) though we will not discuss their findings in this study, as they do not specifically relate to the ethical framework.

The model (illustrated in Figure 1) comprises of four modules. The Regulations module is designed to calculate credits and civil penalties through sales (from the Customer module) emissions and ranges of ZEVs (from the Industry module). These outputs feed in to the Industry module and combine with purchaser behaviour (from the Customer module) to predict adjustments in vehicle purchase prices and fuel consumptions and emissions from the GHG regulations, taking into account learning through experience. ZEV adjustment impacts are also calculated in the Industry module, taking into account

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[4] It should be noted that the model assumes an aggregate manufacturer response so that individual manufacturer responses are not included

targets, actual sales, vehicle range, and costs of new technologies. Vehicle demand is calculated in the Customer module, as a function of population and income, with a purchase probability based on customer awareness (through marketing and “driver interaction), vehicle availability, and utility feeding into the choice model. Both the Customer and Industry modules feed into the Infrastructure module, which models the interdependence of market share and network effects.

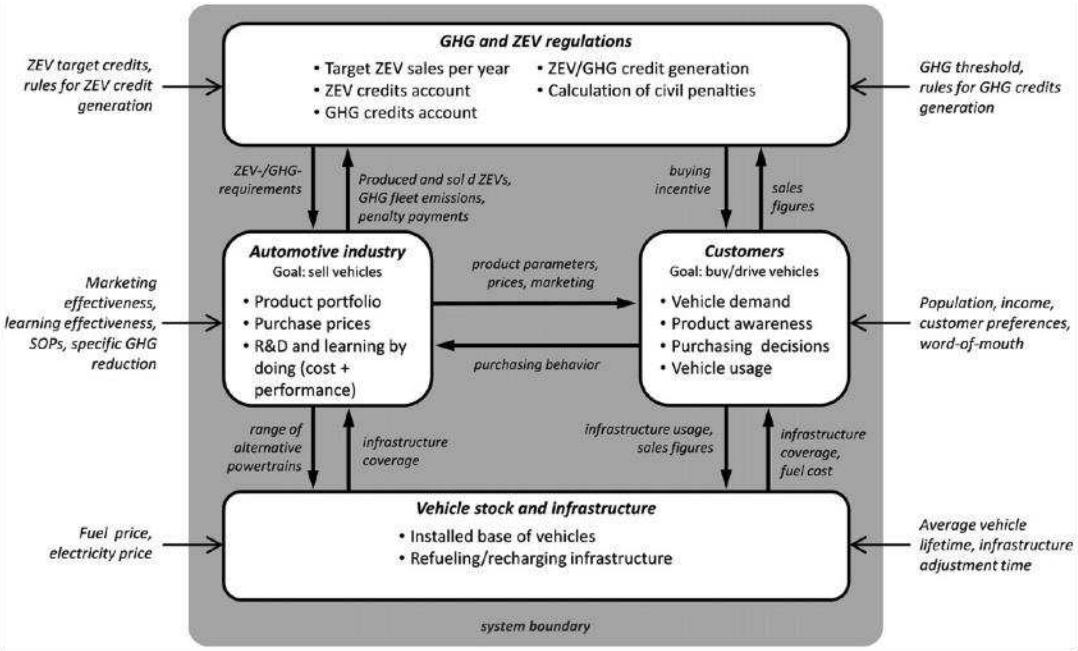

Figure 1: Structure of the model (Source: Walther et al. 2010)

A number of small additions to the original model were required in order to be able to retrieve the information required for this investigation. Firstly it was made possible that the GHG and ZEV penalties were able to be turned off in order to  create a “no penalty” baseline, representative of a ‘Business as Usual’ scenario without *Regulation* in place, as Walther et al. did not consider this scenario. Secondly, a reduction of BEV and PiHEV purchase cost at certain times to imitate a subsidy was included. Thirdly, it was made possible that the BEV models could become available at fixed dates rather than being conditional on infrastructure and range requirements. This was done to allow a fair comparison between certain policy interventions.

All exogenous input data and endogenous feedback equations remained as developed by Walther et al., with the exception of the vehicle availabilities described in the next section.  Input parameters were established in conjunction with the international automobile manufacturer, Volkswagen, and the customer choice and technology diffusion is based on established literature. It was not our purpose to significantly develop or expand the model, but to use it as base to establish and run scenarios of interest in exploring our proposed ethical framework, a focus not taken by the original modellers. Further details of the model are included in Walther et al. (2010).

### ***Scenarios***

Two baselines are considered based on scenarios used by Walther et al. One represents a ‘conservative’ introduction of ZEVs where their availability is dependent upon minimum infrastructural and technical (range) requirements (*Conditional Baseline*), and the other is an ‘aggressive’ introduction, where ZEV models are available on the market at fixed dates (*Fixed Baseline*).

The *Conditional Baseline* best represents a ‘Do Nothing’ scenario, and compares favourably with other predictions for California (Table 2), so can be used as a baseline for market share and emission impacts. However, it cannot be used for direct comparison to the policy scenarios’ impact on vehicle costs because new vehicle models are introduced in response to regulation and subsidies, which makes it difficult to compare with the C*onditional Baseline.*

| **SCENARIO** | **2020 SALES MARKET SHARE (%)** | | |
|---|---|---|---|
| | **PiHEV** | **BEV** | **PiHEV + BEV** |
| **Californian Plug-In Electric Vehicle Collaborative (McCarthy et al, 2010)** | N/A | N/A | 2 – 6 |
| **US Department of Energy (Balducci, 2008)** | N/A | N/A | ~ 10 |
| **Boston Consulting Group (BCG, 2009)** | 29 | 2 | 31 |
| **Conditional Baseline** | 9.34 | 1.91 | 11.25 |
| **Fixed Baseline** | 22.1 | 16 | 38.1 |

Table 2: ZEV market share of sales predictions in 2020

It is recognised that the *Fixed Baseline* is not realistic as manufacturers are much more likely to carry out a conditional production strategy than to develop and release models at fixed times without any government intervention. In effect, the *Conditional Baseline* shows what would happen if no real effort were made to introduce new models, while the *Fixed Baseline* allows the filtering out of policy impacts while accounting for the effect of introducing new models at fixed times in response to or in anticipation of regulations.

Three policy scenarios are tested, all of which have the same fixed introduction of models as the *Fixed Baseline*. The first is the *Regulation* policy, which the model was originally designed around, as explained previously in the case study description. Under Regulation, manufacturers are assumed to meet GHG targets through increased fuel efficiency in all vehicle classes. Second, the current Californian Rebate scheme of $1500 for PiHEV and $2500 for BEV for a 6-year period (as explained in Section 3) is tested in the *Subsidy* scenario. Finally, the two policy scenarios were combined into a *Both Policies* scenario. All input parameters are shown in Table 3.

| **INPUT PARAMETER** | | **SCENARIO** | | | | |
|---|---|---|---|---|---|---|
| | | **Conditional Baseline** | **Fixed Baseline** | **Subsidy** | **Regulation** | **Both Policies** |
| **Model Availability (year)** | **ICEV (XS, S, M, L)** | 2010, 2000, 2000, 2000 | 2010, 2000, 2000, 2000 | | | |
| | **HEV (XS, S, M, L)** | 2014, 2012, 2009, 2010 | 2014, 2012, 2009, 2010 | | | |
| | **PiHEV (XS, S, M, L)** | N/A, N/A, R(60), R(75) | 2016, 2015, 2012, 2013 | | | |
| | **BEV (XS, S, M, L)** | I(0.5), I(0.6), R(200), R(400) | 2011, 2012, 2013, 2015 | | | |
| **Penalties on** | | NO | | | YES | |
| **Subsidy ($)** | **PiHEV** | NO | | 1500 | NO | 1500 |
| | **BEV** | NO | | 2500 | NO | 2500 |
| **Subsidy Duration** | | N/A | | 2011-2017 | N/A | 2011-2017 |

Table 3: Scenario input parameters

## Model Findings

The key outputs of this model that need to be identified and understood in order for the tested policies to satisfy the established ethical framework are GHG emission reductions (regarding long-term climate change targets), and vehicle market shares, vehicle ownership costs and GHG abatement costs to explore policy impacts on social inequalities. We do so by assuming that the four vehicle segments, XS, S, M and L can be taken to be proxy indicators of income. We recognise that this is not always the case, but defend this approach as a starting point that can be built upon in future work.

### *GHG Emissions*

Significant reductions in GHG emissions are witnessed by 2020 under all policy scenarios compared to the *Conditional Baseline,* as shown in Figure 2 as the average fleet GHG emissions (including emissions from tailpipe and/or electricity production).

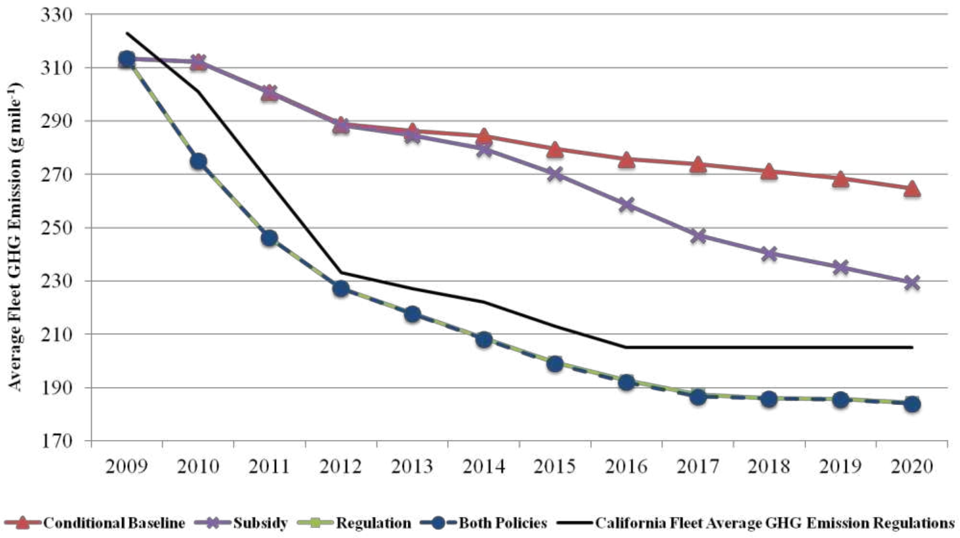

Figure 2: Average fleet GHG emissions (gGHGmile$^{-1}$) for the policy scenarios

Under the Subsidy scenario this is a reduction of around 35 gGHGmile$^{-1}$ and under the Regulation and Both Policies scenarios, the reduction is around 80 gGHGmile$^{-1}$. Assuming an average annual mileage of 15,000 miles per year[5] and a lifetime of 10 years[6], this would equate to total savings of around 34 and 168 Mt GHG (respectively) from all new vehicles produced during the time period. The biggest emission reductions are made when *Regulation* is in place, as manufacturers are set a specific level to aim for within the model, and thus most emission reductions come from efficiencies made with ICE-based vehicles rather than introduction of BEVs. The *Subsidy* scenario does not meet current GHG targets by 2020, as there is no motivation for manufacturers to make efficiencies in ICEV, HEV or PiHEV.

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[5] From registered cars, taken from the California Department of Motor Vehicles (http://apps.dmv.ca.gov/pubs/newsrel/media_center/california_ dmv_statistics.htm, accessed 15th March 2013 and Californian annual mileage (TSI 2009).

[6] The model assumes an average vehicle life of 11 years (Walther et al 2010. We have assumed 10 years so that our calculations are on the conservative side.

### *Market Shares*

Figure 3 shows that compared to the *Conditional Baseline*, the policy scenarios result in more successful BEV and PiHEV new market shares. Under the *Conditional Baseline*, ICEV + HEV retains an almost 90% market share, which is reduced by nearly half with policies in place. The *Regulation* policy was more successful than the *Subsidy* policy, yielding 9.5% more PiHEVs and 17.8% more BEVs by 2020.

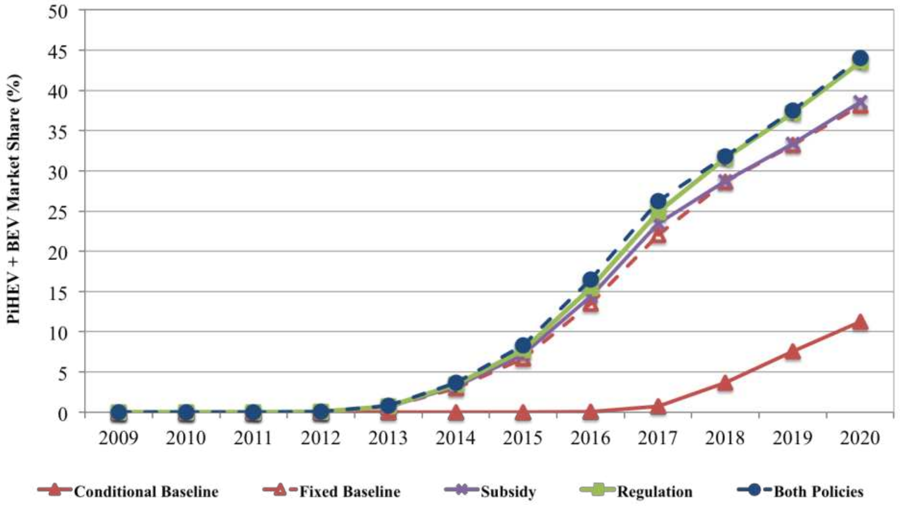

Figure 3: Market share of sales of Zero Emission Vehicles (BEV + PiHEV)

As shown in Table 4 there is only a 1% difference in market share between scenarios with and without subsidies in place. Although the *Fixed Baseline* is not wholly realistic (as explained earlier), this could suggest that the introduction of models at specific times is more important than the *Subsidy* policy being in place. However, the increase due to subsidy is also relatively small when comparing between *Both Policies* and *Regulation.* Yet looking at the difference in shares in the last year of subsidy (2017), they are almost 10% greater in those scenarios with subsidies in place. In fact, this is the peak of the impact and when subsidies are removed, then the share of sales will drop as customers have to pay the full price as under other scenarios. Although this finding may initially suggest that subsidies are not effective, what it may indicate is that subsidies need to be stronger or applied for longer than those tested here to ensure that the learning curve is sustained and prices reduced in the long term. This result is a similar finding to Shepherd, Bonsall, and Harrison (2012) and an effect to be explored through sensitivity testing in future work.

| **SCENARIO** | **SALES MARKET SHARE (%)** | | | |
|---|---|---|---|---|
| | **2017** | | **2020** | |
| | **PiHEV** | **BEV** | **PiHEV** | **BEV** |
| **Fixed Baseline** | 12.6 | 9.4 | 22.1 | 16.1 |
| **Subsidy** | 13.1 | 10.4 | 22.4 | 16.2 |
| **Regulation** | 13.7 | 11.3 | 24.2 | 19.0 |
| **Both Policies** | 14.8 | 12.1 | 24.8 | 19.3 |

Table 4: Market share of sales of PiHEV and BEV in 2017 and 2020 showing the effect of the subsidy that ended in 2017.

As the California Clean Vehicle Rebate Project has been in place now for 3 years, the success of the scheme in reality can be compared to the model. By 2013, 10,036 BEV and 9, 234 PiHEV rebates have been issued. In the model, numbers are only available for year ends, but after the third year of subsidies under *Both Policies*, 8,765 BEV and 3,411 PiHEV have been sold. Although BEV sales are similar, with the model slightly under predicting, PiHEV are a third of reality. These discrepancies could be due to the model having different dates of vehicle availability than in reality and slightly different time scales, as in the fourth year of the subsidies in the model we see the market really take off with sales of over 20,000 PiHEVs and nearly 30,000 BEVs.

### *Cost of Ownership*

To further understand how certain sections of society may be affected by the LCV policies, attention now turns towards the changes in purchase prices over the time scales, shown in Table 5, where for simplicity, only the *Fixed Baseline* and *Both Policies* scenarios are given.

| **VEHICLE SEGMENT** | **PURCHASE PRICE ($)** | | | **% DIFFERENCE between *Fixed Baseline* and *Both Policies* in 2020** |
|---|---|---|---|---|
| | | **2020** | | |
| | **2009** | **Fixed Baseline** | **Both Policies** | |
| **Average** | 19,964 | 22,079 | 25,580 | 15.8 |
| **ICEV** | 19,964 | 21,014 | 26,958 | 28.3 |
| **HEV** | n/a | 19,880 | 23,481 | 18.1 |
| **PIHEV** | n/a | 21,769 | 23,809 | 9.37 |
| **BEV** | n/a | 28,861 | 29,302 | 1.53 |
| **XS** | n/a | 13,432 | 15,048 | 11.9 |
| **S** | 12799 | 16,172 | 20,698 | 28.0 |
| **M** | 17749 | 21,683 | 25,340 | 16.8 |
| **L** | 27649 | 30,365 | 34,413 | 13.2 |

Table 5: Weighted average powertrain and segment purchase prices.

The majority of the price changes witnessed (relative to 2009) came from the introduction of ZEVs that are at a higher cost to begin with (due to being an immature technology with high battery costs). However, under the policy scenario, purchase costs of ICEV also rise due to the cost of technologies to reduce GHG emissions and potential manufacturer policies, which are generally passed on to the customer. The average overall price is 16% higher in 2020 under *Both Policies* than *Fixed Baseline.* The price differential between the policy and no-policy scenario for ICEV and HEV are much greater than those of the two ZEV models, particularly the BEV.

What is of most concern from the point of view of this study is the price differential in segment sizes. Within the model, in order to meet GHG requirements, it is assumed that the manufacturer subjects each segment to the same relative reduction in emissions as the regulation is based on fleet average targets. In 2020, the Small-segment weighted-average purchase price has increased disproportionately compared to other segments, leading to a downsizing to XS-segment and dis-incentivising downsizing from M and L segments. Thus, the greatest price increases compared to a no-regulation scenario will be in the smaller ICEV, which are potentially the most affordable form of LCV. These figures refer to new vehicles, which are most likely to be bought by more affluent members of society, and their decisions will then pass onto the second hand car market, reducing choice for these customers, who represent the majority of society, as (in the UK) less than 10% of car sales are new vehicles to private customers (SMMT 2013).

*Payback*

To understand the type of payback time that a typical driver may expect when purchasing an electric vehicle over a conventional vehicle, the details for a Medium segment vehicle of each powertrain in 2013, under *Both Policies* were taken from the model, and payback time was calculated using Equation (1). This is essentially the purchase price differential divided by the present value of running cost savings. As this uses undiscounted values we recognise the payback period will be an underestimate, but wished to keep to a simple illustrative method.

$$Years\ for\ payback = \frac{PC_{M,BEV} - PC_{M,ICE}}{(RC_{M,ICE} - RC_{M,BEV}) \times AM} \qquad (1)^{7}$$

This optimistic method gives a payback period of 16.2 years, which means that it is unrealistic for a driver to change powertrains if motivated by economic reasons alone in the US. However, although purchase costs in the model are similar to UK prices, running costs are not. For ICEV, HEV and PiHEV, running costs are based on fuel costs alone, and these are approximately two fifths of UK petrol prices, and for BEV electric

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[7] $PC_{s,p}$= Purchase Cost $_{\text{segment, powertrain}}$ (\$); M, ICE = 25,2567.94; M, BEV = 29,549.29; $RC_{s,p}$= Running Cost $_{\text{segment, powertrain}}$ (\$/mile); M, ICE = 0.0523; M, BEV = 0.0359; AM = annual mileage = 15,000.

costs are approximately half of current UK electricity prices[8]. Adjusting for this, the payback time in the UK could be in the region of 4.5 years, a much more attractive proposition to the car buyer.

### *Carbon Abatement Costs*

Finally, abatement costs were calculated for each policy measure, using cumulated discounted costs for customers, government and industry, and compared against the fixed baseline. This was achieved using Equations (2) – (6), a similar method to the EC "GHG TransPoRD" project (Shade et al. 2011) and the well established McKinsey MAC curves (McKinsey 2007).

$$Abatement\ Costs\ (\$/ton) = \frac{C_{FB} - C_P(\$)}{E_{FB} - E_P\ (tons)} \qquad (2)$$[9]

$$GHG\ emissions\ from\ new\ vehicles = \sum_{S,P} EF_{S,P}(t)\ \times NV_{SP}(t)\ \times AM\ \times l \qquad (3)$$[10]

$$NPV\ User\ Costs = \sum_{S,P} \frac{PCs_{S.P}\ (t) \times NV_{S,P}(t)}{(1+r)^t} + \sum_{S,P,t} \frac{(RC_{S.P}\ (t) \times NV_{S,P}(t) \times AM)}{(1+r)^t} \qquad (4)$$[11]

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[8] This is based on publically available prices on websites accessed on 15th March 2013:
http://www.theaa.com/motoring_advice/fuel
http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm? t=epmt_5_3.
http://www.energy.eu/.

[9] $C_{FB}$ = Costs under Fixed Baseline; $C_P$ = Costs under Policy Scenario; $E_{FB}$ = Total GHG Emissions from new vehicles under Fixed Baseline; $E_P$ = Total GHG Emissions from new vehicles under Policy Scenario

[10] $EF_{S,P}$ (t) = emission factor (gGHG/mile) of new vehicles in each segment/powertrain in year t; $NV_{S,P}$ (t) = number of new vehicles in each new segment/powertrain in year t; AM = annual mileage = 15,000 (see previous footnote); l = vehicle lifetime (assumed to be 10 years).

$$NPV\ Government\ Costs = \sum_t \frac{Subsidies\ (t)}{(1+r)^t} \qquad (5)$$

$$NPV\ Industry\ Costs = \sum_t \frac{Industry\ Costs - Industry\ Revenue}{(1+r)^t} \qquad (6)$$

Table 6 shows the discounted costs and emissions of all vehicles bought up to 2020, for the policy scenarios compared to *Fixed Baseline* and corresponding abatement costs are shown in Table 7. With Subsidies, users effectively benefit by $1165 per ton of GHG removed, but at the expense of 1216 $/ton from Government and 138 $/t from Industry. This is because the emission savings from the policy of *Subsidy* alone are relatively small compared to the *Fixed Baseline* and many users are being subsidised to purchase vehicles that would have been purchased anyway as shown in the *Fixed Baseline*. The policy options of *Regulation* or *Both Policies* yield abatement costs more in line with other studies.

| **SCENARIO** | **COSTS ($b)** | | | | | **Emission Reduction (MtGHG)** |
|---|---|---|---|---|---|---|
| | **Users** | | **Government** | **Industry** | **Overall** | |
| | **Purchase** | **Running** | | | | |
| **Subsidy** | -0.95 | -0.18 | 1.18 | 0.13 | 0.18 | 0.97 |
| **Regulation** | 50.66 | -28.58 | 0.00 | -1.05 | 21.03 | 134.95 |
| **Both Policies** | 49.38 | -28.68 | 1.35 | -0.93 | 21.11 | 135.57 |

Table 6: Change in discounted costs ($b) and emission savings (MtGHG) of policies by 2020 (cf Fixed Baseline)

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[11] PCs (t) = Purchase cost of new vehicle after subsidy ($) in each segment/powertrain in year t; r = discount factor = 0.02 (As used within the model. This is consistent with the US discount factor at the time the model was developed); t = number of years since 2009; NB: Industry costs are the negative of profits.

| SCENARIO | CARBON ABATEMENT COSTS ($/tGHG) | | | |
|---|---|---|---|---|
| | Users | Government | Industry | Overall |
| **Subsidy** | -1165.86 | 1216.12 | 137.37 | 187.63 |
| **Regulation** | 163.62 | 0.00 | -7.78 | 155.84 |
| **Both Policies** | 152.67 | 9.95 | -6.88 | 155.74 |

Table 7: Abatement costs of policies in $/t (cf Fixed Baseline)

Although direct comparisons are not possible, urban policy measures studied in GHG-TransPoRD (Schade et al, 2011) have abatement costs between -1159 and €1229 €/t$CO_2$ from a user perspective, -1362 and 3135 €/t$CO_2$ from an authority perspective and -600 and 2535 €/t$CO_2$ from a social perspective. Road technology abatement costs for users range between -€516 (for BEVs) and €106 (for CNG/LPG) €/t$CO_2$ . Under our *Regulation* only scenario, users bear 164 $/tGHG whereas government have no direct costs and Industry benefit -8$/tGHG. Whilst these values appear reasonable per ton of GHG removed, the users incur an additional spend in the region of $50b on purchasing vehicles and only save around $28b from fuel savings under the *Regulation* policies. The manufacturers have passed on the cost of technology improvements to the consumer and see an increase in their profits of around $1b (or 8%) from selling the higher priced vehicles. Industry has a $130m (1%) decrease in profit under *Subsidy* only, and while the overall change in costs for consumers is small when subsidies are applied, they are benefiting only a small share of the consumers, most seeing a significant increase in purchase prices. Thus combining policies distributes cost burdens only at the margin but does lower overall abatement costs.

## Policy Recommendations and Implications

### *Ensure Affordability.*

An overall fleet average emission target may favour owners of larger vehicles if a manufacturer chooses to respond by proportional emission reductions as assumed in this model. As we assume that segments are related to income, this may therefore favour richer segments of society. Moreover, it is smaller ICEV that look to experience the greatest increase in purchase cost under the regulations, and these are the potentially most affordable from of LCV. Further research will be needed to establish if this is due to basic model assumptions of business strategies or within the *Regulation* itself, but could require amendments analogous to existing affordability regulations in the utility sector for those experiencing fuel and water poverty.

If this trend continues into the second hand car market (which we assume it will to a noticeable extent), the poorest may have to keep an older less efficient vehicle, which will counteract GHG concerns and have running costs implications for the owner. Further to this, they may no longer have the opportunity or realistic aspiration to own a car of any type due to higher average costs. The most affluent in society are perhaps the most likely to be purchasing new cars and be realistically and justifiably able to bear these higher purchase costs, however if prices do rise by 16% then some will move to the second hand car market, reducing the new car market. This could have many knock on effects such as increase residual values and a longer average vehicle life. It may be that different ownership models, such as car clubs, could be used to overcome the ownership issue and should perhaps be given greater support, but we do not directly consider them in our study.

### ***Protect Vulnerability***

Segments of society with special claims for car ownership need protection from disproportionate increases in purchase cost or decrease in utility. In order to achieve the emission targets and introduce LCVs, we have discovered in our model that market shares of ICEV + HEV will be reduced greatly from what they are today. Though this is desirable, as we wish to reduce emissions, our ethical framework dictated that the most vulnerable (in terms of mobility) require protection. Even if it is assumed that such a significant change in purchase habits in just over a decade is realistic, it is unlikely that LCV attributes will have improved sufficiently to equal ICEV, particularly in terms of costs. Under this assumption, those segments who have most reliance on car ownership will be most impacted, as they may be priced out from owning a vehicle suiting their needs or bear high costs because of their needs by the introduction of these policies, and thus could qualify for protection from the negative impacts on mobility which are indicated within the model. Further to this, the model suggests that significant downsizing may occur without necessarily providing cost savings. This has ethical implications for those customers who may require a larger vehicle (eg larger families).

### ***Distribute Burdens***

This research found that customers bore the highest costs of the market transformation when *Regulation* is in place. Although customers should expect to bear some costs as car ownership does not outweigh climate change obligations, they should be more equally shared, particularly by industry who pass on a significant amount of their incurred penalties to the customer. The subsidies tested here, which reduced customer costs, were not strong enough to make a noticeable impact to market share, a similar finding to Shepherd, Bonsall, and Harrison (2012). A recent UK report that suggested the significant amount spent on the Plug-in Vehicle Program has only benefited a 'handful' of motorists (Parliament 2012). The Chief Executive of Jaguar Land Rover has also recently spoken out against these subsidies that are 'only for the rich' (*The Guardian,* 5th March 2013), as the high up-front payment and access to off-street parking are required to purchase an EV.

This is perhaps more concerning as the EV owner now benefits from low running costs, and is directly analogous to the feed-in tariffs offered with solar panels which due to their high purchase price and the need to own your own home are only accessible to the wealthier members of society. In both these cases, the tax payer is subsidising the well off at the expense of the less well off (or those without access) to bring down production costs of a technology which will it is argued benefit the whole of society in the longer term. This is though dependent on the lifetime of residual value of batteries in BEV and PiHEV (not needing replacement after 8 years) and availability of off-street charging facilities.

## Conclusion

It is relevant to note at this point that some aspects of this research are restrcited by parameters of the case study itself. Exploring these model limitations and suggested amendments may lead to a model that more accurately reflect the dynamic nature of technological development and demand response, and so be able to make more appropriate policy recommendations. Firstly, it must be remembered that this model only represents purchases of new cars, not the second-hand car market. This is important as those who buy second hand cars are usually the less well off segments of society, many of which may not have access to off-street parking required for charging points. The interaction between new and second hand cars, and the responses of both manufacturer and customer would be very relevant to include but unfortunately there are few models that do explicitly consider the 2$^{nd}$ hand car market. Additionally, as the model is set up to mimic an aggregate manufacturer rather than be representative of the automobile industry with individual players, there is no consideration of competing manufacturer strategies, which has been attempted in a recent model (Boksgerger et al. 2012).

Of particular concern, there are a fixed number of customers in this model, which not alone fails to capture market growth but also restricts the ability of customers to 'drop out' of the market. In addition, the model assumes all choices are relevant for all consumers. Future models should consider restricting the choice set of certain segments of society, for example for those without access to home charging points or high mileage users. These people may already be in categories of higher need (with no home charging likely to be poorer due to housing type and high travel commitment would indicate greater reliance on car ownership) and would therefore be disproportionately affected. Incorporating identifiable segments, such as by income or need would allow a policy maker to understand where inequalities could occur.

Within any model expansion, it is recommended to extend the time period and in doing so consider other LCV technologies and fuels, such as hydrogen fuel cells. This would also require amendment of the ethical framework as claims for car ownership will alter as technology, model options and attitudes develop. Also related to this, it would be more accurate for the model to include GHG emissions as "Well to Wheel" or life cycle emissions, rather than tailpipe only. This is a move currently being given much consideration by the EU for fleet emission regulations (EC 2012b).

In conclusion, the concern of this work is that governments may be obliged to reduce GHG emissions due to climate change, but policies to achieve this via new passenger cars could negatively impact on inequality in society. Overall the findings here have demonstrated the complicated feedbacks that exist within car ownership. It was found that putting regulatory penalties in place would achieve the greatest GHG emission reductions but this also imposes large costs on customers, which are disproportionate across market segments. Subsidies tested here reduce user costs but are not as successful in reducing emissions and may only benefit the more affluent in society who may also benefit from reduced operating costs. However, when combined, these policies can lower overall abatement costs. This appears to defend a claim that governments are indeed obliged to introduce such policies, but also that stronger policies are needed for the substantial reductions required and, as the opportunity for car ownership is affected disproportionately, some policy amendments will be required.

As such, for policies to satisfy an ethical framework that seeks to strike a balance between climate change concerns and protecting claims for car ownership, three key policy recommendations have been made. Firstly, there must be provision in the policy to ensure affordability of car ownership (due to the societal and infrastructural lock-in of car-dependence), but this should not purposefully favour those already most well off. Following this, policies must seek to protect those who may have special claims towards car ownership and are therefore most vulnerable to changes in the opportunity for car ownership. Finally, policy makers should be aware of where the costs related to policy interventions are falling, between customers, government and industry, and make certain that burdens are fairly distributed. Two policy measures related to LCV uptake were considered in this study, subsidy and regulation, both of which are being strongly favoured in both Europe and America. It is the recommendation of this study that they are appropriate mechanisms if they are implemented together and monitored subject to the above recommendations.

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## Acronyms

BEV – Battery Electric Vehicle

DfT – Department for Transport

EU – European Union

GHG – Greenhouse Gas

HEV – Hybrid Electric Vehicle

ICEV – Internal Combustion Engine vehicle (conventionally fuelled)

L - Large segment of vehicles

LCV- Low Carbon Vehicle

M – Medium segment of vehicles

PiHEV – Plug-in Hybrid Electric Vehicle

S – Small segment of vehicles

XS – Extra Small segment of vehicles

ZEV- Zero Emission Vehicle

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