

# Quantifying the role of vehicle size, powertrain technology, activity and consumer behaviour on new UK passenger vehicle fleet energy use and emissions under different policy objectives

Justin D K Bishop<sup>1,1</sup>, Niall P D Martin<sup>1</sup>, Adam M Boies<sup>1,1</sup>

<sup>a</sup>*Energy Efficient Cities Initiative, University of Cambridge Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, United Kingdom*

<sup>b</sup>*Centre for Sustainable Road Freight Transport, University of Cambridge Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, United Kingdom*

---

## Abstract

This paper quantifies the impacts of policy objectives on the composition of an optimum new passenger vehicle fleet. The objectives are to reduce individually absolute energy use and associated emissions of CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>2.5</sub>. This work combines a top down, diversity-led approach to fleet composition with bottom-up models of 23 powertrain variants across nine vehicle segments. Changing the annual distance travelled only led to the smallest change in fleet composition because driving less mitigated the need to shift to smaller vehicles or more efficient powertrains. Instead, managing activity led to a ‘re-petrolisation, of the fleet which yielded the largest reductions in emissions of NO<sub>x</sub> and PM<sub>2.5</sub>. The hybrid approach of changing annual distance travelled and increasing willingness to accept longer payback times incorporates management of vehicle activity with consumers’ demand for novel vehicle powertrains. Combining these changes in behaviour, without feebates, allowed the hybrid approach to return the largest reductions in energy use and CO<sub>2</sub> emissions. Introducing feebates makes low-emitting vehicles more affordable and represents a supply side push for novel powertrains. The largest reductions in energy use and associated emissions occurred without any consumer behaviour change, but required large fees (£79-99 per g CO<sub>2</sub>/km) on high-emitting vehicles and were achieved using the most specialised fleets. However, such fleets may not present consumers with sufficient choice to be attractive. The fleet with best diversity by vehicle size and powertrain type was achieved with both the external incentive of the feebate and consumers modifying their activity. This work has a number of potential audiences: governments and policy makers may use the framework to understand how to accommodate the growth in vehicle use with pledged reductions in emissions; and original equipment manufacturers may take advantage of the bottom-up, vehicle powertrain inputs to understand the role their technology can play in a fleet under the influence of consumer behaviour change, external incentives and policy objectives.

*Keywords:*

CO<sub>2</sub> emissions, local air pollution, energy use, consumer choice, fleet diversity, passenger vehicles

## 1. Nomenclature

- Carbon dioxide, CO<sub>2</sub>
- Tank-to-wheel, the energy use and emissions associated with producing a fuel and delivering it to the filling station, TTW
- Well-to-wheel, the sum of energy use and emissions from TTW and when the vehicle is in use, WTW
- Nitrous oxides, NO<sub>x</sub>
- Particular matter with diameter less 2.5 micrometers ( $\mu$ ), PM<sub>2.5</sub>
- LAP, local air pollutants comprising NO<sub>x</sub> and PM<sub>2.5</sub>
- Business as usual, BAU
- Feebates, a scheme which introduces subsidies for low emitting vehicles and taxes on high emitting vehicles
- Vehicle kilometres travelled in a year, VKT
- Society of Motor Manufacturers and Traders, SMMT
- Hybrid Electric Vehicle, HEV
- Plug-in Hybrid Electric Vehicle, PHEV
- Electric Vehicle, EV
- Port injection spark ignition, PISI
- Direct injection spark ignition, DISI
- Direct injection compression ignition, DICI
- New vehicle fleet size, NVF
- Vehicle footprint (m<sup>2</sup>), the product of wheelbase and width, FP
- Luggage volume (m<sup>3</sup>), LUG
- Time to accelerate from rest to 60 mph or 96.6 km/h (s), Z60
- Effective drag (m<sup>2</sup>), the product of coefficient of drag and frontal area, ED
- Purchase price (£), PP

- Payback time (years), the time taken for marginal vehicle purchase price increase relative to base vehicle to be offset by savings in fuel cost, PBT
- Absolute TTW/WTW CO<sub>2</sub> emissions allowed, C
- Percentage reduction in absolute TTW/WTW CO<sub>2</sub> emissions, C\_RED
- Absolute energy use allowed, E
- Percentage reduction in absolute energy use, E\_RED
- Absolute LAP emissions allowed, N
- Percentage reduction in absolute LAP emissions, N\_RED
- Vehicle Excise Duty, the annual tax on UK vehicles based on their CO<sub>2</sub> emissions (g/km), VED

## 1 2. Introduction

2 This work quantifies the influence of four policy objectives on the composition of an optimum new UK  
 3 passenger vehicle fleet. The individual objectives are to minimise: absolute energy use; the emission of  
 4 tank-to-wheel (TTW) carbon dioxide (CO<sub>2</sub>); the emission of well-to-wheel (WTW)<sup>1</sup> CO<sub>2</sub>; and the emission  
 5 of TTW local air pollutants (LAP, particulate matter and nitrous oxides). The proportion of alternative  
 6 novel powertrains increased from 0.1% in 2000 to 1.4% in 2012. The consequence of a large proportion  
 7 of conventional powertrains means demand for road transport accounted for 27% (40 million tonnes of oil  
 8 equivalent, Mtoe) of all the energy used in the UK in 2012. Consequently, road transport was responsible  
 9 for 23% of all CO<sub>2</sub> (480 Mt), 31% of all nitrous oxides (NO<sub>x</sub>, (340 kt) and 20% of all particulate matter with  
 10 diameter less than 2.5 µm (PM<sub>2.5</sub>, 16 kt)<sup>2</sup>. Therefore, large changes in the composition of the new passenger  
 11 vehicle fleet are required to achieve significant reductions in energy use and emissions. However, it remains  
 12 unclear what that composition – number of vehicles, powertrain type and annual vehicle kilometres travelled  
 13 (VKT) per vehicle – might need to be. This is important because the UK government has committed itself  
 14 to reducing economy-wide GHG emissions by 80% below 1990 levels by 2050 [? ]. Therefore, an important  
 15 contribution of this paper is to highlight the vehicle downsizing, technology switching and changes in VKT  
 16 necessary now to set us on a path to meet future goals.

---

<sup>1</sup>The WTW analysis accounts for the energy used in and associated emissions with the production of fuels, delivery of them to the filling station and their use in the vehicle [? ]. This work considers WTW emissions only.

<sup>2</sup>Data available from the Department for Transport: Tables ENV0102 for energy use, ENV0202 for CO<sub>2</sub> gases; ENV0301 for air pollutants; and VEH0253 for new cars by propulsion/fuel type. Available online at <https://www.gov.uk/government/statistical-data-sets/tsgb03>.

17 Fleet composition and adoption of new technology are modelled in the literature using three main  
18 approaches: diffusion rates; agent-based; and consumer choice [? ]. Diffusion rate models aim to identify  
19 the product life cycle and require both the ultimate market potential and peak year of sales to be known *a*  
20 *priori*. The other two methods consider consumers from the bottom up as individuals or groups, respectively.  
21 Both models require knowledge of consumer preferences. These are represented as a set of weighted attributes  
22 to determine the probability that one of a number of vehicles will be chosen. However, some attributes for  
23 novel powertrains can be difficult to obtain when there is little historical sales data available.

24 This work uses fleet diversity to infer the net result of all consumer preferences from the top down.  
25 Therefore, instead of forecasting new fleet composition based on a host of input assumptions, we determine  
26 what is necessary today (2012) to meet certain policy objectives. There are three advantages to this approach.  
27 First, using current fleet information and data avoids the assumptions and uncertainty associated with long  
28 term scenarios and projections. Second, avoiding speculation by focusing on current state of the art maintains  
29 temporal consistency in the data and avoids technology optimism bias. Third, this work can be updated  
30 periodically using best available information to determine the new, optimum fleet. Gradual changes in  
31 vehicle cost, performance or consumer preference may yield new fleet compositions which evolve predictably  
32 and gradually. Large changes must arise simultaneously to result in a new optimum fleet which deviates  
33 significantly from the trend. Addressing mode shifting, energy use by and emissions from vehicles in service  
34 is beyond the scope of this paper.

35 Diversity is an aggregate measure of the variety of vehicles, classified by Society of Motor Manufacturers  
36 and Traders (SMMT) segment and powertrain technology, which comprise the new fleet due to choices by  
37 individual consumers. The Shannon-Weiner measure (of diversity) [? ] is used for both SMMT segment  
38 and powertrain technology. Customers value diverse powertrain options [? ] and are more satisfied as the  
39 number of technology options, both available and already in circulation, increases [? ]. Initially, however,  
40 alternative technologies may be offered in limited numbers across makes and models which reduces the value  
41 placed on them by consumers [? ]. This work uses bottom-up simulations of 23 powertrain variants across  
42 each of the nine SMMT vehicle segments to maximise the number of options available to a consumer. The  
43 market share and availability of each vehicle powertrain type is an output of the model and serves to avoid  
44 pre-selecting winners and losers.

45 The powertrain technologies considered across the best-selling vehicles in each SMMT vehicle segment [?  
46 ]<sup>3</sup> are: conventional powertrains using advanced internal combustion engines; series hybrid electric vehicles  
47 (HEV); parallel HEV; series plug-in HEV (PHEV); parallel PHEV; fuel cell HEV and PHEV; and electric  
48 vehicles (EV). The internal combustion engine technologies considered were port injection spark ignition

---

<sup>3</sup>The best-selling vehicle reflects the most attractive option to consumers of vehicles in that segment. Competition between makes and models within the same segment does not manifest as a change in diversity of the fleet by SMMT segment.

49 (PISI), turbocharged PISI and turbocharged direct injection spark ignition (DISI), all using petrol. Internal  
50 combustion engines using diesel were all turbocharged, direct injection compression ignition (DICI). The  
51 nine vehicle segments are: the mini, super mini, lower medium, upper medium, executive, luxury, sports,  
52 multi-purpose vehicle (MPV) and sport-utility vehicle (SUV)/4X4 segments. Analysing the vehicle fleet by  
53 SMMT segment, rather than using the average of vehicle sizes, has three advantages: first, the attractiveness  
54 or suitability of certain technologies in specific vehicle segments can be quantified; second, incorporating  
55 the range of vehicle classes accounts explicitly for consumer choice based on the differences in size, price  
56 and performance; and third, changes in the distribution of vehicle number by segment allows the extent of  
57 downsizing to be quantified.

58 In general, scenarios are used to quantify the role of vehicle technology and activity in the fleets of  
59 the future. Often, the scenarios include assumptions on technological learning, performance, costs and can  
60 pre-suppose winners and losers [? ? ? ? ? ? ? ? ? ? ? ? ]. Scenarios extend to include exogenous  
61 factors, such as the price of oil [? ? ] or the extent of biofuel blending [? ? ]. The consensus is that  
62 significant emissions reductions cannot be achieved by a single, silver bullet approach [? ? ? ? ]. Instead, a  
63 low CO<sub>2</sub> emissions solution requires improvements in vehicle technology be paired with consumer behaviour  
64 change [? ? ? ]. Vehicle use is an important factor as growth in travel (activity) implies increasing absolute  
65 emissions which reduces the advantages of fuel efficient powertrains [? ? ? ? ]. Moreover, reducing vehicle  
66 travel can yield greater total benefit (reduced external costs) than may accrue from improved fuel economy  
67 [? ]. Vehicle downsizing, efficiency standards and fuel taxes can deliver large emissions reductions while  
68 mitigating the rebound effect of increased travel demand [? ? ? ]. Therefore, any model which addresses  
69 fleet CO<sub>2</sub> emissions should account for vehicle size, powertrain type and the impact of activity.

70 This work provides novel contributions to the body of knowledge and advances the state of the art in  
71 three main ways. First, we use a novel top-down approach to quantify the composition of the new passenger  
72 vehicle fleet necessary to achieve a suite of policy objectives. Second, the work is diversity-led to ensure  
73 the maximum number of options are available to satisfy consumer preferences and return a realistic fleet.  
74 Third, we optimise simultaneously vehicle segment, powertrain technology and annual VKT to account for  
75 the explicit effects of downsizing, technology switching and change in activity. A summary of the method  
76 is presented in Section ?? where the components of the model are introduced. Consumer behaviour change  
77 is included through soft constraints. This section describes the formulations for achieving the objective via  
78 changes to consumer behaviour and external policy interventions. The impacts of vehicle size, powertrain  
79 technology and activity on fleet diversity, energy use and emission of CO<sub>2</sub> and LAP are presented and  
80 discussed in Section ??.

81 **3. Method**

82 The schematic in Figure ?? illustrates how physical attributes, costs and external fiscal incentives were  
 83 combined in the optimisation routine. The external fiscal incentives considered were fuel duty increases and  
 feebates based on vehicle TTW CO<sub>2</sub> emissions. The optimisation was implemented with Matlab R2015b.

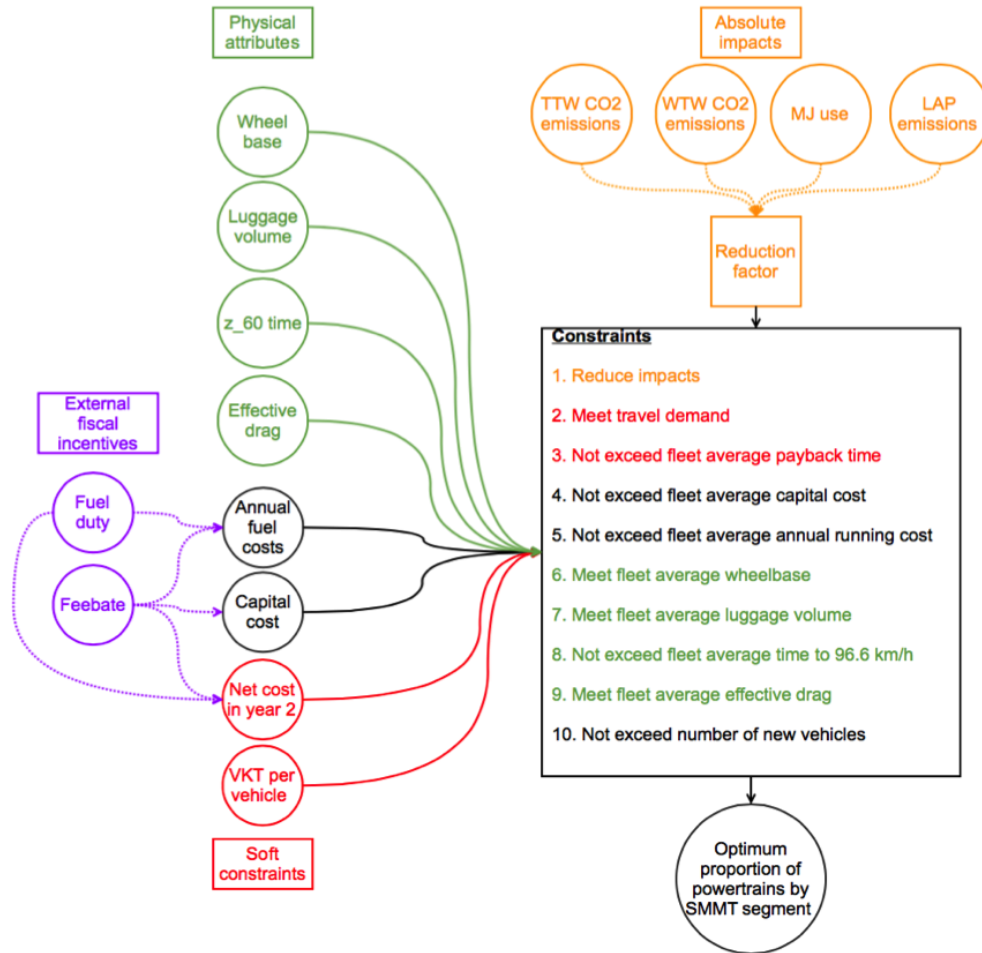


Figure 1: Schematic of methodology. Orange circles illustrate the four policy objectives using consumer behaviour change only. Purple circles illustrate policy objectives to minimise TTW CO<sub>2</sub> emissions with each of fuel duty increases and TTW CO<sub>2</sub> taxes. The red circles represent the soft constraints in the optimisation.

84  
 85 A feasible solution must satisfy the constraints in the optimisation. Therefore, the focus of each policy  
 86 objective – reduction of energy use or emissions – was implemented as a constraint to ensure the new fleet  
 87 met it. The value of the objective function is a consequence of achieving such a solution. The objective of  
 88 the optimisation routine was to maximise fleet diversity (by SMMT segment and powertrain group) using

89 the Shannon-Weiner measure, calculated by:

$$f = - \left( \sum_{j=1}^{n_{SMMT}} x_j \cdot \ln(x_j) \cdot \sum_{i=1}^{n_{powertrain}} x_i \cdot \ln(x_i) \right); \quad (1)$$

90 where:  $f$  is the product of diversities of the fleet by SMMT segment and powertrain group;  $x_j$  is the  
 91 proportion of vehicles in each of the nine SMMT categories,  $n_{SMMT}$ ,  $j$ ;  $x_i$  is the proportion of vehicles in  
 92 each of the powertrain groups,  $n_{powertrain}$ ,  $i$ . Diversity by SMMT segment increased from 1.66 in 2001 to  
 93 1.74 in 2012. Diversity by SMMT segment may change if vehicles possess a similar combination of attributes  
 94 while existing in different size classes. Diversity by powertrain type increased from 0.48 to 0.77 over the  
 95 same period. The latter diversity may be expected to increase as more vehicle manufacturers offer HEV,  
 96 PHEV and EV options. For example, the number of vehicle models with novel powertrains available to the  
 97 market increased from 18 in 2007 to 47 – 24 petrol HEV, five diesel HEV, five PHEV and 12 EV models –  
 98 in 2013 [? ]. Achieving this objective was subject to satisfying the following equality constraints:

99 1. matching sales-weighted average vehicle footprint:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{fp_{i,j} \cdot x_{i,j}}{NVF} = FP; \quad (2)$$

100 where:  $fp_{i,j}$  is the vehicle footprint ( $m^2$ ) of each vehicle: 2.38, mini; 2.49, super mini; 2.65, lower  
 101 medium; 2.76, upper medium; 2.76, executive; 3.04, luxury; 2.43, sports; 2.66, SUV; and 2.70, MPV.  
 102 FP is the sales-weighted average wheelbase in 2012, 4  $m^2$  and NVF is the number of vehicles in the  
 103 new fleet.

104 2. matching sales-weighted average luggage volume:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{lug_{i,j} \cdot x_{i,j}}{NVF} = LUG; \quad (3)$$

105 where:  $lug_{i,j}$  is the luggage volume ( $m^3$ ) of each vehicle: 0.25, mini; 0.29, super mini; 0.32, lower  
 106 medium; 0.46, upper medium; 0.48, executive; 0.45, luxury; 0.34, sports; 0.57, SUV; and 0.14, MPV.  
 107 LUG is the sales-weighted average luggage volume in 2012, 0.34  $m^3$ .

108 3. matching sales-weighted average time to accelerate from rest to 96.6 km/h (60 mph):

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{z60_{i,j} \cdot x_{i,j}}{NVF} = Z60; \quad (4)$$

109 where:  $z60_{i,j}$  is the time (s) to accelerate from rest to 96.6 km/h (60 mph) for each vehicle: 12.1, mini;  
 110 13.3, super mini; 10.8, lower medium; 8, upper medium; 7.4, executive; 7.1, luxury; 6.7, sports; 10.3,  
 111 SUV; and 9.8, MPV. Z60 is the sales-weighted average time to accelerate to 96.6 km/h in 2012, 11 s.

112 4. matching sales-weighted average effective drag, taken as the product of coefficient of drag and frontal  
 113 area and used as a proxy for vehicle attractiveness:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{ed_{i,j} \cdot x_{i,j}}{NVF} = ED; \quad (5)$$

114 where:  $ed_{i,j}$  is the effective drag ( $m^2$ ) of each vehicle: 0.36, mini; 0.68, super mini; 0.65, lower medium;  
 115 0.64, upper medium; 0.55, executive; 0.64, luxury; 0.57, sports; 1.12, SUV; and 0.73, MPV.  $ED$  is the  
 116 sales-weighted average effective drag in 2012,  $0.70 m^2$ .

117 5. matching sales-weighted average annual fuel costs. Fuel costs were the largest activity-related expendi-  
 118 ture for UK motorists in 2011 at £1,500 [? ]. The importance of fuel costs to consumer decision-making  
 119 is such that an estimate for driving 19,000 km (or 12,000 miles) per year is given on the Fuel Economy  
 120 Label on new cars:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{ac_{i,j} \cdot x_{i,j}}{NVF} = AC; \quad (6)$$

121 where:  $ac_{i,j}$  is the annual running cost of each vehicle;  $AC$  is the sales-weighted average running cost  
 122 for the new vehicle fleet in 2012, £1,400. Annual costs were the sum of the capital cost premium and  
 123 annual fuel savings of each vehicle, relative to the base case petrol in each SMMT segment. In April  
 124 2012, petrol and diesel prices were £0.60/l and £0.65/l, respectively [? ]. Costs for electricity and  
 125 hydrogen were £0.51/MJ and £0.11/MJ [? ], respectively. All costs were discounted to present using  
 126 an interest rate of 2.06%<sup>4</sup>.

127 6. matching sales-weighted average vehicle purchase price. Total manufacturing costs are used in [? ].  
 128 These were converted to purchase price using a retail price equivalent of 1.47 which is the median  
 129 value across a number of manufacturers [? ].

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{pp_{i,j} \cdot x_{i,j}}{NVF} = PP; \quad (7)$$

130 where:  $pp_{i,j}$  is the purchase price (£) of each vehicle;  $PP$  is the sales-weighted average purchase price  
 131 for the new vehicle fleet in 2012, £20,000.

132 7. matching new fleet size of 2 million vehicles [? ].

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{x_{i,j}}{NVF} = 1; \quad (8)$$

133 The influence of consumer behaviour change was simulated using two soft constraints: changing how  
 134 far vehicles were driven; increasing the willingness to purchase more expensive vehicles with longer payback

---

<sup>4</sup>Latest UK GDP deflator figures are available from HM Treasury at <https://www.gov.uk/government/publications/gdp-deflators-at-market-prices-and-money-gdp-march-2013>



135 times; or combining both into a third, hybrid approach. These three cases were compared to business as  
 136 usual (BAU).

137 New vehicles (up to three years old) travelled an average 16,000 km annually in 2012. By fuel type,  
 138 new diesel and petrol vehicles travelled 21,000 km and 12,000 km, respectively. Most vehicles (all ages,  
 139 fuels) drove 11,300 km annually in 2012 [? ]. In the model, petrol and diesel vehicle (conventional and  
 140 hybridised) annual mileage was set to 12,000 km and 21,000 km, respectively. Fuel cell and electric vehicles  
 141 were assumed to travel the average annual mileage of new vehicles at 16,000 km which is consistent with the  
 142 findings in Shirk & Carlson, 2015 [? ]. Achieving fleets with a large proportion of novel vehicle powertrains,  
 143 particularly EV and fuel cell vehicles, assumes widespread refuelling/recharging infrastructure exists.

144 Across the total fleet, VKT decreased by 0.86% annually from 16,000 km in 1994 to 13,500 km in 2012  
 145 (total 15%)<sup>5</sup> In the optimisation, annual vehicle mileage could vary between that of new petrol vehicles and  
 146 new diesel vehicles. Total VKT could be up to 0.86% lower than the 2012 value.

$$\left(1 - \frac{0.86}{100}\right) \cdot VKT \leq \sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} vkt_{i,j} \cdot x_{i,j} \leq VKT; \quad (9)$$

147 where: the product of vehicles in each SMMT segment and powertrain group,  $x_{i,j}$  and the annual distance  
 148 travelled per new vehicle,  $vkt_{i,j}$  could be up to 0.86% lower than the 2012 value of 32 billion VKT. The  
 149 total VKT was calculated as:

$$\sum_{k=1}^{fuel_k} x_k \cdot vkt_k \quad (10)$$

150 where k=1 is for petrol and k=2 for diesel;  $x_k$  represents new registered vehicles of fuel k in 2012;  $vkt_k$   
 151 represents annual distance travelled by new vehicles of fuel k. In 2012, there were 970,000 petrol vehicles  
 152 and 1 million diesel vehicles registered for the first time [? ].

153 Payback time was the second of the two soft constraints. Generally, consumers want fuel cost savings  
 154 to offset the capital cost premium of a fuel efficient vehicle within the first two years of ownership [? ? ].  
 155 The number and variety of HEV, PHEV, EV and other powertrain technologies in service currently suggests  
 156 that some consumers accept longer payback times. The payback times for all vehicle powertrain types i per  
 157 SMMT segment j were calculated as in Bishop et al. (2014) [? ] where payback time was the year that  
 158 cumulative annual cash flows became positive. Payback time was set to the vehicle lifetime of eight years  
 159 if cash flows never became positive. Fleet averaged payback time, PBT, could float between one and eight  
 160 years, corresponding to the 2012 fleet average and the vehicle lifetime, respectively.

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} \frac{p_{i,j} \cdot x_{i,j}}{NVF} = PBT; \quad (11)$$

---

<sup>5</sup>Compiled from UK Department for Transport Tables VEH0211 (<https://www.gov.uk/government/statistical-data-sets/veh02-licensed-cars>) and TRA0201 (<https://www.gov.uk/government/statistical-data-sets/tra02-traffic-by-road-class-and-region-kms>).

161 where:  $p_{i,j}$  is the payback time (years) for each vehicle.

### 162 3.1. Sensitivity of optimum fleets to the policy objective

163 The sensitivity of the new vehicle fleet composition was investigated for the four policy objectives to  
164 minimise, individually: TTW CO<sub>2</sub> emissions; WTW CO<sub>2</sub> emissions; energy use; and LAP emissions. Fo-  
165 cusing on the absolute value, instead of those normalised to distance travelled, ensured true reductions were  
166 achieved.

#### 167 3.1.1. Reduce TTW CO<sub>2</sub> emissions

168 Absolute CO<sub>2</sub> emissions from cars and taxis declined by 0.95% annually from 75 Mt in 1999 to 67 Mt in  
169 2010. Over the same period, new vehicle sales declined from over 3.1 million per year to less than 2.5 million  
170 annually. However, the total vehicle fleet grew from 28 million to 34 million because vehicles remain in  
171 service longer now than before [? ].

172 European legislation on CO<sub>2</sub> emissions from passenger vehicles focuses on those at the tailpipe [? ]. By  
173 2015, the new passenger vehicle fleet TTW CO<sub>2</sub> emissions should be 120 g/km, achieved by a combination  
174 of powertrain advances (to 130 g/km) and innovative technologies (the remaining 10 g/km to 120 g/km).  
175 In 2021, the limit falls to 95 g/km with indications of a limit of 68-78 g CO<sub>2</sub>/km in 2025<sup>6</sup>.

176 In 2012, the sales-weighted average TTW CO<sub>2</sub> emissions from new passenger vehicles was 133 g CO<sub>2</sub>/km  
177 [? ]. The average emissions from new cars in Bishop et al. (2014) [? ] was 132 g CO<sub>2</sub>/km. The total  
178 absolute CO<sub>2</sub> emissions of the 2012 and optimum fleets were 4.2 Mt and 4.5 Mt, respectively. The constraint  
179 to reduce absolute fleet TTW CO<sub>2</sub> emissions was:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} c_{i,j} \cdot x_{i,j} \cdot vkt_{i,j} \leq C \cdot (1 - C\_RED); \quad (12)$$

180 where:  $c_{i,j}$  is the TTW CO<sub>2</sub> emissions (g/km) from each vehicle; C is the absolute mass of CO<sub>2</sub> emissions  
181 (g) from the fleet of new vehicles on the road in 2012; and C\_RED is the percentage reduction in absolute  
182 emissions required.

#### 183 3.1.2. Reduce WTW CO<sub>2</sub> emissions

184 The introduction of novel powertrains accompanies the use of alternative transport fuels. The well-to-  
185 tank (WTT) pathway for producing and delivering alternative fuels dominates the vehicle WTW energy  
186 use and emissions [? ? ? ? ? ]. In this work, powertrains use petrol, diesel, hydrogen and electricity.  
187 Best estimates of WTT impacts of delivering the first three fuels are given in Bishop et al. (2012) [? ].

---

<sup>6</sup>Result of a vote in the European Parliament on 24 April 2013 and communicated by press re-  
lease available online at [http://www.europarl.europa.eu/news/en/news-room/content/20130422IPR07527/html/  
Car-CO2-mapping-the-route-to-95g-and-beyond](http://www.europarl.europa.eu/news/en/news-room/content/20130422IPR07527/html/CAR-CO2-mapping-the-route-to-95g-and-beyond)

188 WTT impacts of electricity were 0.42 MJ (chemical energy in fossil-fuels combusted) and 120 g CO<sub>2</sub> per  
 189 MJ delivered to the charging station<sup>7</sup> at a cost of £0.51/MJ<sup>8</sup>. The constraint to reduce absolute fleet WTW  
 190 CO<sub>2</sub> emissions was:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} w_{i,j} \cdot x_{i,j} \cdot vkt_{i,j} \leq C \cdot (1 - C\_RED); \quad (13)$$

191 where:  $w_{i,j}$  is the WTW CO<sub>2</sub> emissions (g/km) from each vehicle.

### 192 3.1.3. Reduce energy use

193 Improving fuel economy of vehicles using conventional fuels can have a positive effect on CO<sub>2</sub> emissions.  
 194 Moreover, mandating an improvement to fuel economy can encourage the increase in supply of more fuel  
 195 economical cars to the market. Therefore, complying with fuel economy legislation requires necessarily that  
 196 losses and inefficiencies in the engine and powertrain be addressed explicitly. Current US legislation focuses  
 197 on improving both fuel economy (reducing energy use) and reducing emissions [? ]. This contrasts the  
 198 European approach which targets TTW CO<sub>2</sub> emissions which are a consequence, rather than a cause, of  
 199 high (conventional) fuel use.

200 Total absolute energy use by the 2012 new passenger fleet was 5 PJ, with average normalised use of  
 201 189 MJ/100 km<sup>9</sup>. Total absolute energy use and sales-weighted energy use per vehicle using vehicle models  
 202 in Bishop et al. (2014) [? ] was 7.3 EJ and 233 MJ/100 km. The base case yielded total and sales-weighted  
 203 energy use of 7.8 EJ and 230 MJ/100 km, respectively. The constraint to reduce absolute energy was:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} e_{i,j} \cdot x_{i,j} \cdot vkt_{i,j} \leq E \cdot (1 - E\_RED); \quad (14)$$

204 where:  $e_{i,j}$  is the energy used by each vehicle, MJ/100 km;  $E$  is average energy use by the fleet of new  
 205 vehicles in 2012; and  $E\_RED$  is the percentage reduction in absolute energy use required.

### 206 3.1.4. Reduce local air pollution

207 Passenger vehicles are responsible for primary non-CO<sub>2</sub> emissions, such as oxides of nitrogen (NO<sub>x</sub>) and  
 208 particulate matter (PM<sub>2.5</sub>). These two pollutants have the largest direct impacts on human health [? ? ? ].

---

<sup>7</sup>These figures correspond to the UK average. See Digest of United Kingdom energy statistics (DUKES) 2012 Tables 5.1 and 5.4 for total electricity generated and total fuel used, respectively. Carbon intensity of electricity fuel mix is available in Table 5A, DUKES 2012 Chapter 5. All available online at [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/65818/5955-dukes-2012-chapter-5-electricity.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65818/5955-dukes-2012-chapter-5-electricity.pdf).

<sup>8</sup>Average of electrical energy used by households in band DC (2,500 kWh < consumption < 5,000 kWh) in the UK in 2012, all taxes included. Data available online in Table nrg\_pc\_204 at [epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main\\_tables](http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables).

<sup>9</sup>See UK Department for Transport Table ENV0103 for sales-weighted fuel economy in 2011. Available online at <https://www.gov.uk/government/statistical-data-sets/env01-fuel-consumption>. 2012 fuel economy was taken as sales-weighted fuel economy of petrols and diesels in the fleet in 2011 [? ].

209 The key benefits of minimising LAP emissions arise from avoided premature deaths due to exposure to PM  
 210 [? ]. In 2012, road transport accounted for 31% and 26% of combustion-related NO<sub>x</sub> and PM<sub>2.5</sub> emissions,  
 211 respectively. Passenger vehicles were responsible for 15% and 6.4%, respectively. Non-combustion related  
 212 PM<sub>2.5</sub> emissions for passenger vehicles accounted for 11% of total emissions (3.9% for road abrasion and  
 213 7.5% for wear to tyres and brakes)<sup>10</sup>.

214 Speed-dependent Euro V emissions factors for NO<sub>x</sub> [? ] and PM<sub>2.5</sub> [? ] were used for petrol and diesel  
 215 vehicles in this work. The speed used to calculate LAP emissions was 44 km/h. This was the weighted average  
 216 of speeds based on VKT travelled per road type. Average road speeds for rural and urban/motorways were  
 217 18 km/h and 63 km/h, respectively. These two road types counted for 42% and 58% of VKT. Additionally,  
 218 the proportion of VKT travelled under urban, rural and motorway conditions was taken as 37%, 42% and  
 219 21%, respectively [? ].

220 LAP emissions factors are sparse for novel vehicle powertrains. Moreover, it cannot be assumed that  
 221 HEV have lower emissions of air pollutants than conventional vehicles [? ]. However, scaling factors have  
 222 been suggested for PHEV which account for the proportion of VKT travelled by road type under all-electric  
 223 power: 0.1 for urban; 0.5 for rural and 0.9 for motorway, all relative to a Euro V petrol vehicle [? ]. Therefore,  
 224 in this work, the conservative approach was adopted where emissions factors for HEV were unchanged from  
 225 conventional vehicles and those from PHEV were scaled using the above factors. Also, the scaling factors  
 226 are given for PM<sub>10</sub> and were assumed to be valid for PM<sub>2.5</sub> which is the focus of this work.

227 Hydrogen- and electricity-fuelled vehicles were assumed to have zero TTW combustion-related LAP  
 228 emissions on account of external fuel production. However, activity-related PM<sub>2.5</sub> emissions arise from wear  
 229 to brakes, tyres (0.0074 g PM<sub>2.5</sub>/km) and the road surface (0.0041 g PM<sub>2.5</sub>/km) [? ]. These emissions  
 230 are independent of the vehicle powertrain technology and SMMT segment. The proportion of total PM<sub>2.5</sub>  
 231 which was activity-related depended on the vehicle powertrain: 30% for diesel vehicles; 70% for DISI vehicles;  
 232 90% for PISI vehicles; and 100% for hydrogen-fuelled and EV. The total suspended particles arising from  
 233 non-combustion sources are dominated by PM<sub>10</sub> which are not considered in this work.

234 LAP emissions from passenger vehicles were 150 kt NO<sub>x</sub> and 4.3 kt PM<sub>2.5</sub> in 2011 [? ]. However, no  
 235 LAP emissions were available for the new vehicle fleet explicitly. Calculated emissions from new vehicles in  
 236 Bishop et al. (2014) [? ] were 15 kt NO<sub>x</sub> (0.38 g/km) and 1 kt PM<sub>2.5</sub> (0.028 g/km). The base case fleet  
 237 emitted 16 kt NO<sub>x</sub> and 1.1 kt PM<sub>2.5</sub>. The constraints to reduce LAP emissions were:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} n_{i,j} \cdot x_{i,j} \cdot vkt_{i,j} \leq N \cdot (1 - N\_RED); \quad (15)$$

---

<sup>10</sup>See National Emission Ceilings (NEC) Directive Inventory for NO<sub>x</sub> emissions (<http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-nec-directive-viewer>) and LRTAP Convention Inventory for PM<sub>2.5</sub> emissions (<http://www.eea.europa.eu/data-and-maps/data/data-viewers/air-emissions-viewer-lrtap>).

238 where:  $n_{i,j}$  = NO<sub>x</sub> or PM<sub>2.5</sub> emissions from each vehicle, g/km;  $N$  = absolute NO<sub>x</sub> or PM<sub>2.5</sub> emissions  
239 from the fleet of new vehicles on the road in 2012, g; and  $N\_RED$  is the proportional reductions in absolute  
240 emissions required.

### 241 3.2. External fiscal incentives

242 Sensitivity of the new vehicle fleet composition to external policies was investigated. Such policies are  
243 designed to encourage a greater shift to low emissions vehicles, while preserving consumer choice and fleet  
244 diversity. The first policy increased duty on fuel and the second policy introduced a feebate. These external  
245 incentives influence running costs and vehicle purchase price, respectively, and associated payback time.

#### 246 3.2.1. Increase fuel costs

247 Increasing fuel taxes can achieve primary policy gains more quickly than new vehicle purchase incentives  
248 because fuel is used by operators of new and existing vehicles. Moreover, increased fuel costs encourage eco-  
249 driving behaviour to conserve fuel and leads both to reduced VKT and associated distance-related external  
250 costs [? ?]. Retail fuel prices are a combination of resource price and tax. Tax comprised 57% of total fuel  
251 prices in the UK in 2012, down from its maximum of 75% in 2000 [? ?]. The policy to increase fuel costs  
252 was implemented by raising taxes to the recent maximum of 75% of retail price. New retail prices at 75%  
253 taxes would be £2.4/l (£0.067/MJ) and £2.6/l (£0.072/MJ) for petrol and diesel, respectively. Electricity  
254 and hydrogen were exempt from tax increases.

#### 255 3.3. Duty on vehicles by CO<sub>2</sub> emissions level

256 An increase in taxes on petrol and diesel targets all vehicles using those fuels. Increasing fuel duties  
257 may have less effect on fuel economy because consumers undervalue fuel savings. Instead, a more effective  
258 approach may be to shift the price signal from the fuel to the vehicle [? ?]. Annually, the UK collects a  
259 vehicle excise duty (VED) based on certified g CO<sub>2</sub>/km<sup>11</sup>. Vehicles are classified into emissions bands with  
260 associated duties. The lowest emitting vehicles receive a reward of no fees.

261 A feebate system introduces capital cost subsidies for vehicles with emissions below a pivot (low-  
262 emissions) and additional fees for vehicles with emissions above the pivot. Such schemes provide consumers  
263 with options to downsize vehicle, shift powertrain technology and switch fuel [? ?]. Feebates may be weighted  
264 according to vehicle attributes, such as mass [? ?] or energy use [? ?]. Some feebates have applied costs per  
265 unit fuel consumed [? ?]. In this work, three pivots of 120 g/km, 95 g/km and 70 g/km were chosen,  
266 corresponding to the TTW CO<sub>2</sub> emissions limits set by the EU, with costs applied to g CO<sub>2</sub>/km emissions  
267 of each vehicle.

---

<sup>11</sup>See the Driver & Vehicle Licensing Agency Rates of vehicle tax. Available online at [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/175492/V149\\_rates\\_of\\_vehicle\\_tax.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/175492/V149_rates_of_vehicle_tax.pdf).

268 The aim of the feebate scheme was to be revenue-neutral and achieved using two costs per g CO<sub>2</sub>/km:  
 269 the first was a rebate for low-emissions vehicles; and the second was a fee for high-emissions vehicles. The  
 270 fees and rebates impacted ownership costs, payback time and the resulting composition of the optimum fleet.  
 271 Therefore, the fees and rebates were not known *a priori*, but were limited to £100 per g CO<sub>2</sub>/km above  
 272 and below the pivot, respectively. These fees align with EU penalties for excess emissions of up to €95 per  
 273 g CO<sub>2</sub>/km [? ]. The feebate was implemented in the model using an equality constraint for the product of  
 274 vehicle number and cost per g CO<sub>2</sub>/km on either side of the pivot:

$$\sum_{j=1}^{n_{SMMT}} \sum_{i=1}^{n_{powertrain}} fee_{i,j} \cdot x_{i,j}^{fee} - rebate_{i,j} \cdot x_{i,j}^{rebate} = 0; \quad (16)$$

275 where:  $fee_{i,j}$  = the fee applied to each g CO<sub>2</sub>/km which a vehicle emits above the pivot;  $rebate_{i,j}$  = the  
 276 rebate applied to each g CO<sub>2</sub>/km which a vehicle emits below the pivot;  $x_{i,j}^{fee}$  = the number of vehicles with  
 277 emissions above the pivot; and  $x_{i,j}^{rebate}$  = the number of vehicles with emissions below the pivot.

#### 278 4. Results and discussion

279 The model was validated by running the BAU case with no reductions in energy use or emissions and  
 280 comparing the result to the 2012 fleet. Figure ??a illustrates the distribution of vehicles by SMMT segment  
 281 in the validated fleet (blue) and the 2012 fleet (yellow). This validated fleet was the base case against which  
 the model outputs under various policy objectives were compared. There was no error between the 2012

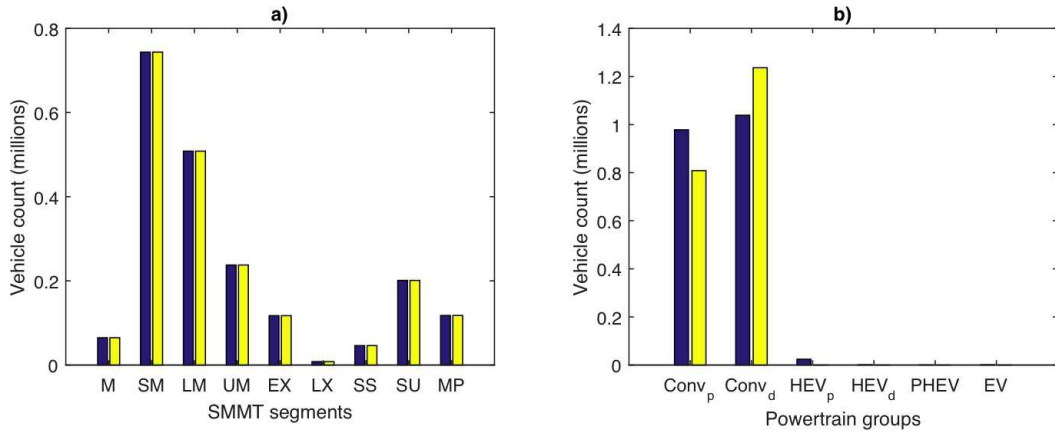


Figure 2: Verification of optimisation model against 2012 new vehicle data to create base case: a) number of new vehicles sold by SMMT segment (yellow bars) [? ] and optimised fleet (blue bars); b) number of new vehicles sold by powertrain group (yellow bars) and optimised fleet (blue bars) [? ]. Label subscripts: p = petrol; and d = diesel.

282  
 283 fleet and base case by SMMT segment. Figure ??b highlights the distribution of powertrains in the 2012  
 284 fleet. There were 17% fewer petrol conventional vehicles in the base case than in 2012, offset by an increase

285 in diesel conventional vehicles and petrol HEV. The difference in energy use and emissions, total or per km,  
286 was less than 10% between the 2012 fleet and base case.

287 There are three main results which are discussed. First, the impact of policy objectives on the composition  
288 of the optimum new vehicle fleet under BAU and consumer behaviour changes. Second, the proportion of  
289 total fleet VKT as a function of SMMT segment and powertrain type and its relation to absolute energy  
290 use and associated emissions. Finally, the influence of BAU and consumer behaviour changes on diversity  
291 of the fleet by SMMT segment and powertrain group.

#### 292 *4.1. Impact of policy objectives on new passenger vehicle fleet composition*

##### 293 *4.1.1. Fleet composition by SMMT segment*

294 Across the policy objectives excluding feebates, the optimum fleets comprised over half small vehicles  
295 (median 53%), represented by dark blue bars in Figure ???. The extent of fleet downsizing is represented by  
296 the magnitude of dark and light blue bars of small and medium vehicles respectively, relative to the yellow  
297 and green bars of utility and specialist vehicles, respectively. Excluding feebates, the market share of small  
298 vehicles increased 8-10% in the optimum fleet under BAU or when changing VKT only. For BAU, meeting  
299 the individual policy objectives was possible with vehicle downsizing only because VKT and payback times  
300 were fixed at base case values. Therefore, the downsizing was accompanied by a 9% shift to utility vehicles  
301 to maintain fleet average values. Changing VKT introduced a multiplicative effect on absolute energy use  
302 and emissions which mitigated the need for extensive downsizing. The concentration of small vehicles was  
303 largest when increasing payback time alone, or as part of the hybrid approach. Here, small and utility  
304 vehicles comprised a median 55% and 26%, respectively, of the new fleet.

305 Including feebates enhanced the downsizing influences of the consumer behaviour changes described,  
306 except with the hybrid approach. Under BAU and when increasing payback time only, a median 82% of  
307 the fleet was small vehicles. The distribution of vehicles by SMMT segment changed least, relative to BAU,  
308 using feebates under the hybrid approach: there was a marginal (median 4%) increase in the proportion of  
309 small vehicles in the fleet, achieved at the expense of the other groups.

##### 310 *4.1.2. Fleet composition by powertrain type*

311 Uptake of novel vehicle powertrains occurred for all policy objectives where vehicle payback time changed,  
312 due either to the supply push of feebates or the demand pull of consumers through behaviour change. The  
313 changes are illustrated in Figure ??? by a shift away from the black and brown bars representing conventional  
314 powertrains using petrol and diesel respectively, to the red, orange and yellow bars for HEV, PHEV and  
315 fuel cell vehicles, respectively.

316 Payback time did not increase under BAU or when changing VKT only. Therefore, the technology shift  
317 was limited to the fuels used in conventional powertrains: petrol and diesel. Under BAU, the proportion of

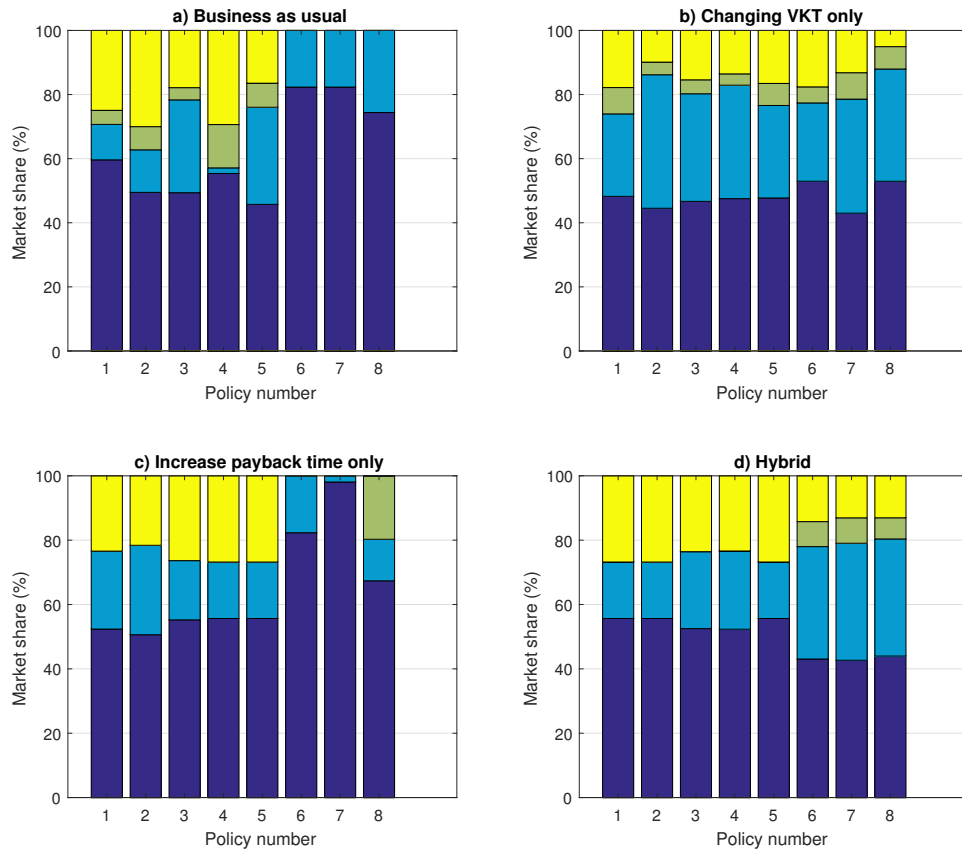


Figure 3: Bar chart showing the market share of vehicles by SMMT in the new fleets under: a) business as usual (BAU); b) changing VKT only; c) increasing payback time only; and d) the hybrid approach. Policy key: 1 = minimising TTW CO<sub>2</sub> emissions; 2 = minimising WTW CO<sub>2</sub> emissions; 3 = minimising energy use; 4 = minimising LAP emissions; 5 = increase fuel duties; 6 = introduce feebate with 120 g CO<sub>2</sub>/km pivot; 7 = introduce a feebate with 95 g CO<sub>2</sub>/km pivot; and 8 = introduce a feebate with 70 g CO<sub>2</sub>/km pivot. Bar colour key: dark blue = small vehicles (mini and super mini); light blue = medium vehicles (lower medium and upper medium); green = specialist vehicles (executive, luxury and sports); and yellow = utility vehicles (SUV and MPV).



318 petrol and diesel vehicles was almost equal. Changing VKT only resulted in a ‘re-petrolisation’ of the fleet,  
319 with only 9% of vehicles using diesel now.

320 Introducing feebates distorted changes in consumer behaviour such that the largest shift to novel pow-  
321 ertrains occurred under BAU and when increasing payback time only. Now, there were no conventional  
322 powertrains using petrol and 68% of new vehicles used novel powertrains. Moreover, fuel cell vehicles ac-  
323 counted for 49% of the new fleet alone. The influence of changing VKT on absolute energy use and emissions  
324 reduced the need for technology switching. Changing VKT only required 26% of the new fleet to use novel  
325 powertrains, decreasing to 10% under the hybrid approach when consumers increased their willingness to  
326 accept longer payback times also.

327 The length of the bars representing novel vehicle powertrains in the presence of feebates, either under  
328 BAU or when increasing payback time only, demonstrated direct capital cost interventions are necessary to  
329 displace a significant proportion of conventional powertrains. However, capital cost subsidies are insufficient  
330 to cause a large shift to low-emitting vehicles: the additional power of the feebate is to raise the purchase  
331 price of high-emitting vehicles ones. In this case, median rebates of £100 per g CO<sub>2</sub>/km for low-emitting  
332 vehicles were paired with median fees of £29 per g CO<sub>2</sub>/km on high-emitting vehicles. Fuel duty increases  
333 did not influence the proportion of novel powertrains more than the other policy scenarios. The data in  
334 Figure ?? is given in Tables ?? and ??.

#### 335 4.2. Impact of policy objectives on fleet VKT, energy use and emissions

336 Figure ?? illustrates the proportion of fleet VKT for vehicles by SMMT segment across the eight policy  
337 objectives. Excluding feebates, the heights of the bars in the small vehicle SMMT group under BAU highlight  
338 the need, not only to downsize the fleet, but to ensure that those small vehicles account for a large proportion  
339 of the total VKT (median 60%). This observation holds true even when novel powertrains enter the fleet.  
340 For example, a median 53% and 65% of fleet VKT was met by small vehicles when increasing payback time  
341 only or under the hybrid approach, respectively. In contrast, changing VKT mitigates the extent of both  
342 technology switching and fleet downsizing, as shown by the distribution of bars in Figures ??b, where small  
343 vehicles met 50% of fleet VKT.

344 Including feebates, small vehicles were responsible for a median 83% of fleet VKT under BAU and when  
345 increasing payback time only. Additionally, novel powertrains accounted for 54% of fleet VKT, dominated  
346 by HEV at 24% and fuel cell vehicles at 17% in both cases. Using feebates under the hybrid approach led  
347 to small vehicles providing only 36% of fleet VKT. Moreover, 79% (26% petrol and 53% diesel) of vehicles  
348 in the optimum fleet used conventional powertrains. Full data used in this figure is available in Tables ??  
349 and ??.

350 Excluding feebates, absolute energy use and CO<sub>2</sub> emissions decreased with increasing consumer behaviour  
351 change, relative to BAU (dark blue). The incremental reduction in energy use and CO<sub>2</sub> emissions grew when

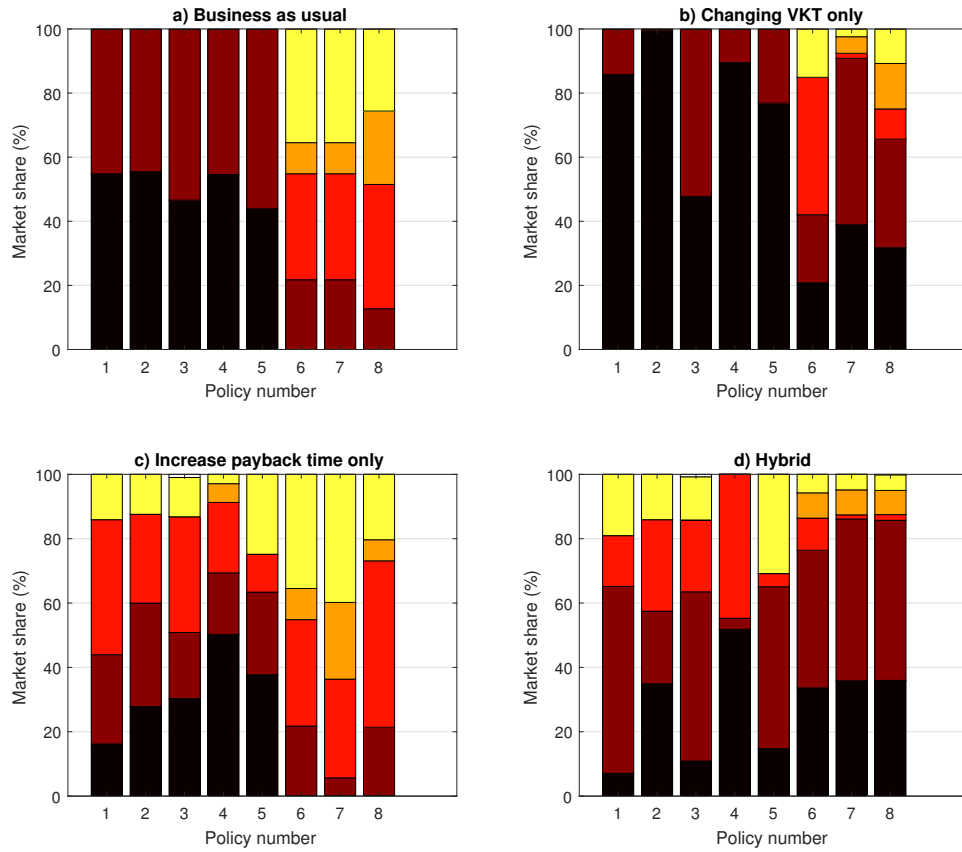


Figure 4: Bar chart showing the market share of vehicles by powertrain type in the new fleets under: a) business as usual (BAU); b) changing VKT only; c) increasing payback time only; and d) the hybrid approach. Policy key: 1 = minimising TTW CO<sub>2</sub> emissions; 2 = minimising WTW CO<sub>2</sub> emissions; 3 = minimising energy use; 4 = minimising LAP emissions; 5 = increase fuel duties; 6 = introduce feebate with 120 g CO<sub>2</sub>/km pivot; 7 = introduce a feebate with 95 g CO<sub>2</sub>/km pivot; and 8 = introduce a feebate with 70 g CO<sub>2</sub>/km pivot. Colour code: black = conventional petrol; brown = conventional diesel; red = petrol and diesel HEV; orange = petrol and diesel PHEV; yellow = fuel cell HEV and PHEV; and white = EV.

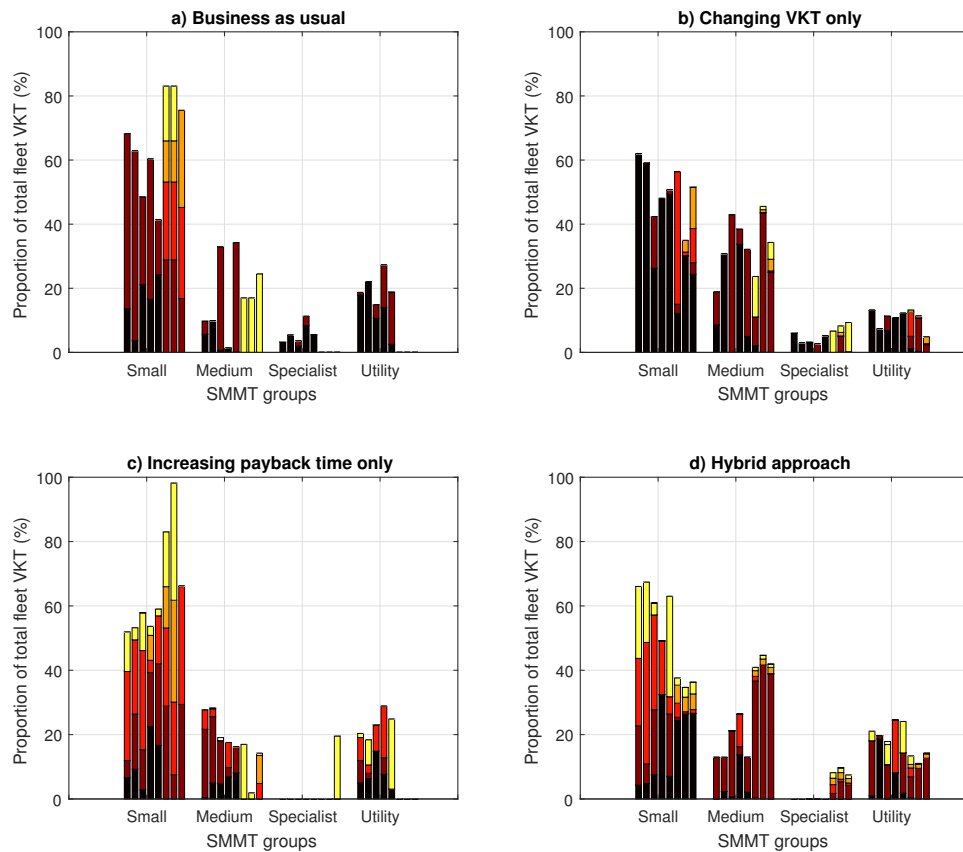


Figure 5: Stacked bar graphs representing the proportion of fleet VKT (product of number of vehicles and VKT per vehicle) per SMMT segment for the eight scenarios under a) business as usual; b) when changing VKT only; c) when increasing payback time only; and d) the hybrid approach. Colour code: black = conventional petrol; brown = conventional diesel; red = petrol and diesel HEV; orange = petrol and diesel PHEV; yellow = fuel cell HEV and PHEV; and white = EV.

352 payback time was increased, either alone (green) or as part of the hybrid approach (yellow). The hybrid  
353 approach returned the largest changes to energy use and CO<sub>2</sub> emissions. These optimum fleets had the  
354 largest proportion of small vehicles (median 56%) and novel powertrains (median 41%), particularly fuel cell  
355 vehicles (median 20%) with zero tailpipe emissions. BAU returned the smallest change in LAP emissions  
356 generally. Small vehicles accounted for 49% of the new fleet. However, there was only a 14% shift towards  
357 petrol from diesel in the conventional powertrains. Consequently, diesel accounted for 49% of new vehicles  
358 with their significantly larger LAP emissions. Recall Euro V diesel vehicles emit 50 times more NO<sub>x</sub> emissions  
359 and five times more PM<sub>2.5</sub> emissions, than spark ignition petrol vehicles.

360 Changing VKT returned the smallest changes in absolute energy use and CO<sub>2</sub> emissions. These optimum  
361 fleets comprised the lowest proportion of small vehicles (median 48%) and highest proportion of conventional  
362 powertrains using petrol (91%) across the SMMT segments. Therefore, the ‘re-petrolisation’ of the fleet  
363 allowed this consumer behaviour change to return the largest fall in LAP emissions in general: NO<sub>x</sub> emissions  
364 by a median 85%; and PM<sub>2.5</sub> emissions by a median 70%.

365 Including feebates, the largest median reductions in energy use and emissions of CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>2.5</sub>,  
366 at 46%, 72%, 57% and 36%, respectively, was achieved under BAU and when increasing payback time only.  
367 These fleets comprised 82% small vehicles and 68% vehicles using novel powertrains (including 49% fuel  
368 cells). Median fees of £79-99 per g CO<sub>2</sub>/km across the pivots were required to reduce the attractiveness of  
369 high-polluting vehicles and push uptake of low-polluting vehicles. The fees were effective enough that there  
370 was no median rebate supplied for the higher feebate pivots. The 70 g CO<sub>2</sub>/km pivot required rebates of  
371 £45 per g CO<sub>2</sub>/km.

372 The hybrid approach, with low median fees (£29) and high rebates (£100) was least able to reduce energy  
373 use and emissions across the policy objectives on account of the smallest proportion of both small vehicles  
374 (median 43%) and novel powertrains (median 10%). Fees may have disproportionate impact on consumer  
375 choice when there is no willingness to accept longer payback times. Across Europe, Mock (2015) observed  
376 that tax thresholds for CO<sub>2</sub> emissions are effective at steering consumer choice, leading to the purchase of  
377 new vehicles with emissions which take advantage of the reduced fees [? ].

378 The bars in Figures ?? and ?? summarise the change in absolute energy use and associated emissions  
379 under BAU and with consumer behaviour changes across the policy objectives. Data related to these figures  
380 is given in Tables ?? and ??.

#### 381 4.3. *Effects of policy objectives on the diversity of vehicle fleet by SMMT segment and powertrain type*

382 In general, there was a trade-off in diversity of the fleet by SMMT segment and powertrain group when  
383 achieving the policy objectives, as shown in Figure ??a.

384 Figure ??b highlights the trade-off in diversity by SMMT segment and powertrain group under BAU  
385 (magenta) and with consumer behaviour changes (blue, green and red). The influence of the policy objectives

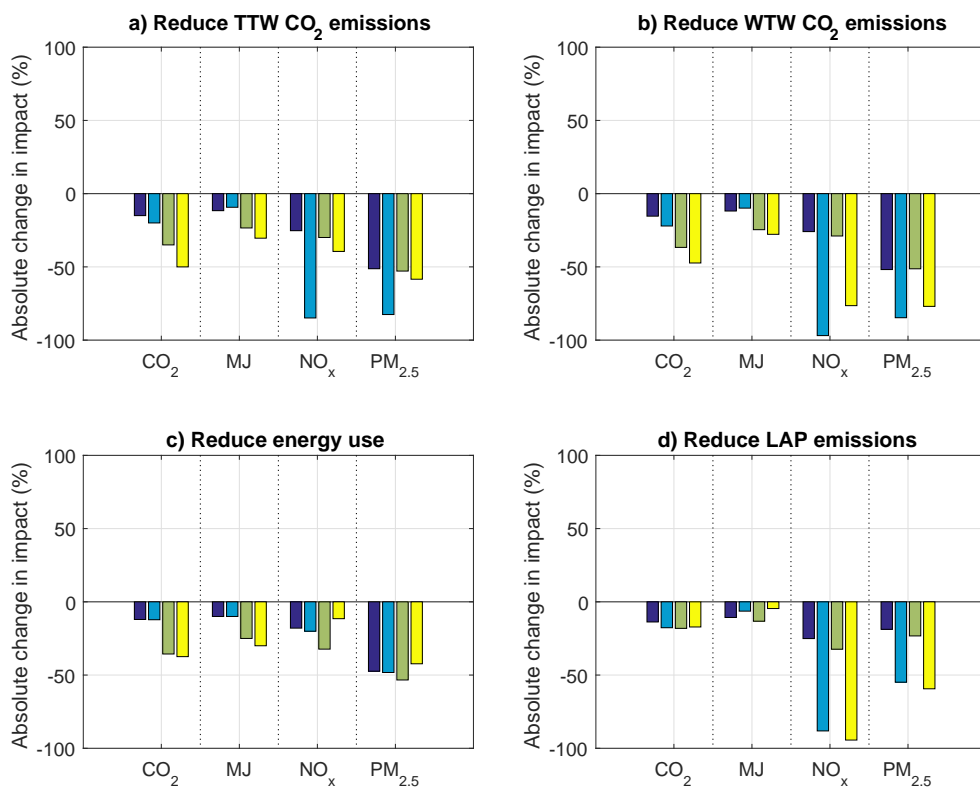


Figure 6: Percentage change in energy use and emissions of CO<sub>2</sub> and LAP for the policy objectives to minimise: a) TTW CO<sub>2</sub> emissions; b) WTW CO<sub>2</sub> emissions; c) energy use; and d) LAP emissions. Colour key: dark blue = business as usual; light blue = reduce VKT only; green = increase payback time only; and yellow = hybrid approach.

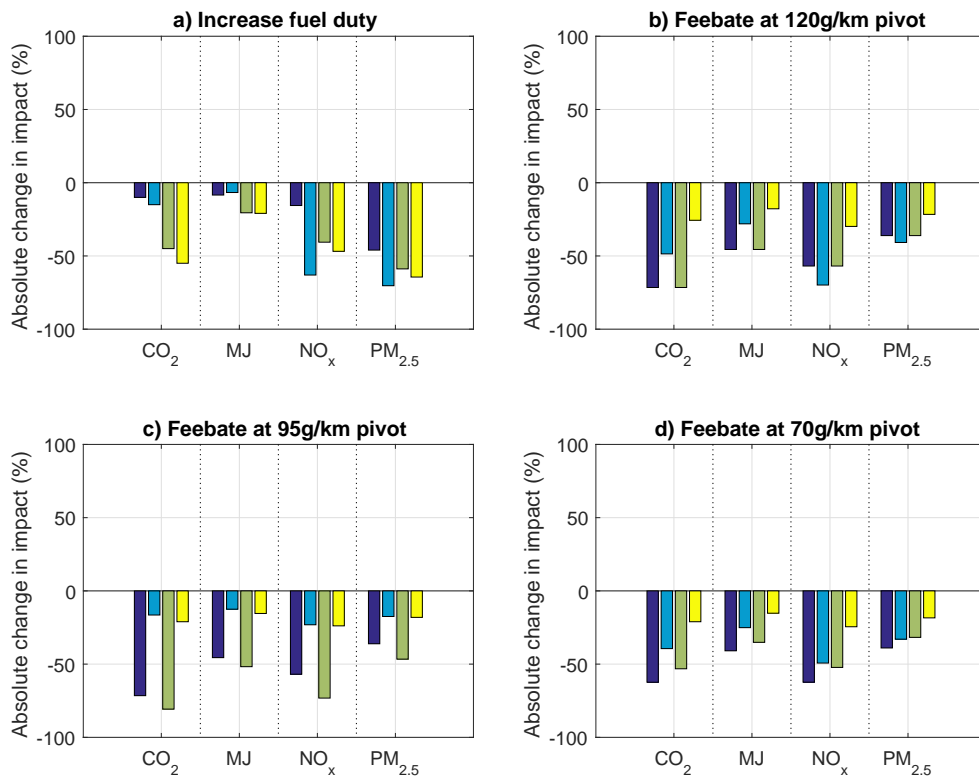


Figure 7: Percentage change in energy use and emissions of CO<sub>2</sub> and LAP for the policy objectives to minimise TTW CO<sub>2</sub> emissions in the presence of: a) increased fuel duties; b) feebate with a 120 g CO<sub>2</sub>/km pivot; c) feebate with a 95 g CO<sub>2</sub>/km pivot; and d) feebate with a 70 g CO<sub>2</sub>/km pivot. Colour key: dark blue = business as usual; light blue = reduce VKT only; green = increase payback time only; and yellow = hybrid approach.

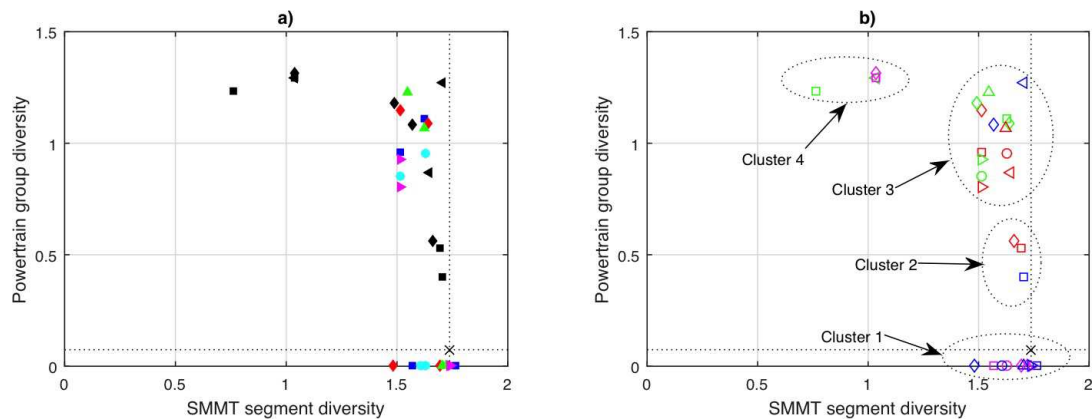


Figure 8: Scatter plot of SMMT segment diversity against technology diversity under BAU and consumer behaviour changes for each policy objective, with and without external incentives. Subplot a) colour key: black cross = diversity of 2012 real-world fleet; blue square = minimising TTW CO<sub>2</sub> emissions; red diamond = minimising WTW CO<sub>2</sub> emissions; green triangle = minimising energy use; cyan circle = minimising LAP emissions; magenta right triangle = increasing fuel duties; black left triangle = feebate with 120 g CO<sub>2</sub>/km pivot; black square = feebate with 95 g CO<sub>2</sub>/km pivot; and black diamond = feebate with 70 g CO<sub>2</sub>/km pivot. Subplots b) colour key: blue = reducing VKT only; green = increasing payback time only; red = hybrid approach; and magenta = business as usual.

386 was seen most in four clusters. The first cluster represented BAU and changing VKT only (blue), excluding  
 387 feebates. These fleets were the most specialised by powertrain type – conventional only – and returned  
 388 the largest reductions in LAP emissions when changing VKT only. The only optimum fleet with higher  
 389 diversity (1.8) by SMMT segment than the base case was achieved when minimising TTW CO<sub>2</sub> emissions  
 390 by changing VKT only (blue square to the right of the vertical dotted line).

391 The second cluster represented the optimum fleets using feebates with a 95 g CO<sub>2</sub>/km pivot when  
 392 changing VKT only (blue squares) and under the hybrid approach (red squares) and using a feebate with  
 393 70 g CO<sub>2</sub>/km pivot under the hybrid approach (red diamond). These three fleets were dominated by vehicles  
 394 with conventional powertrains (86-91%), with the remainder spread over three groups of novel powertrains.  
 395 Diversity was 4-7 times higher than the base case at 0.4-0.6.

396 The third cluster contained fleets where diversity by powertrain group increased 11-17 times to 0.8-1.1  
 397 and occurred when payback time was increased, either alone (green) or part of a hybrid approach (red)  
 398 across the policy objectives, excluding feebates. Under feebates, optimum fleets in this cluster existed with  
 399 pivots at 120 g CO<sub>2</sub>/km (changing VKT only and hybrid approach) and 70 g CO<sub>2</sub>/km (changing VKT only  
 400 and increasing payback time only).

401 The fleets forming the fourth cluster were the most downsized and displayed significantly lower diversity  
 402 by SMMT segment, at 0.8-1. This cluster comprised the BAU fleets across all feebate pivots and those from  
 403 pivots at 120 g CO<sub>2</sub>/km and 95 g CO<sub>2</sub>/km when increasing payback time only. The fall in diversity by SMMT

404 segment was balanced by increased diversity by powertrain type: these fleets displayed the highest diversity  
405 across all the clusters (at 1.3) by consisting of four powertrain groups, with no single group accounting for  
406 more than 40% of new vehicles.

407 The fleets in the second and third clusters provide a good balance in diversity between SMMT segment  
408 and powertrain group. However, the number of SMMT segments with vehicles falls for slight changes in  
409 diversity. For example, diversity of 1.5 may have vehicles in only five of nine segments. Diversity of 1.6  
410 returns vehicles in six of nine segments. Therefore, maximising the number of segments available for choice  
411 requires diversity of 1.7 which is equal to the base case.

412 Introducing a feebate with pivot at 120 g CO<sub>2</sub>/km (fees of £100 per g CO<sub>2</sub>/km and rebates of £9 per  
413 g CO<sub>2</sub>/km) in combination with changing VKT only (blue left triangle in the third cluster) returned the  
414 largest increase in diversity by powertrain type for the smallest reduction in diversity by SMMT segment.  
415 Balancing the diversity of the fleet in these dimensions maximises the number of vehicles sizes and powertrain  
416 types available and may be the most attractive to consumers. The result was a median 28% reduction in  
417 energy use and leading to emissions of CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>2.5</sub> falling by 49%, 70% and 41%, respectively.  
418 This ideal fleet comprised a 14% increase in the market share of small vehicles and a 2:1 ratio of conventional  
419 to novel (HEV and fuel cell HEV) powertrains. Data on diversity of the optimum fleets by SMMT segment  
420 and powertrain group is given in Tables ?? and ??.

## 421 5. Conclusions

422 This work presents a co-optimisation of vehicle segment, powertrain type and activity to account explic-  
423 itly for fleet downsizing, technology switching and changes in demand. It integrates a top-down, diversity  
424 led approach to fleet composition with bottom-up, vehicle powertrain models to give a rich option set for sat-  
425 isfying consumer choice. The impact of this model is a framework to quantify the effect of policy objectives  
426 on the composition of an optimum new vehicle fleet.

427 Fleet downsizing was required in all cases, and when combined with novel vehicle powertrains and reduced  
428 activity, returned the largest reductions in energy use and CO<sub>2</sub> emissions. The extent of fleet downsizing  
429 was mitigated when changing VKT only because the multiplicative effect of activity on absolute energy use  
430 and emissions was exploited to offset vehicle size. Therefore, the composition of optimum fleets by SMMT  
431 segment was closest to the base case. Moreover, these fleets comprised all conventional powertrains to return  
432 the smallest reductions in absolute energy use and CO<sub>2</sub> emissions. However, LAP emissions fell the most  
433 (NO<sub>x</sub> at 85% and PM<sub>2.5</sub> at 70%) under this consumer behaviour change case. Technology switching in  
434 these optimum fleets took the form of fuels used, shifting from diesel back to petrol. This ‘re-petrolisation’  
435 minimised the proportion of diesel vehicles (median 9%) to reduce combustion-related emissions of NO<sub>x</sub> and  
436 PM<sub>2.5</sub> by 50 times and five times, respectively. Finally, changing VKT only addressed the effect of activity



437 on absolute LAP emissions, especially the road, brake and tyre wear associated with PM<sub>2.5</sub> emissions.

438 Introducing feebates maximised reductions in energy use and associated emissions for the least change in  
439 consumer behaviour. The resulting fleets were the most downsized (and specialised by SMMT group with  
440 median 82% small vehicles). However, the fleets were the most diverse in the number of novel powertrains  
441 present as a consequence of the large fees (£79-99 per g CO<sub>2</sub>/km away from the pivot) placed on high-  
442 emitting vehicles. Such external policies may demonstrate how far energy use and emissions might be  
443 reduced in new fleets. Equally, such specialised fleets may be unachievable because they fail to satisfy the  
444 broad range of consumers' preferences.

445 The most balanced fleet by diversity occurred with a combination of consumer behaviour change and  
446 external incentive: by changing VKT only in the presence of a feebate with 120 g CO<sub>2</sub>/km pivot. Here, high  
447 emitting vehicles were penalised at £100 per g CO<sub>2</sub>/km which encouraged novel powertrains into the mix.  
448 Changing vehicle activity mitigated the need for large-scale downsizing of the fleet which allowed vehicles  
449 across a range of segments.

450 This work is set in 2012 to maintain temporal consistency across the data sets and avoid wide-ranging  
451 assumptions on future technology performance, costs and consumer preferences. Moreover, the equality  
452 constraints on the model to meet fleet averaged physical and cost attributes limits the solution set. Op-  
453 timising vehicle number, size, powertrain type and VKT across nine SMMT segments and 23 powertrain  
454 types simultaneously yielded rich results. This work can be extended in two ways: first, the vehicle option  
455 set can be expanded to include more novel powertrain types and vehicles using novel transport fuels, vehi-  
456 cle performance over different driving cycles and different vehicle attributes within SMMT segments; and  
457 second, the number of consumer behaviour changes can be increased to account for a change in preferences  
458 for vehicle attributes.

459 By April 2016, 162 countries (Parties) had promised to reduce their national GHG emissions following  
460 the 2015 Paris Climate Conference<sup>12</sup>. At the same time as trying to reduce GHG emissions, annual global  
461 passenger vehicle sales increased from 66 million in 2005 to 90 million in 2015. Motorisation rates (number  
462 of vehicles per thousand inhabitants) over the same period rose fastest in Asia, Central and South America  
463 and Africa<sup>13</sup>. Therefore, this work may be used by Governments and policy-makers to determine how they  
464 can accommodate both the increase in vehicles circulating and the pledges to reduce GHG emissions. Addi-  
465 tionally, original equipment manufacturers (OEM) may take advantage of the bottom-up vehicle powertrain  
466 simulation inputs to quantify the influence of consumer behaviour change, external incentives and policy  
467 objectives on uptake of their technologies.

---

<sup>12</sup>A register of Intended Nationally Determined Contributions (INDCs) is available from the United Nations Framework Convention on Climate Change at [unfccc.int/focus/indc\\_portal/items/8766.php](http://unfccc.int/focus/indc_portal/items/8766.php).

<sup>13</sup>Global statistics from the International Organization of Motor Vehicle Manufacturers, available online at [www.oica.net](http://www.oica.net).

## 6. Acknowledgements

The authors acknowledge the EPSRC funding provided for this work under the Centre for Sustainable Road Freight Transport (EP/K00915X/1) and the Energy Efficient Cities Initiative (EP/F034350/1).

## 7. References

- [1] R. Edwards, et al., Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Tech. Rep. 4.a, European Commission Joint Research Centre (March 2014).  
URL [http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu/about-jec/files/documents/wtw\\_report\\_v4a\\_march\\_2014\\_final.pdf](http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu/about-jec/files/documents/wtw_report_v4a_march_2014_final.pdf)
- [2] UK, Climate Change Act 2008, Act of parliament, HM UK Government (2008).
- [3] B. M. Al-Alawi, T. H. Bradley, Review of hybrid, plug-in hybrid, and electric vehicle market modelling Studies, *Renewable and Sustainable Energy Reviews* 21 (2013) 190–203. doi:10.1016/j.resr.2012.12.048.
- [4] C. E. Shannon, A Mathematical Theory of Communication, *Bell System Technical Journal* 27 (3) (1948) 379–423. doi:10.1002/j.1538-7305.1948.tb01338.x.
- [5] D. L. Greene, TAFV Alternative Fuels and Vehicles Choice Model Documentation, no. ORNL/TM-2001/134, Oak Ridge National Laboratory, 2001.  
URL [www.cta.ornl.gov/cta/Publications/Reports/ORNL\\_TM\\_2001\\_134.pdf](http://www.cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2001_134.pdf)
- [6] D. J. Santini, A. D. Vyas, Suggestions for a New Vehicle Choice Model Simulating Advanced Vehicles Introduction Decisions (AVID): Structure and Coefficients, no. ANL/ESD/05-1, Argonne National Laboratory, 2005.  
URL <http://www.anl.gov/energy-systems/publication/suggestions-new-vehicle-choice-model-simulating-advanced-vehicles>
- [7] Z. Lin, D. Greene, Who Will More Likely Buy PHEV: A Detailed Market Segmentation Analysis, in: 25<sup>th</sup> World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition (EVS-25), Shenzhen, 2010.  
URL <http://info.ornl.gov/sites/publications/Files/Pub32208.pdf>
- [8] J. D. K. Bishop, N. P. D. Martin, A. M. Boies, Cost-effectiveness of alternative powertrains for reduced energy use and CO<sub>2</sub> emissions in passenger vehicles, *Applied Energy* 124 (2014) 44–61. doi:10.1016/j.apenergy.2014.02.019.
- [9] D. McCollum, C. Yang, Achieving deep reductions in US transport greenhouse gas emissions: Scenario analysis and policy implications, *Energy Policy* 37 (12) (2009) 5580–5596. doi:10.1016/j.enpol.2009.08.038.
- [10] K. Bodek, J. Heywood, Europe’s Evolving Passenger Vehicle Fleet: Fuel Use and GHG Emissions Scenarios through 2035, LFEE 2008-03 RP, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Cambridge, MA, 2008.  
URL <http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/Europe's%20Evolving%20Passenger%20Vehicle%20Fleet.pdf>
- [11] X. Ou, X. Zhang, S. Chang, Scenario analysis on alternative fuel/vehicle for China’s future road transport: Life-cycle energy demand and GHG emissions, *Energy Policy* 38 (8) (2010) 3943–3956. doi:10.1016/j.enpol.2010.03.018.
- [12] M. Ichinohe, E. Endo, Analysis of the vehicle mix in the passenger-car sector in Japan for CO<sub>2</sub> emissions reduction by a MARKAL model, *Applied Energy* 83 (10) (2006) 1047–1061. doi:10.1016/j.apenergy.2005.08.002.
- [13] C. Thiel, A. Perujo, A. Mercier, Cost and CO<sub>2</sub> aspects of future vehicle options in Europe under new energy policy scenarios, *Energy Policy* 38 (11) (2010) 7142–7151. doi:10.1016/j.enpol.2010.07.034.
- [14] M. Kloess, A. Müller, Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria – A model based analysis 2010-2050, *Energy Policy* 39 (9) (2011) 5045–5062. doi:10.1016/j.enpol.2011.06.008.

- [15] C. Thiel, J. Schmidt, A. V. Zyl, E. Schmid, Cost and well-to-wheel implications of the vehicle fleet CO<sub>2</sub> emission regulation in the European Union, *Transportation Research Part A: Policy and Practice* 63 (2014) 25–42. doi:10.1016/j.tra.2014.02.018.
- [16] S. Skippon, S. Veeraraghavan, H. Ma, P. Gadd, N. Tait, Combining technology development and behaviour change to meet CO<sub>2</sub> cumulative emission budgets for road transport: Case studies for the USA and Europe, *Transportation Research Part A: Policy and Practice* 46 (9) (2012) 1405–1423. doi:10.1016/j.tra.2012.05.021.
- [17] V. J. Karplus, S. Paltsev, M. Babiker, J. M. Reilly, Should a vehicle fuel economy standard be combined with an economy-wide greenhouse gas emissions constraint? Implications for energy and climate policy in the United States, *Energy Economics* 36 (2013) 322–333. doi:10.1016/j.eneco.2012.09.001.
- [18] C. Chavez-Baeza, C. Scheinbaum-Pardo, Sustainable passenger road transport scenarios to reduce fuel consumption, air pollutants and GHG (greenhouse gas) emissions in the Mexico City Metropolitan Area, *Energy* 66 (2014) 624–634. doi:10.1016/j.energy.2013.12.047.
- [19] A. Gambhir, L. K. C. Tse, D. Tong, R. Martinez-Botas, Reducing China’s road transport sector CO<sub>2</sub> emissions to 2050: Technologies, costs and decomposition analysis, *Applied Energy* In Press, Corrected Proof. doi:10.1016/j.apenergy.2015.01.018.
- [20] G. Pasaoglu, M. Honselaar, C. Thiel, Potential vehicle fleet CO<sub>2</sub> reductions and cost implications for various vehicle technology deployment scenarios in Europe, *Energy Policy* 40 (2012) 404–421. doi:10.1016/j.enpol.2011.10.025.
- [21] S. Musti, K. M. Kockelman, Evolution of the household vehicle fleet: Anticipating fleet composition, PHEV adoption and GHG emissions in Austin, Texas, *Transportation Research Part A: Policy and Practice* 45 (8) (2011) 707–720. doi:10.1016/j.tra.2011.04.011.
- [22] T. Oxley, A. Elshkaki, L. Kwiatkowski, A. Castillo, T. Scarbrough, H. ApSimon, Pollution abatement from road transport: cross-sectoral implications, climate co-benefits and behavioural change, *Environmental Science & Policy* 19-20 (2012) 16–32. doi:10.1016/j.envsci.2012.01.004.
- [23] C. Yang, D. McCollum, R. McCarthy, W. Leighty, Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California, *Transport Research Part D: Transport and Environment* 14 (3) (2009) 147–156. doi:10.1016/j.trd.2008.11.010.
- [24] A. Boies, S. Hankey, D. Kittelson, J. D. Marshall, P. Nussbaum, W. Watts, E. J. Wilson, Reducing Motor Vehicle Greenhouse Gas Emissions in a Non-California State: A Case Study of Minnesota, *Environmental Science & Technology* 43 (23) (2009) 8721–8729. doi:10.1021/es902019z.
- [25] J. K. Stanley, D. A. Hensher, C. Loader, Road transport and climate change: Stepping off the greenhouse gas, *Transportation Research Part A: Policy and Practice* 45 (10) (2011) 1020–1030. doi:10.1016/j.tra.2009.04.005.
- [26] A. L. Bristow, M. Tight, A. Pridmore, A. D. May, Developing pathways to low carbon land-based passenger transport in Great Britain by 2050, *Energy Policy* 36 (9) (2008) 3427–3435. doi:10.1016/j.enpol.2008.04.029.
- [27] I. Meyer, S. Wessely, Fuel efficiency of the Austrian passenger vehicle fleet – Analysis of trends in the technological profile and related impacts on CO<sub>2</sub> emissions, *Energy Policy* 37 (10) (2009) 3779–3789. doi:10.1016/j.enpol.2009.07.011.
- [28] T. Litman, Comprehensive evaluation of energy conservation and emission reduction policies, *Transportation Research Part A: Policy and Practice* 47 (2013) 153–166. doi:10.1016/j.tra.2012.10.022.
- [29] D. A. Hensher, Climate change, enhanced greenhouse gas emissions and passenger transport – What can we do to make a difference?, *Transport Research Part D: Transport and Environment* 13 (2) (2008) 95–111. doi:10.1016/j.trd.2007.12.003.
- [30] W. R. Morrow, K. S. Gallagher, G. Collantes, H. Lee, Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector, *Energy Policy* 38 (3) (2010) 1305–1320. doi:10.1016/j.enpol.2009.11.006.
- [31] SMMT, New car CO<sub>2</sub> report 2014: The 13<sup>th</sup> report, Tech. rep., The Society of Motor Manufacturers and Traders, London

- (March 2014).
- [32] RAC, RAC Cost of Motoring Index 2011, RAC, 2011.  
URL [www.rac.co.uk/pdfs/report-on-motoring/rac-cost-of-motoring-index-2011.aspx](http://www.rac.co.uk/pdfs/report-on-motoring/rac-cost-of-motoring-index-2011.aspx)
- [33] DfT, Transport Statistics Great Britain, United Kingdom Department for Transport, London, 2012.  
URL [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/71279/tsgb-2012.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/71279/tsgb-2012.pdf)
- [34] USDOE, Clean Cities Alternative Fuel Price Report, US Department of Energy, Washington DC, 2013.  
URL [www.afdc.energy.gov/uploads/publication/alternative\\_fuel\\_price\\_report\\_jan\\_2013.pdf](http://www.afdc.energy.gov/uploads/publication/alternative_fuel_price_report_jan_2013.pdf)
- [35] A. Rogozhin, M. Gallaher, W. McManus, Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers, no. TRI 0211577.002.004, US Environmental Protection Agency, 2009.  
URL <http://www.epa.gov/otaq/ld-hwy/420r09003.pdf>
- [36] DfT, Transport Statistics Great Britain, United Kingdom Department for Transport, London, 2014.  
URL [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/389596/tsgb-2014-print-ready-version.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/389596/tsgb-2014-print-ready-version.pdf)
- [37] DfT, National Travel Survey: Statistical Release, Department for Transport, London, 2014.  
URL <https://www.gov.uk/government/collections/national-travel-survey-statistics>
- [38] M. Shirk, B. Carlson, eVMT analysis of on-road data from plug-in hybrid electric and all-electric vehicles, Tech. rep., Idaho National Laboratory (2015).  
URL [http://avt.inel.gov/pdf/prog\\_info/HybridSymposium2015CarlsonShirk.pdf](http://avt.inel.gov/pdf/prog_info/HybridSymposium2015CarlsonShirk.pdf)
- [39] J. King, The King Review of low-carbon cars (Part I: the potential for CO<sub>2</sub> reduction), HM Treasury, 2007.
- [40] National Travel Survey: Statistical Release, Department for Transport, London, 2012.  
URL [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/35738/nts2011-01.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/35738/nts2011-01.pdf)
- [41] EC, Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO<sub>2</sub> emissions from light-duty vehicles, no. 443/2009, Official Journal of the European Union, 2009.
- [42] SMMT, Motor Industry Facts 2013, London, 2013.  
URL <http://www.smmt.co.uk/wp-content/uploads/SMMT-2013-Motor-Industry-Facts-guide.pdf?9b6f83>
- [43] R. Edwards, J.-F. Larivé, V. Mahieu, P. Rouveiolles, Well-To-Wheels Analysis of Future Automotive Fuels and Powetrains in the European Context, no. 2c, European Commission Joint Research Centre, 2007.  
URL [http://ies.jrc.ec.europa.eu/uploads/media/WTW\\_Report\\_010307.pdf](http://ies.jrc.ec.europa.eu/uploads/media/WTW_Report_010307.pdf)
- [44] ANL, Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions, Argonne National Laboratory, 2005.  
URL <http://www.transportation.anl.gov/pdfs/TA/339.pdf>
- [45] LBST, GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study, L-B-Systemtechnik GmbH, 2002.  
URL [http://www.lbst.de/ressources/docs2002/TheReport\\_Euro-WTW\\_27092002.pdf](http://www.lbst.de/ressources/docs2002/TheReport_Euro-WTW_27092002.pdf)
- [46] M. A. Weiss, J. B. Heywood, E. M. Drake, A. Schafer, F. F. AuYeung, On The Road In 2020: A life-cycle analysis of new automobile technologies, Tech. Rep. MIT EL 00-003, Massachusetts Institute of Technology (2000).  
URL <http://web.mit.edu/energylab/www/pubs/e100-003.pdf>
- [47] ANL, Greenhouse gases, Regulated Emissions and Energy Use in Transportation (GREET), Argonne National Laboratory, 2007.  
URL [www.transportation.anl.gov/modeling\\_simulation/GREET/index.html](http://www.transportation.anl.gov/modeling_simulation/GREET/index.html)
- [48] J. D. K. Bishop, C. J. Axon, M. Tran, D. Bonilla, D. Banister, M. D. McCulloch, Identifying the fuels and energy conversion technologies necessary to meet European vehicle emissions legislation to 2020, Fuel 99 (2012) 88–105. doi: 10.1016/j.fuel.2012.04.045.

- [49] USEPA, Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, EPA-420-R-12-901, US Environmental Protection Agency, 2012.  
URL <http://www.epa.gov/otaq/climate/documents/420r12901.pdf>
- [50] SMMT, New car CO<sub>2</sub> report 2013: The 12<sup>th</sup> report, Tech. rep., The Society of Motor Manufacturers and Traders, London (March 2013).  
URL <http://www.smmt.co.uk/wp-content/uploads/SMMT-New-Car-CO2-Report-2013-web.pdf?9b6f83>
- [51] I. W. H. Parry, M. Walls, W. Harrington, Automobile Externalities and Policies, RFF DP 06-26, Resources for the Future, Washington, DC, 2006.  
URL <http://www.rff.org/rff/Documents/RFF-DP-06-26.pdf>
- [52] C. A. Pope III, D. W. Dockery, Health Effects of Fine Particulate Air Pollution: Lines that Connect, *Journal of Air & Waste Management Association* 56 (6) (2006) 709–742. doi:10.1080/10473289.2006.10464485.
- [53] WHO, Air Quality Guidelines - Global Update 2005, World Health Organization, 2006.
- [54] J. Bollen, B. van der Zwaan, C. Brink, H. Eerens, Local air pollution and global climate change: A combined cost-benefit analysis, *Resource and Energy Economics* 31 (3) (2009) 161–181. doi:10.1016/j.reseneeco.2009.03.001.
- [55] H. Walker, Y. Pang, Road vehicle emission factors for no<sub>x</sub> based on copert 4 v8.1(2011): speed-emission factor equations, Tech. rep., National Atmospheric Emissions Inventory (2012).
- [56] L. Ntziachristos, Z. Samaras, EMEP/EEA air pollutant emission inventory guidebook 2013, European Environment Agency, Copenhagen, 2013, Ch. Exhaust emissions from road transport.  
URL <http://www.eea.europa.eu/publications/emep-eea-guidebook-2013>
- [57] DfT, Transport Statistics Great Britain, United Kingdom Department for Transport, London, 2013.  
URL <https://www.gov.uk/government/publications/transport-statistics-great-britain-2013>
- [58] T. Murrells, Y. Pang, Emissions Factors for Alternative Vehicle Technologies, no. ED57423001, National Atmospheric Emissions Inventory, 2013.  
URL [http://naei.defra.gov.uk/resources/NAEI\\_Emission\\_factors\\_for\\_alternative\\_vehicle\\_technologies\\_Final\\_Feb\\_13.pdf](http://naei.defra.gov.uk/resources/NAEI_Emission_factors_for_alternative_vehicle_technologies_Final_Feb_13.pdf)
- [59] L. Ntziachristos, P. Boulter, EMEP/EEA air pollutant emission inventory guidebook 2013, European Environment Agency, Copenhagen, 2013, Ch. Road vehicle tyre and break wear, road surface wear.
- [60] K. A. Small, Energy policies for passenger motor vehicles, *Transportation Research Part A: Policy and Practice* 46 (6) (2012) 874–889. doi:10.1016/j.tra.2012.02.017.
- [61] T. Litman, Efficient vehicles versus efficient transportation. Comparing transportation energy conservation strategies, *Transport Policy* 12 (2) (2005) 121–129. doi:10.1016/j.tranpol.2004.12.002.  
URL <http://www.vtpi.org/cafe.pdf>
- [62] D. L. Greene, P. D. Patterson, M. Singh, J. Li, Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy, *Energy Policy* 33 (6) (2005) 757–775. doi:10.1016/j.enpol.2003.10.003.
- [63] R. Kok, Six years of CO<sub>2</sub>-based tax incentives for new passenger cars in The Netherlands: Impacts on purchasing behaviour trends and CO<sub>2</sub> effectiveness, *Transportation Research Part A: Policy and Practice* 77 (2015) 137–153. doi:10.1016/j.tra.2015.04.009.
- [64] P. de Haan, M. G. Mueller, R. W. Scholz, How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars—Part II: Forecasting effects of feebates based on energy-efficiency, *Energy Policy* 37 (3) (2009) 1083–1094. doi:10.1016/j.enpol.2008.11.003.
- [65] A. Peters, M. G. Mueller, P. de Haan, R. W. Scholz, Feebates promoting energy-efficient cars: Design options to address more consumers and possible counteracting effects, *Energy Policy* 36 (4) (2008) 1355–1365. doi:10.1016/j.enpol.2007.

12.015.

[66] P. Mock, Optimizing to the last digit: How taxes influence vehicle CO2 emission levels.

URL [http://theicct.org/sites/default/files/publications/Tax\\_Step\\_Analysis\\_201510.pdf](http://theicct.org/sites/default/files/publications/Tax_Step_Analysis_201510.pdf)

## **Appendix A. Results tables**

Table A.1: Percent change of vehicles in the new optimum fleets by SMMT group under each policy objective for the consumer behaviour changes of: 1 = business as usual; 2 = changing VKT only; 3 = increasing payback time only; and 4 = hybrid approach.

SMMT group	Base	TTW				WTW				MJ				LAP			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Small	40	60	48	52	56	49	45	51	56	49	47	55	53	55	48	56	52
Medium	36	11	26	24	18	13	42	28	18	29	34	18	24	2	35	18	24
Specialist	8	4	8	0	0	7	4	0	0	4	4	0	0	14	4	0	0
Utility	16	25	18	23	27	30	10	22	27	18	15	26	24	29	14	27	23
Delta																	
Small	0	20	9	13	16	10	5	11	16	10	7	16	13	16	8	16	13
Medium	0	-25	-11	-12	-19	-23	5	-9	-19	-8	-3	-18	-13	-35	-1	-19	-12
Specialist	0	-4	0	-8	-8	-1	-4	-8	-8	-5	-4	-8	-8	5	-5	-8	-8
Utility	0	9	2	8	11	14	-6	6	11	2	0	11	8	14	-2	11	8
SMMT group	Base	Increasing fuel duties				Feebate, 120 g CO <sub>2</sub> /km				Feebate, 95 g CO <sub>2</sub> /km				Feebate, 70 g CO <sub>2</sub> /km			
Small	40	46	48	56	56	82	53	82	43	82	43	98	43	74	53	70	44
Medium	36	30	29	18	18	18	25	18	35	18	36	2	36	26	35	13	36
Specialist	8	8	7	0	0	0	5	0	8	0	8	0	8	0	7	20	7
Utility	16	16	17	27	27	0	18	0	14	0	13	0	13	0	5	0	13
Delta																	
Small	0	6	8	16	16	43	14	43	4	43	4	59	3	35	14	30	4
Medium	0	6	8	16	16	43	14	43	4	43	4	59	3	35	14	30	4
Specialist	0	-6	-8	-19	-19	-19	-12	-19	-1	-19	-1	-35	0	-11	-1	-23	0
Utility	0	-1	-2	-8	-8	-8	-3	-8	-1	-8	0	-8	0	-8	-1	12	-2

Table A.2: Percent change of vehicles in the new optimum fleets by powertrain group under non-feeback policy objectives for the consumer behaviour changes of: 1 = business as usual; 2 = changing VKT only; 3 = increasing payback time only; and 4 = hybrid approach.

Powertrain group	Base	TTW				WTTW				MJ				LAP			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Petrol	37	53	91	14	6	54	100	26	38	46	47	31	11	51	93	47	62
Diesel	63	47	9	35	53	46	0	37	18	54	53	25	54	49	7	20	2
HEV	0	0	0	37	11	0	0	22	24	0	0	31	21	0	0	25	36
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
Fuel cell vehicles	0	0	0	14	30	0	0	15	20	0	0	12	13	0	0	3	0
EV	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Delta																	
Petrol	0	16	54	-23	-31	17	62	-11	0	8	9	-6	-26	14	56	9	25
Diesel	0	-16	-54	-28	-10	-17	-62	-26	-44	-8	-9	-38	-9	-14	-56	-43	-61
HEV	0	0	0	37	11	0	0	22	24	0	0	31	21	0	0	25	36
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0
Fuel cell vehicles	0	0	0	14	30	0	0	15	20	0	0	12	13	0	0	3	0
EV	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0



Table A.3: Percent change of vehicles in the new optimum fleets by powertrain group under feebate policy objectives for the consumer behaviour changes of: 1 = business as usual; 2 = changing VKT only; 3 = increasing payback time only; and 4 = hybrid approach.

Powertrain group	Base	Increasing fuel duties				Feebate, 120 g CO <sub>2</sub> /km				Feebate, 95 g CO <sub>2</sub> /km				Feebate, 70 g CO <sub>2</sub> /km			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Petrol	37	43	77	32	12	0	22	0	37	0	41	0	37	0	38	0	37
Diesel	63	57	23	28	40	32	16	32	43	32	53	10	53	17	31	28	53
HEV	0	0	0	11	3	13	39	13	9	13	1	13	1	36	8	43	1
PHEV	0	0	0	0	0	6	0	6	4	6	2	17	3	13	7	4	3
Fuel cell vehicles	0	0	0	29	44	49	23	49	8	49	3	60	6	34	16	25	6
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Delta																	
Petrol	0	6	40	-5	-25	-37	-15	-37	-1	-37	4	-37	0	-37	1	-37	0
Diesel	0	-6	-40	-35	-22	-30	-47	-30	-20	-30	-9	-53	-10	-45	-32	-35	-10
HEV	0	0	0	11	3	13	39	13	9	13	1	13	1	36	8	43	1
PHEV	0	0	0	0	0	6	0	6	4	6	2	17	3	13	7	4	3
Fuel cell vehicles	0	0	0	29	44	49	23	49	8	49	3	60	6	34	16	25	6
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.4: Proportion of total fleet VKT by SMMT group and powertrain group (bar colours) for business as usual and changing VKT only across the policy objectives: 1 = minimise TTW CO<sub>2</sub> emissions; 2 = minimise WTW CO<sub>2</sub> emissions; 3 = minimise energy use; 4 = minimise LAP emissions; 5 = increase fuel duties; 6 = introduce feebates at 120 g CO<sub>2</sub>/km pivot; 7 = introduce feebates at 95 g CO<sub>2</sub>/km pivot ; and 8 = introduce feebates at 70 g CO<sub>2</sub>/km pivot.

	Base	Business as usual								Changing VKT only							
Vehicle group		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Small																	
Petrol	29	14	4	21	17	24	0	0	0	62	59	26	48	49	12	30	24
Diesel	0	55	59	27	44	17	29	29	17	0	0	16	0	1	3	0	4
HEV	0	0	0	0	0	0	24	24	28	0	0	0	0	0	41	1	11
PHEV	0	0	0	0	0	0	13	13	30	0	0	0	0	0	0	4	13
Fuel cell vehicles	0	0	0	0	0	0	17	17	0	0	0	0	0	0	0	0	0
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium																	
Petrol	0	6	10	1	1	0	0	0	0	9	31	0	34	5	2	0	0
Diesel	41	4	0	32	0	34	0	0	0	10	0	43	5	27	9	43	25
HEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
Fuel cell vehicles	0	0	0	0	0	0	17	17	25	0	0	0	0	0	13	1	5
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Specialist																	
Petrol	0	3	5	2	8	5	0	0	0	6	3	3	0	5	0	0	0
Diesel	11	0	0	2	3	0	0	0	0	0	0	0	3	0	0	5	0
HEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Fuel cell vehicles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	2	9
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Utility																	
Petrol	0	18	22	11	14	3	0	0	0	13	7	7	11	12	1	0	0
Diesel	19	1	0	4	13	16	0	0	0	0	0	5	0	0	4	10	2
HEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
Fuel cell vehicles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.5: Proportion of total fleet VKT by SMMT group and powertrain group (bar colours) when increasing payback time only and under the hybrid approach across the policy objectives: 1 = minimise TTW CO<sub>2</sub> emissions; 2 = minimise WTW CO<sub>2</sub> emissions; 3 = minimise energy use; 4 = minimise LAP emissions; 5 = increase fuel duties; 6 = introduce feebates at 120 g CO<sub>2</sub>/km pivot; 7 = introduce feebates at 95 g CO<sub>2</sub>/km pivot ; and 8 = introduce feebates at 70 g CO<sub>2</sub>/km pivot.

Vehicle group	Base	Increasing payback time only								Hybrid approach							
		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
<b>Small</b>																	
Petrol	29	7	9	3	22	17	0	0	0	4	5	8	32	7	24	26	27
Diesel	0	5	17	13	17	25	29	8	29	18	6	20	0	19	1	0	0
HEV	0	28	23	31	4	15	24	23	37	21	38	29	17	5	4	1	1
PHEV	0	0	0	0	8	0	13	32	0	0	0	0	0	0	6	5	5
Fuel cell vehicles	0	12	4	12	3	2	17	36	0	22	19	4	0	31	2	3	4
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<b>Medium</b>																	
Petrol	0	0	5	5	7	8	0	0	0	0	2	1	14	2	0	0	0
Diesel	41	21	21	13	3	8	0	0	0	13	11	21	3	11	36	42	39
HEV	0	6	2	0	8	0	0	0	5	0	0	0	10	0	1	0	0
PHEV	0	0	0	0	0	0	0	0	9	0	0	0	0	0	2	2	2
Fuel cell vehicles	0	0	0	0	0	0	17	2	1	0	0	0	0	0	1	1	1
EV	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
<b>Specialist</b>																	
Petrol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diesel	11	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	4
HEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1
Fuel cell vehicles	0	0	0	0	0	0	0	0	20	0	0	0	0	0	2	1	1
EV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<b>Utility</b>																	
Petrol	0	5	6	15	8	3	0	0	0	1	19	0	8	2	0	0	0
Diesel	19	7	2	0	5	0	0	0	0	17	1	11	0	12	7	10	13
HEV	0	7	3	8	16	0	0	0	0	0	0	0	16	0	3	0	0
PHEV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Fuel cell vehicles	0	1	8	0	0	22	0	0	0	3	0	6	0	10	3	0	0
EV	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0



Table A.7: Change in absolute energy use and emissions of CO<sub>2</sub> and LAP under each policy objectives with feebates for consumer behaviour changes of: 1 = business as usual; 2 = changing VKT only; 3 = increasing payback time only; and 4 = hybrid approach.

	Base				Increasing fuel duties				Feebate, 120 g CO <sub>2</sub> /km				Feebate, 95 g CO <sub>2</sub> /km				Feebate, 70 g CO <sub>2</sub> /km			
	1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			
Absolute changes (%)	1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			
CO <sub>2</sub>	0	-10	-15	-45	-55	-72	-49	-72	-26	-72	-16	-81	-21	-62	-39	-53	-21			
MJ	0	-8	-7	-21	-21	-46	-28	-46	-18	-46	-12	-52	-15	-41	-25	-35	-15			
NO <sub>x</sub>	0	-16	-63	-41	-47	-57	-70	-57	-30	-57	-23	-73	-24	-62	-49	-52	-24			
PM <sub>2.5</sub>	0	-46	-70	-59	-64	-36	-41	-36	-22	-36	-17	-47	-18	-39	-38	-32	-18			
Diversity, SMMT segment	1.74	1.74	1.74	1.51	1.52	1.04	1.71	1.04	1.64	1.04	1.7	0.76	1.69	1.04	1.57	1.49	1.66			
Factor change	0	0	0	13	13	40	2	40	5	40	2	56	3	40	10	14	4			
Diversity, powertrain type	0.074	0	0	0.925	0.802	1.292	1.269	1.292	0.868	1.292	0.401	1.234	0.529	1.316	1.081	1.181	0.562			
Factor change	0	-1	-1	11	10	16	16	16	11	16	4	16	6	17	14	15	7			
Average payback time (yr)	1	1	1	3.4	3.8	1	1	5.2	1.5	1	1	5.7	1.4	1	1	2.2	1.4			
Total Fleet VKT (10 <sup>10</sup> km)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2			
% change	0	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9	-0.9			
Fee (£per g CO <sub>2</sub> /km)	-	-	-	-	-	-98	100	23	100	99	16	86	29	100	32	79	11			
Rebate (£per g CO <sub>2</sub> /km)	-	-	-	-	-	0	9	0	63	0	99	0	100	45	100	61	100			