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

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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_2, NO_x and $PM_{2.5}$. 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_x and $PM_{2.5}$. 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_2 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_2/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 powertain 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_2 emissions, local air pollution, energy use, consumer choice, fleet diversity, passenger vehicles

1. Nomenclature

- Carbon dioxide, CO_2
- 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_x
- Particular matter with diameter less 2.5 micrometers (μ), $PM_{2.5}$
- LAP, local air pollutants comprising NO_x and $PM_{2.5}$
- 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^2), the product of wheelbase and width, FP
- Luggage volume (m^3), LUG
- Time to accelerate from rest to 60 mph or 96.6 km/h (s), Z60
- Effective drag (m^2), 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_2 emissions allowed, C
- Percentage reduction in absolute TTW/WTW CO_2 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_2 emissions (g/km), VED

2. Introduction

This work quantifies the influence of four policy objectives on the composition of an optimum new UK passenger vehicle fleet. The individual objectives are to minimise: absolute energy use; the emission of tank-to-wheel (TTW) carbon dioxide (CO_2); the emission of well-to-wheel (WTW)[1] CO_2; and the emission of TTW local air pollutants (LAP, particulate matter and nitrous oxides). The proportion of alternative novel powertrains increased from 0.1% in 2000 to 1.4% in 2012. The consequence of a large proportion of conventional powertrains means demand for road transport accounted for 27% (40 million tonnes of oil equivalent, Mtoe) of all the energy used in the UK in 2012. Consequently, road transport was responsible for 23% of all CO_2 (480 Mt), 31% of all nitrous oxides (NO_x, (340 kt) and 20% of all particulate matter with diameter less than 2.5 µm ($PM_{2.5}$, 16 kt)[2]. Therefore, large changes in the composition of the new passenger vehicle fleet are required to achieve significant reductions in energy use and emissions. However, it remains unclear what that composition – number of vehicles, powertrain type and annual vehicle kilometres travelled (VKT) per vehicle – might need to be. This is important because the UK government has committed itself to reducing economy-wide GHG emissions by 80% below 1990 levels by 2050 [?]. Therefore, an important contribution of this paper is to highlight the vehicle downsizing, technology switching and changes in VKT necessary now to set us on a path to meet future goals.

[1] 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.

[2] Data available from the Department for Transport: Tables ENV0102 for energy use, ENV0202 for CO_2 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`.

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

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

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

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

[3] 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.

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

In general, scenarios are used to quantify the role of vehicle technology and activity in the fleets of the future. Often, the scenarios include assumptions on technological learning, performance, costs and can pre-suppose winners and losers [? ? ? ? ? ? ? ? ? ? ?]. Scenarios extend to include exogenous factors, such as the price of oil [? ?] or the extent of biofuel blending [? ?]. The consensus is that significant emissions reductions cannot be achieved by a single, silver bullet approach [? ? ? ?]. Instead, a low CO_2 emissions solution requires improvements in vehicle technology be paired with consumer behaviour change [? ? ?]. Vehicle use is an important factor as growth in travel (activity) implies increasing absolute emissions which reduces the advantages of fuel efficient powertrains [? ? ? ?]. Moreover, reducing vehicle travel can yield greater total benefit (reduced external costs) than may accrue from improved fuel economy [?]. Vehicle downsizing, efficiency standards and fuel taxes can deliver large emissions reductions while mitigating the rebound effect of increased travel demand [? ? ?]. Therefore, any model which addresses fleet CO_2 emissions should account for vehicle size, powertrain type and the impact of activity.

This work provides novel contributions to the body of knowledge and advances the state of the art in three main ways. First, we use a novel top-down approach to quantify the composition of the new passenger vehicle fleet necessary to achieve a suite of policy objectives. Second, the work is diversity-led to ensure the maximum number of options are available to satisfy consumer preferences and return a realistic fleet. Third, we optimise simultaneously vehicle segment, powertrain technology and annual VKT to account for the explicit effects of downsizing, technology switching and change in activity. A summary of the method is presented in Section **??** where the components of the model are introduced. Consumer behaviour change is included through soft constraints. This section describes the formulations for achieving the objective via changes to consumer behaviour and external policy interventions. The impacts of vehicle size, powertrain technology and activity on fleet diversity, energy use and emission of CO_2 and LAP are presented and discussed in Section **??**.

3. Method

The schematic in Figure **??** illustrates how physical attributes, costs and external fiscal incentives were combined in the optimisation routine. The external fiscal incentives considered were fuel duty increases and feebates based on vehicle TTW CO_2 emissions. The optimisation was implemented with Matlab R2015b.

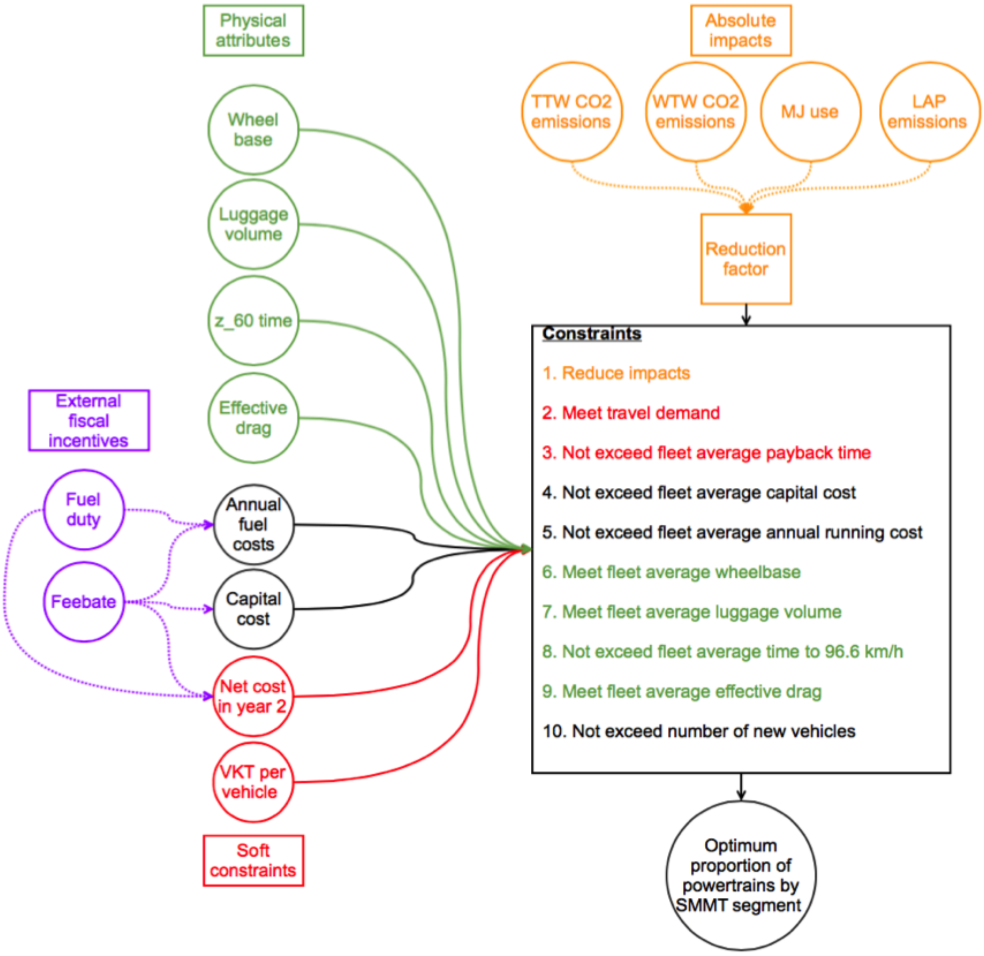

Figure 1: Schematic of methodology. Orange circles illustrate the four policy objectives using consumer behaviour change only. Purple circles illustrate policy objectives to minimise TTW CO_2 emissions with each of fuel duty increases and TTW CO_2 taxes. The red circles represent the soft constraints in the optimisation.

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

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

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

1. matching sales-weighted average vehicle footprint:

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

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

2. matching sales-weighted average luggage volume:

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

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

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

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

   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; 13.3, super mini; 10.8, lower medium; 8, upper medium; 7.4, executive; 7.1, luxury; 6.7, sports; 10.3, SUV; and 9.8, MPV. $Z60$ is the sales-weighted average time to accelerate to 96.6 km/h in 2012, 11 s.

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

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

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

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

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

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

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

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

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

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

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

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

[4]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`

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

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

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

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

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

$$\sum_{k=1}^{fuel_k} x_k.vkt_k \tag{10}$$

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

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

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

[5]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`).

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

3.1. Sensitivity of optimum fleets to the policy objective

The sensitivity of the new vehicle fleet composition was investigated for the four policy objectives to minimise, individually: TTW CO_2 emissions; WTW CO_2 emissions; energy use; and LAP emissions. Focusing on the absolute value, instead of those normalised to distance travelled, ensured true reductions were achieved.

3.1.1. Reduce TTW CO_2 emissions

Absolute CO_2 emissions from cars and taxis declined by 0.95% annually from 75 Mt in 1999 to 67 Mt in 2010. Over the same period, new vehicle sales declined from over 3.1 million per year to less than 2.5 million annually. However, the total vehicle fleet grew from 28 million to 34 million because vehicles remain in service longer now than before [**?**].

European legislation on CO_2 emissions from passenger vehicles focuses on those at the tailpipe [**?**]. By 2015, the new passenger vehicle fleet TTW CO_2 emissions should be 120 g/km, achieved by a combination of powertrain advances (to 130 g/km) and innovative technologies (the remaining 10 g/km to 120 g/km). In 2021, the limit falls to 95 g/km with indications of a limit of 68-78 g CO_2/km in 2025[6].

In 2012, the sales-weighted average TTW CO_2 emissions from new passenger vehicles was 133 g CO_2/km [**?**]. The average emissions from new cars in Bishop et al. (2014) [**?**] was 132 g CO_2/km. The total absolute CO_2 emissions of the 2012 and optimum fleets were 4.2 Mt and 4.5 Mt, respectively. The constraint to reduce absolute fleet TTW CO_2 emissions was:

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

where: $c_{i,j}$ is the TTW CO_2 emissions (g/km) from each vehicle; C is the absolute mass of CO_2 emissions (g) from the fleet of new vehicles on the road in 2012; and C_RED is the percentage reduction in absolute emissions required.

3.1.2. Reduce WTW CO_2 emissions

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

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

WTT impacts of electricity were 0.42 MJ (chemical energy in fossil-fuels combusted) and 120 g CO_2 per MJ delivered to the charging station[7] at a cost of £0.51/MJ[8]. The constraint to reduce absolute fleet WTW CO_2 emissions was:

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

where: $w_{i,j}$ is the WTW CO_2 emissions (g/km) from each vehicle.

3.1.3. Reduce energy use

Improving fuel economy of vehicles using conventional fuels can have a positive effect on CO_2 emissions. Moreover, mandating an improvement to fuel economy can encourage the increase in supply of more fuel economical cars to the market. Therefore, complying with fuel economy legislation requires necessarily that losses and inefficiencies in the engine and powertrain be addressed explicitly. Current US legislation focuses on improving both fuel economy (reducing energy use) and reducing emissions [**?**]. This contrasts the European approach which targets TTW CO_2 emissions which are a consequence, rather than a cause, of high (conventional) fuel use.

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

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

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

3.1.4. Reduce local air pollution

Passenger vehicles are responsible for primary non-CO_2 emissions, such as oxides of nitrogen (NO_x) and particulate matter ($PM_{2.5}$). These two pollutants have the largest direct impacts on human health [**? ? ?**].

[7] 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`.

[8] 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`.

[9] 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 [**?**].

The key benefits of minimising LAP emissions arise from avoided premature deaths due to exposure to PM [?]. In 2012, road transport accounted for 31% and 26% of combustion-related NO_x and $PM_{2.5}$ emissions, respectively. Passenger vehicles were responsible for 15% and 6.4%, respectively. Non-combustion related $PM_{2.5}$ emissions for passenger vehicles accounted for 11% of total emissions (3.9% for road abrasion and 7.5% for wear to tyres and brakes)[10].

Speed-dependent Euro V emissions factors for NO_x [?] and $PM_{2.5}$ [?] were used for petrol and diesel vehicles in this work. The speed used to calculate LAP emissions was 44 km/h. This was the weighted average of speeds based on VKT travelled per road type. Average road speeds for rural and urban/motorways were 18 km/h and 63 km/h, respectively. These two road types counted for 42% and 58% of VKT. Additionally, the proportion of VKT travelled under urban, rural and motorway conditions was taken as 37%, 42% and 21%, respectively [?].

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

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

LAP emissions from passenger vehicles were 150 kt NO_x and 4.3 kt $PM_{2.5}$ in 2011 [?]. However, no LAP emissions were available for the new vehicle fleet explicitly. Calculated emissions from new vehicles in Bishop et al. (2014) [?] were 15 kt NO_x (0.38 g/km) and 1 kt $PM_{2.5}$ (0.028 g/km). The base case fleet emitted 16 kt NO_x and 1.1 kt $PM_{2.5}$. The constraints to reduce LAP emissions were:

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

[10] See National Emission Ceilings (NEC) Directive Inventory for NO_x emissions (`http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-nec-directive-viewer`) and LRTAP Convention Inventory for $PM_{2.5}$ emissions (`http://www.eea.europa.eu/data-and-maps/data/data-viewers/air-emissions-viewer-lrtap`).

where: $n_{i,j}$ = NO_x or $PM_{2.5}$ emissions from each vehicle, g/km; N = absolute NO_x or $PM_{2.5}$ emissions from the fleet of new vehicles on the road in 2012, g; and N_RED is the proportional reductions in absolute emissions required.

3.2. External fiscal incentives

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

3.2.1. Increase fuel costs

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

3.3. Duty on vehicles by CO_2 emissions level

An increase in taxes on petrol and diesel targets all vehicles using those fuels. Increasing fuel duties may have less effect on fuel economy because consumers undervalue fuel savings. Instead, a more effective approach may be to shift the price signal from the fuel to the vehicle [? ?]. Annually, the UK collects a vehicle excise duty (VED) based on certified g CO_2/km[11]. Vehicles are classified into emissions bands with associated duties. The lowest emitting vehicles receive a reward of no fees.

A feebate system introduces capital cost subsidies for vehicles with emissions below a pivot (low-emissions) and additional fees for vehicles with emissions above the pivot. Such schemes provide consumers with options to downsize vehicle, shift powertrain technology and switch fuel [?]. Feebates may be weighted according to vehicle attributes, such as mass [?] or energy use [?]. Some feebates have applied costs per unit fuel consumed [? ?]. In this work, three pivots of 120 g/km, 95 g/km and 70 g/km were chosen, corresponding to the TTW CO_2 emissions limits set by the EU, with costs applied to g CO_2/km emissions of each vehicle.

[11] 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`.

The aim of the feebate scheme was to be revenue-neutral and achieved using two costs per g CO_2/km: the first was a rebate for low-emissions vehicles; and the second was a fee for high-emissions vehicles. The fees and rebates impacted ownership costs, payback time and the resulting composition of the optimum fleet. Therefore, the fees and rebates were not known *a priori*, but were limited to £100 per g CO_2/km above and below the pivot, respectively. These fees align with EU penalties for excess emissions of up to €95 per g CO_2/km [?].The feebate was implemented in the model using an equality constraint for the product of vehicle number and cost per g CO_2/km on either side of the pivot:

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

where: $fee_{i,j}$ = the fee applied to each g CO_2/km which a vehicle emits above the pivot; $rebate_{i,j}$ = the rebate applied to each g CO_2/km which a vehicle emits below the pivot; $x_{i,j}^{fee}$ = the number of vehicles with emissions above the pivot; and $x_{i,j}^{rebate}$ = the number of vehicles with emissions below the pivot.

4. Results and discussion

The model was validated by running the BAU case with no reductions in energy use or emissions and comparing the result to the 2012 fleet. Figure ??a illustrates the distribution of vehicles by SMMT segment 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

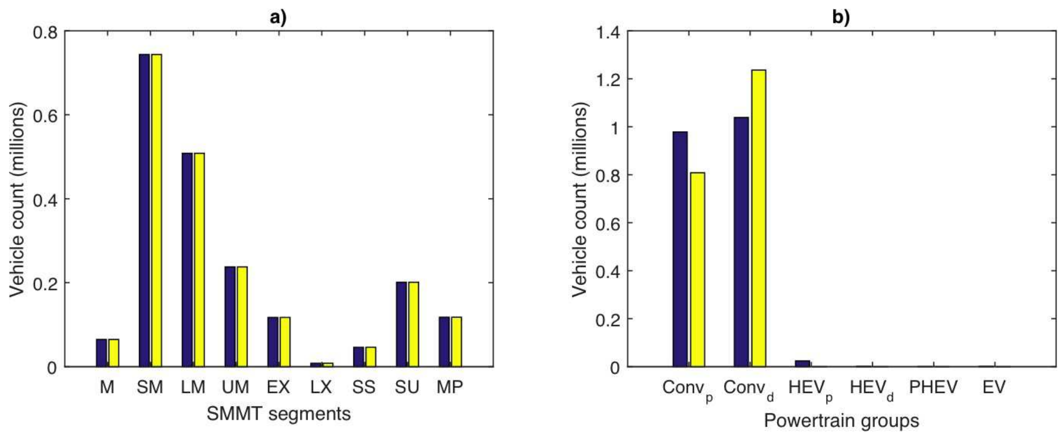

Figure 2: Verification of optimisation model against 2012 new vehicle data to create base case: a) number of new vehicles sold by SMMT segment (yellow bars) [?] and optimised fleet (blue bars); b) number of new vehicles sold by powertrain group (yellow bars) and optimised fleet (blue bars) [?]. Label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

fleet and base case by SMMT segment. Figure ??b highlights the distribution of powertrains in the 2012 fleet. There were 17% fewer petrol conventional vehicles in the base case than in 2012, offset by an increase in diesel conventional vehicles and petrol HEV. The difference in energy use and emissions, total or per km, was less than 10% between the 2012 fleet and base case.

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

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

4.1.1. Fleet composition by SMMT segment

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

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

4.1.2. Fleet composition by powertrain type

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

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

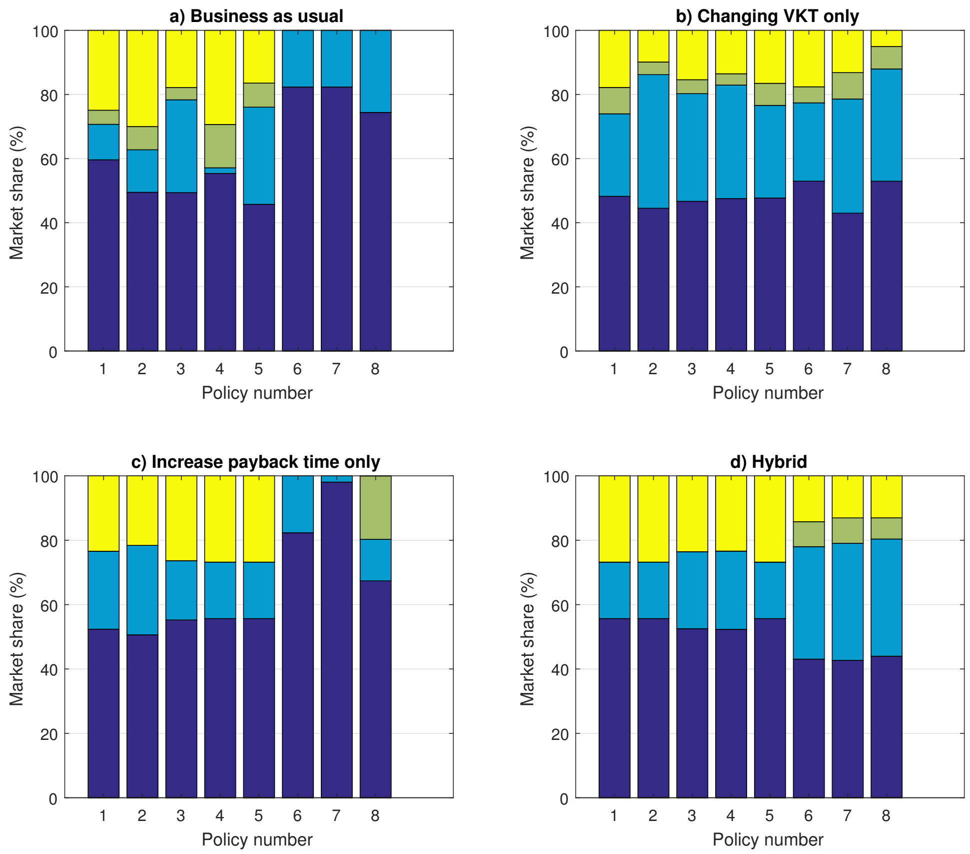

Figure 3: Bar chart showing the market share of vehicles by SMMT in the new fleets under: a) business as usual (BAU); b) changing VKT only; c) increasing payback time only; and d) the hybrid approach. Policy key: 1 = minimising TTW CO_2 emissions; 2 = minimising WTW CO_2 emissions; minimising energy use; 4 = minimising LAP emissions; 5 = increase fuel duties; 6 = introduce feebate with 120 g CO_2/km pivot; 7 = introduce a feebate with 95 g CO_2/km pivot; and 8 = introduce a feebate with 70 g CO_2/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).

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

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

The length of the bars representing novel vehicle powertrains in the presence of feebates, either under BAU or when increasing payback time only, demonstrated direct capital cost interventions are necessary to displace a significant proportion of conventional powertrains. However, capital cost subsidies are insufficient to cause a large shift to low-emitting vehicles: the additional power of the feebate is to raise the purchase price of high-emitting vehicles ones. In this case, median rebates of £100 per g CO_2/km for low-emitting vehicles were paired with median fees of £29 per g CO_2/km on high-emitting vehicles. Fuel duty increases did not influence the proportion of novel powertrains more than the other policy scenarios. The data in Figure **??** is given in Tables **??** and **??**.

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

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

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

Excluding feebates, absolute energy use and CO_2 emissions decreased with increasing consumer behaviour change, relative to BAU (dark blue). The incremental reduction in energy use and CO_2 emissions grew when

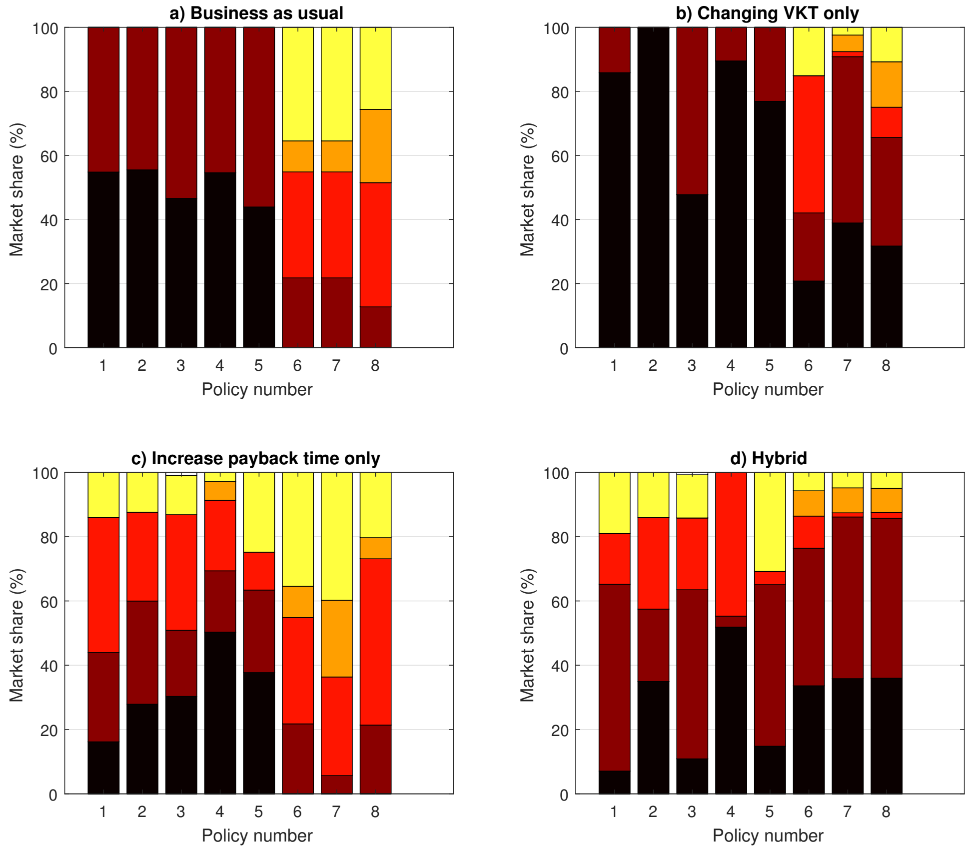

Figure 4: Bar chart showing the market share of vehicles by powertrain type in the new fleets under: a) business as usual (BAU); b) changing VKT only; c) increasing payback time only; and d) the hybrid approach. Policy key: 1 = minimising TTW CO_2 emissions; 2 = minimising WTW CO_2 emissions; minimising energy use; 4 = minimising LAP emissions; 5 = increase fuel duties; 6 = introduce feebate with 120 g CO_2/km pivot; 7 = introduce a feebate with 95 g CO_2/km pivot; and 8 = introduce a feebate with 70 g CO_2/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.

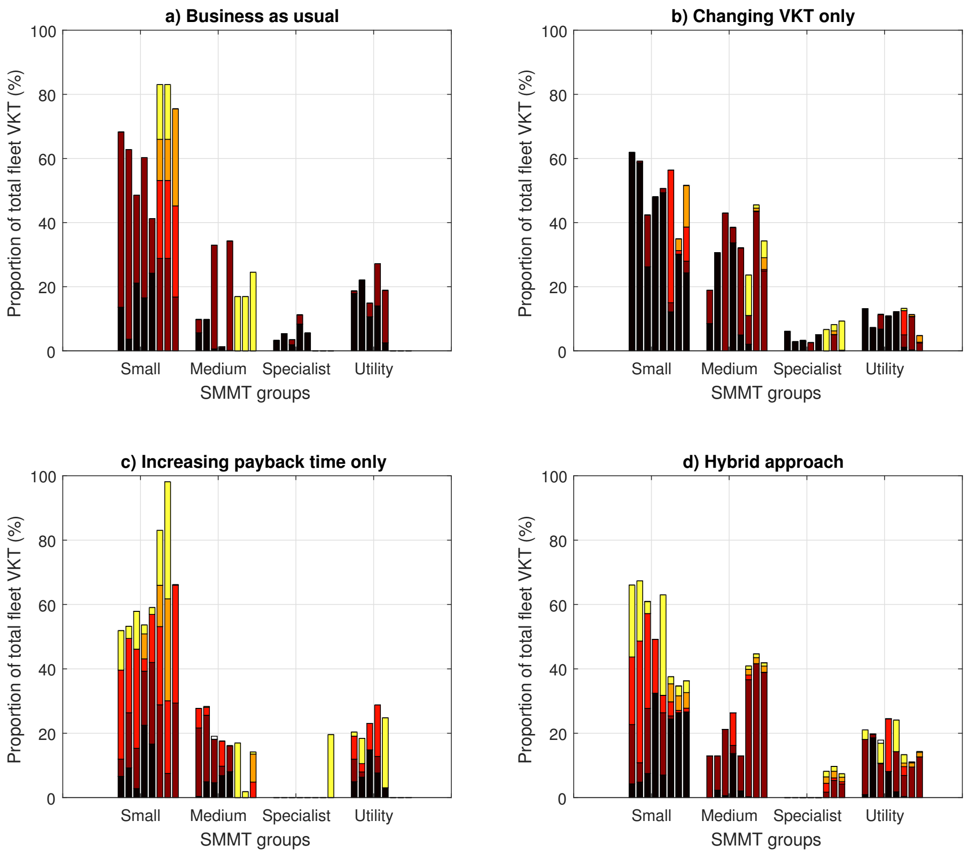

Figure 5: Stacked bar graphs representing the proportion of fleet VKT (product of number of vehicles and VKT per vehicle) per SMMT segment for the eight scenarios under a) business as usual; b) when changing VKT only; c) when increasing payback time only; and d) the hybrid approach. Colour code: black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

payback time was increased, either alone (green) or as part of the hybrid approach (yellow). The hybrid approach returned the largest changes to energy use and CO_2 emissions. These optimum fleets had the largest proportion of small vehicles (median 56%) and novel powertrains (median 41%), particularly fuel cell vehicles (median 20%) with zero tailpipe emissions. BAU returned the smallest change in LAP emissions generally. Small vehicles accounted for 49% of the new fleet. However, there was only a 14% shift towards petrol from diesel in the conventional powertrains. Consequently, diesel accounted for 49% of new vehicles with their significantly larger LAP emissions. Recall Euro V diesel vehicles emit 50 times more NO_x emissions and five times more $PM_{2.5}$ emissions, than spark ignition petrol vehicles.

Changing VKT returned the smallest changes in absolute energy use and CO_2 emissions. These optimum fleets comprised the lowest proportion of small vehicles (median 48%) and highest proportion of conventional powertrains using petrol (91%) across the SMMT segments. Therefore, the 're-petrolisation' of the fleet allowed this consumer behaviour change to return the largest fall in LAP emissions in general: NOx emissions by a median 85%; and $PM_{2.5}$ emissions by a median 70%.

Including feebates, the largest median reductions in energy use and emissions of CO_2, NO_x and $PM_{2.5}$, at 46%, 72%, 57% and 36%, respectively, was achieved under BAU and when increasing payback time only. These fleets comprised 82% small vehicles and 68% vehicles using novel powertrains (including 49% fuel cells). Median fees of £79-99 per g CO_2/km across the pivots were required to reduce the attractiveness of high-polluting vehicles and push uptake of low-polluting vehicles. The fees were effective enough that there was no median rebate supplied for the higher feebate pivots. The 70 g CO_2/km pivot required rebates of £45 per g CO_2/km.

The hybrid approach, with low median fees (£29) and high rebates (£100) was least able to reduce energy use and emissions across the policy objectives on account of the smallest proportion of both small vehicles (median 43%) and novel powertrains (median 10%). Fees may have disproportionate impact on consumer choice when there is no willingness to accept longer payback times. Across Europe, Mock (2015) observed that tax thresholds for CO_2 emissions are effective at steering consumer choice, leading to the purchase of new vehicles with emissions which take advantage of the reduced fees [**?**].

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

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

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

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

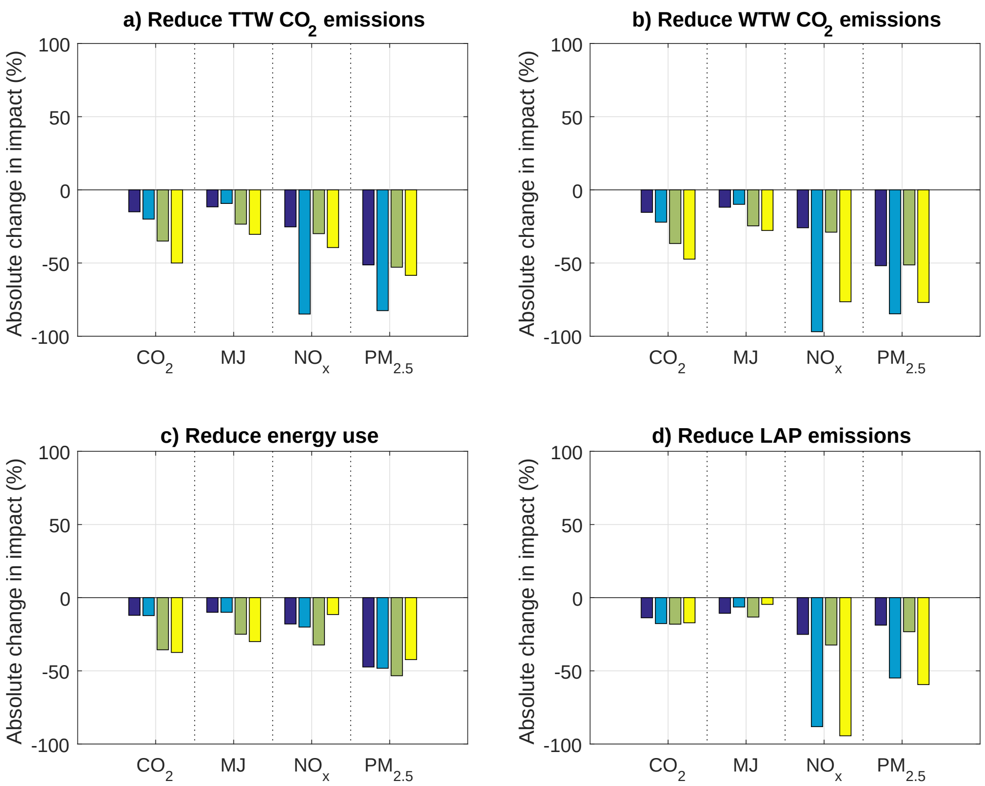

Figure 6: Percentage change in energy use and emissions of CO_2 and LAP for the policy objectives to minimise: a) TTW CO_2 emissions; b) WTW CO_2 emissions; c) energy use; and d) LAP emissions. Colour key: dark blue = business as usual; light blue = reduce VKT only; green = increase payback time only; and yellow = hybrid approach.

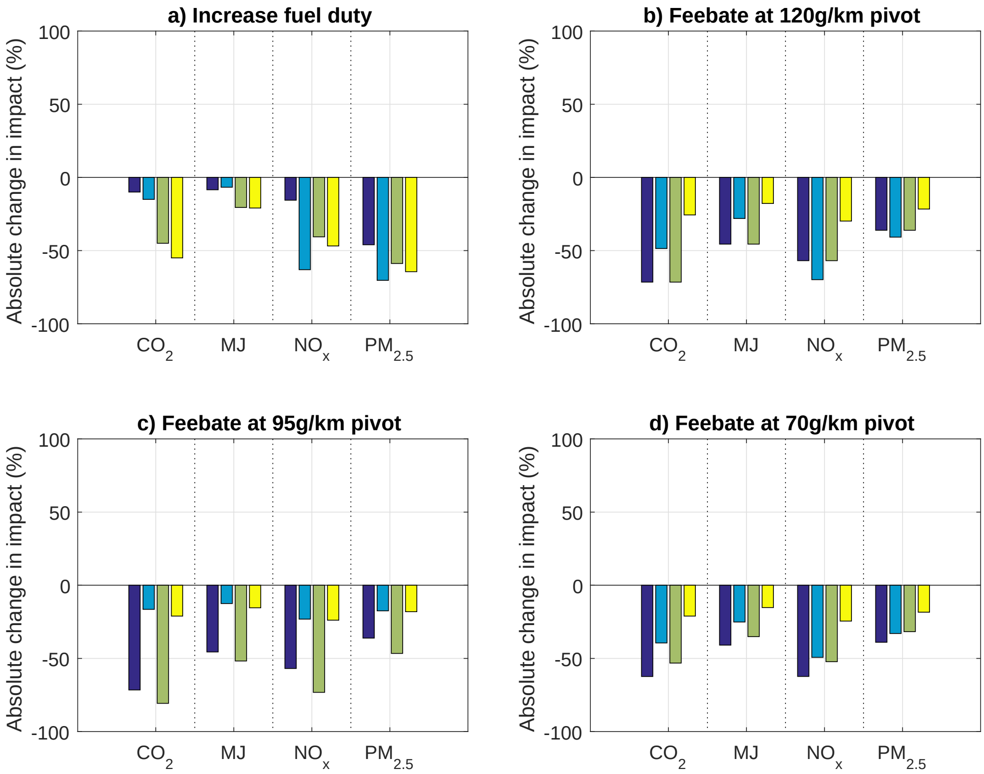

Figure 7: Percentage change in energy use and emissions of CO_2 and LAP for the policy objectives to minimise TTW CO_2 emissions in the presence of: a) increased fuel duties; b) feebate with a 120 g CO_2/km pivot; c) feebate with a 95 g CO_2/km pivot; and d) feebate with a 70 g CO_2/km pivot. Colour key: dark blue = business as usual; light blue = reduce VKT only; green = increase payback time only; and yellow = hybrid approach.

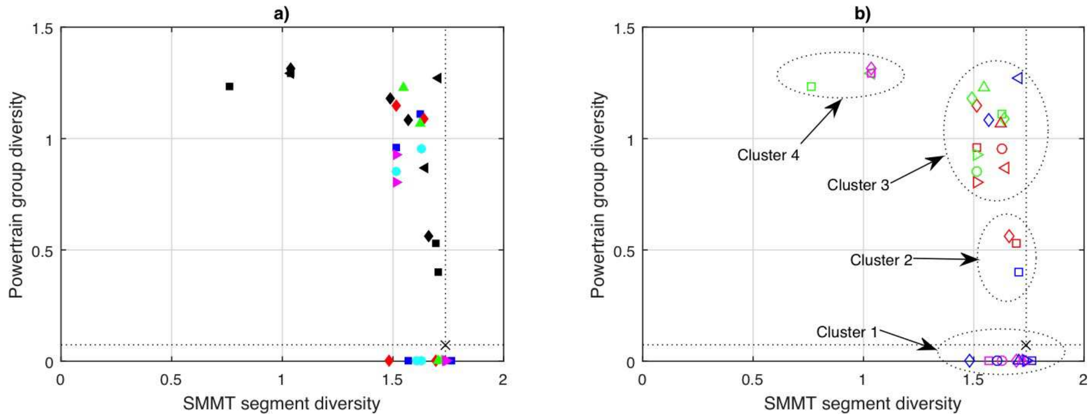

Figure 8: Scatter plot of SMMT segment diversity against technology diversity under BAU and consumer behaviour changes for each policy objective, with and without external incentives. Subplot a) colour key: black cross = diversity of 2012 real-world fleet; blue square = minimising TTW CO_2 emissions; red diamond = minimising WTW CO_2 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_2/km pivot; black square = feebate with 95 g CO_2/km pivot; and black diamond = feebate with 70 g CO_2/km pivot . Subplots b) colour key: blue = reducing VKT only; green = increasing payback time only; red = hybrid approach; and magenta = business as usual.

was seen most in four clusters. The first cluster represented BAU and changing VKT only (blue), excluding feebates. These fleets were the most specialised by powertrain type – conventional only – and returned the largest reductions in LAP emissions when changing VKT only. The only optimum fleet with higher diversity (1.8) by SMMT segment than the base case was achieved when minimising TTW CO_2 emissions by changing VKT only (blue square to the right of the vertical dotted line).

The second cluster represented the optimum fleets using feebates with a 95 g CO_2/km pivot when changing VKT only (blue squares) and under the hybrid approach (red squares) and using a feebate with 70 g CO_2/km pivot under the hybrid approach (red diamond). These three fleets were dominated by vehicles with conventional powertrains (86-91%), with the remainder spread over three groups of novel powertrains. Diversity was 4-7 times higher than the base case at 0.4-0.6.

The third cluster contained fleets where diversity by powertrain group increased 11-17 times to 0.8-1.1 and occurred when payback time was increased, either alone (green) or part of a hybrid approach (red) across the policy objectives, excluding feebates. Under feebates, optimum fleets in this cluster existed with pivots at 120 g CO_2/km (changing VKT only and hybrid approach) and 70 g CO_2/km (changing VKT only and increasing payback time only).

The fleets forming the fourth cluster were the most downsized and displayed significantly lower diversity by SMMT segment, at 0.8-1. This cluster comprised the BAU fleets across all feebate pivots and those from pivots at 120 g CO_2/km and 95 g CO_2/km when increasing payback time only. The fall in diversity by SMMT segment was balanced by increased diversity by powertrain type: these fleets displayed the highest diversity across all the clusters (at 1.3) by consisting of four powertrain groups, with no single group accounting for more than 40% of new vehicles.

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

Introducing a feebate with pivot at 120 g CO_2/km (fees of £100 per g CO_2/km and rebates of £9 per g CO_2/km) in combination with changing VKT only (blue left triangle in the third cluster) returned the largest increase in diversity by powertrain type for the smallest reduction in diversity by SMMT segment. Balancing the diversity of the fleet in these dimensions maximises the number of vehicles sizes and powertrain types available and may be the most attractive to consumers. The result was a median 28% reduction in energy use and leading to emissions of CO_2, NO_x and $PM_{2.5}$ falling by 49%, 70% and 41%, respectively. This ideal fleet comprised a 14% increase in the market share of small vehicles and a 2:1 ratio of conventional to novel (HEV and fuel cell HEV) powertrains. Data on diversity of the optimum fleets by SMMT segment and powertrain group is given in Tables **??** and **??**.

5. Conclusions

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

Fleet downsizing was required in all cases, and when combined with novel vehicle powertrains and reduced activity, returned the largest reductions in energy use and CO_2 emissions. The extent of fleet downsizing was mitigated when changing VKT only because the multiplicative effect of activity on absolute energy use and emissions was exploited to offset vehicle size. Therefore, the composition of optimum fleets by SMMT segment was closest to the base case. Moreover, these fleets comprised all conventional powertrains to return the smallest reductions in absolute energy use and CO_2 emissions. However, LAP emissions fell the most (NO_x at 85% and $PM_{2.5}$ at 70%) under this consumer behaviour change case. Technology switching in these optimum fleets took the form of fuels used, shifting from diesel back to petrol. This 're-petrolisation' minimised the proportion of diesel vehicles (median 9%) to reduce combustion-related emissions of NO_x and $PM_{2.5}$ by 50 times and five times, respectively. Finally, changing VKT only addressed the effect of activity on absolute LAP emissions, especially the road, brake and tyre wear associated with $PM_{2.5}$ emissions.

Introducing feebates maximised reductions in energy use and associated emissions for the least change in consumer behaviour. The resulting fleets were the most downsized (and specialised by SMMT group with median 82% small vehicles). However, the fleets were the most diverse in the number of novel powertrains present as a consequence of the large fees (£79-99 per g CO_2/km away from the pivot) placed on high-emitting vehicles. Such external policies may demonstrate how far energy use and emissions might be reduced in new fleets. Equally, such specialised fleets may be unachievable because they fail to satisfy the broad range of consumers' preferences.

The most balanced fleet by diversity occurred with a combination of consumer behaviour change and external incentive: by changing VKT only in the presence of a feebate with 120 g CO_2/km pivot. Here, high emitting vehicles were penalised at £100 per g CO_2/km which encouraged novel powertrains into the mix. Changing vehicle activity mitigated the need for large-scale downsizing of the fleet which allowed vehicles across a range of segments.

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

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

[12]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`.

[13]Global statistics from the International Organization of Motor Vehicle Manufacturers, available online at `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).

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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.

	Base	TTW				WTW				MJ				LAP			
SMMT group		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

	Base	Increasing fuel duties				Feebate, 120 g CO_2/km				Feebate, 95 g CO_2/km				Feebate, 70 g CO_2/km			
SMMT group		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
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 powertain group under non-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.

	Base	TTW				WTW				MJ				LAP			
Powertrain group		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 powertain 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.

	Base	Increasing fuel duties				Feebate, 120 g CO_2/km				Feebate, 95 g CO_2/km				Feebate, 70 g CO_2/km			
Powertrain group		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_2 emissions; 2 = minimise WTW CO_2 emissions; 3 = minimise energy use; 4 = minimise LAP emissions; 5 = increase fuel duties; 6 = introduce feebates at 120 g CO_2/km pivot; 7 = introduce feebates at 95 g CO_2/km pivot ; and 8 = introduce feebates at 70 g CO_2/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_2 emissions; 2 = minimise WTW CO_2 emissions; 3 = minimise energy use; 4 = minimise LAP emissions; 5 = increase fuel duties; 6 = introduce feebates at 120 g CO_2/km pivot; 7 = introduce feebates at 95 g CO_2/km pivot ; and 8 = introduce feebates at 70 g CO_2/km pivot.

	Base	Increasing payback time only								Hybrid approach							
Vehicle group		1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Small																	
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
Medium																	
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
Specialist																	
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
Utility																	
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.6: Change in absolute energy use and emissions of CO_2 and LAP under each policy objective without feebates for consumer behaviour changes of: 1 = business as usual; 2 = changing VKT only; 3 = increasing payback time only; and 4 = hybrid approach.

	Base	TTW				WTW				MJ				LAP			
	1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Absolute changes (%)																	
CO_2	0	-15	-20	-35	-50	-15	-22	-37	-47	-12	-12	-36	-37	-14	-18	-18	-17
MJ	0	-12	-9	-23	-30	-12	-10	-25	-28	-10	-10	-25	-30	-11	-6	-13	-5
NO_x	0	-25	-85	-30	-39	-26	-97	-29	-76	-18	-20	-32	-12	-25	-88	-32	-94
$PM_{2.5}$	0	-51	-83	-53	-58	-52	-85	-51	-77	-47	-48	-53	-42	-19	-55	-23	-59
Diversity, SMMT segment	1.74	1.57	1.76	1.63	1.52	1.7	1.48	1.64	1.51	1.72	1.7	1.55	1.62	1.63	1.61	1.51	1.63
Factor change	0	10	-2	6	13	2	15	6	13	1	2	11	7	6	8	13	6
Diversity, powertrain type	0.074	0	0	1.108	0.959	0	0	1.086	1.148	0	0	1.23	1.069	0	0	0.855	0.953
Factor change	0	-1	-1	14	12	-1	-1	14	14	-1	-1	16	13	-1	-1	11	12
Average payback time (yr)	1	1	1	2.7	2.9	1	1	2.4	2.6	1	1	2.5	2.5	1	1	1.5	1.5
Total fleet VKT (10^{10} 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

Table A.7: Change in absolute energy use and emissions of CO_2 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_2/km				Feebate, 95 g CO_2/km				Feebate, 70 g CO_2/km			
	1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Absolute changes (%)																	
CO_2	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_x	0	-16	-63	-41	-47	-57	-70	-57	-30	-57	-23	-73	-24	-62	-49	-52	-24
$PM_{2.5}$	0	-46	-70	-59	-64	-36	-41	-36	-22	-36	-17	-47	-18	-39	-33	-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^{10} 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_2/km)	-	-	-	-	-	-98	100	23	100	99	16	86	29	100	32	79	11
Rebate (£per g CO_2/km)	-	-	-	-	-	0	9	0	63	0	99	0	100	45	100	61	100