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CAN VEHICLE EFFICIENCY BEAT FUEL EFFICIENCY IN CUTTING FUEL USE

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Can vehicle efficiency beat fuel efficiency in cutting fuel use?

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Abstract

This paper demonstrates the importance of considering both energy and non-energy efficiency improvements in the provision of energy intensive household services. Using the example of private transport, we analyse whether vehicle efficiency can beat fuel efficiency in cutting fuel use. We find that this ultimately depend on the elasticity of demand for transport, the substitutability between vehicles and fuels and the initial share of fuel use in private transport. The framework also allows to identify 'multiple benefits' of technical progress in private transport by considering both the ability of such policy to reduce fuel demand and to increase the consumer's surplus. We extend the partial equilibrium framework by using computable general equilibrium (CGE) simulations to identify the system-wide impacts on total fuel use of the two alternative efficiency changes. Simulation results suggest that the substitution effects identified in the partial equilibrium analysis are an important element in determining the change in total fuel use resulting from these consumption efficiency changes. However, the identification of associated changes in intermediate fuel demand, plus the potential expansionary effects of the improvements in household efficiency transmitted through the labour market can generate general equilibrium effects that vary substantially from those derived using partial equilibrium analysis.

Key words: energy-services, technical progress, energy efficiency, partial equilibrium, general equilibrium

JEL Codes: C68, D58, Q43, Q48

Households primarily consume energy directly through the use of energy-intensive household services, such as space heating, refrigeration, air-conditioning and private transport.[1] These services are typically generated by combining energy and some domestic durable good. The present paper investigates the impact of efficiency improvements in the provision of such energy-intensive services. It takes as an example the provision of private transport through the combination of household fuel and vehicle use and has three main objectives.

The first is to extend the analysis in Figus et al (2018) which focussed on the impact of vehicle-augmenting efficiency changes in fuel use in the household provision of private transport services. Initially we use partial equilibrium analysis to compare fuel- and vehicle-augmenting efficiency improvements and identify the combinations of key parameter values for which these efficiency changes are effective in reducing fuel use. The second aim is to augment this approach by incorporating the notion of the multiple benefits of fuel efficiency improvement. In the partial equilibrium framework, we construct a multiple benefits index that combines reductions in household fuel use and the increase in consumer surplus generated by the reduction in private transport price. We investigate the sensitivity of the change in the multiple benefits index to changes in fuel and vehicle efficiency. The third aim is to widen the analysis by using computable general equilibrium (CGE) simulations to identify the system wide impacts of the alternative efficiency changes. This allows for a more extensive representation of the multiple benefits of efficiency improvements. Whilst the analysis specifically addresses fuel use in the provision of private transport, the general arguments apply to all examples of household energy used in the delivery of energy-intensive domestic services.

The paper continues as follows. Section 1 outlines the background literature. Section 2 details the way in which we conceptualise the production of private transport services. Section 3 presents the partial equilibrium analysis of the determinants of household energy use and Section 4 comments on this. Section 5 extends the partial equilibrium analysis to encompass the multiple benefits perspective. Section 6 is a brief outline of the CGE simulation approach. Section 7 lists the key characteristics of the specific CGE model of the UK economy, UK-ENVI, which is used in this paper. Section 8 gives the simulation strategy and Section 9 summarises the simulation results. Section 10 comprises a short conclusion.

1. Background

Many studies that investigate the effect of energy-saving technical improvements in consumption have the common characteristic that physical energy is modelled as being consumed directly (Chitnis and Sorrell, 2015; Duarteet al., 2016; Druckman et al., 2011; Frondel et al., 2012; Lecca et al., 2014; Schwarz and Taylor, 1995; and West, 2004). Contributions to this literature normally identify rebound whose size varies, partly depending on the modelling method adopted. Whilst some of this work relates energy efficiency improvements to the capital costs associated with the increase in efficiency (Chitnis et al. 2015;

[1] This is in contrast to the energy that is consumed indirectly through the energy embodied in the industrial production of the goods and services households purchase.

Mizobuchi, 2008; Sorrell, 2008), none explores the relationship between the physical energy and the capital appliances used in the household production of the energy-intensive consumer services.

A small number of other papers specifically attempt to model energy-intensive consumer services as a combination of physical energy and technology (Haas et al., 2008; Hunt and Ryan, 2015; and Walker and Wirl, 1993). Gillingham et al. (2016) aims to consolidate this literature and Figus et al. (2018) expands on this consolidation to consider explicitly the impact on economy-wide fuel use of vehicle-augmenting technical change in the production of private transport. The central issue in Figus et al. (2018) is whether efficiency improvements in the use of an input that operates in combination with energy can be an effective means of reducing energy use. In the present paper we widen this approach to investigate the relative effectiveness of vehicle-augmenting, as against fuel-augmenting efficiency improvements, in reducing fuel use. Also if extend this comparison to incorporate a multiple benefits approach.

2. Specifying the production of household services

Following Gillingham et al. (2016) and Figus et al. (2018), this paper takes as an example the households production of private transport, measured in miles travelled, *m*, which is generated using inputs of refined fuel, *f*, and vehicles, *v*. This implies that households have a derived demand for fuel, stemming from their requirement for private transport with the analysis adopting a Marshallian long-run perspective, so that households are fully adjusted to the efficiency shocks. To produce private transport, the household uses a conventional, well-behaved production function expressed as:

(1) $$m = m(f^e, v^e)$$

The inputs to this production function are specified in efficiency units, denoted by the *e* superscripts, where the relationship between inputs measured in efficiency and natural units is:

(2) $$f^e = f^n(1+\gamma_f), \quad v^e = v^n(1+\gamma_v)$$

In equation (2) the *n* superscript indicates natural units and the parameters γ_f, γ_v are the corresponding efficiency parameters. Initially natural and efficiency units coincide so that the efficiency parameters are set to zero. An improvement in the efficiency of either input is then represented as an increase in the corresponding value of γ and implies an increase in the effective services provided by a given physical quantity of that input. For example, an increase in fuel efficiency, which we also refer to as fuel-augmenting technical change, increases the effective services provided by fuel. Such an efficiency improvement would allow a reduction in the physical use of fuel whilst output and all other inputs were held constant (though this would not typically be the cost minimising reaction for the firm).

If the price of fuel and vehicles, measured in natural units, p_f^n and p_v^n, remains constant, the impact of input augmenting technical change reduces the price of the corresponding inputs measured in efficiency units, so that:

(3) $$p_f^e = \frac{p_f^n}{(1+\gamma_f)}, \quad p_v^e = \frac{p_v^n}{(1+\gamma_v)}$$

A comprehensive diagrammatic analysis of the partial equilibrium impact of a vehicle-augmenting efficiency change is given in Figus et al. (2018). In the present paper, a more detailed algebraic account is given which covers both inputs. Holding the price of inputs constant in natural units, an increase in either fuel or vehicle efficiency reduces the price of that input measured in efficiency units and therefore reduces the cost (and price) of private transport. Other things being equal, this will increase the demand for fuel. Where the efficiency increase is in vehicles, there will also be a substitution away from fuel: fuel use per mile travelled will fall. Where the efficiency increase is fuel augmenting, fuel use per mile measured in efficiency units will rise. However, the corresponding use in natural units needs to be adjusted downwards using equation (2). But before we analyse this in more detail, it will prove useful to give examples of such efficiency improvements.

It is important to stress that the nature of the efficiency change does not depend on its means of delivery. That is to say, changes in vehicle design, fuel composition or household behaviour can all generate efficiency changes that are energy or vehicle augmenting. This means, for example, that improvements in vehicle construction can be vehicle or energy augmenting. Imagine technical changes embedded in the vehicle that do not reduce the cost of the vehicle but relate solely to the materials out of which the vehicle is made. One improvement would be to reduce the vehicles weight and therefore increase the fuel efficiency. This is the type of change envisaged by Gillingham et al. (2016) and is purely fuel augmenting. On the other hand, improvements in the durability, but not the weight, of the vehicle reduce maintenance costs but not fuel efficiency and are purely vehicle augmenting. Similarly changes in the refining of the fuel could either reduce the fuel consumption or the wear on the engine. The first would represent fuel, the second vehicle, augmenting technical progress. Again by adjusting driving habits fuel efficiency can be improved, whilst changes in maintenance practices can be vehicle augmenting through reducing depreciation costs.

3. Partial Equilibrium Analytical Model: Fuel Use

In this section we focus solely on the impact of efficiency improvements on household fuel use in a partial equilibrium setting. Our approach adapts the results generated in Holden and Swales (1993), which analyses the effect of a factor subsidy in a perfectly competitive industry where the output is produced by a two-factor production function. The aim of that paper was to identify the employment impacts of labour and capital subsidies. The same analytical framework can be applied to improvements in efficiency in the production of private transport using inputs of vehicles and fuel. As demonstrated in Section 2, the effect of input-augmenting technical change is similar to an input price reduction, as long as the inputs are measured in efficiency units. However, we have an additional twist in that, where appropriate, changes in fuel use in efficiency units need to be converted to the corresponding change measured in natural units.

The results from Holden and Swales (1993) are used to obtain the appropriate elasticity of demand for fuel use with respect to the price of fuel and vehicles. In the household production of private transport,

σ is the elasticity of substitution between fuel and vehicles and η is the price elasticity of demand for private transport. The value of the initial share of fuel is *s*. The fuel demand elasticity expressions are derived in Appendix 1 and are given by equations (4) and (5).

(4) $$\frac{p_f^e}{f^e}\frac{df^e}{dp_f^e} = \sigma(1-s) + s\eta > 0$$

(5) $$\frac{p_v^e}{f^e}\frac{df^e}{dp_v^e} = (1-s)(\eta - \sigma) > 0 \quad iff \quad \eta > \sigma$$

On the assumption that natural prices remain constant, equation (3) links the change in fuel and vehicle prices to changes in efficiency and equation (2) adjusts the demand in efficiency units to natural units so that:

(6) $$\frac{1}{f^n}\frac{\partial f^n}{\partial \gamma_f} = \sigma(1-s) + s\eta - 1$$

(7) $$\frac{1}{f^n}\frac{df^n}{d\gamma_v} = (1-s)(\eta - \sigma)$$

Equations (6) and (7) are the elasticities of demand for fuel with respect to changes in fuel- and vehicle-efficiency respectively.

In both equations, the higher is the value of the elasticity of demand for private transport, η, the less likely that there are fuel savings following an increase in input efficiency. This is straightforward; other things being equal, the higher the output response to this reduction in price, the greater is the subsequent positive stimulus to fuel use. On the other hand, the impact of variations in the elasticity of substitution differs between the efficiency shocks. For fuel-augmenting technical change there is a positive relationship between the value of σ and the change in fuel use, whilst for increased vehicle efficiency the relationship is negative. This reflects the substitution impacts of lower input prices, measured in efficiency units.

The parameter combinations required to produce a given value, ϕ, for the elasticities of demand for fuel with respect to changes in fuel- and vehicle-efficiency can be found by setting $\frac{1}{f^n}\frac{\partial f^n}{\partial \gamma_f}$ and $\frac{1}{f^n}\frac{\partial f^n}{\partial \gamma_v}$ equal to ϕ in equations (6) and (7) and rearranging produces:

(8) $$\eta = -\frac{(1-s)}{s}\sigma + \frac{1+\phi}{s}$$

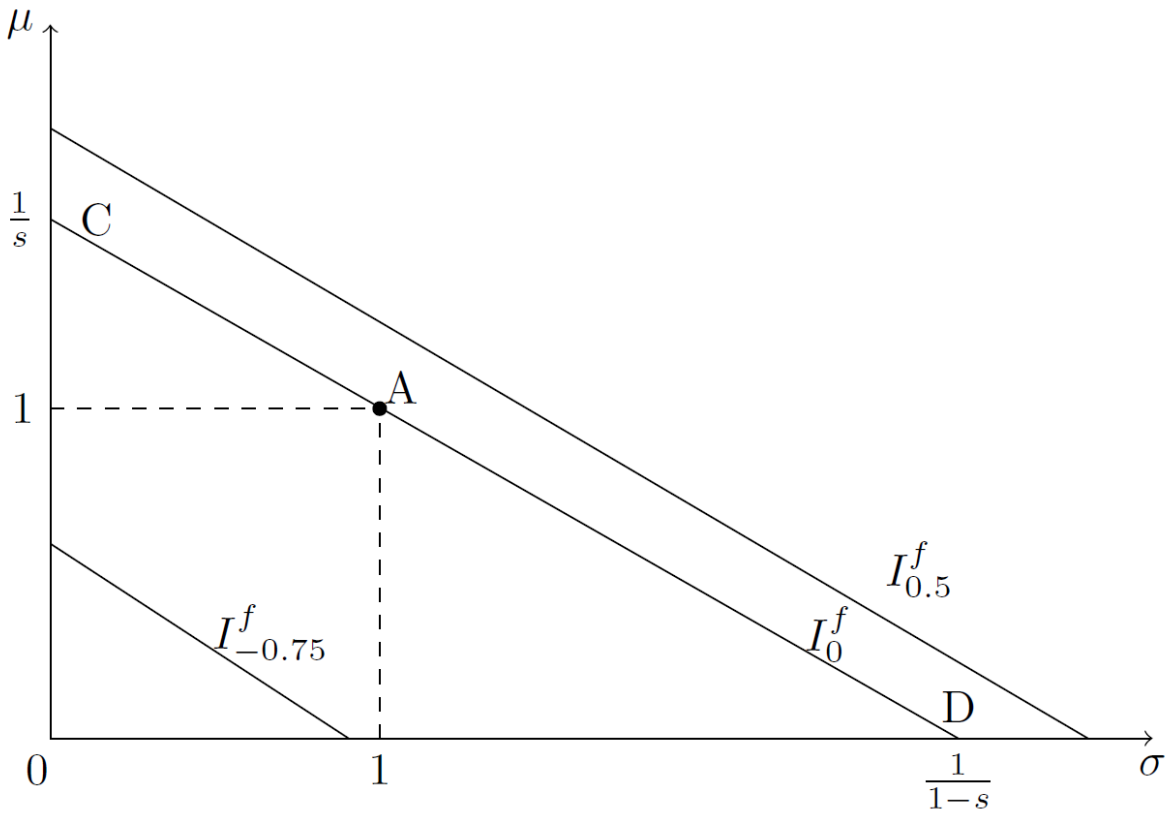
(9) $$\eta = \sigma + \frac{\phi}{1-s}$$

Equations (8) and (9) identify the locus of values for the elasticities η and σ which give the same proportionate change in fuel use change, ϕ, for the respective changes in fuel and vehicle efficiency. We refer to these as iso-fuel change functions, I_{ϕ}^{z}, where the z superscript denote the source of the efficiency change, *f* or *v*.

3.1 Increases in fuel efficiency

Figure 1 illustrates a selection of the I_{ϕ}^{f} functions. The superscript indicates that they are associated with an increase in fuel efficiency. Using equation (8) we can locate the intercepts on the η and σ axes.

Figure 1. The iso-fuel change lines for an increase in fuel efficiency I_{ϕ}^{f} in the domestic household production of private transport



It proves useful to identify some benchmark I_{ϕ}^{f} functions. To begin, the iso-fuel change line I_{0}^{f} is the locus of elasticity values where any increase in fuel efficiency leads to no change in total fuel use; with these parameters the elasticity of fuel use with respect to fuel efficiency equals zero.[2] This line cuts the η

[2] As discussed later, the composition of the change in fuel use will differ across these sets of parameter values but the change in total fuel use at each of these points is zero.

and σ axes at the values $\frac{1}{s}$ and $\frac{1}{1-s}$ and also passes through the point $(1,1)$. These points are labelled C, A and D in Figure 1. The line CAD marks the boundary between parameter values which give positive and negative fuel-use responses to increases in the efficiency of fuel. In the terminology of the rebound literature, CAD identifies the frontier for backfire. Parameter combinations below and to the left of CAD generate fuel use reductions with increased fuel efficiency, whilst points above and to the right produce fuel use increases.

The change in fuel use can be decomposed into two elements: the change in fuel intensity of private transport and the change in expenditure on private transport. Where there is no change in fuel use, a positive proportionate change in one of these elements must be offset by a corresponding negative reduction in the other. Point A, where σ and η are both unity, lies on I_0^f. The underlying intuition is straightforward. If the elasticity of demand for private transport equals unity, the total expenditure on private transport is invariant to changes in its price; adjustments in quantity demanded just counter any change in the price. But also if the elasticity of substitution between fuel and vehicles equals one, the share of output going to both inputs does not vary with changes in their relative prices. Given that the price of fuel is held constant in physical units, this means that where $\sigma = \eta = 1$, the physical use of fuel is invariant to any changes in efficiency.[3] The proportionate changes in fuel intensity and the private transport expenditure are each equal to zero in this case.

The zero iso-fuel change line, CAD, therefore pivots around A, its specific position depending on the value of s, the share of fuel expenditure in the household production of private transport. The lower the value of s, the higher the intercept on the η axis and the steeper is the negative slope of line CAD.

Consider the point C, which locates the value of η where $\sigma = 0$. At this point, the proportionate reduction in energy use per unit of private transport is equal to the proportionate efficiency gain. The only source of rebound is the increase in demand for private transport. This is greater, the larger the proportionate reduction in the price of private transport, which is itself positively related to the share of fuel. Therefore where $\sigma = 0$, the value of η at which energy use increases falls as the share of fuel in the production of private transport rises.

Where $\eta = 0$, any increase in fuel use associated with fuel augmenting technical change is solely driven by the substitution of fuel for vehicles in the production of private transport; there is no increase in output as the result of the lower price. The substitution depends upon the fall in the price of fuel, in efficiency units, relative to the price of private transport. This is lower, the higher the share of fuel. Therefore the elasticity of substitution at which fuel use actually increases is higher the higher the share of fuel.

[3] This argument also applies, as will be shown later, for the corresponding iso-fuel change function associated with the vehicle efficiency change, I_0^v.

I_{ϕ}^{f} lines that are parallel to, and lie above, the line CAD identify parameter values where the elasticity of fuel use with respect to fuel efficiency is positive. Therefore the line $I_{0.5}^{f}$ gives those elasticity values for which a 10% increase in fuel efficiency leads to a 5% increase in fuel use. Of course we are more interested in fuel use reductions. Given that we define η and σ as positive, this means parameter values within the area C0D in Figure 1. These lie on iso-fuel change lines for values of ϕ between 0 and -1, with lines closer to the origin represent larger negative values. We have noted already that the I_{0}^{f} function is the line CAD and the I_{-1}^{f} is represented by the single point at the origin. As an example, with parameter values on the $I_{-0.75}^{f}$ iso-fuel change line, a 10% increase in fuel efficiency would generate a 7.5% reduction in fuel use. This represents a 25% rebound.[4] Elasticity values below and to the left of the $I_{-0.75}^{f}$ line produce rebound values less than 25%, whilst those above and to the right generate rebound higher than 25%.

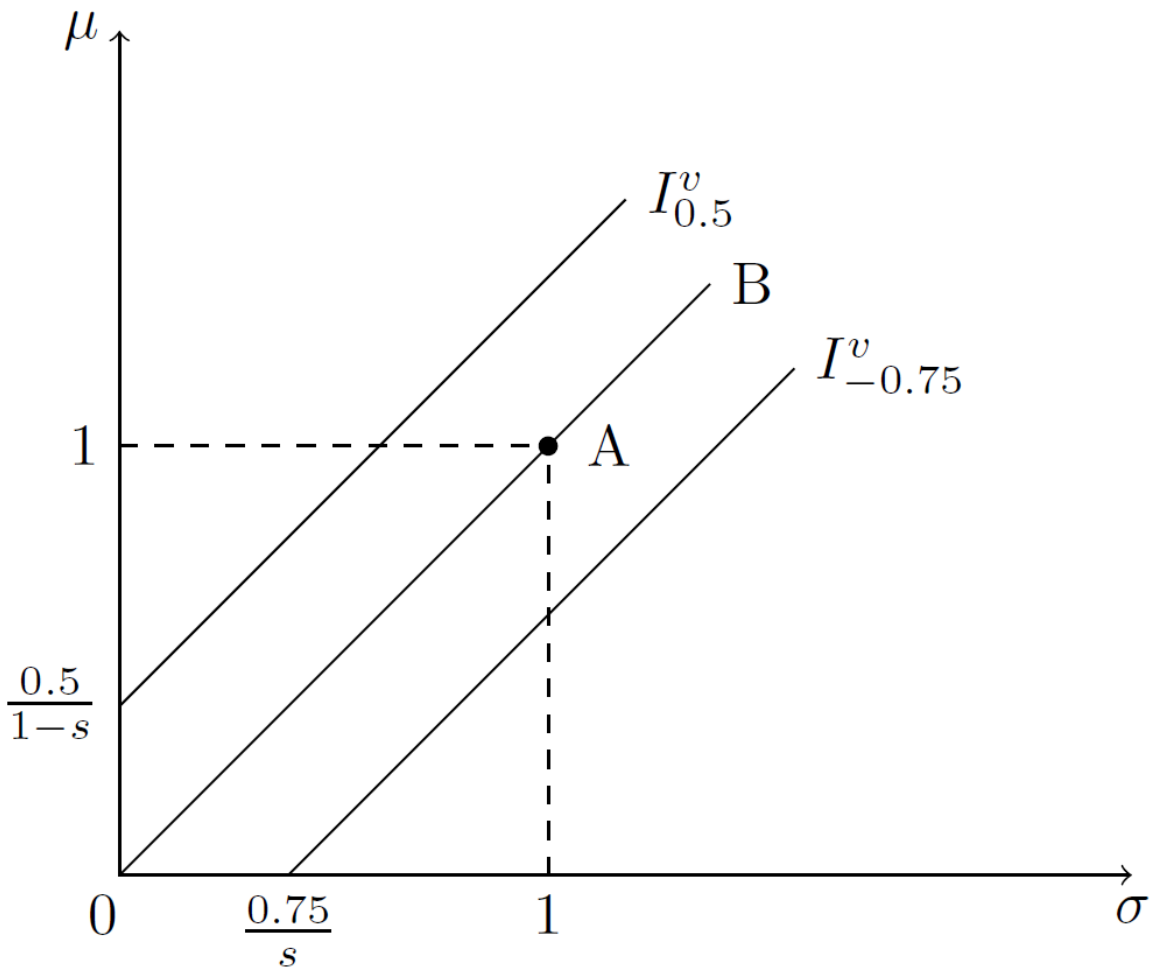
3.2 Increases in vehicle efficiency

From equation (9), the relevant set of iso-fuel change I_{ϕ}^{v} functions for an increase in vehicle efficiency are shown in Figure 2. Where ϕ, takes a negative value, the iso-fuel change curve has an intercept on the σ axis at $-\frac{\phi}{1-s}$, whilst for a positive value the intercept on the η axis is $\frac{\phi}{1-s}$. In all cases the slope positive and is equal to 1.

Again it is useful to identify I_{0}^{v} as a benchmark. This identifies parameter values where an increase in vehicle efficiency generates no change in fuel use. It is shown in Figure 2 by the 45 degree line 0AB through the origin. Points lower and to the right of the line 0AB represent parameter combinations on iso-fuel change lines where the fuel use will fall with vehicle-augmenting technical change. Points above and to the left of the line 0AB give elasticity combinations that generate an increase in fuel use. The higher the elasticity of substitution, the greater the substitution of vehicles for fuel as the price of vehicles in efficiency units falls and therefore the higher the value that the elasticity of demand for private transport that is consistent with fuel use still falling.

[4] The rebound value, R_{ϕ} is defined as $R_{\phi} = 1 + \frac{df^{n} / f^{n}}{d\gamma^{f} / \gamma^{f}} = 1 - \phi$.

Figure 2. The iso-fuel change lines for an increase in vehicle efficiency I_{ϕ}^{v} in the domestic production of private transport



It is straightforward to intuitively locate the zero iso-fuel change line for the improvement in vehicle efficiency. Where I_0^v a there is no change in the fuel use per mile travelled. This means that for there to be no change fuel use, the miles travelled must remain unchanged, even though the price of private transport has fallen. This requires $\eta = 0$, so that the (σ, η) elasticity combination (0,0) is on the I_0^v line. Similarly, where $\sigma = 1$, the share of fuel in the production of private transport remains constant. For fuel use to remain unchanged, the total expenditure on private transport must also remain unchanged, so that $\eta = 1$. As with the fuel efficiency improvement, point A must lie on the zero iso-fuel change line. The impact of vehicle efficiency improvements on fuel use is explored in more detail in Figus at al (2018).

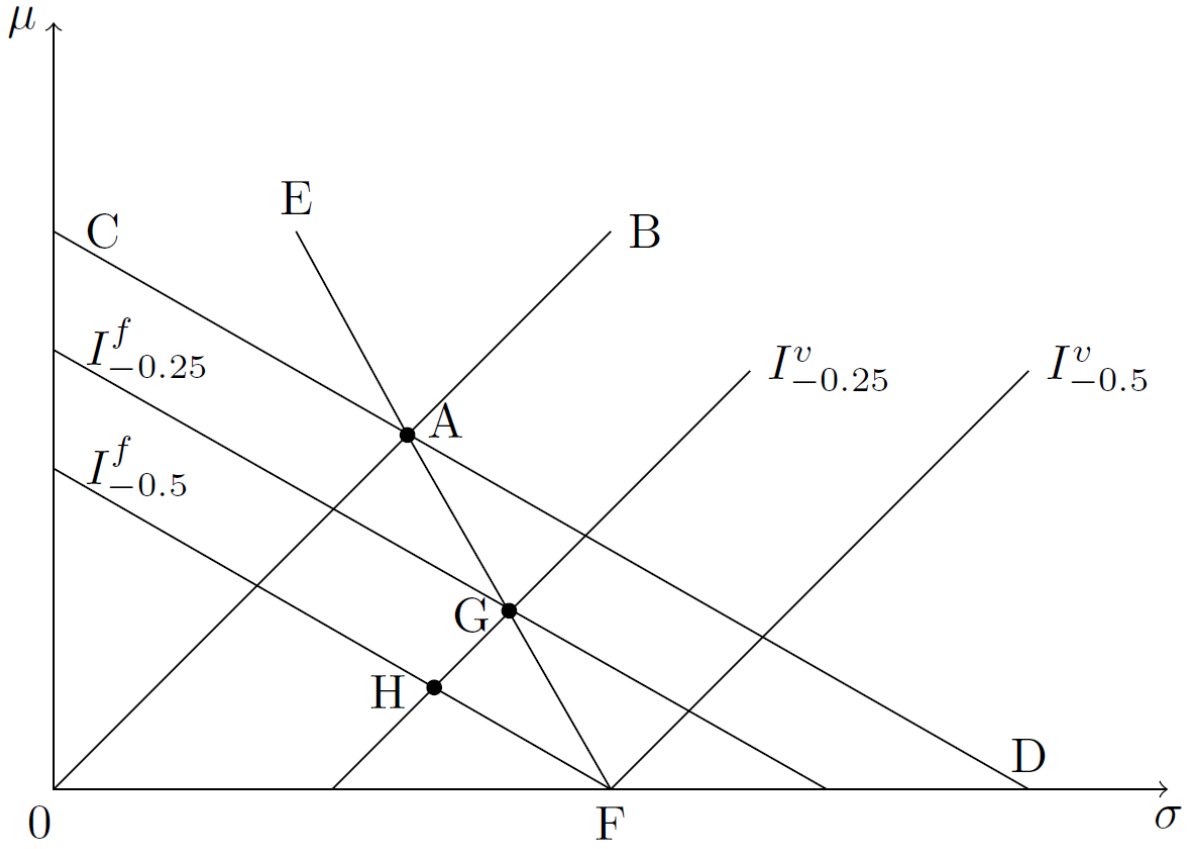
3.3 Comparing the efficiency impacts

Equations (8) and (9) can be used to identify combinations of parameter values where efficiency improvements in both vehicles and fuel will reduce fuel use and others where an improvement in neither is able to do this. There are also combinations where either one or the other efficiency improvement will

reduce fuel demand. This is illustrated in Figure 3. As in Figures 1 and 2, the lines 0AB and CAD identify the zero iso-fuel change functions are given for fuel and vehicle efficiency improvements.

It is clear from Figure 3 that there will always be a range of parameter values where any increase in either fuel or vehicle efficiency will produce a reduction in fuel use. This is the elasticity combinations in the area 0AD. Also in the areas 0AC and BAD only fuel and vehicle efficiency improvements, respectively, produce fuel reductions. In the area CAB fuel use always increases with any improvement in efficiency.

Figure 3. Comparing I_{ϕ}^{f} and I_{ϕ}^{v} functions



It is also quite straightforward to identify the locus of parameter values where a given proportionate improvement in fuel or vehicle efficiency a proportionate change in fuel use that is the same for both efficiency shocks. This is where:

$$(10) \qquad \frac{1}{f^n}\frac{\partial f^n}{\partial \gamma_f} = \frac{1}{f^n}\frac{\partial f^n}{\partial \gamma_v}$$

Substituting expressions (6) and (7) into (10) and simplifying gives the result that equation (10) holds where:

(11) $$\eta = -\frac{2(1-s)}{(1-2s)}\sigma + \frac{1}{(1-2s)}$$

This boundary between parameter values where the change in fuel use is equal with the same proportionate increase in vehicle, as against fuel, efficiency is given by the line EAF in Figure 3. Combinations of parameters that lie to the right of this line are where the improvements in vehicle efficiency give the lower increase (or larger fall) in fuel use. This line cuts the σ axis at point F, where σ takes the value $\frac{1}{2(1-s)}$, half-way between 0 and D. The line EAF takes a positive, vertical or negative slope as the value of s is less, equal or greater than 0.5. In this section of the paper our sole focus is on fuel reduction so that we are particularly interested in situations where both efficiency elasticities are negative. For parameter values in the area OAD in Figure 3 both elasticities are negative and with parameters in the area OFA an increase in fuel efficiency is more effective in reducing fuel use, whilst in area FAD an equal proportionate improvement in vehicle efficiency is more effective.

We can also identify the line EAF as joining all the points where the iso-fuel change lines with equal ϕ values intersect. Examples are the points A, G and F.[5] Points such as H are on iso-fuel change lines where the ϕ values differ between fuel and vehicle efficiency improvements. A 10% increase in fuel efficiency at H leads to a 5% reduction in fuel use but a similar improvement in vehicle efficiency will reduce fuel use by only 2.5%.

Finally, summing equations (6) and (7) gives the fuel impact of an equal simultaneous efficiency improvement to both inputs. In a standard production function this would be a Hicks-neutral technical improvement. Under the present circumstances, the necessary and sufficient condition for the fuel use to fall is simply that the elasticity of demand for private transport is inelastic. With any value of σ ,an equal proportionate improvement in the efficiency of fuel and vehicles will reduce fuel use, as long as $\eta < 1$. If the technological change is an unequally weighted set of input efficiency improvements the fuel outcome will be the weighted sum of equations (6) and (7).

4. Comments on the Use of Efficiency Improvements to Reduce Domestic Energy Use

Figure 1 can be used to derive some helpful rules of thumb for thinking about the impact of fuel and vehicle efficiency improvements in the delivery of private transport services. First, where the demand for private transport is price inelastic so that $\eta < 1$, there is some increase in either fuel or vehicle efficiency (or both) which will reduce direct household fuel use for any combination of the values of s and σ. If the fuel and vehicle inputs are complements, implying that, $\sigma < 1$, this is more likely to be an

[5] It is an interesting result that at point F, where the AGF curve intercepts the σ axis, the elasticities of fuel use with respect a change in fuel and vehicle efficiency parameters always equals -0.5. This reflects the geometry of the constructed diagram.

improvement in fuel efficiency. On the other hand, where the inputs are competitors, so that $\sigma > 1$, it is improvements in vehicle efficiency that will more probably reduce household fuel use. Also, when the price elasticity of demand falls, the range of substitution elasticities where efficiency improvements in either input reduce fuel use increases. Further, as the share of vehicles in the cost of private transport rises, the range of parameter values where improvements in vehicle efficiency produces the larger reduction in fuel use also increases.

Second, clearly the values of σ, η and s are important for determining whether fuel or vehicle efficiency improvements can be effectively used to reduce direct household fuel use. However, from a policy perspective, the cost of, or difficult involved in, implementing fuel and vehicle efficiency changes also need to be addressed. That is to say, if the government wishes to encourage such technical change, considerations wider than those encapsulated in equations (6) and (7) need also to be addressed.

Third, in this paper we use the provision of private transport simply as an example of an energy-intensive household service. That is to say, the analysis in Sections 3 and 4 applies in general to the potential for energy saving in the supply of any of these services. Moreover, these are likely to differ in terms of their key parameters, σ, η and s, and in the challenges in making fuel and domestic capital efficiency improvements. Therefore individual cases should be dealt with individually. It would be wrong to suggest any rigid rule for all energy-intensive household services.

Fourth, we have focussed in the analysis in Sections 2 and 3 on fuel use. But efficiency improvements supply other economic benefits. In the next section we explore the impact of efficiency improvements in the provision of household-supplied energy-intensive services from the wider multiple-benefits perspective (IEA, 2014).

5. Partial Equilibrium Multiple Benefits

In the recent literature, the IEA (2014) argues that rather than focus on the possible rebound effects researchers should stress the multiple benefits of energy efficiency improvements. The issue is partly rhetorical. Rebound suggests weaknesses in policies to encouraging efficiency improvements in order to reduce energy use. However, rebound might reflect other benefits accompanying efficiency improvements, such as increased economic activity. In the present case, as we note in Section 3, increasing the efficiency of the domestic provision of private transport has an impact not just on fuel use but also on the price of private transport. In a partial equilibrium context, this benefit is typically measured as an increase in consumer surplus.[6] We therefore define here the change in multiple benefits, *dM*, as comprising the weighted sum of two elements. The first is the increase in consumer surplus, *dc*. The

[6] Given that we assume competitive markets and completely supply elasticities there is no consumer surplus or supernormal profits.

second is the benefit generated by the reduction in fuel use df, multiplied by a weight, w. This weight is the benefit to the environment of each unit reduction in fuel use.[7] Therefore:

(12) $$dM = dc - wdf^n$$

In making these calculations, we calibrate the model so that the initial prices of all commodities are equal to unity, as are the price and total expenditure on private transport. The change in consumer surplus is then given as:

(13) $$dc = -dp_m\left[1-\frac{\eta dp_m}{2}\right]$$

where $\frac{\partial(dc)}{\partial(dp_m)} < 0.$

5.1 Increased fuel efficiency

For an increase in fuel efficiency, $d\gamma_f$, the corresponding change in the price of private transport is given as:

(14) $$dp_m^f = -sd\gamma_f < 0$$

where the f superscript indicates a change generated by an increase in fuel efficiency. Substituting equation (14) into (13) gives the increase in consumer surplus as:

(15) $$dc^f = sd\gamma_f\left[1+\frac{s\eta d\gamma_f}{2}\right] > 0$$

where $\frac{\partial(dc^f)}{\partial\eta}, \frac{\partial(dc^f)}{\partial s}, \frac{\partial(dc^f)}{\partial\gamma_f} > 0$ and $\frac{\partial^2(dc^f)}{\partial s^2}, \frac{\partial^2(dc^f)}{\partial\gamma_f^2} > 0, \frac{\partial^2(dc^f)}{\partial\eta^2} = 0.$

Equation (15) shows that fuel-augmenting technical change always has a positive effect on the consumer surplus. Further, the size of this change in consumer surplus is an increasing function of the elasticity of demand for private transport, the share of fuel and the size of the efficiency increase.

Using equation (6), and recalling that the initial household fuel use is s, the value of the change in fuel use from an increase in fuel efficiency in private transport is:

(16) $$wdf^{f,n} = wsd\gamma_f(\sigma(1-s)+s\eta-1) > 0 \; iff \; \sigma(1-s)+s\eta > 1$$

[7] For example, if the use of one unit of fuel in private transport produces λ units of greenhouse gas (GHG) and each unit of GHG has an environmental cost of β, then $w = \lambda\beta$.

The characteristics of this relationship simply replicate those of the elasticity of fuel use with respect to a change in fuel efficiency which are discussed in Section 3. An environmental cost is produced where the efficiency increase leads to higher fuel use.[8] This occurs where the weighted sum of the elasticities of substitution between fuel and vehicles, and between private motoring and all other consumption goods is greater than 1. Otherwise the fall in fuel use produces an environmental benefit.

Also $\frac{\partial(wdf^{f,n})}{\partial\sigma}, \frac{\partial(wdf^{f,n})}{\partial\eta} > 0$ and $\frac{\partial(wdf^{f,n})}{\partial(d\gamma_f)}, \frac{\partial(wdf^{f,n})}{\partial w} > 0 \; iff \; (\sigma(1-s)+s\eta > 1$. The cost of the change in fuel use increases, or the benefit falls, with a rise in either elasticities of substitution, η or σ. Increases in the weight going to the change in fuel use, *w*, or in the size of efficiency shock, $d\gamma_f$, increase the absolute size of the environmental impact, increasing the benefit where this is positive and cost where it is negative.

Substituting equations (15) and (16) into equation (12) and simplifying produces:

$$(17) \qquad dM^f = \frac{sd\gamma_f}{2}\left[2 + s\eta d\gamma_f - 2w(\sigma(1-s)+s\eta-1)\right]$$

As in the analysis of the change in fuel use, it is helpful to consider combinations of elasticity values which produce the same change in multiple benefits as the result of an increase in fuel efficiency and thereby construct iso-multiple benefit functions. This is done in Figure 4.

From equation (17), for a given value of $dM^f = \kappa$, the associated iso-multiple benefits line, M_κ^f, is given as:

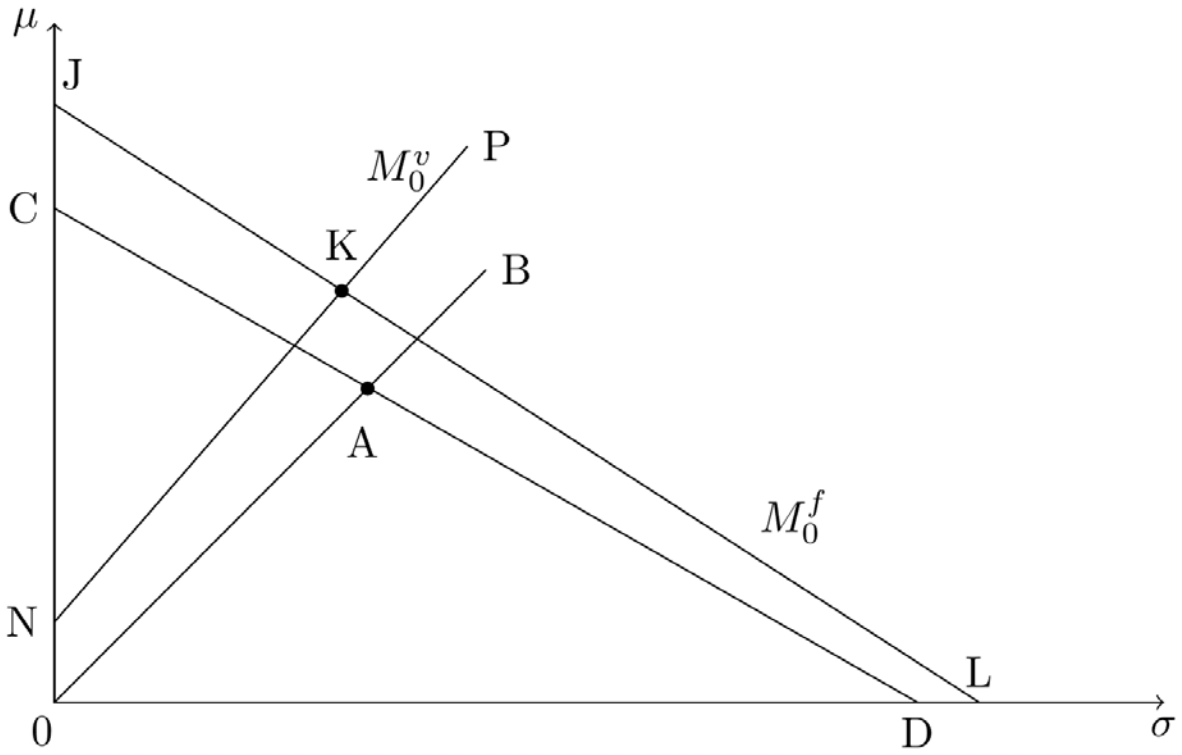
$$(18) \qquad \eta = -\frac{2w(1-s)}{s(2w-d\gamma_f)}\sigma + \frac{2(w+1)}{s(2w-d\gamma_f)} - \frac{2\kappa}{s^2 d\gamma_f(2w-d\gamma_f)}$$

Equation (18) can be used to construct a whole family of M_κ^f lines. As long as the parameter restriction $w > \frac{d\gamma_f}{2}$ holds, these lines are qualitatively similar to the corresponding iso-fuel change lines. The zero iso-multiple benefits line, M_0^f, has a positive intercept on the η axis equal to $\frac{2(w+1)}{s(2w-d\gamma_f)}$, a slope of $-\frac{2w(1-s)}{s(2w-d\gamma_f)}$ and an intercept on the σ axis of $\frac{(w+1)}{w(1-s)}$. The M_0^f function is represented in Figure

[8] That is to say, these parameters generate backfire.

4 as JK. It is useful to compare this zero iso-multiple benefits curve with the zero iso-fuel use function, I_0^f , also mapped in Figure 4 as the line CAD.

Figure 4. Iso-multiple benefit and iso-fuel use lines



The M_0^f line, JKL, is above, steeper and to the right of the CAD line. The iso-multiple benefit lines that are lower and parallel to JKL identify parameter values which give higher (and therefore positive) multiple benefits. This has the following implications. First, because the slopes of the M_κ^f and the I_τ^f differ, parameter values which generate the same change in fuel use, and therefore also the same rebound value, will have different multiple benefit values. Second, if we hold constant one of the σ and η elasticities and then vary the other, if the rebound value rises, the multiple benefits measure will fall and vice versa. The multiple benefits here do not increase as the rebound value increases. Third, there are a set of parameter values, identified as those in the area CDLJ, where both the fuel use and multiple benefits score increase with an improvement in fuel efficiency. That is to say, if the multiple benefits index were being used as an appraisal criterion, these efficiency improvements would be encouraged, even though fuel use would rise.[9]

5.2 Increased vehicle efficiency

[9] Only as $w \to \infty$ will the CAD and JKL lines converge.

For the increases in vehicle efficiency, the resulting change in the price of private transport is given as:

$$(19) \qquad dp_m^v = -(1-s)d\gamma_v$$

Substituting equation (19) into (13) gives the increase in consumer surplus as:

$$(20) \qquad dc^v = (1-s)d\gamma_v\left[1+\frac{(1-s)\eta d\gamma_v}{2}\right] > 0$$

where $\frac{\partial(dc^v)}{\partial\eta}, \frac{\partial(dc^v)}{\partial\gamma_v} > 0, \frac{\partial(dc^v)}{\partial s} < 0$ and $\frac{\partial^2(dc^v)}{\partial s^2}, \frac{\partial^2(dc^v)}{\partial\gamma_f^2} > 0, \frac{\partial^2(dc^v)}{\partial\eta^2} = 0$.

Again equation (20) indicates that the increase in consumer surplus is always positive and is positively related to the elasticity of demand for private transport and the size of the efficiency change. In this case it is negatively related to the share of fuel in private transport.

For the change in fuel use, adapting equation (7) gives:

$$(21) \qquad wdf^{v,n} = ws(1-s)(\eta-\sigma)d\gamma_v$$

Again, the nature of this relationship is simply that of the elasticity of fuel use with respect to a change in vehicle efficiency which is outlined in Section 3. The sensitivity of the change in environmental cost is given as: $\frac{\partial wdf^{v,n}}{\partial\eta} > 0, \frac{\partial wdf^{v,n}}{\partial\sigma} < 0$ and $\frac{\partial wdf^{v,n}}{\partial d\gamma_v}, \frac{\partial wdf^{v,n}}{\partial w} > 0$ *iff* $\eta > \sigma$. An increase in the elasticity of demand for private transport increases the environmental cost, or reduces the benefit, whilst a rise in the substitution elasticity between fuel and vehicles works in the opposite direction. Any increase in the weight applied to changes in fuel use or the size of the efficiency shock increase the absolute size of the positive or negative environmental impact. Finally, a change in the share of fuel in private transport has a complex impact. Specifically:

$$(22) \qquad \frac{\partial wdf^{v,n}}{\partial s} = (1-2s)w(\eta-\sigma)d\gamma_v$$

Equation (22) implies that where the share of fuel is less than a half, any increase in the share increases the absolute size of the environmental effect, whether that is positive or negative. However, where s is greater than a half, further increases reduce the absolute size of the environmental impact.

Substituting (20) and (21) into (12) and simplifying produces:

$$(23) \qquad dM^v = \frac{(1-s)d\gamma_v}{2}\left[2+(1-s)\eta d\gamma_v - 2ws(\eta-\sigma)\right]$$

Following the analysis in Section 3, using equation (23), the values of η and σ that generate a change in multiple benefits of the amount κ through an increase in vehicle efficiency is given by:

$$\eta = \frac{2ws}{2ws-(1-s)d\gamma_v}\sigma + \frac{2((1-s)d\gamma-\kappa)}{(2ws-(1-s)d\gamma_v)(1-s)d\gamma_v} \quad (24)$$

Equation (24) can be used to construct iso-multiple benefits lines for vehicle-augmenting technical change. The zero value line M_0^v is shown as NKP in Figure 4. This has an intercept on the η axis equal to $\frac{2}{2ws-(1-s)d\gamma_v}$ and a slope of $\frac{2ws}{2ws-(1-s)d\gamma_v}$. This line is constructed on the assumption that the inequality $w > \frac{(1-s)d\gamma_v}{2s}$ holds. This is similar to the corresponding requirement for the analysis of multiple benefits with the fuel efficiency increase. Essentially it ensures that the negative weight on any increased fuel use is large enough to cause the multiple benefits to fall as the price elasticity of demand increases. Note again that the M_0^v line, NKP, is above but this time to the left of the corresponding I_0^v line, 0B, and has a steeper slope. Again, points representing sets of elasticities above and to the left of the line represent reductions in multiple benefits and those below and to the right increases.

Combining the M_0^f and M_0^v lines in the same diagram reveals a set of parameter values where both a fuel and vehicle efficiency improvement will produce an increase in multiple benefits. This is shown as the area 0NKL. Members of a subset of these parameter values, defined as the area 0NKL, generate an increase in multiple benefits but also an increase in fuel use.

5.3 Low values of the environmental weight on fuel use, *w*

If the negative weight on the fuel use in the multiple benefits calculation is small, so that $w < \frac{(1-s)d\gamma_v}{2s}, \frac{d\gamma_f}{2}$, then the corresponding M_0^v and M_0^f functions would become mirror images of those shown in Figure 4, rotated around the σ axis. That is to say, both functions would have a negative intercept on the η axis and the slopes of both functions would be reversed. It would still be the case that parameter combinations that give the same percentage change in fuel use would have different multiple benefit values. However, parameter values that generated a lower reduction in fuel use for a given efficiency improvement (and therefore a higher rebound where this is a fuel efficiency improvement)) would typically also now exhibit a higher multiple benefit value.

6. General Equilibrium

The previous three sections adopt a partial equilibrium approach. Whilst this focusses on key economic mechanisms in operation, a general equilibrium analysis produces additional insights. There are four main issues. First, in so far as the pattern of household consumption is changed by these efficiency improvements, there will be corresponding adjustments to other elements of household expenditure. Second, there is fuel embedded in the intermediate goods that make up the production of vehicles, fuel

and all other consumption goods and services. These are neglected in partial equilibrium analysis. Third, there will typically be changes in the prices of other goods and services that accompany the efficiency improvements. One source of these price changes is the labour market where the relationship between the nominal and real wage is affected by the efficiency changes. Also where bargaining determined the real wage, this will be sensitive to changes in labour demand. Any price changes will affect the relative competitiveness of the output of domestic sectors against one another and also against foreign goods and services. Recall that under partial equilibrium the price of other goods is assumed to be constant. Finally, there will be endogenous changes in household income following from policy interventions on environmental grounds. Again in partial equilibrium nominal income is taken to be fixed.

In this particular case, improvements in the efficiency with which the private transport is delivered imply that the price of this service will fall. Typically such efficiency improvements are not fully captured in the calculation of the consumer price index (CPI). This point is made forcefully by Gordon (2016) who argues that the neglect of these effects has led to the US real growth rate being severely underestimated, particularly in the period 1890-1940. In fact attempts have been made to capture the impact of improvements in vehicle and fuel efficiency in the US CPI (Gordon, 1990). We replicate such adjustments here and incorporate the subsequent additional labour market and household income effects generated by the increased efficiency of household consumption. This is important for in the calculation of positive economic impacts of the efficiency improvements that can be used to construct a general equilibrium index of multiple benefits.

7. The CGE Model:

We operationalise the general equilibrium approach using the UK-ENVI Computable General Equilibrium (CGE) model. This model is parameterised on a 2010 UK Social Accounting Matrix with 30 production sectors and is designed specifically for analysing the impacts of environmental policies. In the following sections we outline the main features of the model, focussing particularly on the structure of household consumption. A more detailed account and full model listing is available in Figus et al (2018).

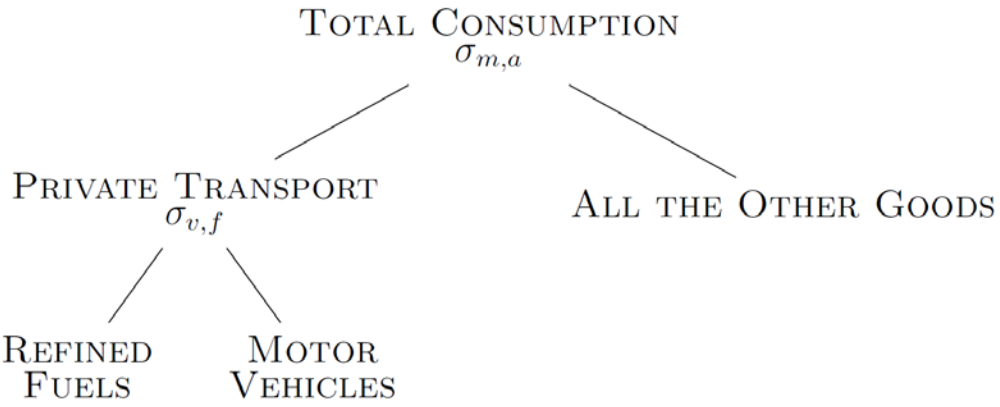
7.1 Consumption

In each time period, t, (taken to be one year) a representative household makes an aggregate consumption decision, *C*, determined by its disposable income, so that:

$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \quad (25)$$

In equation (25), total consumption is a function of income, *YNG*, minus savings, *SAV*, income taxes, *HTAX*, and direct taxes on consumption, *CTAX*. Total consumption is allocated to sectors in a manner shown in Figure 5.

Figure 5. The structure of consumption



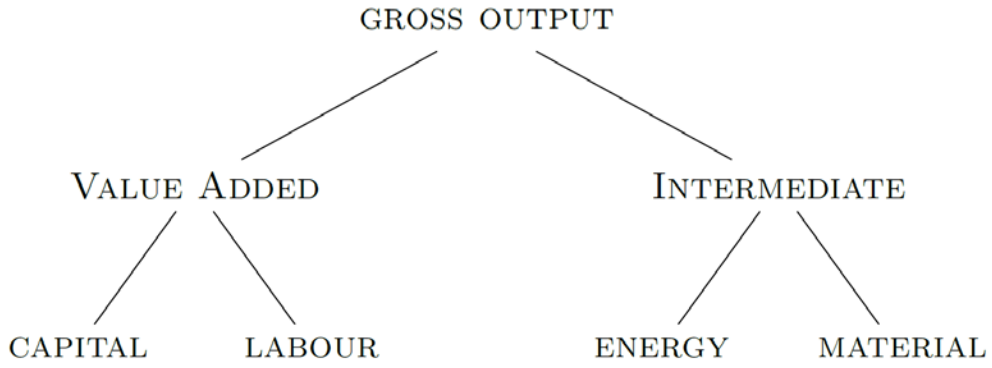
At the top level, the representative household divides consumption between private transport and all other goods via a CES function. At the second level, private transport is a CES combination of refined fuels and motor vehicles; the "all other goods" is a Leontief composite comprising all the other household purchases. Essentially we assume that households produce, and then directly consume, private transport through purchasing vehicles and fuel inputs. The price of private transport is unobserved in the standard production accounts. However, it can be modelled through this adjustment to the consumption structure and is equal to the cost of self-production. We note that motor vehicles are consumer durables and should be treated as household investments. For this reason we focus on long-run equilibrium results here, where the household stock of motor vehicles is at its long-run equilibrium level. At this point the desired level of vehicle expenditure, determined by the cost minimising function and implicitly equal to depreciation, equals the actual level of motor vehicle expenditure.

Whilst this adjustment deals with the provision of private transport in more appropriately manner, other energy-intensive services, such as heating, refrigeration, air conditioning and lighting, can similarly be treated as self-produced composite goods. However, to enhance tractability and to simplify the interpretation of the results, we here isolate the example of private transport and assume that the remaining consumption comprises a single composite good. We hope to extend this framework in future research. Further, household consumption comprises goods produced in the UK and imported goods from the rest of the World, and these are taken to be imperfect substitutes (Armington, 1969).

7.2 Production and investment

In each sector, the production structure is as outlined in Figure 6. Output is produced via a capital, labour, energy and material (KLEM) CES function. At the top level, value added and intermediate inputs combine to generate output. At the second level, labour and capital produce value added, while energy and materials form a composite of intermediate inputs. Again, imported and locally produced intermediate inputs are assumed to be imperfect substitute, via an Armington link (Armington, 1969).

Figure 6. The structure of production



In this paper, model results are reported solely for the long run where in each sector the capital stock is fully adjusted to the ruling market and factor prices. In this case, in each sector, *i*, actual capital stock, K_i, is equal to the desired capital stock, K_i^*, where the desired capital stock is the that required to produce the existing output at the minimum cost, so that:

(26) $$K_i = K_i^*(va_i, pva_i, p_k)$$

where va_i, pva_i and p_k are the value added, price of value added and price of capital respectively. Because desired and actual capital stocks are in equilibrium, investment in sector *i* is equal to depreciation, so that::

(27) $$I_i = \delta K_i$$

where δ is the rate of depreciation.

7.3 The labour market

The labour market determines the real and nominal wage and employment, where the real wage is defined as the nominal after tax wage, w, divided by the CPI^τ. In the calculation of the CPI^τ, the prices of vehicles and fuel are replaced by the price of private transport, so that:

(28) $$CPI^\tau = CPI^\tau(p_a, p_m(\gamma_f, \gamma_v, p_f^n, p_v^n))$$

Improvements in the efficiency of fuel or vehicle efficiency in the household production of private transport therefore will reduce CPI^τ.

We use three alternative labour market models. In all three the labour force is taken to be fixed. In our preferred model, the real wage is determined via bargaining and the outcome given by the following wage curve:

(29) $$\ln\left[\frac{w}{CPI^\tau}\right] = \theta - \varepsilon \ln(u)$$

In this equation, the bargaining power of workers, and hence the real consumption wage, is negatively related to the rate of unemployment, u (Blanchflower, 2009). The parameter θ is calibrated to the steady state and ϵ is the elasticity of wage related to the level of unemployment, u, and takes the value of 0.069 (Layard et al., 1991). Other labour market options that we use in order to identify key aspects of the macroeconomic impact are fixed nominal and fixed real wage closures. The fixed nominal wage closure is given as:

(30) $$W = W_B$$

and the fixed real wage as:

(31) $$w = w_B \left[\frac{CPI^{\tau}}{CPI_B^{\tau}} \right]$$

where the B subscripts represents the base year value.

7.4 The Government

We assume that the Government faces a balanced budged constraint. This implies that the initial deficit is maintained. Tax rates are held constant. Any variation in revenues driven by variations in economic activity is absorbed by adjusting Government current spending on goods and services proportionately.

8. Simulation Set up

In Section 9, using CGE numerical simulations, we investigate the impact of separate 5% efficiency improvements in household vehicle and fuel use. For each simulation, the efficiency shock is the only exogenous disturbance and we report the long-run results, so that the capital stock and fuel and vehicle use are fully adjusted to the efficiency change.

In Section 9.1 we focus on the sensitivity of changes in total fuel use to changes in two key parameters. These are the price elasticity of demand for private transport, η, and the elasticity of substitution between vehicles and fuel use, σ, in its household production. The simulations are performed using the bargained real wage closure. Values are calculated for all the combinations of the two elasticities, η and σ from 0.1 to 2, taking 0.1 increments. This implies that we undertake 400 simulations for each efficiency change. The results are represented both graphically and in a numerical grid. The change in total fuel use is reported relative to the base year value and is expressed as a proportion of initial household fuel use.

In Section 9.2, we examine in more detail the results from two simulations using a specific combination of η and σ values that generate the same reduction in fuel use for the same proportionate fuel and vehicle efficiency change. The impacts on a variety of variables are shown. These include; the prices of key inputs, the characteristics of household consumption and the change in macroeconomic variables, such as GDP, employment and the real wage. These simulations results perform two primary functions.

The first is to compare the different ways that the two simulations generate the same change in total fuel use. The second is to identify the impact of the general equilibrium elements on the fuel use results. This involves comparing the partial equilibrium outcome with the general equilibrium simulations using the range of labour market closures outlined in Section 7.3.

We use the information in Table 1 to explore two issues. One is to assess the size and nature of the general equilibrium impacts on the fuel use and other economic variables accompanying the efficiency improvement. The other is to see how these impacts differ between the two efficiency disturbances, even though the final outcome in the default model specification, in terms of change in total fuel use, is the same.

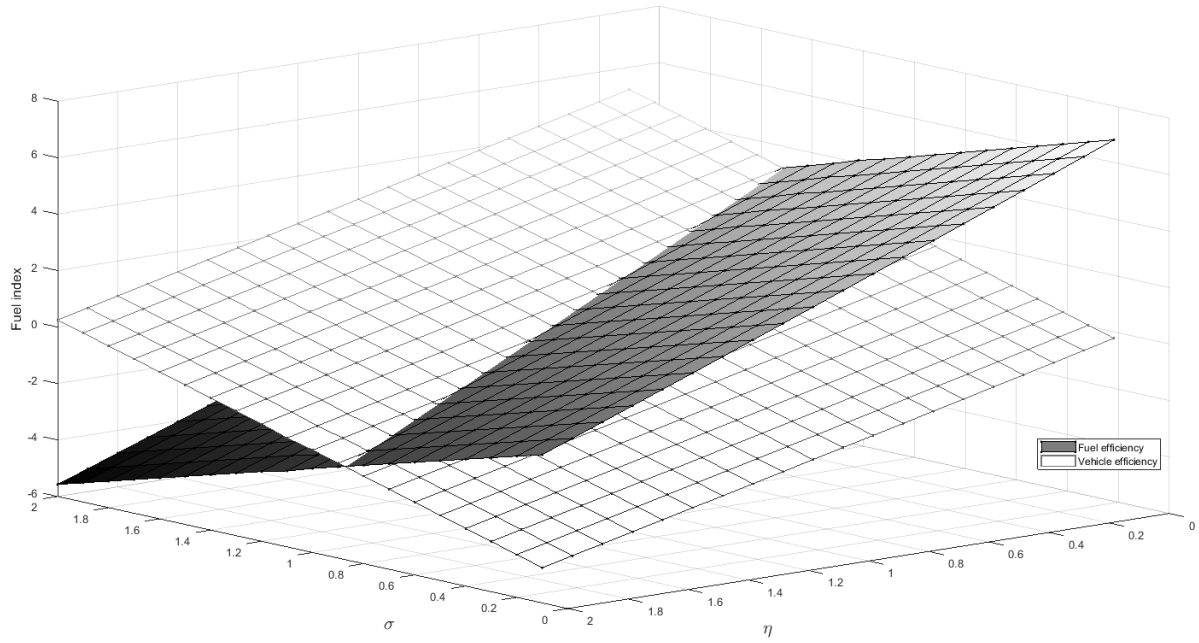
In Section 9.3 results for a range of multiple benefits indices are calculated. These are reported for the same grid of σ and η elasticity values as used in analysing the fuel use changes for the same fuel and vehicle 5% efficiency improvements, employing the default (bargaining) labour market closure. The multiple benefits indices values are calculated as the weighted sum of the absolute change in GDP and the absolute reduction in the total fuel use for four different weights on the fall in the use of fuel. These weights are 0.5, 1.0, 1.5 and 2.0.

9. Simulation Results

9.1 Fuel Use

Figure 7 shows the two surfaces representing the change in total fuel use subsequent to a 5% increase in either fuel or vehicle efficiency. The total fuel use change is expressed as a proportion of the initial household fuel use, with detailed numerical results presented in Table B1 in Appendix B. In Table B1 each row and column represents a specific value for the elasticity and elasticity of substitution between fuel and vehicles, σ, and the price elasticity of demand for private transport, η, so that the table's layout follow that of Figure 1. Although the results are derived from general equilibrium simulations, they are qualitatively similar to the results presented in the partial equilibrium analysis. For example, for both efficiency improvements the change in fuel use is positively related to the elasticity of demand for private transport, η, and is close to zero where both elasticity parameters approach unity. Further, the fuel use moves in opposite directions for the two efficiency shocks in response to changes in the elasticity of substitution between fuel and vehicles, σ. For the fuel efficiency improvement, fuel use is positively related to the value of σ, whilst for the vehicle efficiency increase the relationship is negative. These results are as predicted in the partial equilibrium analysis in Section 3. However, there is an additional stimulus to fuel use that comes from the increase in economic activity that accompanies the efficiency improvement.

Figure 7. Percentage change in total fuel use as share of initial household fuel use (fuel index) from a 5% increase in either fuel or vehicle efficiency



For the fuel-augmenting efficiency improvement, a downward sloping diagonal line passing through the (σ,η) values (0.1, 1.5), (0.4, 1.3), (0.7, 1.1), (1.3, 0.7), (1.6, 0.5) and (2.0, 0.2) marks the upper bound of the parameter combinations that provide positive fuel savings. Those parameter combinations above this line show positive, and those below negative, fuel use changes. Essentially, this corresponds to the line CAD in Figure 1. The fuel saving is highest where both elasticities are at their minimum (0.1) values and equals -5.58%. If both elasticities equal 2, the maximum values shown here, domestic fuel use increases by 7.20% as a result of the 5% increase in fuel efficiency.

These results reported for the improvement in fuel efficiency translate directly into rebound values. In the general equilibrium case, the rebound value, R^G, is given as:

$$R^G = 1 + \frac{df_T^n / f_H^n}{d\gamma^f / \gamma^f} \tag{32}$$

where the H and T subscripts stand for household and total respectively. Positive values for the change in fuel use for as the result of a fuel efficiency increase represents backfire. The maximum rebound in the results presented here, R^G_{Max}, is reported for the elasticity values (2.0, 2.0), and takes the value:

$$R^G_{Max} = 1 + \frac{7.2}{5} = 2.44 \tag{33}$$

The minimum rebound, R^G_{Min}, is given for the (0.1, 0.1) combination of elasticities. In this case the rebound value is negative, and its value is given as:

$$R^G_{Min} = 1 - \frac{5.58}{5} = -0.116 \tag{34}$$

The negative result implies that the reduction in total fuel use is greater than the direct fuel efficiency improvement. This reflects the fact that the direct fall in household consumption of fuel will be close to 5%, but there is an additional reduction in the intermediate use of fuel as consumers shift consumption to goods and services with less fuel intensive intermediate inputs (Turner 2009).

Figure 7 also shows the fuel use changes associated with a 5% improvement in vehicle efficiency. Again this is given as the change in total fuel use as a proportion of the initial household fuel use. The precise figures are reported in Table B2 in Appendix B. Though the simulation results broadly follow the partial equilibrium analysis, it is straightforward to identify general equilibrium effects. In particular, for all entries where $\sigma = \eta$ there is a small, between 0.25% and 0.18%, increase in total fuel use, as measured as a proportion of initial household fuel use. This compares with the zero figure that apples for the same parameter values in partial equilibrium. General equilibrium effects are increasing the fuel use slightly above the partial equilibrium values. The upper bound sets of parameter values which generate a negative change in fuel consumption for vehicle-augmenting technical change is determined by the diagonal 45 degree line going through the (σ,η) values (0.2,0.1), (0.6,0.5), (1.0, 0.9), (1.5,1.4) and (2.0, 1.9).

For vehicle augmenting change the rebound concept is not applicable: there is no direct fuel efficiency improvement. However, for the range of elasticity values reported here, the proportionate changes in fuel use are within the same order of magnitude as for the improvements in fuel efficiency itself. The maximum value is an increase in fuel use of 5.21% for the elasticity combination (0.1, 2.0), whilst the minimum figure is a reduction of 4.75% with the parameters (2.0, 0.1).

Where the two planes in Figure 7 intersect gives the parameter combinations where 5% efficiency improvements in either fuel or vehicles produce is the same proportionate change in fuel use. From inspection of the results in Tables B1 and B2, this is represented by a line passing through the points (0.75, 2.0) and (1.25, 0.1). For points on this line with values of $0 \leq \eta < 1$, the change in fuel use is negative and equal for efficiency improvements in both fuel and vehicles. In this range, for parameter values to the right of the line, that is to say higher values of σ, an improvement in vehicle efficiency gives a larger reduction in fuel use. For points to the left, with therefore lower σ values, improved fuel efficiency gives a greater fuel reduction.

9.2 Detailed Comparison of Fuel and Vehicle Efficiency Improvements across Different Model Closures

In Table 1 we show the long-run simulated impacts of equal, 5%, fuel and vehicle efficiency improvements for a specific set of σ and η elasticity values. These efficiency changes generate the same change in total fuel use when implemented with our default model specification. These are the results reported in the seventh and eighth data columns in Table 1, under the wage curve labour market closure. This set of elasticities identifies a specific point on the line where the two planes cross in Figure 7, as discussed in the previous sub-section. The particular (σ,η) values used are (1.2, 0.2) and these generate a reduction in total fuel use, measured as a proportion of initial household fuel use, of 2.37% and 2.38%, respectively, for the fuel and vehicle efficiency shocks. We call this ratio the fuel index.

Table 1. Partial and general equilibrium impact of a 5% efficiency improvement in fuel and vehicle use, for η=0.2 and σ=1.2

	Partial Equilibrium		General Equilibrium					
			Fix nominal wage		Fix real wage		Wage curve	
	Fuel	Vehicles	Fuel	Vehicles	Fuel	Vehicles	Fuel	Vehicles
Prices								
Price of fuels (natural units)	0	0	0.00	0	-0.05	-0.03	0.01	0.01
Price of vehicles (natural units)	0	0	0.00	0	-0.06	-0.04	0.02	0.01
Price of vehicles (efficiency units)	0	-5.00	0.00	-5.00	-0.06	-5.04	0.02	-4.99
Price of fuel (efficiency units)	-5.00	0	-5.00	0	-5.05	-0.03	-4.99	0.01
Price of private transport	-3.05	-1.95	-2.93	-1.89	-2.99	-1.93	-2.92	-1.88
Household consumption								
Fuel	-2.05	-1.95	-1.84	-1.80	-1.71	-1.72	-1.88	-1.82
Vehicles	-3.05	-0.95	-2.80	-0.84	-2.65	-0.74	-2.83	-0.86
Private Transport	0.61	0.39	0.74	0.48	0.88	0.57	0.71	0.45
All other Goods	-	-	0.19	0.12	0.33	0.21	0.15	0.10
Fuel Intensity of Transport	0.42	-0.41	-0.59	0.60	-0.59	0.60	-0.60	0.59
Vehicle Intensity of Transport	-0.66	0.60	0.38	-0.38	0.37	-0.39	0.38	-0.38
Fuel use								
Total fuel use	-	-	-0.39	-0.41	-0.20	-0.29	-0.44	-0.44
Fuel index	-	-	-2.10	-2.20	-1.08	-1.54	-2.37	-2.38
Macroeconomic effect								
GDP	-	-	0.12	0.08	0.36	0.23	0.06	0.04
CPI^{τ}	-	-	-0.05	-0.03	-0.13	-0.08	-0.03	-0.02
Nominal wage	-	-	0	0	-0.13	-0.08	0.03	0.02
Real wage	-	-	0.05	0.03	0	0	0.07	0.04
Employment	-	-	0.13	0.09	0.38	0.25	0.06	0.04
Unemployment rate	-	-	-2.00	-1.34	-5.97	-3.88	-0.97	-0.63
Investment	-	-	0.12	0.08	0.33	0.21	0.06	0.04
Household consumption	-	-	0.15	0.10	0.29	0.19	0.11	0.07
Export	-	-	0	0	0.14	0.09	-0.04	-0.03

As discussed in Section 8, we consider simulation results under partial equilibrium and three general equilibrium variants, each general equilibrium specification having a different labour market closures. These are the fixed nominal, fixed real and wage curve (bargaining) closures. Whilst our preferred model set up uses the wage curve, these other models specifications allow clearer separation and identification of demand-composition, competitiveness and labour scarcity effects.

9.2.1 Partial Equilibrium

We begin with the partial equilibrium results. These are calculated under the assumption that prices, measured in natural units, do not change, that household income is fixed and the analysis focuses solely on the impact on household consumption, particularly the use of fuel in private transport. The results are calculated using variants of the expressions discussed in Section 3 and are shown in the first two data columns in Table 1.

The partial equilibrium effects can be represented as a combination of the change in expenditure on private transport and the change in the share of that expenditure which goes to fuel. Formally, fuel use, f^n, can be expressed as a function of the expenditure on fuel, mp_m, the price of fuel, p_f^n, and the share of fuel in the total cost of private transport, s.

$$f^n = s\frac{mp_m}{p_f^n} \tag{35}$$

Given that there is no change in the price of fuel, equation (35) implies that the proportionate change in fuel use equals the proportionate change in household expenditure on private transport plus the proportionate changes in the share of fuel in the cost of private transport. The quantitative and qualitative differences in the decomposition of the fuel change figure for the different efficiency improvements helps explain the way each operates.

Both the fuel and the vehicle efficiency increases produce a fall in the price of private transport. The share of fuel in the production of private transport is just over 60%. This means that the 5% fuel and vehicle efficiency increases generates 3.05% and 1.95% reductions respectively in the private transport price. However, the demand for private transport is assumed to be inelastic here, through the adoption of the 0.2 price elasticity of demand. Therefore although the number of miles travelled increases, this is less than the proportionate reduction in price, so total expenditure on private transport falls by 2.44% and 1.56% respectively. This is a major source of the reduction in fuel use in both cases.

However, the change in the relative prices of the two inputs, measured in efficiency units, means that the value of s, the share of fuel in the cost of private transport, will change. Given the relatively high elasticity of substitution between fuel and vehicles, 1.2, the improvement in fuel efficiency increases the fuel intensity of private transport by 0.42%; the improvement in vehicle efficiency, on the other hand reduces

it by the same proportionate amount. That is to say, the fuel savings with the improvement in vehicle efficiency are enhanced by the substitution of vehicles for fuel, so that the final fall in fuel use is 1.95%. For the fuel augmenting technical change, the substitution of fuel for vehicles limits the fuel reduction accompanying the fall in private transport expenditure to 2.05%.[10] Note that as it happens, under partial equilibrium, with these parameter values the fuel reduction with the fuel efficiency improvement has a slightly greater absolute value than that with the vehicle efficiency improvement.

These results are recorded in Table 1. Note that the macroeconomic variables are not recorded here. It is not that partial equilibrium assumes that such impacts do not occur. Rather it is that their feedback to the original market can be ignored. We shall see that this is not necessarily correct but we are also concerned in the general equilibrium analysis with the impact on fuel use in other markets.

9.2.2 General Equilibrium: Fixed Nominal Wage

The results shown in the data columns three and four of Table 1 are for CGE simulations with a fixed nominal wage. Because these are long-run results, and therefore incorporate full capital stock adjustment, there is no change in the price of commodities produced in industrial sectors. In terms of its macro-economic characteristics, the approach is similar to an extended fixed-price Keynesian or Input-Output model with endogenous consumption, investment and government expenditures. In this simulation, these efficiency improvements generate a change in the composition of household consumption which alone have three broad effects.

First, there is an impact on the direct fuel intensity of household consumption. However, because the prices of the industrially produced commodities do not change, the adjustment to the composition of household consumption is the same as in the partial equilibrium analysis. Household consumption shifts between fuel, vehicles and other consumer goods and services in exactly the same way. The real wage rises, where the consumer price index, CPI^{τ}, appropriately takes into account the fall in the price of private transport. But this has an effect which is observationally equivalent to a simple change in consumer tastes, as far as the wider economy is concerned.

The second effect is the change in the indirect fuel intensity of household consumption. That is to say, total fuel use driven by a given level of household expenditure is determined not only by the direct

[10] Although the fuel intensity rises under fuel augmenting technical progress here but the fuel use per mile must fall, given that the number of miles travelled increases. Fuel per mile can be expressed as $\frac{f^n}{m} = s\frac{p_m}{p_f^n}$. Given no change in the price of fuel, the proportionate change in the fuel use per mile equals the sum of the proportionate changes in the share of fuel in the cost of private transport and the price of private transport. For the improvement in fuel efficiency the proportionate fall in p_m is greater than the corresponding proportionate increase in s so that the fuel use per mile also falls.

consumption of fuel, but also the fuel used as intermediate inputs. Changing the composition of consumption could increase or reduce the level of intermediate fuel use.

Finally there is the change in the aggregate level of economic activity with the change in consumption pattern. Typically, if expenditure moves towards commodities and services that have higher value added and local intermediate content, then this will lead to an expansion of output, domestic income and investment. This again can increase or reduce total fuel use. Therefore in incorporating the intermediate demand for fuel and the endogeneity of the total household income, general equilibrium analysis augments the partial equilibrium approach.

There are a number of important points here. The first is that both the efficiency changes stimulate economic activity, generating an increase in GDP, employment and household consumption. For example, employment increases by 0.13% and 0.09% respectively with the fuel and vehicle efficiency improvements. Further, this impact is greater for the fuel, rather than vehicle, augmenting efficiency change. Other things being equal, one would therefore expect the saving in fuel use to be lower than under partial equilibrium. However, the opposite is the case, with a larger fall in the fuel index than under partial equilibrium, particularly for the improvement in vehicle efficiency. It is clearly the case that the change in the composition of household consumption alone operates to reduce the overall indirect use of fuel, and also to stimulate economic activity.

9.2.3 General Equilibrium: Fixed Real Wage

In the fixed nominal wage closure, there are no direct supply-side impacts associated with the efficiency changes. That is to say, there are no competitiveness effects and the supply side of the model adjusts in a passive, and linear, manner to any changes in demand. In this sub-section we impose a fixed real wage, calculated using a consumer price index, CPI^{τ}, which correctly adjusts for changes in the price of private transport. This creates a model where increased efficiency in household consumption affects industrial competitiveness through the labour market. However, there are still no scarcity constraints; the supply of labour and capital are infinitely elastic at the base-period interest rate and real wage.

The results from this simulation are reported in columns 5 and 6 in Tables 1. The key to understanding this simulation is to note that the constant real wage translates to 0.13% and 0.08% falls, respectively, in the nominal wage associated with the fuel and vehicle efficiency improvements. These reductions match the corresponding reductions in the CPI^{τ}. The different proportionate changes in CPI^{τ} reflects the differential direct price impact of the same proportionate fuel and vehicle efficiency improvements on the price of private transport. Note that the reductions in the CPI^{τ} values are greater than the corresponding figures in the fixed nominal wage simulations. This reflects the fact that the accompanying reductions in the nominal wages themselves have further impacts on industry prices, setting off a downward price multiplier process.

The lower prices stimulate exports and import substitution. This further increasing GDP, employment and investment above the purely demand-driven expansion reported for the fixed nominal wage closure. For all these variables, the additional competitiveness more than doubles, and in some cases almost trebles, the expansionary impact. Not surprisingly these increases in activity reduce the savings in total fuel use. For the increase in fuel efficiency, the fuel index, the ratio of the change in total fuel use as a percentage of initial household fuel use, is almost halved, from a fall in 2.10% to a fall of 1.08%. For the vehicle efficiency improvement the reduction is more limited, from 2.20% to 1.54%.

Finally note that although there are changes in the price of fuel and vehicles, as measured in natural units, in these simulations, this has very little impact on the direct substitution between fuel and vehicles in the production of private transport. There is almost no difference between the changes in vehicle and fuel intensity in transport between the results reported for these simulations and those for the fixed nominal wage closure reported in columns 3 and 4 of Table 1, where prices measured in natural units are unchanged.

9.2.4 General Equilibrium: Wage Bargaining

The simulation results with the wage bargaining closure, our preferred model, are reported in the data columns 7 and 8 in Table 1. In this case, workers and firms bargain over the real wage, which results in a wage curve in which the real wage is positively related to the employment rate. Again, we measure the real wage using the CPI^{τ} price index, so that there is a potential positive supply-side disturbance delivered through the improvement in the efficiency of private transport, as demonstrated in the fixed real-wage closure. However, the increase in employment that the demand and supply-side positive shocks produce has an impact on the nominal wage which will operate in the opposite direction, thereby limiting the macro-economic expansion and the increase in fuel use.

A key characteristic of these simulation results is that with both of the efficiency disturbances there is an increase in the nominal wage. One way to think about this is to go back to the simulations using the fixed nominal wage and to examine the results for the fuel efficiency shock as an example. With the fixed nominal wage, the increase in employment is 0.13%, whilst the increase in the real wage is 0.05%. Once a bargained real wage is introduced, this increase in the real wage fails to fully reflect the increase in bargaining power that workers now have and the nominal wage needs to rise. This will itself reduce competitiveness, exports will fall, import penetration will increase, which will restrict the rise in the employment rate until the labour market reaches equilibrium. For the fuel efficiency increase, this is where employment increases by 0.06%, the real wage by 0.07% and the nominal wage by 0.03%. The corresponding figures for the increase in vehicle efficiency are 0.04%, 0.02% and 0.02%.

This implies that the expansion in economic activity that accompanies the efficiency improvements is the smallest of the three macro-economic closures that we study in this case. GDP and employment increase by 0.6% with the fuel efficiency improvement and by 0.4% with the improvement in vehicle efficiency. This also means that the fall in fuel use is the largest in this case. As with the other macroeconomic

closures, although there are changes in the prices of commodities measured in natural units, these have a very small effect on the change in the composition of household consumption that follows the efficiency changes. The fuel and vehicle intensity of private transport remains essentially unchanged. In this case, the incorporation of intermediate inputs increases the fuel saving, and the imposition of the wage curve limits the expansion in economic activity.

9.2.5 General Equilibrium Closures: Comments

These results suggest three clear conclusions. The first is that the incorporation of general equilibrium effects is important for the correct identification of the impact of efficiency improvements in the production of energy-intensive household consumer services. The direct effect of the change in the composition of household consumption, which is the focus of the partial equilibrium analysis, does play the major part in determining the change in fuel use. Moreover, this effect is little changed across the different CGE simulations. However, the fuel reductions with our preferred general equilibrium simulations are between 15% and 20% greater than those measured using the partial equilibrium analysis.

Secondly, incorporating general equilibrium effects does not necessarily imply that the fuel use savings will fall. Importantly, in this case the change in the composition of household expenditure has an important impact on the aggregate use of fuel as an intermediate input. Whilst there is an expansion in output, which would typically increase fuel use, this is more than offset here by the compositional intermediate fuel use effects.

Third, there are big differences between the changes in fuel use, depending on the labour market closure that is adopted. Where the increased efficiency is allowed to affect competitiveness through the labour market, with no employment constraints, as in the fixed wage closure, the fuel savings can be substantially reduced. For example, the UK-ENVI model is a national model of the UK economy. A regional model would typically face fewer labour market constraints because of the greater availability of labour through inter-regional migration. Also a region would typically be more open to trade and therefore more strongly stimulated by positive competitiveness effects.

A final comment is that these simulations concern comparisons of the impacts of efficiency improvements in the two inputs for a specific, given set of parameter values. They illustrate some of the key issues which will affect the simulated outcomes, particularly the effect on fuel use. However, the outcomes and qualitative differences between the results from the different efficiency improvements will differ, depending on the values of σ, η and s.

9.3 Multiple Benefits of Efficiency Improvements in Private Transport.

It is instructive to compare the multiple benefits generated by the 5% fuel and vehicle efficiency improvements and the insights this gives for policy. These are results produced using our preferred model, where the labour market is characterised by a wage curve. We take a very straightforward approach here, defining the change in the general equilibrium multiple benefit index, dM^G, as the sum of the absolute change in the GDP, $dGDP$, plus the weighted change in the total value of fuel use $d(p_f^n f^n)$, with the weight represented by w, so that:

$$dM^G = dGDP - wd\left(p_f^n f^n\right) \quad (36)$$

We experiment with four values for w. These are: 0.5, 1.0, 1.5 and 2.0. Note that we are weighting absolute reductions in the value of total fuel use against changes in total GDP. This means that the cost of the pollutant produced by the burning the fuel is being valued as a proportion of the fuel price. Therefore where the value of w equals 0.5, this means that the pollution generated by one unit of fuel is 50% of the price of that fuel. The multiple benefit values calculated for the four different weights and shown for combinations of values for the elasticity of substitution between fuel and vehicles in the production of private transport, σ, and the elasticity of demand for private transport, η, in Tables B3 to B6 in the Appendix.

Figure 8 maps the values of the multiple benefits index where the weight takes the value 2. The two planes report the change in multiple benefit values for the fuel and vehicle efficiency improvements for a grid of σ and η parameter values. A number of points should be noted. First, with this closure the efficiency improvements always generate an increase in GDP so that there is always a bias towards a positive multiple benefits value. Note that even with a high weight negative weight on increased fuel use, negative multiple benefits apply only in a minority of the parameter value combinations. In particular, negative values occur where the efficiency improvement leads to an increase in fuel intensity in the production of private transport, together with high values of the elasticity of demand for private transport, so that fuel makes up a larger share of household consumption expenditure.

For fuel efficiency changes, with a weight of 2, negative multiple benefit values occur in the top right hand corner of the grid. These lie above the straight line between the (σ, η) values (0.7, 2.0) and (2.0,1.3). For the improvement in vehicle efficiency, negative multiple benefit values are observed in the top left-hand corner, with relatively low values of σ and high values of η. The boundary between positive and negative values here lies on a straight line between the (σ, η) points (0.1, 1.0) and 1.2, 2.0). As the weight on fuel saving is reduced, the set of parameter combinations where the multiple benefits change is negative is reduced. Fr example, with a weight on fuel-use reduction of 0.5, there are no (σ, η) combinations in the (0,0) to (2,2) range where either a fuel of vehicle-augmenting improvement in efficiency will not increase multiple benefit index.

A second point is that for inelastic values of σ and η, that is values less than unity, the fuel efficiency improvement gives the highest multiple benefits. However, it is also the case that for all these elasticity

values, an improvement in vehicle efficiency would also show positive multiple benefits, even where, as a result, fuel use increases. For the weight of 2, the border between (σ,η) values for which a fuel efficiency improvement produces a higher increase in multiple benefit than does an equal vehicle efficiency improvement takes the following form. It is a straight line between the (σ,η) points (1.0,1.7) and (1.5,0.1). For parameter combination to the left of this line, fuel efficiency improvements give the higher increase in multiple benefits; to the right of the line, improvements in vehicle efficiency produce the higher increase.

Finally the multiple benefits expression adopted here is very basic. A more complex formulation could be devised, incorporating variables such as employment, household income or income distribution, as policy variables with appropriate weights.

10. Conclusion

In this paper we investigate the impact of efficiency improvements in the production of an energy-intensive household services. The example we take involves the analysis of improvements in the use of fuel and vehicles in the production of private transport. Although the focus of the work is the impact on fuel use, we also include consideration of the multiple benefits approach suggested by the IEA (2014). We follow Gillingham et al, (2016) in taking the output to be miles travelled and treat the inputs of fuel and vehicles as in a conventional production function. The paper extends Figus et al (2018) in two important ways. First, it compares the effectiveness of fuel and vehicle efficiency improvements in reducing fuel use. This is done in both a partial and computable general equilibrium (CGE) framework. Second, it also reports the impact on multiple benefits indices, where the positive changes in economic activity are also counted as additional benefits to the efficiency improvements. In the partial equilibrium analysis the additional benefit is the change in consumer surplus; in the CGE simulations it is the change in GDP.

The analysis suggests that for appropriate elasticity values, both fuel and vehicle efficiency improvements can generate reductions in fuel use in private transport. Further, both forms of increased efficiency are associated with additional economic benefits. The CGE simulation suggests that the substitution effects identified in the partial equilibrium analysis are an important element in change in total fuel use resulting from these consumption efficiency changes. However, the identification of associated changes in intermediate fuel demand, plus the potential expansionary effects of the improvements in household efficiency transmitted through the labour market can generate general equilibrium effects that vary substantially from those derived using partial equilibrium analysis.

The analysis work presented here is essentially illustrative. In future work we plan to refine the treatment of private transport to reflect its multi-faceted nature. Whilst mobility is central, the provision of comfort, vehicle reliability and safety are also important components of the private transport service. By treating the output solely as miles travelled we severely simplify the analysis and we aim to address this in future work. We also wish to explicitly extend the approach to other elements of household expenditure, such as space heating, air conditioning, refrigeration and lighting, where energy combines with other inputs to

produce energy-intensive services. In these extensions, the search for appropriate parameter values will also prove important.

References

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production. IMF Staff Papers, 16(1):159–178.

Blanchflower, D. G. and Oswald, A. J. (2009). The Wage Curve. Europe, 92:215–235.

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., and Jackson, T. (2014). Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. Ecological Economics, 106:12–32.

Chitnis, M. and Sorrell, S. (2015). Living up to expectations: Estimating direct and indirect rebound effects for UK households. Energy Economics, 52:S100-S116.

Druckman, A., Chitnis, M., Sorrell, S., and Jackson, T. (2011). Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy, 39(6):3572–3581.

Duarte, R., Feng, K., Hubacek, K., Snchez-Chliz, J., Sarasa, C., and Sun, L. (2016). Modeling the carbon consequences of pro-environmental consumer behavior. Applied Energy, 184:1207 – 1216.

Dubin, J. A., Miedema, A. K., and Chandran, R. V. (1986). Price Effects of Energy-Efficient Technologies: A Study of Residential Demand for Heating and Cooling. The RAND Journal of Economics, 17:310–325.

Figus, G., Swales, J. K., & Turner, K. (2018). Can private motor vehicle-augmenting technical progress reduce household and total fuel use? Ecological Economics, 146, 136-147. DOI: 10.1016/j.ecolecon.2017.10.005

Frondel, M., Peters, J., and Vance, C. (2008). Identifying the rebound: Evidence from a German household panel. Energy Journal, 29:145–163.

Frondel, M., Ritter, N., and Vance, C. (2012) Heterogeneity in the rebound effect: Further evidence for Germany. Energy Economics, 34(2):461-467.Gillingham, K., Rapson, D., and Wagner, G. (2016). The Rebound Effect and Energy Efficiency Policy. Review of Environmental Economics and Policy, 10(1):68–88.

Gordon, R. J. (2016). The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War. The Princeton Economic History of the Western World. Princeton University Press.

Gordon, R.J. (1990), The measurement of Durable Goods Prices, National Bureau of Economic Research Monograph, University of Chicago Press, Chicago.

Greening, L., Greene, D. L., and Difiglio, C. (2000). Energy efficiency and consumption the rebound effect a survey. Energy Policy, 28(6¬7):389–401.

Haas, R., Nakicenovic, N., Ajanovic, A., Faber, T., Kranzl, L., Müller, A., and Resch, G. (2008). Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy, 36(11):4012–4021.

Holden, D. and Swales, J. K. (1993). Factor Subsidies, Employment Generation, and Cost per Job: A Partial Equilibrium Approach. Environment and Planning A, 25(3):317–338.

Hunt, L. C. and Ryan, D. L. (2015). Economic modelling of energy services: Rectifying misspecified energy demand functions. Energy Economics, 50:273–285.

IEA (2014). Capturing the Multiple Benefits of Energy Efficiency: A Guide to Quantifying the Value Added. IEA, Paris.

Jorgenson, D. W. (1963) (1968?). Capital Theory and Investment Behavior. The American Economic Review, 53(2):pp. 247–259.

Layard, R., Nickell, S., and Jackman, R. (1991). Unemployment: Macroeconomic Performance and the Labour Market. Oxford University Press, Oxford.

Lecca, P., McGregor, P. G., Swales, J. K., and Turner, K. (2014). The added value from a general equilibrium analysis of increased efficiency in household energy use. Ecological Economics, 100:51–62.

Lin, C.-Y. C. and Zeng, J. J. (2013). The elasticity of demand for gasoline in China. Energy Policy, 59(0):189–197.

McGregor, P. G., Swales, J. K., and Yin, Y. P. (1996). A Long-Run Interpretation Of Regional Input-Output Analysis. Journal of Regional Science, 36(3):479–501.

Mizobuchi, K. (2008). An empirical study on the rebound effect considering capital costs. Energy Economics, 30(5):2486–2516.

Schwarz, P. M. and Taylor, T. N. (1995). Cold hands, warm hearth?: climate, net takeback, and household comfort. Energy Journal, 16:41– 54.

Sorrell, S. and Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. Ecological Economics, 65(3):636–649.

Turner, K. (2009). "Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK Economy." Energy Economics 31: 648-666.

Walker, I. O. and Wirl, F. (1993). Irreversible Price-Induced Efficiency Improvements: Theory and Empirical Application to Road Transportation. The Energy Journal, Volume. 14(4):183–205.

West, S. E. (2004). Distributional effects of alternative vehicle pollution control policies. Journal of Public Economics, 88:735–757.

Appendix A

Holden and Swales (1993) analyse, in a partial equilibrium setting, the impact of a factor subsidy in a perfectly competitive industry. Where the output is produced by two inputs, capital and labour (K and L) in a two-factor production function. The partial elasticities of a labour subsidy are as follows:

(1) $$\frac{1}{L}\frac{dL}{dr} = -\frac{\varepsilon_L\left[\sigma(\eta+\varepsilon_K)+s\varepsilon_K(\eta-\sigma)\right]}{\Lambda} > 0$$

(2) $$\frac{1}{K}\frac{dK}{dr} = -\frac{\varepsilon_K\varepsilon_L s(\eta-\sigma)}{\Lambda} > 0 \quad iff \quad \eta > \sigma$$

In (1) and (2):

$$\Lambda = (1-r)\left[s(\eta-\sigma)(\varepsilon_L-\varepsilon_K)-(\varepsilon_L+\sigma)(\eta+\varepsilon_K)\right] < 0$$

and $\varepsilon_K, \varepsilon_L$ are the elasticities of supply of capital and labour, σ is the elasticity of substitution between capital and labour, η is the elasticity of demand for the product, s is the share of labour in production. Note that σ and η take non-negative values and s lies between and zero and one, so that $\eta, \sigma \geq 0$ and $0 > s > 1$. The subsidy operates so that the price of labour to the firm is $w_L(1-r)$, where w_L is the wage paid to the worker.

As $\varepsilon_K, \varepsilon_L \to \infty$, the supplies of capital and labour become infinitely elastic, so that the market prices for capital and labour are fixed. In equations (1) and (2) dividing both numerator and denominator by $\varepsilon_K\varepsilon_L$ and then letting both approach infinity gives:

(3) $$\frac{1}{L}\frac{dL}{dr} = \sigma + s(\eta-\sigma) = \frac{\sigma(1-s)+s\eta}{1-r} > 0$$

(4) $$\frac{1}{K}\frac{dK}{dr} = \frac{s(\eta-\sigma)}{1-r} > 0 \quad iff \quad \eta > \sigma$$

In transferring this analysis to the domestic production of private transport, capital and labour are replaced by inputs of vehicles and fuel, v and f. However, a more fundamental difference is the fact that this case considers not a subsidy but rather a change in the efficiency of one input. The initial value of the efficiency parameter (and subsidy) is also taken to be zero. It transpires that in this case, the subsidy and efficiency analyses are very similar and many of the results from the impact of the subsidy apply equally to the analysis of the efficiency improvement. There are two issues. The first is the effect on the price of the input paid by the firm or household. The second is the relationship between the use measured in efficiency and natural units of the input receiving the efficiency improvement.

Equation (5) gives the price paid by the firm, $\overline{p}_w^r$, for an input, labour, after the introduction of a labour subsidy, r, or an increase in labour efficiency, γ_L:

$$(5) \qquad \overline{p}_w^r = p_w(1-r), \quad \frac{\partial \overline{p}_w^r}{\partial r} = -p_w$$

$$(6) \qquad \overline{p}_w^{\gamma_L} = \frac{p_w}{1+\gamma_L}, \quad \frac{\partial \overline{p}_w^{\gamma_L}}{\partial \gamma_L} = -\frac{p_w}{(1+\gamma_L)^2}$$

Note from equations (5) and (6) that if we have an initial value for γ_L as zero, the impact on the price of the input is the same. Because the impact on input use comes through the change in the input price:

$$(7) \qquad \frac{1}{L}\frac{dL}{dr} = \frac{1}{L}\frac{dL}{d\gamma_L}, \quad \frac{1}{K}\frac{dK}{dr} = \frac{1}{K}\frac{dK}{d\gamma_L}$$

Equation (7) implies that equations (3) and (4) apply equally to the case of an improvement in factor efficiency, as to the introduction of a subsidy. However, there is one difference. With an efficiency improvement the price is measured in per efficiency units of the input (L^e). If the outcome is needed in natural units (L^n), which is typically the case, then the change is determined using the following equation:

$$(8) \qquad L^n = \frac{L^e}{(1+\gamma_L)}$$

Therefore:

$$(9) \qquad \frac{1}{L^n}\frac{\partial L^n}{\partial \gamma_L} = \frac{1}{L^n}\frac{(1+\gamma_L)\partial L^e / \partial \gamma_L - L^e}{(1+\gamma_L)^2}$$

Using equations (3), (7), (8) and (9) and imposing $\gamma = 0$, gives:

$$(10) \qquad \frac{1}{L^n}\frac{\partial L^n}{\partial \gamma^L} = \sigma(1-s) + s\eta - 1 > 0 \quad iff \quad \eta > \frac{1}{s} - \frac{(1-s)\sigma}{s}$$

$$(11) \qquad \frac{1}{K}\frac{dK}{d\gamma^L} = s(\eta - \sigma) > 0 \quad iff \quad \eta > \sigma$$

Appendix

Table B1. Percentage change in the fuel index from a 5% increase in vehicle efficiency

σ \ η	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
2	2.0	2.2	2.5	2.8	3.1	3.3	3.6	3.9	4.2	4.5	4.7	5.0	5.3	5.6	5.8	6.1	6.4	6.7	6.9	7.2
1.9	1.6	1.8	2.1	2.4	2.7	2.9	3.2	3.5	3.8	4.1	4.3	4.6	4.9	5.1	5.4	5.7	6.0	6.2	6.5	6.8
1.8	1.1	1.4	1.7	2.0	2.3	2.5	2.8	3.1	3.3	3.7	3.9	4.2	4.4	4.7	5.0	5.3	5.5	5.8	6.1	6.3
1.7	0.7	1.0	1.3	1.6	1.8	2.1	2.4	2.7	2.9	3.2	3.5	3.8	4.0	4.3	4.6	4.8	5.1	5.4	5.6	5.9
1.6	0.3	0.6	0.9	1.2	1.4	1.7	2.0	2.3	2.5	2.8	3.1	3.3	3.6	3.9	4.1	4.4	4.7	5.0	5.2	5.5
1.5	-0.1	0.2	0.5	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.7	2.9	3.2	3.5	3.7	4.0	4.3	4.5	4.8	5.1
1.4	-0.5	-0.2	0.1	0.4	0.6	0.9	1.2	1.4	1.7	2.0	2.2	2.5	2.8	3.0	3.3	3.6	3.8	4.1	4.4	4.6
1.3	-0.9	-0.6	-0.3	-0.1	0.2	0.5	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.6	2.9	3.2	3.4	3.7	4.0	4.2
1.2	-1.3	-1.0	-0.7	-0.5	-0.2	0.1	0.3	0.6	0.9	1.2	1.4	1.7	1.9	2.2	2.5	2.7	3.0	3.3	3.5	3.8
1.1	-1.7	-1.4	-1.1	-0.9	-0.6	-0.3	-0.1	0.2	0.5	0.7	1.0	1.3	1.5	1.8	2.1	2.3	2.6	2.9	3.1	3.4
1	-2.1	-1.8	-1.5	-1.3	-1.0	-0.7	-0.5	-0.2	0.1	0.3	0.6	0.9	1.1	1.4	1.7	1.9	2.2	2.4	2.7	3.0
0.9	-2.5	-2.2	-1.9	-1.7	-1.4	-1.1	-0.9	-0.6	-0.3	-0.1	0.2	0.5	0.7	1.0	1.2	1.5	1.8	2.0	2.3	2.5
0.8	-2.8	-2.6	-2.3	-2.1	-1.8	-1.5	-1.3	-1.0	-0.7	-0.5	-0.2	0.0	0.3	0.6	0.8	1.1	1.4	1.6	1.9	2.1
0.7	-3.2	-3.0	-2.7	-2.4	-2.2	-1.9	-1.7	-1.4	-1.1	-0.9	-0.6	-0.4	-0.1	0.2	0.4	0.7	0.9	1.2	1.5	1.7
0.6	-3.6	-3.4	-3.1	-2.8	-2.6	-2.3	-2.1	-1.8	-1.5	-1.3	-1.0	-0.8	-0.5	-0.2	0.0	0.3	0.5	0.8	1.0	1.3
0.5	-4.0	-3.8	-3.5	-3.2	-3.0	-2.7	-2.5	-2.2	-1.9	-1.7	-1.4	-1.2	-0.9	-0.6	-0.4	-0.1	0.1	0.4	0.6	0.9
0.4	-4.4	-4.2	-3.9	-3.6	-3.4	-3.1	-2.9	-2.6	-2.3	-2.1	-1.8	-1.6	-1.3	-1.1	-0.8	-0.5	-0.3	0.0	0.2	0.5
0.3	-4.8	-4.5	-4.3	-4.0	-3.8	-3.5	-3.3	-3.0	-2.7	-2.5	-2.2	-2.0	-1.7	-1.5	-1.2	-0.9	-0.7	-0.4	-0.2	0.1
0.2	-5.2	-4.9	-4.7	-4.4	-4.2	-3.9	-3.6	-3.4	-3.1	-2.9	-2.6	-2.4	-2.1	-1.9	-1.6	-1.4	-1.1	-0.8	-0.6	-0.3
0.1	-5.6	-5.3	-5.1	-4.8	-4.6	-4.3	-4.0	-3.8	-3.5	-3.3	-3.0	-2.8	-2.5	-2.3	-2.0	-1.8	-1.5	-1.3	-1.0	-0.7

Table B2. Percentage change in the vehicle index from a 5% increase in fuel efficiency

σ \ η	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
2	5.2	5.0	4.7	4.4	4.2	3.9	3.6	3.4	3.1	2.9	2.6	2.3	2.0	1.8	1.5	1.2	1.0	0.7	0.4	0.2
1.9	4.9	4.7	4.4	4.2	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.0	1.8	1.5	1.2	1.0	0.7	0.4	0.2	-0.1
1.8	4.7	4.4	4.2	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.0	1.8	1.5	1.2	1.0	0.7	0.4	0.2	-0.1	-0.4
1.7	4.4	4.2	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6
1.6	4.2	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.0	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.9
1.5	3.9	3.6	3.4	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.9	-1.1
1.4	3.6	3.4	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.9	-1.1	-1.4
1.3	3.4	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.9	-1.1	-1.4	-1.7
1.2	3.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.9	-1.1	-1.4	-1.7	-1.9
1.1	2.8	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	-0.1	-0.3	-0.6	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2
1	2.6	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2	-2.4
0.9	2.3	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2	-2.4	-2.7
0.8	2.1	1.8	1.5	1.3	1.0	0.7	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2	-2.4	-2.7	-3.0
0.7	1.8	1.5	1.3	1.0	0.8	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.4	-1.6	-1.9	-2.2	-2.4	-2.7	-2.9	-3.2
0.6	1.5	1.3	1.0	0.8	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.3	-1.6	-1.9	-2.1	-2.4	-2.7	-2.9	-3.2	-3.5
0.5	1.3	1.0	0.8	0.5	0.2	0.0	-0.3	-0.6	-0.8	-1.1	-1.3	-1.6	-1.9	-2.1	-2.4	-2.7	-2.9	-3.2	-3.5	-3.7
0.4	1.0	0.8	0.5	0.2	0.0	-0.3	-0.5	-0.8	-1.1	-1.4	-1.6	-1.9	-2.1	-2.4	-2.7	-2.9	-3.2	-3.5	-3.7	-4.0
0.3	0.8	0.5	0.2	0.0	-0.3	-0.5	-0.8	-1.1	-1.3	-1.6	-1.9	-2.1	-2.4	-2.7	-2.9	-3.2	-3.4	-3.7	-4.0	-4.2
0.2	0.5	0.2	0.0	-0.3	-0.5	-0.8	-1.1	-1.3	-1.6	-1.9	-2.1	-2.4	-2.6	-2.9	-3.2	-3.4	-3.7	-4.0	-4.2	-4.5
0.1	0.2	0.0	-0.3	-0.5	-0.8	-1.1	-1.3	-1.6	-1.8	-2.1	-2.4	-2.6	-2.9	-3.2	-3.4	-3.7	-4.0	-4.2	-4.5	-4.8