Can a reduction in fuel use result from an endogenous technical progress in motor vehicles? A partial and general equilibrium analysis.

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Abstract

In this paper we employ a partial equilibrium approach to model private transport consumption as a household self-produced commodity formed by vehicle and fuel use. We show that under certain conditions vehicle-augmenting technical improvements can reduce fuel use. We then extend the analysis through Computable General Equilibrium simulations for the UK in order to investigate the wider implications of vehicle-augmenting efficiency improvements when prices and nominal income are endogenous. With a conventional macroeconomic approach, improvements in the efficiency of household consumption simply change the composition of household demand. However, when we adjust the consumer price index for changes in the price of private transport service (not observable via a market price), as advocated in Gordon (2016) there is an additional supply-side stimulus to competitiveness.

1. Introduction

Technical progress in household consumer services may be major but underestimated element in the improvement in the standard of living (e.g. see Gordon 2016 for the US). Becker (1965) identifies services that may be thought of as self-produced and consumed directly by households (Becker, 1965). Following Gillingham et al. (2016), we apply this conceptual approach to the provision of household energy-intensive services, which may include domestic space heating and light, but operationalise using the specific example of private transport, produced using refined fuel and motor vehicles. We are particularly interested in the way in which improvements in the efficiency of vehicles and fuel affect the implicit price and quantity consumed of private transport and the subsequent derived demand for fuel and vehicles. In particular, we wish to investigate the way in which an increase in the efficiency of vehicles affects the consumption of fuel. This is highly relevant in the context of policy initiatives to reduce carbon emissions whilst maintaining economic growth.

In economics, the standard definition of an energy efficiency improvement is an intervention whereby the same level of output can be obtained using less physical energy, holding all the other inputs constant. However, the introduction of an energy efficiency improvement does not imply that the output or the use of other inputs will remain constant. For example, an improvement in fuel efficiency would imply that the same level of private transport could be provided with a given vehicle and less fuel, but it also means that the price of fuel, in efficiency units, falls. Given that it is generally possible to substitute between inputs in the production of services, improving energy efficiency typically leads to lower energy savings than expected via a rebound effect; in extreme cases, an increase in the use of energy (or backfire) can result (Khazzoom, 1980; 1987; Saunders 2000). In this paper we investigate whether substitution possibilities imply that fuel savings can be obtained in the provision of private transport as a result of technical improvements in vehicles. That is, we focus on the question of whether a reduction in energy use could result as an endogenous response to efficiency improvements in the other inputs.

Our analysis initially uses a partial equilibrium model. A simple relationship is adopted between vehicle and fuel use in the production of private transport, and between private transport and all other goods in the determination of the household consumption vector. We hold household income and the prices of all inputs and other consumption goods constant. The approach is then extended through simulation using a Computable General Equilibrium (CGE) model, parameterised on UK data. This framework allows the incorporation of endogenous changes in nominal income, market prices and supply responses. Efficiency improvements in household consumption affects the implicit price of the corresponding household service. However, these prices are not normally used in the standard calculation of the consumer price index (*cpi*), leading to potential underestimations of the economy-wide impact of household efficiency improvements (Gordon, 2016). In a final set of simulations, we recalculate the *cpi* using the endogenous price changes for private transport services. This reduction in the *cpi* has implications for the determination of the real wage and produces additional positive competitiveness effects.

The remainder of the paper is organised as follows. Section 2 reviews the current literature on energy efficiency in the context of modelling the household consumption of energy-intensive services. Section 3 outlines the partial equilibrium analysis. Section 4 describes the CGE model and Section 5 the various simulation set ups. The simulation results are reported in Section 6 and further discussed in Section 7. Section 8 is a short conclusion.

2. Background

Many studies have analysed the impact of energy-saving technical improvements in consumption in order to assess the potential net impact on final energy use (see, for example, Chitnis et al., 2014; Chitnis and Sorrell, 2015; Duarteet al., 2015; Druckman et al., 2011; Frondel et al., 2008; Frondel et al. 2012; Lecca et al., 2014; Schwarz and Taylor, 1995; West, 2004). A common characteristic of this literature is that physical energy is modelled as if it were consumed directly. Increased energy efficiency is normally found to reduce final energy use but with some rebound effect. The size of this rebound varies across the studies, partly depending on the modelling approach. Some of this work relates energy efficiency improvements to the capital costs associated with the increase in efficiency (Chitnis et al. 2015; Mizobuchi, 2008; Sorrell, 2008). However, in making the rebound calculation none explores the relationship between the physical energy and the capital appliances used in the production of the energy-intensive consumer services.

Three papers specifically attempt to model energy-intensive consumer services as composite goods combining physical energy and technology. Walker and Wirl (1993) model the demand for private transport as a service obtained by a combination of fuels and technology. This technology converts fuel use into miles travelled. In this approach, where the consumer allocates all her budget to private transport services, the marginal utility of consumption is given by price of the energy-intensive service. This price is calculated as the price of fuel divided by the efficiency of vehicles. If this efficiency increases, the price of the energy-intensive service decreases, stimulating a rise in the quantity demanded. Haas et al. (2008) adopt the same method but focus on residential energy use. They find that technical progress has the effect of reducing the price of residential energy services, leading to significant increases in the demand for these services and the derived demand for physical energy, producing a direct rebound effect.

Hunt and Ryan (2015) extend Walker and Wirl (1993), developing a model of household consumption that separately identifies several energy-intensive services (heating, lighting, motoring, etc.), each formed as a combination of physical energy and technology. These services, together with all other consumption goods, are elements of total household expenditure. Hunt and Ryan (2015) assert that models that do not consider consumer energy demand in the context of providing a service are misspecified and likely to produce biased estimation of key behavioural parameters, such as the price and income elasticities of energy demand. They demonstrate this point by using UK data to econometrically estimate two models. The first includes energy on the same footing as any other good or service. The second is augmented with technology that converts energy into energy services. The results show that the income and price elasticities of energy demand are quite different in the two models. In particular, when technology is introduced, its coefficient is statistically significant, indicating that the augmented specification is preferred.

In an attempt to consolidate this literature, Gillingham et al. (2016) argue 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 implies that the price of the energy service would depend on both the price of energy and the price of the product that deliver the service. Although they do not discuss specifically how to model such energy intensive services, and are mostly interested in the implications of energy efficiency for the calculation of the rebound effect, Gillingham et al. (2016) offer an interesting starting point. In this paper we operationalise this approach, starting using a partial equilibrium analysis and them moving to a Computable General Equilibrium approach.

3. Modelling household production of motoring services

3.1 The basic model

Initially, suppose that a consumer allocates a given nominal budget to private transport and that market prices are fixed, so that the analysis takes a partial equilibrium form. The output of the energy-intensive private transport service is given by miles travelled, *m,* which is produced by households through a combination of motor vehicles, v^e, and refined fuel (petrol and diesel),f^e. It is convenient to express these inputs in terms of efficiency units, indicated by the e superscript. However, it should be noted that in the present analysis, the efficiency of fuels often does not change, so that for the fuel input, efficiency and natural inputs are typically identical. The household production function for private transport is therefore given as:

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

The consumer will choose the combination of vehicles and fuel that maximises the amount of miles travelled, *m*, given her budget constraint.

Suppose that the production of private transport becomes more efficient due to technical progress.[1] To investigate the implications we employ a graphical analysis in which motor vehicles and refined fuels are represented in efficiency units. We specify the relation between natural and efficiency units in the household utility maximisation problem as follows:

$$\begin{aligned}
&\max\ m = m(v^e, f^e) \\
&subject\ to \\
&p_f^n f^n + p_v^n v^n - y \geq 0 \\
&where \\
&z^e = \varepsilon^z z^n \text{ and} \\
&p_z^e = \frac{p_z^n}{\varepsilon_z} \text{ for } z = (f, v)
\end{aligned} \tag{2}$$

In equation (2) *p* indicates a price, *ε* is an efficiency parameter, *e* is a superscript for efficiency units and *n* for natural units. From maximisation we have that:

$$\begin{aligned}
&\frac{\partial m}{\partial z^n} = p_z^n = \frac{\partial m}{\partial z^e}\varepsilon_z \\
&\frac{\partial m}{\partial z^e} = p_z^e = \frac{p_z^n}{\varepsilon_z}
\end{aligned} \tag{3}$$

[1] There are three primary benchmark cases: a) motor vehicles and fuels become equally more efficient; b) only motor vehicles become more efficient; c) fuels become more efficient. However, hybrid cases are also possible where both inputs become more efficiency but at different rates.

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.

Let us consider the case where only one input becomes more efficient, specifically motor vehicles. This represents vehicle-augmenting technical progress.[2] In this case the technical improvement decreases the price of vehicles in efficiency units, while the price of fuel is unchanged. The impact of the reduction in the price of vehicles on the consumption of fuel depends on the elasticity of substitution between the two inputs:

$$\sigma_{v,f} = \frac{-\partial(f^e/v^e)(MRS_{f^e,v^e})}{\partial(MRS_{f^e,v^e})(f^e/v^e)} \qquad (4)$$

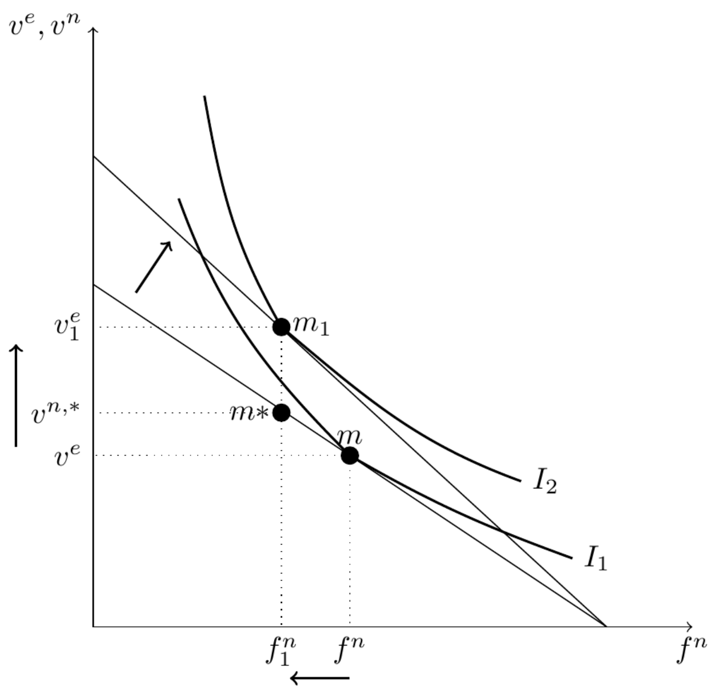
where MRS is the marginal rate of substitution between vehicles and fuel, and relates to the slope of the isoquant.[3] When $\sigma_{v,f}$ is greater than 1, the two goods are competitors. This implies that a reduction in the price of vehicles, in efficiency units, leads to a reduction in expenditure on fuel and therefore fuel use, as the consumer substitutes heavily towards vehicles. On the other hand, when $\sigma_{v,f}$ is less than 1 the two inputs are complements.[4] Here, with a fixed nominal budget and fixed natural input prices, as the efficiency price of vehicles falls, the corresponding increase in consumption of vehicles is insufficient for expenditure on vehicles to increase. Thus, following the increase in vehicle efficiency the expenditure on fuel will rise and the use of both inputs – vehicles measured in efficiency units and fuel in natural units - will rise. For these reasons, the effectiveness of the technical change in reducing fuel use per unit of output is determined endogenously and depends on the substitutability between the two inputs.

[2] The fuel augmenting technical change case would be identical but opposite to the vehicle augmenting case.
[3] The fixed elasticity of substitution measures the proportionate, not absolute, changes in each input required to maintain a constant output.
[4] An elasticity of substitution of zero implies that the two goods are perfect complements. This is where the inputs have to be used in fixed proportions and is the Leontief production technology case.

In Figure 1 we show the case where vehicles and fuel are competitive and vehicle efficiency increases. We parametrise the model so that the initial quantity of fuels, vehicles and motoring are all equal to one, so that in absence of efficiency changes, natural and efficiency units are equal. The vertical axis represents vehicles in natural and efficiency units, while the horizontal axis represents fuels in natural units (fuel efficiency does not change in this analysis).

Initially the consumer is at point *m* on the isoquant I_1. The technical improvement in motor vehicles 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.[5] If we project m_1 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 $v^{n,*}$ inputs, both measured in natural units.

Figure 1. Technical progress in motor vehicles



[5] For convenience, because the efficiency of fuel does not change we measure the use of fuel in natural units.

The vehicle-saving technical change will always reduce fuel use per unit of output but not necessarily per £1 spent on motoring. In Figure 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

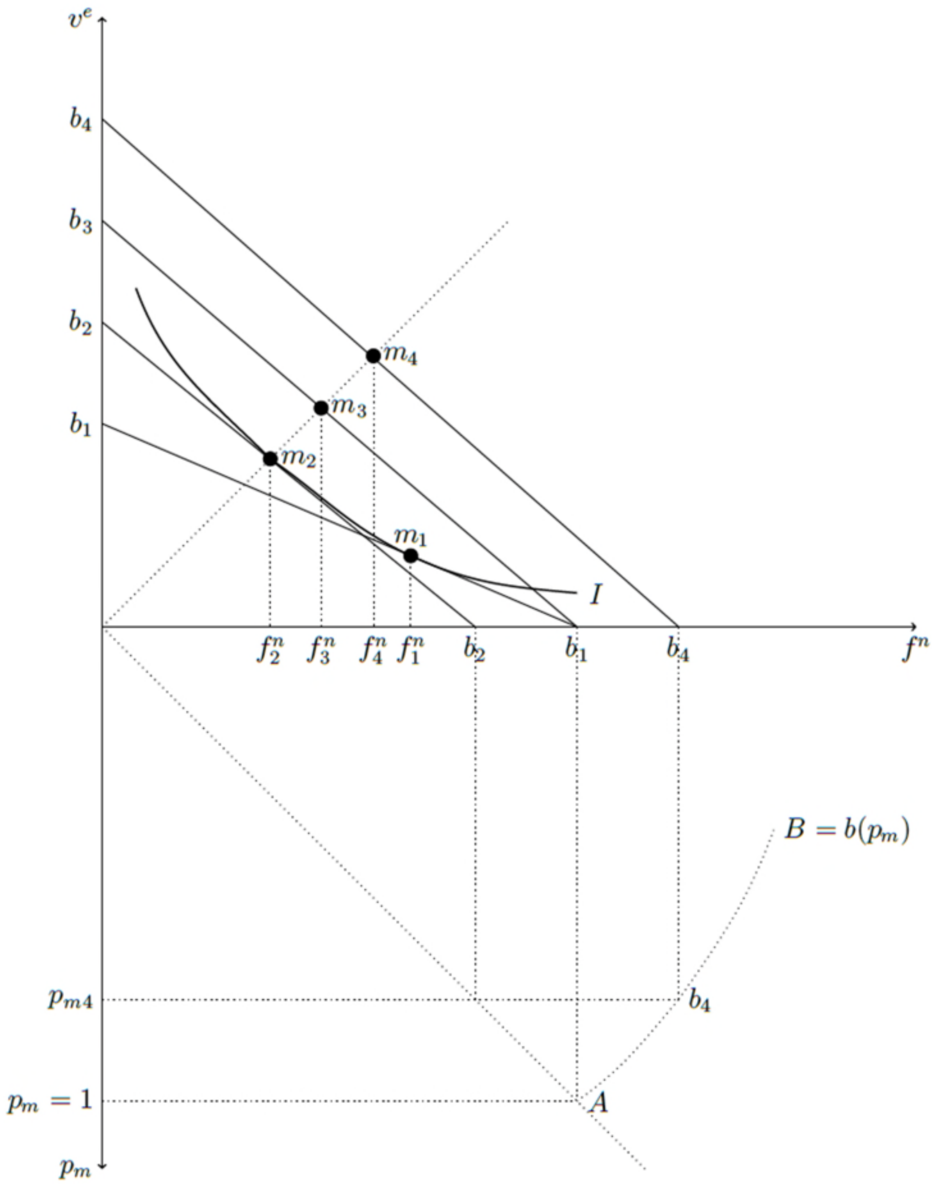
So far we have assumed that the consumer has a nominal fixed budget to be spent on private transport. However, consumers allocate their income on a number of different goods and services, only one of which is private transport. Consider now a household allocating its total household budget between private 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:

$$c = c(a, m(v^e, f^e)) \tag{5}$$

In this case, the consumption of fuel depends partly on the degree of substitution between private transport and all the other goods, $\sigma_{m,a}$. Figure 2 presents a graphical analysis similar to that shown in Figure 1. The diagram has two panels. The top panel has vehicles in efficiency units on the vertical axis and refined fuel on the horizontal axis, in natural units. In the bottom panel the price of motoring p_m is on the downward-pointing vertical axis.

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 m_1 private transport using f_1^n fuel and some quantity of motor 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 Figure 1 and implies that a constant budged 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.

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



The lower panel of the diagram can also be used to show the new price of private transport. This is given by point b_2 as measured along the fuel axis. Because b_1 is calibrated initially as unity, b_2 is the new price of motoring, which is now less than 1. If the demand for private transport is price elastic, as its price falls total private transport expenditure will rise. Similarly if private transport is price inelastic, with the price reduction total expenditure on private transport will fall. In Figure 2, we illustrate the case where the elasticity of substitution between private transport and all other goods and services $(\sigma_{m,a})$ is greater than 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 budget constraint line cuts the fuel axis. In this case we are assuming motoring consumption is elastic, so expenditure rises (>1). The new budget constraint is b_4b_4, parallel to b_2b_2. The point that maximises the private transport output is at m_4 with an input of fuels of f_4^n. If the private transport production function, as represented in equation (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 distance from the origin indicates the change, so that in this case output 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 Figure 2. Total expenditure on private transport would fall as efficiency increases.

In Figure 2 energy use decreases from f_1^n to f_4^n following technical progress in vehicles. However, while in Figure 1 the only condition for a reduction in fuel use is for the elasticity of substitution between refined fuels and vehicles to be greater than 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 the $\sigma_{v,r}$ and $\sigma_{m,a}$.

From what we already know, we can deduce ranges of values where we can unambiguously sign the change in fuel use. When $\sigma_{v,f} > 1$ and $\sigma_{m,a} < 1$, both expenditure on private transport and the share of fuel in private transport expenditure fall. There is therefore a clear reduction in fuel consumption in this case. Using an analogous argument, if $\sigma_{v,f} < 1$, and $\sigma_{m,a} > 1$ fuel use unambiguously increase. However, when the two elasticities of substitution are both positive, a reduction in fuel use will occur only if the increase in motoring expenditure is not sufficiently large to offset the reduction in the share of fuel in private transport expenditure. Similarly, where both elasticities are negative, fuel consumption will fall only if the reduction in expenditure on private transport is sufficiently large to offset a rise in fuel expenditure as a share of total expenditure on private transport.

Holden and Swales (1993) undertakes partial equilibrium analysis in a more conventional industrial production setting where output is produced with capital and labour and sold in a perfectly competitive product market. The paper derives an expression for the cross price elasticity of one input with respect to a change in the price of a second input.[6] 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. 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 $\sigma_{v,f} > \sigma_{m,a}$, the negative substitution effect dominates

[6] Holden and Swales (2013) analyse what happens to capital use, when a subsidy on labour is introduced.

the output effect, and as vehicles become more efficient, and their efficiency price falls, fuel use will also fall. On the other hand, if $\sigma_{v,f} < \sigma_{m,a}$, fuel use increases accompany any efficiency improvements in vehicles.

As noted, this partial equilibrium approach is based on the assumption of a fixed nominal income and market prices. Below we extend this analysis in a general equilibrium framework. This allows the assessment of the impact of three additional effects. First, in general equilibrium the production side of the economy is endogenous to the model, implying that nominal income is also endogenous. Any change in nominal income further affects consumption decisions. Second, prices in natural units are exogenous in the partial equilibrium approach above. In general equilibrium these are endogenous 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 motor vehicles and by the production characteristics of the commodities whose demand is changing.

A third issue is linked to the calculation of the *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. This, in turn, has led to an underestimation of the US growth of real GDP in the past. However, in the US figures, private transport has been treated as a special case and improvements in both fuel and vehicle efficiency have been incorporated in the calculation of the *cpi* and therefore also the growth of GDP. Standard CGE models would typically fail to account for the impact on the *cpi* of improvements in household efficiency. However, in the present simulations we can include the private transport price in an adjusted calculation of the consumer price index. We label this adjusted index cpi_τ . An efficiency increase in vehicles will reduce the price of private transport, whose impact on the cpi_τ will reduce the nominal wage for any given real wage. This will increase competitiveness with accompanying positive impacts on the economy.

4. A computable general equilibrium modelling application

We incorporate the conceptual framework developed in Section 3 in an analysis using the UK-ENVI Computable General Equilibrium (CGE) model. UK-ENVI is a dynamic CGE model designed for the analysing disturbances in the energy sector of the UK economy. It is used here to assess the impact of an illustrative 10% efficiency increase in the vehicle input in the household production of private transport. In this version, the model is calibrated on a 2010 Social Accounting Matrix (SAM) reporting transactions between 30 productive sectors[7], UK households, government, corporate sectors and the rest of the world (imports and exports). In the following sections we outline the main features of the model, focussing particularly on the structure of household consumption.

4.1 Consumption

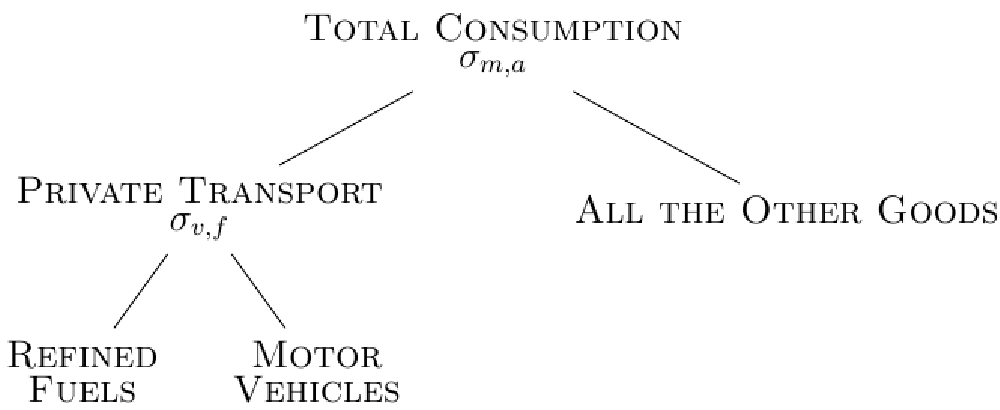
In UK-ENVI, in each time period, a representative household makes an aggregate consumption decision, C, determined by its disposable income, so that:

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

In (6), total consumption is a function of income, YNG, savings, SAV, income taxes, HTAX, and direct taxes on consumption, CTAX, and t indicates the time period, which is considered to be one year. Total consumption is allocated to sectors through the structure described in Section 3.1. This is a nested constant elasticity of substitution (CES) function, illustrated in Figure 3.

[7] The full list of sectors is reported in Appendix A.

Figure 3. The structure of consumption



This implies that household divides consumption between private transport and all other goods, where private transport is a CES combination of refined fuels and motor vehicles and "all other goods" is a Leontief composite. Here, the central point is that in the standard UK-ENVI model there is no private transport supply sector. For this reason, we assume that households buy vehicles and fuel inputs, for which there are supply sectors, to self-produce private transport which they then directly consume. The price of private transport, albeit unobserved in the standard production accounts, can be captured through this adjustment to the consumption structure and is equal to the cost of self-production.

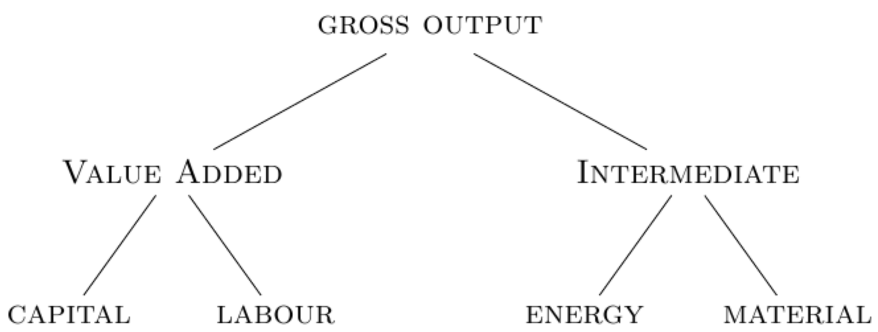
The optimal vehicle input is determined by cost-minimising private transport production. The demand function for the optimal level of vehicle expenditure is given by equation B.34 in Appendix B. We note that motor vehicles are consumer durables and that expenditure in any period should be considered in a long-term perspective. Essentially expenditure on such items should be treated similarly to an investment in capital in conventional production sectors. For this reason we focus on long-run equilibrium results here where the desired level of vehicle expenditure, determined by the cost minimising function, equals, by definition, the actual level of motor vehicle expenditure.

Clearly, even after this adjustment, in practice consumption choices are the result of a more complicated set of consumption decisions. In particular, other energy-intensive services, such as heating and lighting, can be similarly seen as self-produced composite goods. However, to enhance tractability and to simplify the interpretation of the results, here we isolate the example of private transport and assume that the remaining consumption comprises a single composite good, leaving the extension of this framework to 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).

4.2 Production and investment

The production structure (see Figure 4), is represented by a capital, labour, energy and material (KLEM) CES function. Labour and capital are combined to form value added, while energy and materials form a composite of intermediate inputs. In turn, the combination of intermediate and value added gives total output. Again, imported and locally produced intermediate inputs are assumed to be imperfect substitute, via an Armington link (Armington, 1969).

Figure 4. The structure of production



For simplicity we assume that investment is determined by a myopic[8] agent according to the following partial adjustment mechanism:

[8] The model offers the possibility of forward-looking expectation in investment. Given that in this application we are primarily interested in long-run outcomes, the two specifications would produce identical results as the long-run equilibrium conditions are identical (Lecca et al., 2013). We therefore adopt the simpler option.

$$I_{i,t} = v \cdot \left[K^{\star}_{i,t} - K_{i,t}\right] + \delta \cdot K_{i,t} \tag{7}$$

In equation (7), investment is a function of the gap between the actual and desired capital stock, $K_{i,t}$* and $K_{i,t}$ respectively, plus depreciation which occurs at the rate δ. The parameter v is an accelerator (Jorgensen, 1963) and represents the speed at which the capital stock adjusts to the desired level of capital. In steady state the following conditions are satisfied:

$$\begin{aligned} &K^{\star}_{i,t} = K_{i,t} \\ &\text{therefore} \\ &I_{i,t} = \delta \cdot K_{i,t} \end{aligned} \tag{8}$$

Equation (8) simply states that the desired and actual capital stocks levels are equal. From equation (7) this implies that in long-run equilibrium gross investment just covers depreciation.

4.3 The labour market

We assume that the working population is fixed and explore two alternative labour market closures; fixed real wage and wage bargaining. The fixed-real-wage closure is motivated by the 'real wage resistance hypothesis', which implies that the bargaining power of workers precludes any reduction in the real wage.

$$\frac{w_t}{cpi_t} = \frac{w_0}{cpi_0} \tag{9}$$

Equation (9) represents the conventional fixed real wage closure, calculated as the after tax wage w divided by the standard *cpi*. However, in this paper we argue that in calculating the *cpi*, the price of private transport, p_m, which is normally unobserved, should replace the natural prices of refined fuel and vehicles in an augmented *cpi*. This means that:

$$cpi_{\tau,t}(p_a, p_m(p_v, p_f)) \tag{10}$$

When motor-vehicle efficiency improves, the price of vehicles falls thereby reducing the price of private transport. In the absence of other price variations, there will also be a corresponding reduction in the adjusted cpi_τ. The labour market can then be closed using the adjusted fixed real wage:

$$rw_{\tau,t} = \frac{w_t}{cpi_{\tau,t}} \tag{11}$$

If $cpi_{\tau,t}$ falls, the nominal wage decreases and this has wider competitiveness effects across the whole economy.

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

$$ln\left[\frac{w_t}{cpi_t}\right] = \varphi - \epsilon ln(u_t) \tag{12}$$

In this equation, the bargaining power of workers, and hence the real consumption wage, is negatively related to the rate of unemployment (Blanchflower, 2009). In equation (12), w_t/cpi_t is the real consumption wage, φ is a parameter calibrated to the steady state, ϵ is the elasticity of wage related to the level of unemployment, u, and takes the value of 0.069 (Layard et al., 1991). Again, we can use the adjusted *cpi*, $cpi_{\tau,t}$, to calculate the adjusted real wage.

4.4 The Government

We assume that the Government faces a balanced budged constraint, as illustrated in equation B.46 Appendix B. 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.

5. Simulation strategy

The simulations are divided into three main Scenarios. In each Scenario we introduce a 10% efficiency improvement in vehicles and explore four variants. These variants exhibit different elasticities of substitution between private transport and all the other goods and between motor vehicles and refined fuels. These combinations of elasticities are given in Table 1. We have chosen two specific values for each of the two key elasticities, one elastic (>1) and the other inelastic (<1) and then run simulations for each of the four possible combinations. This extends the partial equilibrium analysis outlined in Section 3.1 to general equilibrium.

The Scenarios differ in that we impose a different wage setting process in each. In Scenario 1, we assume that the real wage is fixed and calculated using the standard cpi. This produces simulations where, in the long run, all the prices in natural units are unchanged. In this sense we retain one of the key assumptions of the partial equilibrium analysis, fixed prices, whilst allowing the aggregate level of economic activity to change.

Table 1. Summary of sub-scenario simulation parameter values

	Transport & Non Transport		Motor vehicles & Refined Fuels	
A)	Competitive	$\sigma_{m,a} = 1.5$	Competitive	$\sigma_{v,f} = 1.2$
B)	Complementary	$\sigma_{m,a} = 0.5$	Competitive	$\sigma_{v,f} = 1.2$
C)	Competitive	$\sigma_{m,a} = 1.5$	Complementary	$\sigma_{v,f} = 0.3$
D)	Complementary	$\sigma_{m,a} = 0.5$	Complementary	$\sigma_{v,f} = 0.3$

In the second Scenario, we again impose a fixed real wage, but in this case calculated using the adjusted $cpi_{\tau,t}$, as defined in equation (10). As anticipated, the reduction in the price of private transport caused by the increase in efficiency in motor vehicles reduces $cpi_{\tau,t}$. The nominal wage therefore falls, reflecting the fact that a lower nominal wage will maintain the constant real wage, measured using the adjusted $cpi_{\tau,t}$. The reduction in the real wage increases competitiveness.

In the third Scenario, we incorporate the wage bargaining function, detailed in equation (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 partly mitigated by a reduction in competitiveness.

6. Simulation results

We report only long-run equilibrium results, where the conditions in equation (8) are satisfied because we are primarily concerned with the steady-state impacts, rather than the short-term dynamics of adjustment. However, it was also the case that in earlier test simulations the short- and long-run results were in fact very similar.

6.1. Scenario 1: The model with fixed real wage and standard *cpi*

Table 2 reports simulation results for Scenario 1. It has two sections: the upper reporting percentage changes in the composition of household consumption; the lower, the impact on key macroeconomic indicators. Each column represents a different simulation. For each case we report the results for particular values for the elasticity of substitution between refined fuels and motor vehicles, $\sigma_{v,f}$, and between private transport and all other goods, $\sigma_{m,a}$.

Table 2. Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption

	A	B	C	D
	$\sigma_{m,a}$=1.5 $\sigma_{v,f}$=1.2	$\sigma_{m,a}$=0.5 $\sigma_{v,f}$=1.2	$\sigma_{m,a}$=1.5 $\sigma_{v,f}$=0.3	$\sigma_{m,a}$=0.5 $\sigma_{v,f}$=0.3
	Household consumption			
All other goods	-0.05	0.04	-0.06	0.03
Private transport	5.82	1.97	5.65	1.90
Price of transport	-3.67	-3.67	-3.58	-3.58
Motor vehicles	3.12	-0.64	-2.24	-5.71
Price of vehicles	0.00	0.00	0.00	0.00
Price of vehicles eff units	-10.00	-10.00	-10.00	-10.00
Fuels	1.18	-2.51	4.50	0.79
Price of fuel	0.00	0.00	0.00	0.00
Vehicles intensity in transport	1.16	1.16	-4.03	-4.04
Fuels intensity in transport	-0.75	-0.74	2.58	2.58
	Macroeconomic impacts			
GDP	-0.02	0.02	-0.03	0.00
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	-0.04	0.00
Unemployment rate	0.29	-0.27	0.60	0.04
Investment	-0.02	0.01	-0.03	0.01
Household consumption	-0.02	0.01	-0.03	0.00
Household income	-0.01	0.01	-0.02	0.00
Exports	0.00	0.00	0.00	0.00

The macro-economic changes reported for this Scenario are very small, so that initially we focus on the micro-economic results for specific sectors. Because the income variations are slight, the qualitative results are very close to those derived in the partial equilibrium analysis from Section 3.1. First, note that in the long run there are no changes in the price of vehicles, fuel or the *cpi* in any of the simulations in this Scenario. This is as we would expect: the fixed real wage assumption, together with unvarying, exogenous interest rates and import prices, ensures that once capacity is fully adjusted, there are no endogenous changes in the market prices of goods.

Because there is no change in the price of fuel or vehicles measured in natural units, in all of the simulations reported in Table 2, the price of vehicles, measured in efficiency units, falls by 10%, the full amount of the efficiency gain. This fall in the price of vehicles lowers the price of private transport. The change in this price varies across the simulations, reflecting the different elasticities of substitution between vehicles and fuel imposed in each case. However, this price variation is quite limited, the range being between reductions of 3.56% and 3.67%. 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 very similar –across simulations - reductions in the price of private transport.

The results reported in column A are for elasticity values for which both fuel and vehicles, and private transport and other commodities are competitors. The values of $\sigma_{v,f}$ and $\sigma_{m,a}$ are 1.2 and 1.5 respectively, so that $\sigma_{v,f} < \sigma_{m,a}$. Therefore from the analysis in Section 3, we expect fuel use to rise. In this case, the price of transport falls by 3.67% which translates to a 5.82% increase demand for, and a 2.15% increase in expenditure on private transport. This output is generated by a 13.12% increase in vehicles use (in efficiency units) and 1.8% increase in fuels.

With the specific elasticity values adopted in this simulation, the change in fuel use is positive. Although the share of fuel in private transport, as measured by $\frac{p_f^n f^n}{p_m m}$, decreases by 0.75%, reflecting the high elasticity of substitution between fuel and vehicles, this is not large enough to offset the impact of the increased demand for private transport on the derived demand for fuels. There is a small, 0.05%, contraction in the consumption of all other goods.

In column B, the relatively high value of the elasticity of substitution between vehicles and fuel, $\sigma_{v,f}$, is retained, but $\sigma_{m,a}$ is reduced to 0.5, so that private transport and all other goods are now complements. Because the elasticity of substitution between vehicles and fuel has not changed, the reduction in price of private transport is the same as in column A. Following this reduction, the consumption of private transport increases. However, the value of $\sigma_{m,a}$ is smaller than for the simulation reported in column A, so that output of private transport rises only by 1.97% and expenditure on private transport falls by 1.70%. Vehicle consumption increases by 9.36% in efficiency units, which corresponds to a 0.64% reduction in physical units, while fuel input falls by 2.51%. In this case, consumption of all other goods slightly increases by 0.04%.

In the partial equilibrium analysis in Section 3, with the parameter values used in the simulation reported in column B we know unambiguously that refined fuels use will fall. This is because there must be a lower share of fuels in private transport production and the expenditure on private transport must also fall and there is no change in the price of fuel. If this simulation were represented in Figure 2, the B curve would be sloped in the opposite direction.

In the simulation reported in column C, $\sigma_{m,a}$ equals 1.5, as in column A, while $\sigma_{v,f}$ equals 0.3. In this simulation, private transport and all other goods are competitors, but refined fuels and motor vehicles are complements. This is another case where in the partial equilibrium analysis in Section 3 the outcome is unambiguous; fuel use will rise. The reduction in the price of private transport is here slightly less than in simulations A and B. This reflects the lower elasticity of substitution between fuel and vehicles which restricts substitution into the use of the input whose price has fallen. As a result of the price reduction, consumption of private transport increases by 5.65%. As expected, this increase in the consumption of private transport is very similar to the corresponding result in column A. In this case, the complementarity between motor vehicles and fuels means that the use of both increases. Consumption of vehicles increases by 7.76%, measured in efficiency units, and the consumption of refined fuels increases by 4.50%, measured in natural units. As in column A, the consumption of all other goods decreases, in this case by 0.06%.

Finally, for the simulation results reported in column D, we use the same value for $\sigma_{m,a}$ and $\sigma_{v,f}$ as in simulation B and C respectively. Both elasticities are less than 1 which implies that both private transport and all other goods, and refined fuels and motor vehicles are complements. But again, because$\sigma_{v,f} < \sigma_{m,a}$, we expect fuel use to rise. The 3.58% reduction in the price of private transport equals the corresponding figure in Simulation C, whilst the 1.90% increase in the output of private transport is similar, but slightly less, than the corresponding result in Simulation B. Total expenditure on private transport falls by 1.68% but the share of fuel in private transport increases. The net result is that fuel use increases by 0.79 %. There is also a small increase in the consumption of all other goods of 0.03%.

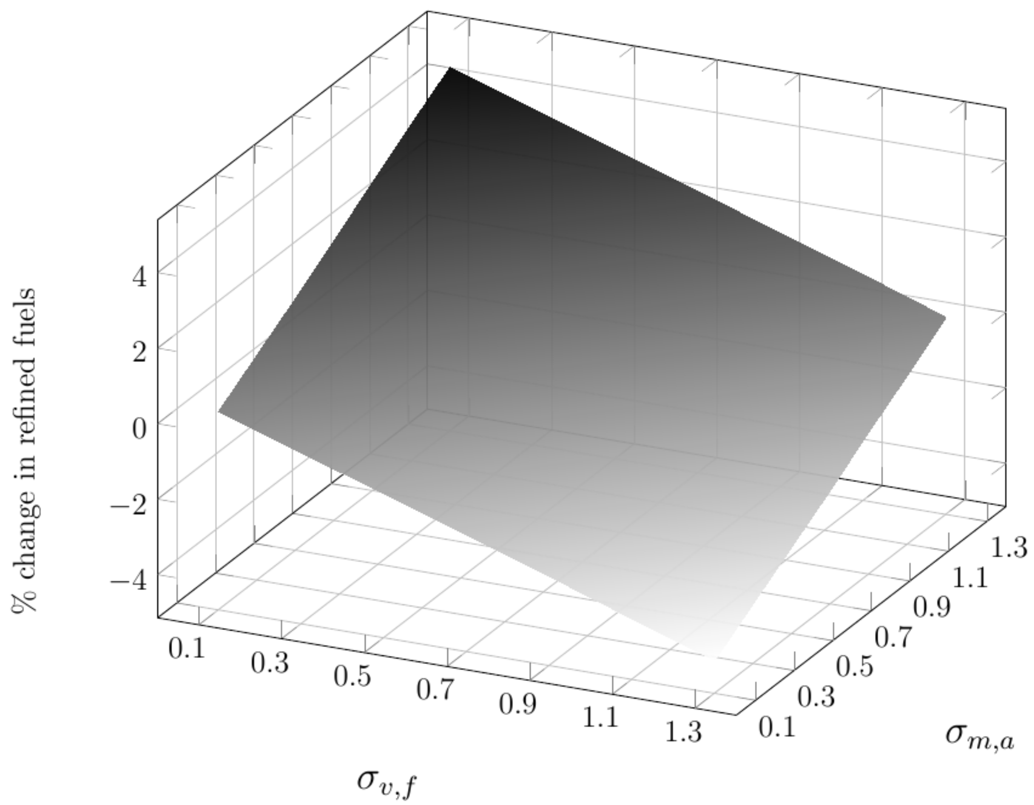
To investigate in more detail the sensitivity of fuel consumption to changes in elasticity values, we conduct a sensitivity exercise where we vary in turn both $\sigma_{m,a}$ and $\sigma_{v,f}$. In these simulations these elasticity values take 0.2 increments between the values of 0.1 to 1.3 inclusive. Results are represented in Figure 5, where the percentage change in refined fuels is plotted for each combination of $\sigma_{m,a}$ and $\sigma_{v,f}$. The figures suggest 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 These simulation results clearly support the analysis of Holden and Swales, (1993).

Recall that in the discussion in Section 3.1, we argued that we had no prior expectation as to the direction of the macroeconomic impact of the technical progress in vehicles where the natural prices of inputs were held constant. In the long-run simulations reported in Table 3, the product prices (and therefore also the conventional cpi) do not change. This reflects the fixed real-wage labour market closure. In these circumstances, the macro-economic impact is similar to that generated by a change in consumer tastes affecting the composition of consumption. If the change in vehicle efficiency in the production of private transport 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.[9]

[9] The model here operates as an extended SAM multiplier where exports are exogenous. The change in the consumption vector therefore changes the multiplier values. The exogenous export expenditure remains unchanged.

In the simulations A and C, the consumption of all other goods falls and the consumption of fuel rises. Both simulations exhibit a 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 economic activity rise. In simulation D the consumption of both all other goods and fuel increases and this produces a neutral impact on economic activity. In this simulation the only aggregate variable that shows any change is investment which increases by 0.01%. These results are consistent with the intuitive notion that all other goods have a relatively high domestic content, whilst fuel has a relatively low one. Outcomes which shift consumption towards the former and away from the latter have a small stimulating impact on aggregate economic activity. Note that in this Scenario there is no conflict between energy reduction and economic expansion: in these simulations, where fuel use falls, output increases.

Figure 5. Percentage change in refined fuels use from a 10% increase in motor vehicles efficiency increase



6.2. Scenario 2: The adjusted *cpi* and fixed real wage.

In Scenario 1, the long-run *cpi*, conventionally measured, is unchanged from its baseline value because the real wage is fixed and no other market price is changing. However, the price of private transport falls by approximately 3.7%. This price is normally unobserved, as households self-produce this service and consume it directly without selling it in a market. It is therefore not included in the standard calculation of the *cpi*. As we argue in previous discussion, this may lead to bias in the calculation of *cpi*, as stressed by Gordon (2016). For this reason, we here calculate an adjusted consumer price index,cpi_{τ} , in which the fuel and vehicle prices are replaced by the price of private transport. We then use this adjusted consumer price index to derive an adjusted real wage, as explained in Section 4.3.

Table 3 reports the simulation results for this Scenario including the adjusted consumer price index, cpi_{τ} , and both the conventional and adjusted real wage. The private transport price reduction triggers a drop in the cpi_{τ} . In all the simulations where the cpi_{τ} is used to calculate a constant adjusted real wage, both the adjusted consumer price index and the nominal wage fall by 0.10%. The conventionally calculated real wage falls between 0.05% and 0.06%.

The fall in the nominal wage 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 is reflected in higher employment and in a corresponding reduction in unemployment. It is important to remember that the import prices are exogenous and are therefore unchanged. This means that there will be some additional substitution of vehicles for fuel in the household production of private transport. 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 cases reported in Table 3.

Table 3. Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption with adjusted cpi

	A	B	C	D
	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5
	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=0.3	$\sigma_{v,f}$=0.3
	Household consumption			
All other goods	0.01	0.10	-0.01	0.09
Private transport	5.87	2.02	5.69	1.95
Price of transport	-3.71	-3.71	-3.61	-3.61
Motor vehicles	3.17	-0.57	-2.20	-5.66
Price of vehicles	-0.04	-0.04	-0.04	-0.04
Price of vehicles eff units	-10.04	-10.04	-10.04	-10.04
Fuels	1.21	-2.46	4.54	0.84
Price of fuel	-0.03	-0.03	-0.03	-0.03
Vehicles intensity in transport	1.17	1.17	-4.03	-4.03
Fuels intensity in transport	-0.75	-0.75	2.58	2.58
	Macroeconomic impacts			
GDP	0.10	0.15	0.09	0.13
cpi_τ	-0.10	-0.10	-0.10	-0.10
Nominal wage	-0.10	-0.10	-0.10	-0.10
Real wage	-0.05	-0.06	-0.05	-0.06
Real wage (cpi_τ deflated)	—	—	—	—
Employment	0.11	0.16	0.09	0.13
Unemployment rate	-1.80	-2.48	-1.42	-2.11
Investment	0.09	0.13	0.08	0.12
Household consumption	0.04	0.07	0.03	0.06
Household income (cpi_τ deflated)	0.10	0.13	0.08	0.11
Exports	0.09	0.09	0.09	0.09

In Scenario 2, in all the simulations GDP is higher, by 0.12% or 0.13%, 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. Consumption of all other goods, vehicles and fuel all rise, relative to the corresponding figures in Table 2, by between 0.03% and 0.07%. These changes are relatively small so as not to affect the qualitative fuel use results. However, in simulation A the sign on the change in the consumption of all other goods is affected, with the -0.05% figure in Scenario 1 replaced by 0.01% in Scenario 2.

6.3. Scenario 3: Wage bargaining and the adjusted *cpi*.

In Scenario 2 we introduced cpi_{τ} but maintained a fixed real wage. This has an impact on key macroeconomic indicators, such as employment, investment and exports. 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 explore an intermediate case, where the adjusted consumer price index is used to calculate the real wage but we relax the fixed real wage assumption by imposing the wage curve from Equation (12). The key 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 wage reduces some of the impact of the efficiency improvement on competitiveness.

Table 4. Long-run % change from the baseline values from a 10% efficiency improvement in household motor vehicles consumption with adjusted cpi and wage curve

	A	B	C	D
	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5	$\sigma_{m,a}$=1.5	$\sigma_{m,a}$=0.5
	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=1.2	$\sigma_{v,f}$=0.3	$\sigma_{v,f}$=0.3
	Household consumption			
All other goods	-0.03	0.05	-0.04	0.04
Private transport	5.84	1.98	5.67	1.91
Price of transport	-3.68	-3.68	-3.59	-3.59
Motor vehicles	3.14	-0.63	-2.22	-5.70
Price of vehicles	-0.01	-0.01	-0.02	-0.01
Price of vehicles eff units	-10.01	-10.00	-10.02	-10.01
Fuels	1.19	-2.50	4.52	0.80
Price of fuel	-0.01	-0.01	-0.01	-0.01
Vehicles intensity in transport	1.17	1.16	-4.03	-4.03
Fuels intensity in transport	-0.75	-0.75	2.58	2.58
	Macroeconomic impacts			
GDP	0.02	0.04	0.02	0.03
cpi_τ	-0.08	-0.07	-0.08	-0.08
Nominal wage	-0.04	-0.01	-0.05	-0.03
Real wage	-0.02	-0.01	-0.02	-0.01
Real wage (cpi_τ deflated)	0.04	0.06	0.03	0.05
Employment	0.03	0.04	0.02	0.03
Unemployment rate	-0.43	-0.60	-0.34	-0.51
Investment	0.02	0.03	0.02	0.03
Household consumption	0.00	0.02	0.00	0.01
Household income (cpi_τ deflated)	0.07	0.09	0.06	0.08
Exports	0.03	0.01	0.04	0.02

Table 4 reports results for this Scenario. It is useful to compare these with the corresponding figures given in Table 3 for Scenario 2. Note first that the long-run adjusted real wage now increases for all the simulations as employment rises. Whilst in Table 3 the nominal wage across all simulations falls by 0.10%, this reduction now lies between 0.05% and 0.01%, which limits the reduction in product prices as reflected in the cpi_τ . Also, in the fixed real wage Scenario 2, exports increased by 0.09% across all simulations. With the wage curve 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 impacts on the components of consumption (fuel, vehicles and all other goods) lie between the Scenario 1 and Scenario 2 values.

7. Discussion

The simulations report the results from 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-saving technical improvement can lead to a reduction in fuel consumption, depending upon the values of key elasticities. However, such a reduction in both the fuel-intensity of private transport and the use of refined fuels is not brought about by an exogenous improvement in fuel efficiency, but as an endogenous reaction to an improvement in the efficiency of a good closely linked, either as a substitute or complement, in this case motor 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 motor vehicles on the demand for fuel, it is fundamental to take into account changes in the demand for private transport. Such changes in the quantity demanded of the energy-intensive service generate an additional increase or reduction in the derived demand for the input goods.

When the *cpi* is calculated using the conventional method, 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* 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 is because the nominal wage falls. This reduces 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*, the nominal wage and the subsequent increase in economic activity.

8. Conclusions

In this paper we have four main aims. First, we attempt to model the use of energy-intensive consumer services in a more appropriate manner than the conventional approach in the literature. In particular, we operationalise the approach suggested by Gillingham et al. (2016) by explicitly incorporate both energy and non-energy inputs to the supply of the energy-intensive service and the determination of its price. We adopt, as an example, the household production of private transport services using inputs of refined fuels and motor vehicles and we incorporate this approach into a Computable General Equilibrium model for the UK.

Second, we analyse the impact of an efficiency improvement in the provision of this energy-intensive service. We distinguish between energy- and vehicle-improving technical changes and discuss this in a partial and general equilibrium context.

Third, we investigate, through simulation, the conditions under which an increase in the efficiency of vehicles in the production of private transport reduces the fuel use in the economy as a whole. The empirical results from our CGE modelling show that when the elasticity of substitution between motor vehicles and refined fuels is greater than the elasticity of substitution between private transport and all other goods, as long as any positive aggregate output effects are not too large, the consumption of refined fuels falls.

Fourth, we consider the impact of technical change in the household consumption sector on the aggregate level of economic activity. Where the consumer price index is calculated in the standard way, the aggregate effect on economic activity is very small and can be positive or negative. This impact is driven solely by the changes in the composition of household demand and the direct, indirect and induced domestic content of the affected sectors. However, when the price of private transport, which is normally not observed, is included in the calculation of *cpi*, the fall in the price index reduces the nominal wage and improves competitiveness in the economy as a whole. This produces a positive stimulus to employment and GDP.

This work provides a more sophisticated treatment of private transport demand, as a household self-produced energy-intensive service. A natural extension would be to model other energy services in a similar way. Here it is crucial to obtain accurate estimates of the relevant elasticities of substitution because the results are sensitive to their values. Furthermore, the adoption of new technological vintages, such as in motor vehicles, require investment. The accumulation of the new stock of vehicles should be modelled as a formal investment process similar to the way we model the production side of the economy. However, whilst this will affect 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, fuels savings from efficiency improvement have been often offset by the increase in size and weight of vehicles. A more sophisticated way of modelling private transport services should therefore identify a framework where variations in these characteristics are linked to fuel efficiency.

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Appendix A

Table 1A. List of production sectors in the UK- ENVI model, corresponding sectors in the 2010 UK IO tables, Standard Industrial Classification (SIC) codes.

Sector name	**SIC**
Agriculture, forestry and fishing	01-03.2
Mining and quarrying	05
Crude petroleum and natural gas + coal	06-08
Other Mining and mining services	09
Food (and tobacco)	10.1-10.9,12
Drink	11.01-11.07
Textile, leather, wood	13-16
Paper and printing	17-18
Coke and refined petroleum products	19-20B
Chemicals and pharmaceuticals	20.3-21
Rubber, cement, glass	22-23other
Iron, steel and metal	24.1-25
Electrical manufacturing	26-28
Manufacture of motor vehicles, trailers etc.	29
Transport equipment and other manufacturing	30-33
Electricity, transmission and distribution	35.1
Gas distribution	35.2-35-3
Water treatment and supply and sewerage	36-37
Waste management and remediation	38-39

Construction-Buildings	41-43
Wholesale and retail trade	45-47
Land and transport	49.1-49.2
Other transport	49.3-51
Transport support	52-53
Accommodation and food and services	55-56,58
Communication	59-63
Services	64-82,97
Education health and defence	84-88
Recreational	90-94
Other private services	95,97

Appendix B The mathematical presentation of the UK ENVI model

Prices

$$PM_{i,t} = \overline{PM_i} \tag{B.1}$$

$$PE_{i,t} = \overline{PE_i} \tag{B.2}$$

$$PQ_{I,T} = \frac{PR_{i,t} \cdot Ri,t + PM_{i,t} \cdot Mi,t}{Ri,t + Mi,t} \tag{B.3}$$

$$PIR_{I,T} = \frac{\sum_i VR_{i,j,t} \cdot PRj,t + \sum_i VI_{i,j,t} \cdot \overline{PI}_{j,t}}{\sum_i VIRi,j,t} \tag{B.4}$$

$$PY_{j,t} \cdot a_j^Y = \left(PR_{j,t} \cdot (1 - btax_j, sub_j, dep_j) - \sum_i a_{i,j}^y PQj,t \right) \tag{B.5}$$

$$UCK_t = PK_t \cdot (r + \delta) \tag{B.6}$$

$$PC_t^{1-\sigma^C} = \sum_j \delta_j^f \cdot PQ_t^{1-\sigma^C} \tag{B.7}$$

$$PG_t^{1-\sigma^G} = \sum_j \delta_j^g \cdot PQ_t^{1-\sigma^G} \tag{B.8}$$

$$w_t^b = \frac{w_t}{1 + \tau_t} \tag{B.9}$$

$$ln \left[\frac{w_t}{cpi_t} \right] = \varphi - \epsilon ln(u_t) \tag{B.10}$$

$$rk_{j,t} = PY_{j,t} \cdot \delta_j^k \cdot A^{Y \varrho_j} \cdot \left(\frac{Y_{j,t}}{Kj,t} \right)^{1-\varrho_j} \tag{B.11}$$

$$Pk_t = \frac{\sum_j PY_{j,t} \cdot \sum_i KM_{i,j}}{\sum_{i,j} KM_{i,j}} \tag{B.12}$$

$$PF_t = \frac{\sum_f PQ_{f,t} \cdot \bar{QH}_f}{\sum_f PQ_f \cdot \bar{QH}_f} \tag{B.13}$$

Consumption

$$C_t = YNG_t - SAV_t - HTAX_t - CTAX_t \tag{B.14}$$

Production technology

$$X_{i,t} = A_i^X \cdot \left[\delta_i^y \cdot Y_{i,t}^{\rho_i^X} + (1-\delta_i^V) \cdot V^{\rho_i^X} i,t\right]^{\frac{1}{\rho_i^X}} \tag{B.15}$$

$$Y_{j,t} = \left(A^{x\rho_j^X} \delta_i^y \cdot \frac{PQ_{j,t}}{PY_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{B.16}$$

$$V_{j,t} = \left(A^{x\rho_j^X} (1-\delta_i^y) \cdot \frac{PQ_{j,t}}{PV_{j,t}}\right)^{\frac{1}{1-\rho_j^x}} \cdot X_{i,t} \tag{B.17}$$

$$v_{i,t} = A_i^v \cdot \left[\delta_i^v \cdot E_{i,t}^{\rho_i^V} + (1-\delta_i^V) \cdot NE^{\rho_i^V} i,t\right]^{\frac{1}{\rho_i^V}} \tag{B.18}$$

$$\frac{E_{j,t}}{E_{j,t}} = \left[\left(\frac{\delta_j^v}{1-\delta_j^v}\right) \cdot \left(\frac{PNE_{j,t}}{PE_{j,t}}\right)\right]^{\frac{1}{1-\rho_j^v}} \tag{B.19}$$

$$VV_{ze,j,t} = \left(A^{z\rho_j^z} (1-\delta^E N_i) \cdot \frac{PNE_t}{PQ_{E,t}}\right)^{\frac{1}{1-\rho_j^E}} \cdot E_{i,t} \tag{B.20}$$

$$Y_{i,t} = A_i^Y \cdot \left[\delta_i^k \cdot K_{i,t}^{\rho_i^Y} + \delta_i^l \cdot L^{\rho_i^Y} i,t\right]^{\frac{1}{\rho_i^Y}} \tag{B.21}$$

$$L_{j,t} = \left(A^{x\rho_j^Y} \delta_i^l \cdot \frac{PY_{j,t}}{w_t}\right)^{\frac{1}{1-\rho_j^Y}} \cdot Y_{j,t} \tag{B.22}$$

Trade

$$VV_{i,j,t} = Y_i^{vv} \cdot \left[\delta_i^{vm} \cdot VM_{i,t}^{\rho_i^A} + (1-\delta_i^{vir}) \cdot VIR^{\rho_i^A} i,t\right]^{\frac{1}{\rho_i^A}} \tag{B.23}$$

$$\frac{VM_{i,j,t}}{VIR_{i,j,t}} = \left[\left(\frac{\delta_j^{vm}}{1-\delta_j^{vir}}\right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}}\right)\right]^{\frac{1}{1-\rho_j^A}} \tag{B.24}$$

$$VIR_{i,j,t} = Y_i^{vir} \cdot \left[\delta_i^{vi} \cdot VI_{i,t}^{\rho_i^A} + (1-\delta_i^{vr}) \cdot VM^{\rho_i^A} i,t\right]^{\frac{1}{\rho_i^A}} \tag{B.25}$$

$$\frac{VR_{i,j,t}}{VI_{i,j,t}} = \left[\left(\frac{\delta_j^{vr}}{1-\delta_j^{vi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho_j^A}} \tag{B.26}$$

$$E_{i,t} = \bar{E}_t \cdot \left(\frac{PE_{i,t}}{PQ_{i,t}}\right)^{\rho_i^x} \tag{B.27}$$

$$R_{i,t} = \sum_i VR_{i,j,t} + \sum_i QHR_{i,h,t} + QVR_{i,t} + QGR_{i,t} \tag{B.28}$$

Total absorption equation

$$X_{i,t} + M_{i,t} = \sum_i VV_{i,j,t} + \sum_i QH_{i,h,t} + QV_{i,t} + QG_{i,t} + E_{i,t} \tag{B.29}$$

Households and other domestic institutions

$$C_t = \left[\delta^T R(\sigma_{m,a} TR_t)^{\frac{\sigma_{m,a}-1}{\sigma_{m,a}}} + (1-\delta^T R) A_{h,t}^{\frac{\sigma_{m,a}-1}{\sigma_{m,a}}}\right]^{-\frac{\sigma_{m,a}-1}{\sigma_{m,a}}} \tag{B.30}$$

$$TR_t = \left(\gamma_h^{\sigma_{m,a}} \delta^T R \cdot \frac{PC_t}{PTR_t}\right)^{\frac{1}{1-\sigma_{m,a}}} \cdot C_t \tag{B.31}$$

$$A_t = \left(\gamma^{\sigma_{m,a}} (1-\delta^T R) \cdot \frac{PC_t}{PA_t}\right)^{\frac{1}{1-\sigma_{m,a}}} \cdot C_t \tag{B.32}$$

$$TR_t = \left[\delta^V (\gamma V_t)^{\frac{\sigma_{v,r}-1}{\sigma_{v,r}}} + (1-\delta^V) F_t^{\frac{\sigma_{v,r}-1}{\sigma_{v,r}}}\right]^{-\frac{\sigma_{v,r}-1}{\sigma_{v,r}}} \tag{B.33}$$

$$V_t = \left(\gamma_h^{\sigma_{v,r}} \delta^V \cdot \frac{PTR_t}{PV_t}\right)^{\frac{1}{1-\sigma_{v,r}}} \cdot TR_t \tag{B.34}$$

$$F_t = \left(\gamma^{\sigma_{v,r}} \delta^F \cdot \frac{PTR_t}{PF_t}\right)^{\frac{1}{1-\sigma_{v,r}}} \cdot TR_t \tag{B.35}$$

$$QH_{a,t} = delta^A \cdot \left(\frac{PC_t}{PQ_{a,t}}\right)^{\frac{1}{1-\sigma_a}} \cdot A_t \tag{B.36}$$

$$QH_{veichles,t} = VC_t \tag{B.37}$$

$$QH_{fuels,t} = F_t \tag{B.38}$$

$$Trf_t = Pc_t \cdot \overline{Trf} \tag{B.39}$$

$$S_t = mps \cdot \left[(1-\tau_t)\, L_t^s (1-u_t) w_t + Trf_t\right] \tag{B.40}$$

$$QH_{z,t} = \left(\delta^{f \rho_i^c} \cdot \frac{Pc_t}{PQ_{z,t}}\right)^{rho_i^c} \cdot NEc_t \tag{B.41}$$

$$QH_{I,t} = \gamma_i^f \left[\delta^{hir} QHIR_t^{\rho_i^A} + (1-\delta^{hm}) QHM_t^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{B.42}$$

$$\frac{QHIR_{i,t}}{QHM_{i,t}} = \left[\left(\frac{\delta_i^{hir}}{1-\delta_i^{hm}}\right) \cdot \left(\frac{PM_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho^A}} \tag{B.43}$$

$$QHIR_{I,t} = \gamma_i^{fir} \left[\delta^{hr} QHR_t^{\rho_i^{hr}} + \delta^{hi} QHI_t^{\rho_i^A}\right]^{\frac{1}{\rho_i^A}} \tag{B.44}$$

$$\frac{QHR_{i,t}}{QHI_{i,t}} = \left[\left(\frac{\delta_i^{hr}}{1-\delta_i^{hi}}\right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}}\right)\right]^{\frac{1}{1-\rho^A}} \tag{B.45}$$

Government

$$\overline{FD_t} = G_t \cdot PG_t + \sum_{dgins} TRGdngins, t \cdot PC_t - \left(d^g \cdot \sum_i rk_{i,t} \cdot K_{i,t} + \sum_i IBTi, t + \sum_i Li, t \cdot w_t + \overline{FE}\epsilon_t \right) \tag{B.46}$$

$$QG_{i,t} = \delta_i^g \cdot G_t \tag{B.47}$$

$$QGR_i, t = QG_i, t; QGM_i, t = 0; \tag{B.48}$$

Investment demand

$$QV_{i,t} = \sum_j KM_{i,j} \cdot J_{j,t} \tag{B.49}$$

$$QV_{I,t} = \gamma_i^v \left[\delta^{qvm} QVM_t^{\rho_i^A} + (1 - \delta^{qvir}) QVIR_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{B.50}$$

$$\frac{QVM_{i,t}}{QVIR_{i,t}} = \left[\left(\frac{\delta_i^{qvm}}{\delta_i^{qvir}} \right) \cdot \left(\frac{PIR_{i,t}}{PM_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{B.51}$$

$$QVIR_{I,t} = \gamma_i^{vir} \left[\delta^{qvi} QVI_t^{\rho_i^A} + (1 - \delta^{qvr}) QVR_t^{\rho_i^A} \right]^{\frac{1}{\rho_i^A}} \tag{B.52}$$

$$\frac{QVR_{i,t}}{QVI_{i,t}} = \left[\left(\frac{\delta_i^{qvr}}{\delta_i^{qvi}} \right) \cdot \left(\frac{PI_{i,t}}{PR_{i,t}} \right) \right]^{\frac{1}{1-\rho^A}} \tag{B.53}$$

Time path of investment

$$I_{i,t} = v \cdot \left[KS_{i,t}^* - KS_{i,t} \right] + \delta \cdot KS_{i,t} \tag{B.54}$$

$$KS_{j,t}^* = \left(A^{x\rho_j^X} \delta_i^k \cdot \frac{PY_{j,t}}{uck_t} \right)^{\frac{1}{1-\rho_j^x}} \cdot Y_{i,t} \tag{B.55}$$

Factors accumulation

$$KS_{i,t+1} = (1-\delta)KS_{i,t} + I_{i,t} \tag{B.56}$$

$$K_{i,t} = KS_{i,t} \tag{B.57}$$

$$LS_{t+1} = \left(1+\zeta - v^u \left[ln(u_t) - ln(\bar{u}^N)\right] + v^w \left[ln(w_t/cpi_t) - ln(\bar{w}_t^N/\overline{cpi}_t^N)\right]\right) \cdot LS_t \tag{B.58}$$

Indirect taxes and subsidies

$$IBT_{i,t} = btax_i \cdot X_{i,t} \cdot PQ_{i,t} \tag{B.59}$$

Total demand for import and current account

$$M_{i,t} = \sum_i VI_{i,j,t} + \sum_i VM_{i,j,t} + \sum_i QHM_{i,h,t} + QGM_{i,t} + QVI_{i,t} + QVM_{i,t} \tag{B.60}$$

$$TB_t = \sum_i M_{i,t} \cdot PM_{i,t} - \sum_i E_{i,t} \cdot PE_{i,t} + \epsilon \cdot \left(\sum_{dngins} \overline{REM}_{dngind} + \overline{FE} \right) \tag{B.61}$$

Assets

$$VF_{i,t} = \lambda_{i,t} \cdot K_{i,t} \tag{B.62}$$

$$D_{t+1} = (1+r) \cdot D_t + TB + t \tag{B.63}$$

$$Pg_{t+1} \cdot GD_{t+1} = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1 \right) \right] \cdot PG_t \cdot Gd_t + FD_t \tag{B.64}$$

Steady state conditions

$$\delta \cdot KS_{i,T} = I_{i,t} \tag{B.65}$$

$$R^k_{i,T} = \lambda_{i,T}(r + \delta) \tag{B.66}$$

$$FD_t = \left[1 + r + \left(\frac{Pc_{t+1}}{Pc_t} - 1\right)\right] \cdot PG_t \cdot Gd_t \tag{B.67}$$

$$TB_T = r \cdot D_t \tag{B.68}$$

$$NFW_t \cdot r = (1 - \tau_t)L^s_t(1 - u_t)w_t + Trf_t \tag{B.69}$$

$$FW_t \cdot r = \Pi - S_t + Trf_t \tag{B.70}$$

To produce short-run and long-run results

$$KS_{i,t=1} = KS_{i,t=0} \tag{B.71}$$

$$LS_{i,t=1} = LS_{i,t=0} \tag{B.72}$$

$$GD_{i,t=1} = GD_{i,t=0} \tag{B.73}$$

$$D_{i,t=1} = D_{i,t=0} \tag{B.74}$$

$$QH_{ele,t} = Ec_t \tag{B.75}$$

$$QH_{GAS,t} = GAS_t \tag{B.76}$$

$$QH_{Coal,t} = CL_t \tag{B.77}$$

$$QH_{OIL,t} = OIL_t \tag{B.78}$$

B.1 Glossary

Set

$i, j \; i = j$	the set of goods or industries
ins	the set of institutions
$dins(\subset ins)$	the set of domestic institutions
$dngins(\subset dins)$	the set of non-government institutions
$fins(\subset dins)$	the set of foreign institutions
$h(\subset dngins)$	the set of households
$Z(\subset i)$	the set of energy sectors including transport
$E(\subset i)$	the set of energy sectors excluding fuels transport
$NE(\subset i)$	the set of non-energy
$(a \subset i)$	the set of non-private transport
$(m \subset i)$	the set of private transport
$(v \subset m)$	the set of motor vehicles
$(r \subset m)$	the set of refined fuels

Prices

$PY_{i,t}$	value added price
$PR_{i,t}$	regional price
$PQ_{i,t}$	output price
$PIR_{i,t}$	national commodity price
w_t	unified nominal wage
wb_t	after tax wage

$rk_{i,t}$	rate of return to capital
Pk_t	capital good price
UCK_t	user cost of capital
λ_t	shadow price of capital
Pc_t	aggregate consumption price
PE_t	consumption price of energy
PNE_t	consumption price of non-energy
PRE_t	consumption price of residential energy
$PNEN_t$	consumption price of non-energy and transport
PTR_t	consumption price of private transport
PA_t	consumption price non private transport
PV_t	consumption price motor vehicles
PR_t	consumption price refined fuels
Pk_t	aggregate price of Government consumption goods
ϵ_t	exchange rage (fixed)
Endogenous variables	
$X_{i,t}$	total output
$R_{i,t}$	regional supply
$M_{i,t}$	total import
$E_{i,t}$	total export (interregional+regional)
$Y_{i,t}$	value added
$L_{i,t}$	labour demand
$K_{i,t}$	physical capital demand
$KS_{i,t}$	capital stock
$LS_{i,t}$	labour supply
$VV_{i,j,t}$	total intermediate inputs
$V_{i,t}$	total intermediate inputs in i
$VR_{i,j,t}$	regional intermediate inputs
$VM_{i,j,t}$	ROW intermediate inputs

$VIR_{i,j,t}$	national intermediate inputs
$VI_{i,j,t}$	RUK intermediate inputs
G_t	aggregate Government expenditure
$QG_{i,t}$	Government expenditure by sector i
$QGR_{i,t}$	regional Government expenditure by sector i
$QGM_{i,t}$	national Government expenditure by sector i
C_t	aggregate household consumption
Ec_t	household consumption of energy
NEc_t	household consumption of non-energy goods
CO_t	household consumption of coal and oil
EG_t	household consumption of electricity and gas
ELE_t	household consumption of electricity
GAS_t	household consumption of gas
CL_t	household consumption of coal
OIL_t	household consumption of oil
$RE_{h,t}$	household consumption of residential energy
$TNEC_{h,t}$	household consumption of non-energy and transport
TR_t	household consumption of private transport
A_t	household consumption of non-private transport
VC_t	household consumption of motor vehicles
F_t	household consumption of refined fuels
$QH_{i,t}$	household consumption by sector i
$QHR_{i,t}$	household regional consumption by sector i
$QHIR_{i,t}$	regional+RUK consumption by sector i
$QHM_{i,t}$	imported consumption bys sector i
$QV_{i,t}$	total investment by sector of origin i
$QVR_{i,t}$	regional investment by sector of origin i
$QIR_{i,t}$	ROW investment demand by sector i
$QVI_{i,t}$	RUK investment demand by sector i

$I_{j,t}$	investment by sector of destination j
$J_{j,t}$	investment by destination j with adjustment cost
u_t	regional unemployment rate
u_t^N	national unemployment rate
$R_{i,t}^k$	marginal revenue of capital
S_t	domestic non-government savings
Trf_t	household net transfer
$Trsf_{dngins,dnginsp,t}$	transfer among *dngins*
$HTAX_t$	total household tax
TB_t	current account balance
Exogenous variables	
$\overline{REM}_t$	remittance for *dngins*
$\overline{FE}_t$	remittance for Government
$GSAV_t$	Government savings
r	interest rate
Elasticities	
σ	constant elasticity of marginal utility
ρ_i^X	elasticity of substitution between intermediate and value added
ρ_i^Y	elasticity of substitution between capital and labour
ρ_i^A	elasticity of substitution in Armington function
σ_i^x	elasticity of export with respect to term trade
σ_i^e	substitution in consumption between energy and non-energy
σ_i^g	substitution in consumption between CO and EG
σ_i^o	substitution in consumption between coal and oil
σ_i^{el}	substitution in consumption between electricity and gas
Parameters	
$\alpha_{i,j}^V$	input-output coefficients for i used in j
α_j^Y	share of value added in production
$\delta_j^{Y,V}$	share in CES output function in sector j

$\delta_j^{k,l}$	share in value added function in sector j
$\delta_{i,j}^{vir,vm,vr,vi}$	share in CES function for intermediate goods
$\delta_{i,j}^{qvvir,qvm,qvr,qvi}$	share in CES function for investment
$\delta_{i,j}^{E,co,cl}$	share in CES function for household consumption
$\delta_{i,j}^{hr,hm}$	share in CES function for household consumption
$\delta_{i,j}^{gr,gm}$	share in CES function for Government consumption
$\gamma_{i,j}^{vv,vir}$	shift paramenter in CES for intermediate goods
γ_i^f	shift paramenter in CES for household consumption
γ_i^g	shift paramenter in CES for Government consumption
$btax_i$	rate of business tax
$KM_{i,j}$	physical capital matrix
mps	rate of saving *dngins*
τ	rate of income tax
ρ	pure rate of consumer time preference
bb	rate of distortion or incentive to invest
δ	depreciation rate