Figus, Gioele and Swales, J. Kim and Turner, Karen (2018) Can private motor vehicle-augmenting technical progress reduce household and total fuel use? Ecological Economics, 146. pp. 136-147. ISSN 0921-8009 , http://dx.doi.org/10.1016/j.ecolecon.2017.10.005

Ecological Economics 146 (2018) 136–147

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Can Private Vehicle-augmenting Technical Progress Reduce Household and Total Fuel Use?

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ARTICLE INFO

JEL Codes:
C68
D58
Q43
Q48

Keywords:
Technical progress
Energy efficiency
Private transport
Energy service

ABSTRACT

This paper demonstrates the importance of modelling energy-intensive household services in general, and private transportation in particular, as combinations of energy and other inputs. Initially a partial equilibrium approach is used to analyse private transport consumption as a self-produced commodity formed by household vehicle and fuel use. We particularly focus on the impact of private vehicle-augmenting technical progress in this framework. We show that household fuel use will fall if it is easier to substitute between vehicles and fuel in the household production of private transport services than it is to substitute between private transport and the composite of all other goods in overall household consumption. The analysis is then extended, through Computable General Equilibrium simulation, to investigate the wider implications of similar efficiency improvements when intermediate demand, prices and nominal income are endogenous. The subsequent reduction in the price of private transport service (not observable in market prices) allows the wage measured relative to the CPI to rise whilst the wage relative to the price of foreign goods falls. This simultaneously increases UK international competitiveness, encouraging increased exports and reduced import penetration whilst allowing employment to rise. This provides an additional supply-side stimulus to production, employment and household income.

1. Introduction

This paper has three main aims. The first is to model the use of energy-intensive consumer services in a more appropriate manner than in the existing literature. In particular, we operationalise the approach suggested in Gillingham et al. (2016) by explicitly incorporating both energy and non-energy inputs to both the supply of energy-intensive services and the determination of their price. We take, as an example, the household production of private transport services using inputs of refined fuel and motor vehicles.

The second aim is to analyse the impact of technical change in the household provision of this energy-intensive service, focussing on improvements in vehicle efficiency. To be clear, we have in mind efficiency improvements in the use of these inputs in the act of consumption, not in the production of the vehicles that are consumed.[1] Adapting a general result derived in Holden and Swales (1993) to this particular setting, we identify the condition under which such an efficiency increase reduces the household fuel use in a partial equilibrium analysis. This occurs where the elasticity of substitution between fuel and vehicles in the household production of private transport is greater than the elasticity of substitution between private transport and the composite of all other goods in household consumption.

The third aim is to extend the analysis through simulation using the UK-ENVI Computable General Equilibrium model. These simulations investigate the wider implications of household vehicle-augmenting efficiency improvements where prices, real and nominal incomes are endogenous. This captures the impact on the system-wide change in fuel use, including its use as an intermediate in production. The subsequent reduction in the price of private transport services (not observable in market prices) allows the real wage, measured against the adjusted consumer price index (CPI^r), to rise, enabling employment to increase. However, simultaneously the nominal wage, measured against foreign prices, can fall, stimulating UK international competitiveness, increasing exports and reducing import penetration. The increase in household vehicle efficiency thereby provides an additional combined demand- and supply-side stimulus to production, employment and household income. In general, the CGE work supports and extends the partial equilibrium findings.

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[1] However, a neutral efficiency increase in the production of only those vehicles destined for household use would have the same impact.

http://dx.doi.org/10.1016/j.ecolecon.2017.10.005
Received 31 May 2017; Received in revised form 29 August 2017; Accepted 2 October 2017

2. Background

Many studies have analysed the impact of energy-saving technical improvements in consumption so as to assess the potential impact on final energy use (see, for example, Chitnis and Sorrell, 2015; Duarte et al., 2016; Druckman et al., 2011; Frondel et al., 2008; Frondel et al., 2012; Lecca et al., 2014; Schwarz and Taylor, 1995; West, 2004).[2] These technical improvements simply mean that the same amount of fuel services can be delivered with less physical fuel (and no change in the consumption of any other commodity). However, households typically use energy as one element in the technology that delivers energy-intensive consumption services (Becker, 1965). Examples of such services include domestic space heating, air-conditioning, lighting and cooking.[3] In the present paper we treat these consumption services as though they are produced by the household using the appropriate inputs. Therefore in this case we assume households produce private transport using inputs of fuel and vehicles.[4]

A small number of papers do attempt to model domestic energy use explicitly in the context of the generation of energy-intensive services (Haas et al., 2008; Hunt and Ryan, 2015; Walker and Wirl, 1993). However, the technology implicitly used in these papers is extremely rudimentary. Output is a linear (fixed-coefficient) function of energy use, so that technical improvements simply reduce that coefficient. Therefore, for example, in Walker and Wirl (1993) private transport is obtained by combining fuel and technology. This technology converts fuel use into miles travelled. In this approach, the price of private transport is calculated as the price of fuel divided by the fuel efficiency of vehicles. The cost of the vehicle, its role in determining the price of private transport and the possible substitution between expenditure on the vehicle and fuel is not discussed.

Wirl (1997) makes the case for explicitly treating household energy use as a derived demand, as one element of the inputs to domestically produced consumer services and Gillingham et al. (2016) similarly argues that producing vehicles using a lighter material would improve fuel efficiency of motoring services and increase the number of miles travelled per unit of fuel. This approach implies that the price of the energy-intensive service depends on the price of energy and all the other inputs that combine to deliver the service. Although it does not discuss specifically how this should be modelled and is mostly interested in the implications of energy efficiency for the calculation of the rebound effect, Gillingham et al. (2016) offers an interesting starting point. In the present paper we operationalise this approach, beginning with a partial equilibrium analysis and them moving to a Computable General Equilibrium simulation.

3. Modelling Household Production of Motoring Services

3.1. The Basic Model

In this model households produce private transport, measured here as miles travelled, *m*, over a given time period, by combining vehicles, *v*, and fuel, *f*. Consumption demand for fuel is therefore a derived demand stemming from the household requirement for private transport. It is important to stress that this is essentially an illustrative example and it has been chosen primarily because of data availability in the general equilibrium modelling.

[2] These studies primarily attempt to identify rebound from the endogenous price and redirected expenditure effects of efficiency changes in consumption.

[3] In investigating rebound, Chitnis et al. (2015), Mizobuchi (2008) and Sorrell (2008) relate energy efficiency improvements to linked capital costs but fail to explore the relationship between the physical energy and the capital appliances used in the production of the energy-intensive consumer services.

[4] We assume that the efficiency improvement is limited to household private transport, although it would be likely that these would also apply to at least some transport use as an intermediate in production.

We use a conventional, well-behaved production function to determine the relationship between the inputs of vehicles and fuel and the miles travelled. This is a standard approach in economics, but we detail some of its key features for two main reasons. First, the notion of a production function is being applied here in an unusual setting. Second, given the way in which the relationship is characterised we adopt particular definitions of improvements in fuel and vehicle efficiency. These may differ from the definitions used in other disciplines.

It is convenient to express the inputs in terms of efficiency units, indicated by an e superscript. The household production function for private transport is therefore given as:

$$m = m(f^e, v^e) \tag{1}$$

There are a number of general features of a well-behaved production function that are of interest here. First it is linear homogeneous and therefore exhibits constant returns to scale. If all inputs are doubled, output is doubled. This implies that the household private-transport technology can be studied by focussing on the unit-isoquant, the set of techniques that could be used to produce one unit, say 100 miles travelled per week. Given our formulation, more expensive vehicles are less fuel intensive.[5] The consumer chooses the combination of vehicles and fuel that maximises the amount of miles travelled, *m*, given her budget constraint. This involves a trade-off between the increased vehicle cost and the lower fuel cost per mile.

Suppose that the production of private transport becomes more efficient due to technical progress.[6] To investigate the implications we employ a graphical analysis in which refined fuel and motor vehicles are represented in efficiency units. If the household allocates expenditure y to private transport we specify the relation between natural and efficiency units in the household utility maximisation problem as follows:

$$\max \quad m = m(f^e, v^e) \text{ subject to } p_f^n f^n + p_v^n v^n - y \leq 0 \tag{2}$$

where $z^e = \varepsilon_z z^n$ and $p_z^e = \frac{p_z^n}{\varepsilon_z}$ for $z = f, v$.

In Eq. (2), p indicates a price, ε is an efficiency parameter and n is a superscript for natural units. In the base period $\varepsilon_z = 1 \;\; \forall_z$ so that initially natural and efficiency units are the same for both inputs.[7] To increase the efficiency of a particular input z, we increase the value of ε_z.

From the first order conditions we have that:

$$\frac{\partial m}{\partial z^n} = p_z^n = \frac{\partial m}{\partial z^e}\varepsilon_z \text{ and } \frac{\partial m}{\partial z^e} = p_z^e = \frac{p_z^n}{\varepsilon_z} \tag{3}$$

Expression (3) implies that for any input whose efficiency is increased, technical progress is reflected in a change in its price, expressed in efficiency units. Technical changes can therefore be represented through adjustments in the budget constraint, specified in efficiency units.

The impact of the reduction in the price of vehicles on the consumption of fuel depends on the elasticity of substitution, $\sigma_{v,f}$, between the two inputs:

$$\sigma_{v,f} = \frac{\%\Delta(v^e/f^e)}{\%\Delta(p_f^e/p_v^e)} \tag{4}$$

[5] This is a simplification and more expensive vehicles are likely to offer other characteristics such as comfort or security. We plan to investigate this aspect in future research.

[6] There are three primary benchmark cases. In these vehicles and fuel either individually become more efficient or both become equally more efficient. Hybrid cases are where the efficiency of both inputs increases at different rates. If the elasticity of substitution between fuel and vehicles equals unity, so that the function takes a Cobb-Douglas form, there is no difference in the qualitative operation of an increased in efficiency in either of the inputs.

[7] For the aggregate US economy, Hassler et al. (2012) identify the efficiency units of capital and energy used in production using Maximum Likelihood Estimation.

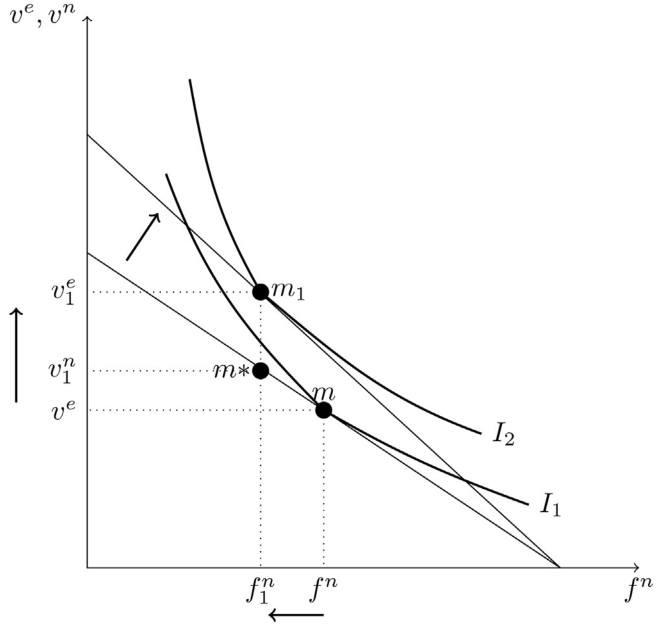

Fig. 1. Technical progress in motor vehicles.

If the price of one input falls, its use per unit of physical output will rise. However, the share of the unit cost that goes to that input will fall only if the inputs are complements ($\sigma < 1$) and rise if they are competitors ($\sigma > 1$).

Fig. 1 shows vehicles and fuel as competitors with vehicle efficiency increasing. We parametrise the model so that the initial quantity of fuel, vehicles and motoring are all equal to unity, so that in the absence of efficiency changes, natural and efficiency units are equal. The vertical axis represents vehicles in natural and efficiency units, while the horizontal axis simply represents fuel in natural units as fuel efficiency does not change in this analysis.

Initially the consumer is at point m on the isoquant I_1. The technical improvement in vehicles, represented by an increase in ε_v, pivots the budget constraint, expressed in efficiency units, clockwise, as the price of vehicle in efficiency units decreases. At point m_1 the consumer chooses the combination of $f_1{}^n$ and $v_1{}^e$ that maximises the output of private transport. This is where the new budget constraint is tangent to the highest attainable isoquant, I_2. If we project the fuel consumption figure onto the initial budget constraint expressed in natural units, we see that private transport output m_1 is produced at $m*$ using $f_1{}^n$ and $v_1{}^n$inputs, both measured in natural units.

At this point it would be useful to clarify the nature of pure vehicle augmenting technical change. This does not depend on how the efficiency improvement is delivered. That is to say, changes in vehicle design, fuel composition or household behaviour can all generate efficiency changes that are purely vehicle augmenting. Imagine a technical change that does not reduce the cost of the vehicle but improves its durability, thereby reducing maintenance and depreciation costs, but has no direct impact on fuel efficiency. Such a change would be purely vehicle augmenting. This could be embodied in vehicle design through the use of more robust materials, result from changes in fuel refining which reduce engine wear or adjustments in owner/driver behaviour leading to lower maintenance or depreciation.

With a standard production function, and constant input prices measured in natural units, such vehicle-augmenting technical change will always reduce fuel use per mile travelled. This is because the price of vehicles has fallen, leading to the substitution of vehicles for fuel in the households production of private transport. Note that this is not due to energy augmenting technical change but rather an endogenous choice of less fuel intensive, but already existing, technology.[8] However, fuel use per £1 spent on motoring does not necessarily fall. In Fig. 1 we assume that the two goods are competitive. In this case, the efficiency improvement in vehicles reduces the quantity of fuels necessary to deliver the increase in private transport services, while the use of vehicles, measured in natural units, increases. Clearly for energy-intensive household services in general, technical improvements in the non-energy inputs generate endogenous changes in fuel use which can be positive or negative.

3.2. Incorporating the Consumption of Multiple Goods

So far we have assumed that the consumer has a nominal fixed budget to be spent on private transport. Consider now a household allocating its total household budget between private transport and a composite that comprises all the other goods, a. Also assume that private transport is still a combination of vehicles and fuel. The consumption choice can then be represented by following nested function:

$$c = c(a, m(v^e, f^e)) \quad (5)$$

In this case, the consumption of fuel depends not only on the substitution between vehicles and fuel, $\sigma_{v,f}$, but also on the degree of substitution between private transport and all the other goods, $\sigma_{m,a}$. Fig. 2 presents a graphical analysis which extends that shown in Fig. 1. The diagram has two panels. The top panel has vehicles in efficiency units on the vertical axis and refined fuel in natural units on the horizontal axis. In the bottom panel the price of motoring p_m is on the downward-pointing vertical axis.

Again, we parametrise the model so that the initial quantity, price, and therefore the total budget for private transport (m, p_m and b) are all unity. The consumer initially produces using the technique m_1 which includes $f_1{}^n$ fuel together with a quantity of vehicles. With a fixed nominal budget, technical progress in vehicles has the effect of pivoting the budget line (in efficiency units) from b_1b_1 to b_1b_3. This replicates Fig. 1 and implies that a constant budget can now produce more private transport because the increased efficiency of vehicles reduces the price of private transport. At this point, if the new budget line is moved parallel downwards until it is just tangent to the initial (unit) isoquant, we identify the cost-minimising way for the household to produce one physical unit of private transport. Here we are essentially using the budget constraint as an isocost curve. The unit cost-minimising point is m_2.

The lower panel of the diagram can also be used to show the new price of private transport. The reduction in unit cost is given by $\frac{b_2}{b_1}$.[9] But given that b_1 is calibrated initially as unity, b_2 is the new price of motoring, which is now < 1. If the demand for private transport is price elastic, as its price falls total private transport expenditure will rise; similarly if it is price inelastic, total expenditure on private transport will fall. In Fig. 2, we illustrate the case where the elasticity of substitution between private transport and all other goods and services, $\sigma_{m,a}$ is > 1 and hence motoring is price elastic.

In the lower part of the diagram, the 45 degree line through the origin simply transfers the private transport price, given by the point where the minimum unit isocost curve hits the fuel axis (here b_2) onto the vertical axis. The B curve then gives the total expenditure associated with private transport at this price. Where this expenditure figure is translated to the horizontal axis, it gives the point where the new

[8] It is important to state that we do not define an increase in fuel efficiency as m/f, as in Rausch and Schwerin (2016). We would rather refer to the inverse of this measure, f/m, as the fuel intensity of the production of private transport. As Rausch and Schwerin quite correctly argue, the energy intensity will be affected by changes in the relative prices of inputs, measured in natural units, and they attempt to standardise for this before empirically identifying the effect of efficiency improvements.

[9] This is because the price of fuel does not change and the point where the budget constraint cuts the fuel axis identifies the consumption of fuel if none of the budget were spent on vehicles.

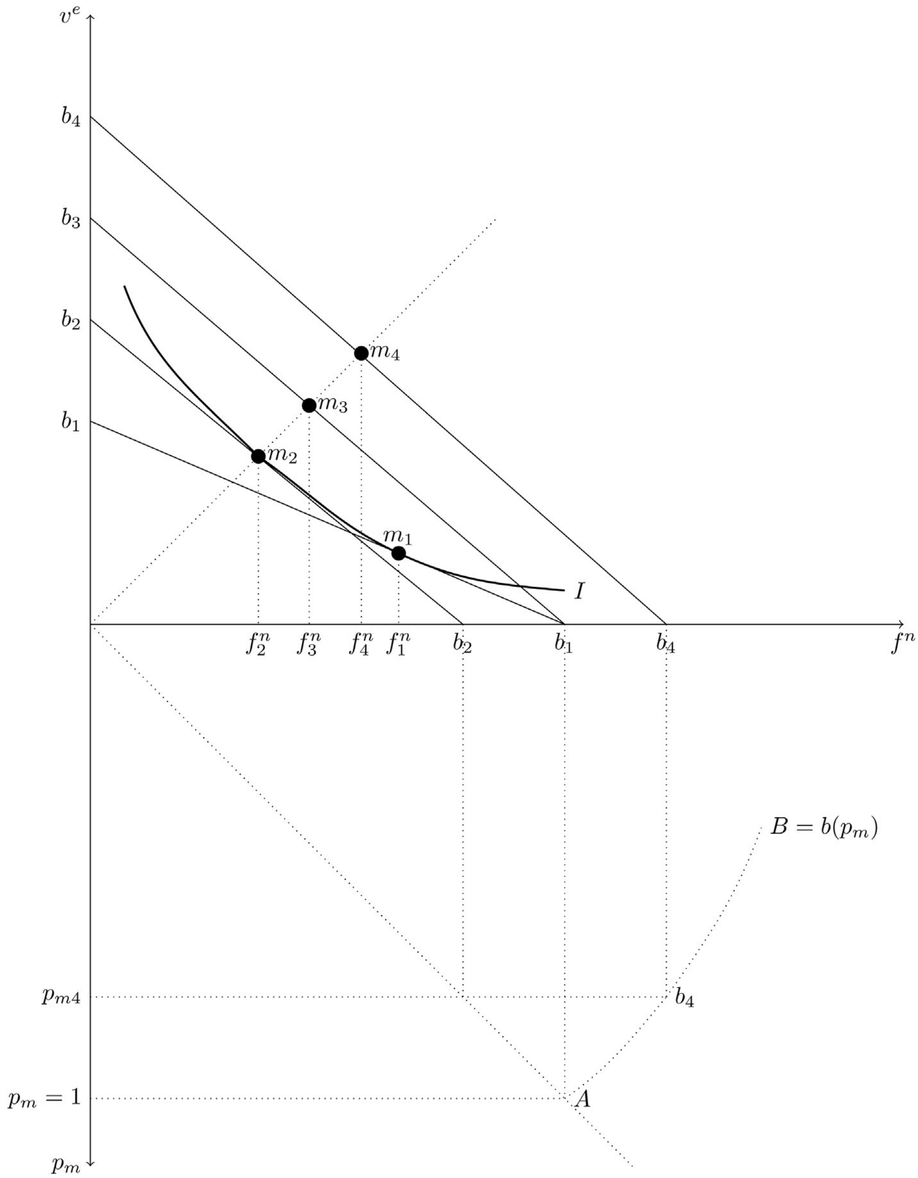

Fig. 2. Technical change in motor vehicles with non-fixed budget.

budget constraint line cuts the fuel axis. In this case we are assuming motoring consumption is elastic (> 1), so expenditure rises generating a new budget constraint, b_4b_4, parallel to b_2b_2 but further from the origin The point that maximises the private transport output is at m_4 with an input of fuel of $f_4{}^n$. If the private transport production function, as represented in Eq. (5), is linear homogeneous, m_2, m_3 and m_4 will all lie on a straight line through the origin, each having the same fuel/vehicle ratio. Also the ratios of the distances from the origin indicate the change, so that in this case output of private transport increases by $0m_4/0m_2$.

If the private transport price elasticity of demand has unitary elasticity, the *B* curve is vertical and passes through b_1 ($f^n = 1$) and also A (1,1). For unitary elasticity, the total expenditure on private transport remains constant and the new budget constraint is b_1b_3. If the demand for private transport were price inelastic, the B curve would still go through point A but would slope in the opposite direction to the curve shown in Fig. 2. Total expenditure on private transport would fall as efficiency increases.

In Fig. 2 energy use decreases from $f_1{}^n$ to $f_4{}^n$ following technical progress in vehicles. However, while in Fig. 1 the only condition for a reduction in fuel use is for the elasticity of substitution between refined fuels and vehicles to be > 1, here we need to account also for the substitutability between private transport and all other goods. It transpires that in the partial equilibrium setting, whether fuel use rises or falls in response to an increase in vehicle efficiency depends solely on the values of $\sigma_{v,f}$ and $\sigma_{m,a}$.

Holden and Swales (1993) address this issue in a more conventional industrial production setting, where output is produced with capital and labour and sold in a perfectly competitive product market. An expression is then derived for the cross price elasticity of one input with respect to a change in the price of a second input. A key result is that a reduction in the price of one input leads to an increase in the use of the second input where the price elasticity of demand for the output is greater than the elasticity of substitution between the two inputs.[10] This result translates directly to the household production of energy-intensive services in general and to private transport in particular. In a partial equilibrium setting, if $\sigma_{v,f} > \sigma_{m,a}$ then the negative substitution effect dominates the output effect, and as vehicles become more efficient, and their efficiency price falls, fuel use will also fall. On the other

[10] The primary focus in Holden and Swales (1993) is the impact on employment of a capital subsidy. The cross elasticity of substitution of fuel with respect to the price of vehicles is given as $s(\sigma_{m,a} - \sigma_{v,f})$.

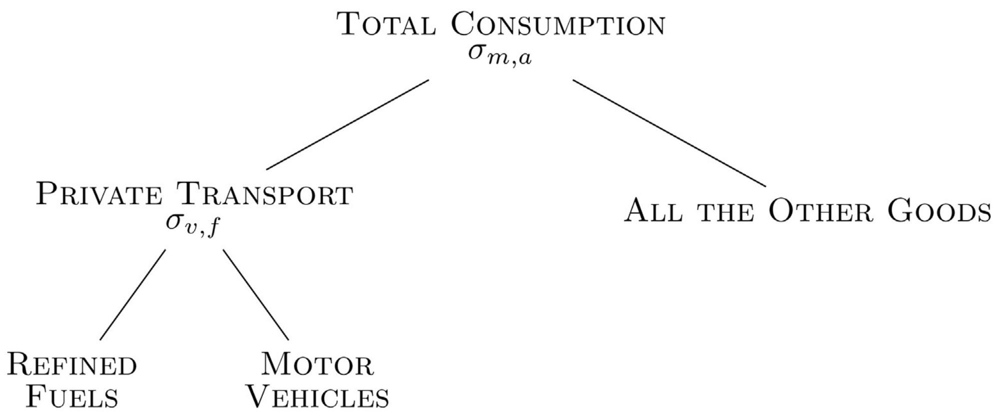

Fig. 3. The structure of consumption.

hand, if $\sigma_{v,f} < \sigma_{m,a}$, any efficiency improvements in vehicles is accompanied by an increase in fuel use. This has the implication that even if the household production of energy services has unitary elasticity of substitution, so that $\sigma_{v,f} = 1$, the fuel-use response to an increase in vehicle efficiency is ambiguous; it will rise or fall depending on whether $\sigma_{m,a}$ is greater than or less than one.

As noted, this partial equilibrium approach is based on the assumption of a fixed nominal income and unchanging market prices. In Sections 4, 5 and 6 we extend this analysis within a general equilibrium framework. This allows the assessment of the impact of three additional effects. It also allows us to track the impact on total fuel demand, which includes its use as an intermediate input in production.

First, in general equilibrium the production side of the economy is endogenous to the model, implying that nominal income and intermediate demands are is also endogenous, affecting both the consumption and total demand for fuel. Second, input prices in natural units which are exogenous in the partial equilibrium are endogenous in general equilibrium and are likely to change responding to macroeconomic factors. In the standard formulation of our CGE model, we have no prior expectation as to whether incorporating these two effect will have positive or negative impacts on the level of economic activity or prices. In fact, this will depend on the composition of the demand shifts triggered by the reduction in the efficiency price of household vehicles and by the production characteristics of the commodities whose demand is changing.

A third issue is linked to the calculation of the consumer price index (*CPI*). Gordon (2016) argues that efficiency improvements in household services, especially energy-intensive services such as domestic lighting, heating and air conditioning, are a significant source of bias in the calculation of the consumer price index. The claim is that national statisticians generally fail to account fully for these technical improvements, although there is a more concerted attempt to identify important efficiency improvements in private transport. Standard CGE simulation models also do not typically incorporate the impact of improvements in household efficiency on the *CPI*. This is because such improvements do not directly change the production technology, and therefore the price, of commodities produced by firms. And it is these prices which comprise the CPI in the standard CGE treatment, CPI^c.

However, in the present simulations we can incorporate the private transport price in an adjusted consumer price index, CPI^r. An efficiency increase in vehicles will reduce the price of private transport, which will lead to a reduction in CPI^r. It is important to note that the prices in the UK-ENVI model are measured relative to foreign prices (which are fixed in this simulation).[11] If the CPI^r falls with no change in the nominal wage, the worker's real wage, which is here measured relative to the CPI^r, increases. But this leads to disequilibrium in the labour market: the real wage has increased with no change in the underlying labour market conditions. If bargaining in the labour market occurs over the real wage, the nominal wage will fall and the quantity demanded of labour will rise until the tightening of the labour market matches the increase in the real wage. In the model the stimulus to output will be seen as an increase in exports and a reduction in import penetration and there will be an additional boost to employment as the nominal wage falls by more than the cost of capital.

4. A CGE Model: UK-ENVI

We operationalise the general equilibrium approach using UK-ENVI. This is a dynamic CGE model designed specifically for analysing the impacts of environmental policies, parameterised on a 2010 UK Social Accounting Matrix (SAM) with 30 production sectors.[12] In the following sections we outline the main features of the model, focussing particularly on the structure of household consumption.

4.1. Household Consumption

In each time period, t, (taken to be one year) a representative household makes an aggregate consumption decision, C, which is a function of income, YNG, minus savings, SAV, income taxes, $HTAX$, and direct taxes on consumption, $CTAX$, so that:

$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \tag{6}$$

Total consumption is then allocated to sectors as shown in Fig. 3.

At the top level, the representative household divides consumption between private transport and all other goods via a CES function:

$$C_t = A_C\,[\delta^C m_t^{\rho_{ma}} + (1-\delta^C) a_t^{\rho_{ma}}] \tag{7}$$

At the second level, "all other goods" is a Leontief composite, so that:

$$a_t = \min\left[\frac{c_{j,t}}{\lambda_j}\right] \tag{8}$$

In Eq. (8) c_i is the consumption of commodity j and $\lambda_j = \frac{c_{j0}}{\sum_{i \neq j} c_{i0}}$, where j applies to all sectors except fuel and vehicles. Private transport is a CES combination of refined fuel and vehicles as shown in Eq. (9):

$$m_t = A_m\,[\delta^m(\varepsilon_{v,t} v_t^n)^{\rho_{vf}} + (1-\delta^m)(f_t^n)^{\rho_{vf}}] \tag{9}$$

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 unit cost of self-

[11] Essentially foreign prices are taken as the numeraire.

[12] A full mathematical presentation of the model, together with the sectoral disaggregation, is given in Figus et al. (2017).

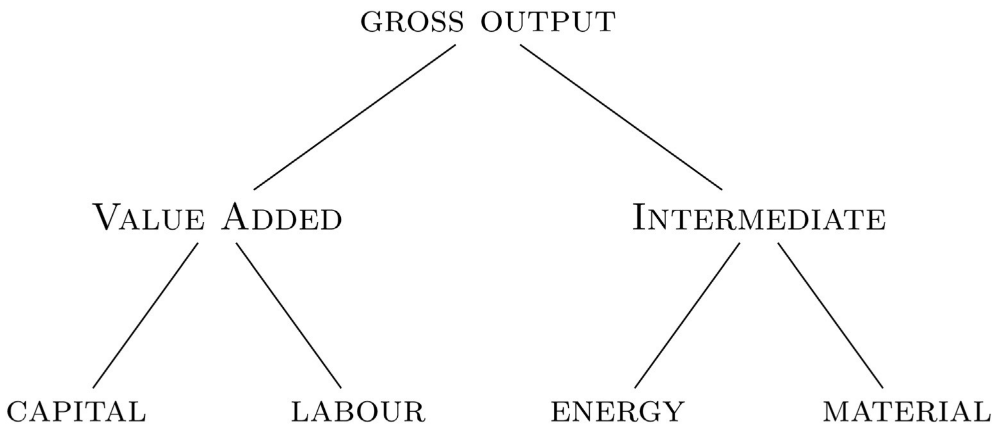

Fig. 4. The structure of production.

production. We note that vehicles are consumer durables and should be treated as household investments. For this reason we focus in this paper on long-run equilibrium results where the household stock of vehicles is at its equilibrium level. At this point the level of expenditure on vehicles just equals depreciation. 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, via an Armington link (Armington, 1969).

4.2. Production and Investment

In each sector, the production structure is as outlined in Fig. 4. 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.

For simplicity we assume that investment is determined by a myopic agent according to the following partial adjustment mechanism[13]:

$$I_{i,t} = \beta\left[K^{*}_{i,t} - K_{i.t}\right] + \phi K_{i,t} \tag{10}$$

In Eq. (10), investment is a function of the gap between the desired, $K_{i,t}*$, and actual, $K_{i,t}$, capital stock, plus depreciation which occurs at the rate,ϕ. The parameter β determines the speed at which the capital stock adjusts to its desired level (Jorgenson, 1963). Steady state equilibrium requires that the desired and actual capital stocks levels are equal, so that $K_{i,t}^{*} = K_{i.\ t}$ and therefore $I_{i,t} = \phi K_{i,t}$.

4.3. The Labour Market

The labour market determines the real wage and employment, where the real wage is defined as the nominal after tax wage, w, divided by the *CPI*. We use two alternative labour market models. In both the labour force is taken to be fixed. One reflects 'real wage resistance', which implies that the bargaining power of workers precludes any reduction in the real wage, so that:

$$\frac{w_t}{CPI_t} = \frac{w_0}{CPI_0} \tag{11}$$

Alternatively, in the wage bargaining closure, the real wage is determined according to the following wage curve:

$$\ln\left[\frac{w_t}{CPI_t}\right] = \theta - \gamma \ln(u_t) \tag{12}$$

In this equation, the bargaining power of workers, and hence the real consumption wage, is negatively related to the rate of unemployment, u (Blanchflower and Oswald, 2009). The parameter θ is calibrated to the steady state and γ is the elasticity of wage related to the level of unemployment, u, and takes the value of 0.069 (Layard et al., 1991).

4.4. Consumer Price Index

We calculate the *CPI* in two different ways. CPI^c is the conventional CPI, calculated as the sum of the prices of the domestic and foreign prices of the 30 production sectors, weighted by their initial shares in the household consumption vector. The CPI^τ, replaces the prices of vehicles and fuel by the price of private transport. Therefore:

$$CPI_t^{\tau} = CPI_t^{\tau}\left(p_{a,t}, p_{m,t}\left(p_{f,t}, p_{v,t}\right)\right) \tag{13}$$

Improvements in fuel or vehicle efficiency in the household production of private transport have no direct impact on CPI^c but will reduce CPI^τ.

4.5. The Government

We assume that the Government faces a balanced budged constraint with constant tax rates so that any variation in revenues driven by changes in economic activity is absorbed by proportionate adjustments to Government current spending on goods and services.

5. Simulation Strategy

There are two main sets of simulations reported in Sections 6. In all the simulations we introduce an exogenous 10% permanent step increase in the efficiency of the vehicle input in the household production of private transport. We report long-run equilibrium results where the conditions discussed around Eq. (10) are satisfied. We are primarily concerned with the steady-state impacts, rather than the short-term dynamics of adjustment. However, earlier test simulations suggest that the short- and long-run results are in fact very similar.

In Section 6.1 we attempt to replicate, in a general equilibrium setting, the partial equilibrium analytical results reported in Section 4. Specifically we initially hold the real wage constant, as in Eq. (11), and use the unadjusted CPI^c, so that the input prices, measured in natural units, remain unchanged. In a set of simulations, the values of $\sigma_{v,f}$ and $\sigma_{m,a}$ are systematically varied and the impact on fuel use is tracked. These simulations are designed to produce a minimal effect on aggregate variables and in fact the impact on these variables is small.

[13] UK-ENVI also has an alternative forward-looking investment closure but both the forward-looking and myopic specifications produce identical long-run equilibria (Lecca et al., 2013). We therefore adopt the more straightforward option.

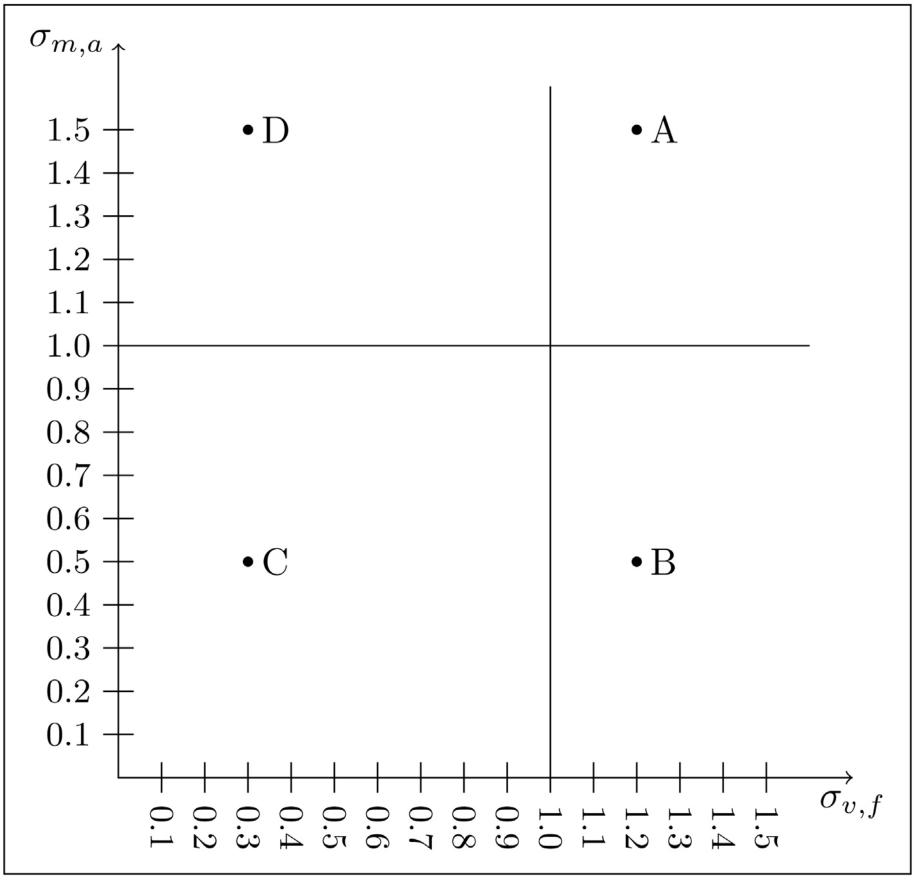

Fig. 5. Parameter values in simulation scenarios.

In Section 6.2 we quantify the cumulative effect of introducing a more appropriate adjustment to the CPI^{τ} and an active labour market closure. In these simulations we detail the results for the four combinations of $\sigma_{v,f}$ and $\sigma_{m,a}$ values shown in Fig. 5, where they are labelled A to D. For each of these key elasticities we choose two specific values, one elastic (> 1) and the other inelastic (< 1). The values for $\sigma_{v,f}$ are 1.2 and 0.3 and for $\sigma_{m,a}$ 1.5 and 0.5. We then run simulations for each of the four possible combinations. With each simulation it is therefore straightforward to show the impact of varying one, or both of the elasticities.

Note that from the partial equilibrium analysis we expect that with models A, C and D an increase in vehicle efficiency should be associated with increased fuel use. Only with the elasticities given in model B do we expect a reduction in fuel use.

In the Section 6.2 we report the simulation results from three separate scenarios. The aim is to show the effect of introducing additional macroeconomic elements whose impacts are excluded from the partial equilibrium analysis but which can be identified through the CGE simulations. In Scenario 1, we assume that the real wage is fixed and calculated using the standard CPI^{c}. That is to say, the same model specification as used to generate the results in Section 6.1. In Scenario 2 we again impose a fixed real wage, but in this case calculated using the adjusted CPI^{τ}, as defined in Eq. (13). The fall in the price of private transport caused by the increase in vehicle efficiency reduces CPI^{τ} which has knock-on effects on the nominal wage and competitiveness. In Scenario 3, we incorporate the wage bargaining function, detailed in Eq. (12), but again use the adjusted CPI^{τ} to calculate the real wage. In this case, any aggregate stimulus to the domestic economy that generates a reduction in the unemployment rate will be partly mitigated by an increase in the real wage and an accompanying reduction in competitiveness.

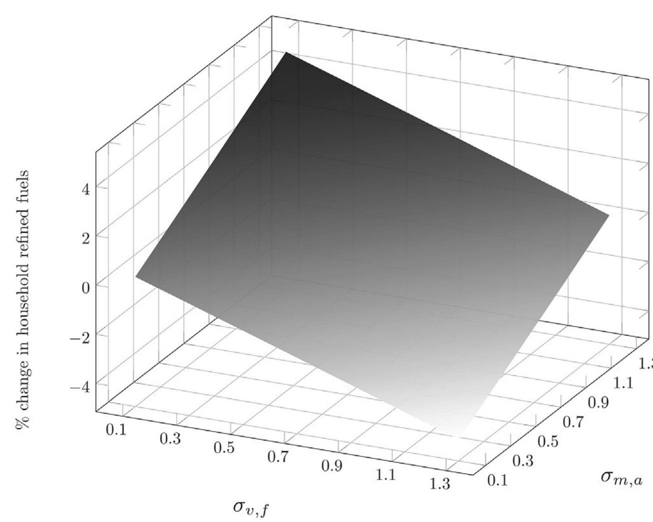

Fig. 6. Percentage change in household refined fuels use from a 10% increase in motor vehicles efficiency increase.

6. Simulation Results

6.1. Varying the Consumption Demand Elasticities with a Fixed Real Wage and Standard CPI^{c}

To investigate the sensitivity of household fuel use to changes in the consumption elasticity values in a general equilibrium context, we conduct a sensitivity exercise where we systematically vary both $\sigma_{m,a}$ and $\sigma_{v,f}$. In these simulations the elasticities take 0.2 increments

Table 1
The Impact of a 10% increase in vehicle efficiency in the production of household private transport, under various scenarios and substitution elasticity values (% change from baseline).

Scenario substitution elasticities[a]	Household fuel consumption				Total fuel use				Non-household fuel use			
	A	B	C	D	A	B	C	D	A	B	C	D
1. Efficiency improvement only	1.18	− 2.51	0.79	4.50	0.29	− 0.63	0.21	1.13	0.08	− 0.20	0.07	0.36
2. Add CPI adjustment	1.21	− 2.46	0.84	4.54	0.38	− 0.53	0.30	1.22	0.18	− 0.09	0.18	0.46
3. Add bargained real wage	1.19	− 2.50	0.80	4.52	0.32	− 0.62	0.23	1.17	0.12	− 0.19	0.10	0.40

Scenario substitution elasticities[a]	CPI[b]				Nominal wage				GDP			
	A	B	C	D	A	B	C	D	A	B	C	D
1. Efficiency improvement only	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	− 0.02	0.02	0.00	− 0.03
2. Add CPI adjustment	− 0.10	− 0.10	− 0.10	− 0.10	− 0.10	− 0.10	− 0.10	− 0.10	0.10	0.15	0.13	0.09
3. Add bargained real wage	− 0.08	− 0.07	− 0.08	− 0.08	− 0.04	− 0.01	− 0.03	− 0.05	0.02	0.04	0.03	0.02

[a] Simulation A, $\sigma_{m,a} = 1.5, \sigma_{v,f} = 1.2$; Simulation B, $\sigma_{m,a} = 0.5, \sigma_{v,f} = 1.2$; Simulation C, $\sigma_{m,a} = 0.5, \sigma_{v,f} = 0.3$; Simulation D, $\sigma_{m,a} = 1.5, \sigma_{v,f} = 0.3$.
[b] Scenario 1 uses $CPI^c$and Scenarios 2 and 3 use CPI^r.

between the values of 0.1 to 1.3 inclusive.[14] Results are represented in Fig. 6, where the percentage change in the use of refined fuels is plotted for each combination of $\sigma_{m,a}$ and $\sigma_{v,f}$. This shows that the percentage change in fuel consumption is positively related to the value of $\sigma_{m,a}$ and negatively related to the value of $\sigma_{v,f}$. In particular, within the accuracy of the elasticity values used here, where $\sigma_{m,a} > \sigma_{v,f}$ then fuel use increases with an increase in vehicle efficiency; where $\sigma_{v,f} > \sigma_{m,a}$, fuel use falls. Within this range of elasticity values the largest fall in fuel use, 4.27%, occurs where $\sigma_{v,f} = 1.3$ and $\sigma_{m,a} = 0.1$. These simulation results clearly reinforce the partial equilibrium analysis in Section 3.

6.2. The Impact of Adopting CPI^r and the Wage Curve

Table 1 gives the values of six key endogenous variables under the three macroeconomic scenarios. It reports the percentage changes in three fuel use and three aggregate economic variables, all measured as percentage deviations from their baseline values. These are household, total and total non-household fuel use, and the CPI, nominal wage and GDP. A more detailed set of results is given in Appendix A. As discussed in Section 5, there are three scenarios and four combinations of substitution parameters, so that we report results from twelve simulations in all.

The results from Scenario 1 are shown along the top lines in Table 1 panel a and b. The combinations of substitution elasticities are as shown in Fig. 5, labelled A to D, and the real wage is held constant using the conventional (CPI^c) consumer price index measure. As a result, the impact of the efficiency increase on the price of inputs does not vary across the four simulations. There is no change in the price of fuel and vehicles in natural units and the price of vehicles measured in efficiency units falls by 10%. There are differences in the change in the price of private transport, reflecting the different elasticities of substitution between vehicles and fuel, but this price variation is quite limited. Essentially, the differences between the outcomes in the individual simulations in this scenario reflect how consumers react to the same reduction in the price of vehicles, in efficiency units, and the corresponding similar – across simulations - reductions in the price of private transport.

In this scenario, the impact on household fuel consumption is very close to that given in the partial equilibrium analysis.[15] Clearly, as shown in Section 6.1, fuel use is positively related to $\sigma_{m,a}$ and negatively to $\sigma_{v,f}$. The interaction between the size of the increase in demand for private sector transport and the fuel intensity of its household production determines the overall change in the fuel use. This falls only in Simulation B, where the value of $\sigma_{v,f}$ is high (1.2) and $\sigma_{m,a}$ is low (0.5). The more detailed results in Appendix A show that the value of $\sigma_{m,a}$ controls the size and composition of the changes in demand for private transport and all other goods, whilst the value of $\sigma_{v,f}$ determines the changes in vehicle and fuel intensity of the household production of private transport.

In the model used in Scenario 1 the macro-economic impact is similar to that which would be generated by a change in tastes that affects the composition of household consumption. If the change in vehicle efficiency leads to the household consumption vector having a higher direct, indirect and induced domestic content, then economic activity will rise: if the change in consumption choice leads to a reduction in domestic content, aggregate economic activity will fall.[16] There is no additional accompanying supply-side shock.

In the simulations A and D, the consumption of all other goods falls and the consumption of fuel rises. Both simulations exhibit a small decline in GDP, together with employment, investment, household income and aggregate household consumption. On the other hand, in simulation B, where the consumption of all goods increases and the consumption of fuel falls, all indicators of aggregate economic activity rise. In simulation C the consumption of both all other goods and fuel increases and this produces a neutral impact on economic activity.[17] These results are consistent with the intuitive notion that fuel has a relatively low, and all other goods a relatively high, domestic content. Outcomes which shift consumption towards the former and away from the latter have a stimulating impact on aggregate economic activity, though this is very small. Note that in this scenario there is no conflict between energy reduction and economic expansion: in these simulations, where fuel use falls, output increases.

Table 1 indicates that any variation in household fuel consumption is accompanied by a change of between a third and a half in non-household fuel use. For example, in simulation B the 2.51% reduction in household fuel consumption also generates a 0.20% fall in non-household fuel use, so that total fuel use falls by 0.63%.[18] The fact that household and non-household fuel use move in the same direction suggests that this result is driven by the high fuel intensity of fuel production itself.

[14] We do not use values of 1 for either$\sigma_{v,f}$ or $\sigma_{m,a}$ in the simulations because we employ a CES function which is not defined for unitary elasticity values. However, we do use values at either side of unity.

[15] The actual partial equilibrium proportionate changes in household consumption for simulation elasticities given in simulations A to D are 1.17%, − 2.73%, 0.78% and 4.68% respectively.

[16] The CGE model here operates as an extended SAM multiplier model. The adjustment to the consumption vector changes the SAM multiplier values used to calculate the domestic impact of the exogenous export expenditure (Round, 2003).

[17] In this simulation the only aggregate variable that shows any change is investment which increases by 0.01%.

[18] The share of household fuel use in total fuel use is 18.39%.

The results from Scenario 2 are shown on the second rows of Tables 1, panel a and b. In this scenario we use the adjusted consumer price index, CPI^r, in which the fuel and vehicle prices are replaced by the price of private transport. This adjusted price index is then used to calculate the adjusted nominal wage corresponding to the fixed real wage, as explained in Section 4.4. The private transport price reduction directly triggers a drop in the CPI^r. Maintaining the real wage leads to a reduction in the nominal wage - that is the wage relative to foreign prices – equal to the fall in the CPI^r and this further reduces commodity prices. Across all the simulations the CPI^r decreases by 0.10%.

This has three primary impacts. First, the reduction in product prices, triggered by the fall in the cost of labour, generates competitiveness-driven expansionary effects. This is reflected in an increase in export demand, which rises in the long run by 0.09% in all the simulations in Scenario 2. Second, the lower nominal wage leads producers to substitute labour for capital in production and reduce the relative price of labour intensive commodities. This results in higher employment and in a corresponding reduction in unemployment. Third, household nominal income increases as employment rises, stimulated by the substitution and output effects already identified, so that household total consumption increases.

In all the simulations covered by Scenario 2, GDP is higher, by 0.12 or 0.13 percentage points, than the comparable figure for Scenario 1. This means that there is a positive increase in GDP for all the simulations of between 0.09% and 0.15%. Further, the adjustment to the consumer price index increases the consumption of particular commodities, as compared to the results for Scenario 1; the consumption of vehicles, fuel and all other goods are between 0.03% and 0.07% higher. This leads to an increase in total fuel use of around 0.10 percentage points across all simulations, as compared to Scenario 1. However, these changes are relatively small so as not to affect the qualitative fuel-use results.

In Scenario 2 the economic stimulus from the increased competitiveness delivers a boost to GDP and all the other measures of aggregate economic activity. In Scenario 3 we further add a bargained real wage, determined by the wage curve as specified in Eq. (12). The central point is that in this case, if employment increases with a fixed labour force the accompanying fall in the unemployment rate drives an increase in the real wage. In the simulations in Scenario 3 this increase in the real wage reduces some of the impact of the efficiency improvement on competitiveness.

The results for Scenario 3 are shown in the last rows of Tables 1, panel a and b. Note first that the long-run adjusted real wage now increases for all the simulations as employment rises; the nominal wage falls by less than the adjusted consumer price index. Whilst in Scenario 2 the nominal wage across all simulations falls by 0.10%, this reduction now lies between 0.05% and 0.01%, which limits the fall in product prices as reflected in the CPI^r. Also, in the fixed real wage Scenario 2, exports increased by 0.09% across all simulations whilst in Scenario 3, the long-run stimulus to exports is now much lower, between 0.01% and 0.04%. Whilst all simulations in Scenario 3 register increases in GDP and the other indicators of aggregate economic activity, these are smaller than the corresponding figures in Scenario 2. The long-run Scenario 3 values for all the fuel use variables lie between the Scenario 1 and Scenario 2 figures.

7. Discussion and Conclusions

The simulations results show the impact of modelling private transport as an energy-intensive self-produced household service. Investigating variation across the simulations produces an increased understanding of the relationship between the inputs in the production of this service. Specifically, when considering improvements in the efficiency in the production of private transport, a vehicle-augmenting technical improvement can lead to a reduction in fuel consumption, depending upon the values of key substitution elasticities.

Any reduction here in the fuel-intensity of private transport, and the possible lower household and total use of refined fuels in aggregate, is not brought about by an exogenous improvement in fuel efficiency. Rather it is driven by an endogenous reaction to an improvement in the efficiency of a closely-linked good, either as a substitute or complement, in this case vehicles. This shows the importance of modelling energy-intensive household services in general, and private transport in particular, as the output of a number of inputs. Moreover, in determining the overall impact of technical progress in vehicles on the demand for fuel, it is fundamental to take into account changes in the quantity demanded of private transport. Such changes in the demand for the energy-intensive service generate an additional increase or reduction in the derived demand for the input goods. Whilst there are general equilibrium effects on household fuel consumption, these are dominated by the impacts identified in partial equilibrium. Using general equilibrium simulation to incorporate endogenous variation in intermediate fuel use suggests that these reinforce changes in household fuel consumption.

When the CPI^c is calculated using the conventional method and the real wages are held constant, the macroeconomic impact of the technical improvement simply reflects the switching of demand between different commodities within the household budget. Commodities, which have, directly or indirectly, more domestic content will have a larger impact on GDP. In the present case, this switching depends on the degree of substitution between private transport and the composite commodity “all other goods”, and between fuel and vehicles in the production of private transport. When, as a result of the efficiency change, the consumer reduces expenditure on the consumption of all other goods competing with private transport, and increases the consumption of fuel, GDP falls. However, we need to recognise that the structure of consumption adopted here is extremely rudimentary. In practice the demand impact will depend heavily on changes in demand for other commodities that are close substitutes and complements to private transport. For example, we would expect consumers to substitute between public and private transport.

When the adjusted CPI^r is used, the price of private transport, which is normally unobserved, is incorporated into the calculation of the real wage. With a fixed real wage, we then report an increase in competitiveness and a productivity-led economic stimulus. This arises because the nominal wage falls, lowering domestic prices, stimulating the demand for exports, and reducing the demand for imports. It also leads to some substitution of labour for capital. When workers are able to bargain, the real wage will rise as the unemployment rate falls, limiting the reduction in the CPI^r, the nominal wage and the subsequent increase in economic activity.

This work provides a more sophisticated treatment of private transport demand, as a household self-produced energy-intensive service. Although we use the example of private transport, our framework can be applied to other energy-intensive services such as home heating. Other extensions include recognising that the adoption of new technological vintages, such as in vehicles, require investment. The accumulation of the new stock of vehicles should be modelled as a formal investment process similar to the way in which investment is modelled in the production side of the economy. However, whilst this will influence the time path of the introduction of the more efficient technology, it does not affect the long-run analysis applied here. Finally, in the specific case of motor vehicles, fuel saving from efficiency improvement has often been offset by the increase in size and weight of vehicles. A more nuanced way of modelling private transport services should therefore employ a framework which incorporates variations in other inputs and vehicle characteristics and their impact on fuel intensity and use.

Acknowledgements

Turner and Swales acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC grant ref. EP/M00760X/1). Figus acknowledges the support of ClimateXChange, the Scottish Government-funded Centre for Expertise in Climate Change (noting that the opinions in the paper are the sole responsibility of the authors, and not necessarily those of the ClimateXChange or the Scottish Government), and the UK Economic and Social Research

Council (ESRC) via the Scottish Graduate School in Social Science Doctoral Training Centre, Environment, Climate Change and Energy Pathway studentship programme (award ref. 1562665). The authors are very grateful to two anonymous referees for their extensive comments on an earlier version of this paper. This study uses existing data that are publically available from the Fraser of Allander Institute website https://www.strath.ac.uk/media/1newwebsite/departmentsubject/economics/fraser/UK_SAM_2010_FAI.XLSX. No new data were created during this study.

Appendix A. Additional table results

Table A.1
Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption (Scenario 1).

	A	B	C	D
Elasticities				
$\sigma_{m,a}$	1.5	0.5	0.5	1.5
$\sigma_{v,f}$	1.2	1.2	0.3	0.3
Prices				
Price of fuel	0.00	0.00	0.00	0.00
Price of vehicles	0.00	0.00	0.00	0.00
Price of vehicles eff units	− 10.00	− 10.00	− 10.00	− 10.00
Price of transport	− 3.67	− 3.67	− 3.58	− 3.58
Household consumption				
Fuels	1.18	− 2.51	0.79	4.50
Motor vehicles	3.12	− 0.64	− 5.71	− 2.24
Private transport	5.82	1.97	1.90	5.65
All other goods	− 0.05	0.04	0.03	− 0.06
Vehicles intensity transport	1.16	1.16	− 4.04	− 4.03
Fuels intensity in transport	− 0.75	− 0.74	2.58	2.58
Fuel use				
Total fuel use	0.29	− 0.63	0.21	1.13
Non-household fuel use	0.08	− 0.20	0.07	0.36
Macroeconomic effects				
GDP	− 0.02	0.02	0.00	− 0.03
CPI	0.00	0.00	0.00	0.00
Nominal wage	0.00	0.00	0.00	0.00
Real wage	–	–	–	–
Employment	− 0.02	0.02	0.00	− 0.04
Unemployment rate	0.29	− 0.27	0.04	0.60
Investment	− 0.02	0.01	0.01	− 0.03
Household consumption	− 0.02	0.01	0.00	− 0.03
Household income	− 0.01	0.01	0.00	− 0.02
Exports	0.00	0.00	0.00	0.00

Table A.2
Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption with adjusted CPI (Scenario 2).

	A	B	C	D
Elasticities				
$\sigma_{m,a}$	1.5	0.5	0.5	1.5
$\sigma_{v,f}$	1.2	1.2	0.3	0.3
Prices				
Price of fuel	− 0.03	− 0.03	− 0.03	− 0.03
Price of vehicles	− 0.04	− 0.04	− 0.04	− 0.04
Price of vehicles eff units	− 10.04	− 10.04	− 10.04	− 10.04
Price of transport	− 3.71	− 3.71	− 3.61	− 3.61
Household consumption				
Fuels	1.21	− 2.46	0.84	4.54
Motor vehicles	3.17	− 0.57	− 5.66	− 2.20
Private transport	5.87	2.02	1.95	5.69
All other goods	0.01	0.10	0.09	− 0.01
Vehicles intensity transport	1.17	1.17	− 4.03	− 4.03

Fuels intensity in transport	− 0.75	− 0.75	2.58	2.58
Fuel use				
Total fuel use	0.38	− 0.53	0.30	1.22
Non-household fuel use	0.18	− 0.09	0.18	0.46
Macroeconomic effects				
GDP	0.10	0.15	0.13	0.09
CPI^{r}	− 0.10	− 0.10	− 0.10	− 0.10
Nominal wage	− 0.10	− 0.10	− 0.10	− 0.10
Real wage	− 0.05	− 0.06	− 0.06	− 0.05
Real wage (CPI^{r} deflated)	Eps	Eps	Eps	Eps
Employment	0.11	0.16	0.13	0.09
Unemployment rate	− 1.80	− 2.48	− 2.11	− 1.42
Investment	0.09	0.13	0.12	0.08
Household consumption	0.04	0.07	0.06	0.03
Household income (CPI^{r} deflated)	0.10	0.13	0.11	0.08
Exports	0.09	0.09	0.09	0.09

Table A.3
Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption with adjusted CPI and wage curve (Scenario 3).

	A	B	C	D
Elasticities				
$\sigma_{m,a}$	1.5	0.5	0.5	1.5
$\sigma_{v,f}$	1.2	1.2	0.3	0.3
Prices				
Price of fuel	− 0.01	− 0.01	− 0.01	− 0.01
Price of vehicles	− 0.01	− 0.01	− 0.01	− 0.02
Price of vehicles eff units	− 10.01	− 10.00	− 10.01	− 10.02
Price of transport	− 3.68	− 3.68	− 3.59	− 3.59
Household consumption				
Fuels	1.19	− 2.50	0.80	4.52
Motor vehicles	3.14	− 0.63	− 5.70	− 2.22
Private transport	5.84	1.98	1.91	5.67
All other goods	− 0.03	0.05	0.04	− 0.04
Vehicles intensity transport	1.17	1.16	− 4.03	− 4.03
Fuels intensity in transport	− 0.75	− 0.75	2.58	2.58
Fuel use				
Total fuel use	0.32	− 0.62	0.23	1.17
Non-household fuel use	0.12	− 0.19	0.10	0.40
Macroeconomic effects				
GDP	0.02	0.04	0.03	0.02
CPI^{r}	− 0.08	− 0.07	− 0.08	− 0.08
Nominal wage	− 0.04	− 0.01	− 0.03	− 0.05
Real wage	0.04	0.06	0.05	0.03
Real wage (CPI^{r} deflated)	0.04	0.06	0.05	0.03
Employment	0.03	0.04	0.03	0.02
Unemployment rate	− 0.43	− 0.60	− 0.51	− 0.34
Investment	0.02	0.03	0.03	0.02
Household consumption	0.00	0.02	0.01	0.00
Household income (CPI^{r} deflated)	0.07	0.09	0.08	0.06
Exports	0.03	0.01	0.02	0.04

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