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Do light vehicle emissions standards promote environmental goals in Australia?

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Abstract

Policy makers around the world deem fuel-efficiency improvement schemes as a cost-effective way to reduce energy consumption and greenhouse gas emissions in the private transport sector. However, there has been heated discussion over whether the mechanical approach of improved fuel efficiency may be offset by behavioural changes that lead to more consumption of energy goods and services. In previous literature, economists have defined this adjustment on the consumer side as the “rebound effect”, and if the rebound effect were larger than the “mechanical effect”, there would be a “backfire effect”, meaning that total energy consumption would soar after a technological improvement in energy efficiency. To investigate this effect, first I examine theoretically the possible results of an exogenous technological improvement in fuel use, and then empirically analyse the magnitude of the rebound, adopting a computable general equilibrium (CGE) model of the Australian economy. We simulate a 3% increase in fuel efficiency in the transport sector, in accordance with the target of the mandatory policy on light-vehicle emission standards proposed by the Climate Change Authority (CCA) of Australia in 2014. The simulation results show that for the Australian economy, although a specific technological improvement in transport fuel produces a rebound effect, it still results in an overall fuel saving. In addition, a 0.02% growth in GDP is achieved, meaning that the overall energy efficiency is improved, since fuel consumption has been reduced. However, the results and policy implications of this analysis should be taken cautiously, as this simulation applies only to one specific improvement in fuel efficiency; not to a general energy-efficiency improvement. In addition, all other industrial sectors are assumed to have no technological change in this simulation.

Key words

Rebound Effect, CGE Modelling, Policy Performance, Energy Consumption, Fuel Efficiency, Sustainable Development

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1. Introduction and background

Worldwide, climate policy is a grave concern (Sinn 2012). Even though an increasing number of climate policies have been implemented in various countries, the pace of carbon emissions increase has not slowed down. The transport sector, in particular, is a significant source of carbon emissions. In Australia, this sector contributes around 15% of the total carbon emissions, and has consequently drawn the attention of policy makers throughout the country. The Climate Change Authority (CCA), an Australian governmental agency that makes policy recommendations regarding emissions reduction, initiated light vehicle emissions standards in 2014. The CCA's report claimed that the carbon emissions reduction target would be achieved by improving automobile fuel efficiency, as fuel consumption would decrease following a technical improvement in fuel use, thus achieving the target of carbon emissions reduction.

However, the effects of policies aimed at improvements in energy efficiency have been questioned for a long time (Brookes 1990; Hanley et al. 2009; Khazzoom & Miller 1982). It has been observed that savings from higher energy or fuel efficiency usually are partially or even wholly offset by the "rebound effect", an energy-economic term used to describe an increase in the consumption of energy-goods or services following a technological improvement that results from indirect price decreases brought about by the increased efficiency (Greening, Greene & Difiglio 2000; Sorrell 2007).

Drawing on previous studies on rebound effects, in this study we investigated potential rebounds for the Australian economy caused by implementing mandatory light vehicle emission standards. First, we carried out a theoretical analysis on the impacts of improved fuel efficiency at the macro level, or the "economy-wide effect" (Sorrell & Dimitropoulos 2007). Next, we simulated the policy instrument in both the short run and the long run. Evidence was obtained using the ORANI-G model—a generic multi-sectoral computable general equilibrium (CGE) model—of the Australian economy.

Our objective was to provide an academic-oriented recommendation for policy formulation in Australia, where emissions reduction targets are becoming an increasing concern for regional and national governments. Standards on automobile emissions have been promoted as beneficial to both consumers and the environment, according to a cost-benefit analysis performed by CCA (2014).This optimistic belief on fuel efficiency is based purely upon engineering calculations: that is, fuel consumption would decrease if economic activities remain the same after a technological improvement in automobile fuel use. This assumption, however, ignores behavioural changes following efficiency advancement, which can ruin the efficiency gains.

In section 2 we illustrate the rebound effects using neo-classical economic theory. After reviewing the theoretical and empirical analyses, we explain the mechanism of rebounds in an economy-wide system. In Section 3 we describe the generic multi-sectoral CGE model of Australia, ORANI-G. Section 4 presents the results of six simulations regarding different levels of standards in short-run and long-run scenarios. Section 5 is the conclusion. Section 6 lists a few limitations of this study.

2. Effects of fuel efficiency improvements on fuel consumption

2.1 Theoretical explanations

There has been a heated discussion on the existence and magnitude of the rebound effect for more than three decades. The origin of the rebound phenomenon on energy consumption actually dates back to “Jevons Paradox”, from the economist Jevons, who observed that with an improvement in energy efficiency, energy consumption increases instead of decreasing (Jevons 1865). In the late twentieth century, as climate policy came to the attention of policy makers, energy efficiency has been widely touted as an effective way to reduce energy consumption and, thereby, carbon emissions (Chu & Majumdar 2012; Lovins 1976).

Here we adopt neoclassical economic theory to explore the possible results from a technology shock on fuel input use in transport service production. First, we assume that the production function that the transport sector faces follows the Leontief form, meaning that there is no substitution between factors.

Rather than writing

$$Y_j = f(X_{1j}, X_{2j}, \dots) = \min(\frac{X_{1j}}{A_{1j}}, \frac{X_{2j}}{A_{2j}}, \dots), \quad (1)$$

where Y_j is the output of industry j and X_i is the input, as defined in a computable general equilibrium model, we use the linear percentage change form

$$y_j = \min[(x_{1j} - a_{1j}), (x_{2j} - a_{2j}), \dots], \quad (2)$$

where a_{ij} is the percentage technical change in input i from producing industry j. Here the production sector is assumed to behave as if effective units of inputs are non-substitutes, i.e. Equation (1) has a Leontief form. Assuming cost-minimising behaviour, the firms have to solve the problem as follows;

$$\min_{X_1, X_2, \dots} \sum_{i=1}^{37} P_i X_{ij} \quad (3)$$

The solutions for this minimisation problem in linear form are

$$x_{ij} = y_j + a_{ij} \quad (4)$$

In this model and the corresponding database, the number of transport sector is 27 and the number of input fuel is 14. Now let’s take a closer look at the transport sector and its fuel consumption.

If technology improves, the input fuel $x_{14,27}$ to produce transport goods or services y_{27} reduces by 10%, indicated by $a_{14,27} = -10$. Here 14 is the number of petrol use and 27 is the number of transport industry. In this case, if the output of transport holds constant, $x_{14,27} = -10$, indicating that the total fuel saved by the improved technology is $0.1X_{14,27}$, which is the engineering calculation of a technological shock on fuel efficiency. In our study, we defined the direct total fuel savings from advanced technology as the "mechanical effect". Figure 1 gives an illustrative explanation of the mechanical effect. The thick curve Y_{27} is the production possibility curve of the transport sector, given input fuel and other commodities. Since we rule out the possibility of substitution, the quantity of production remains the same if we increase fuel use, holding other input factors constant. Suppose Y_{27} is the current transport supply that meets transport demand in the general equilibrium framework. If a technological improvement occurs in fuel use, the production possibility curve would shift to the left, shown by Y'_{27}, holding production constant. Therefore, fuel input is reduced, where the reduction is AB, namely, the mechanical effect.

In a general equilibrium framework, technical changes are expected to lead to economic growth. The overall industry output would grow after a technical advancement since cost of production is lowered by the higher technology. The cost of transport in linear form can be represented as

$$c_{27} = \sum_{i=1}^{37} \alpha_{i,27}(p_{i,27} + y_{27} + a_{i,27}) \tag{5}$$

where c_{27} denotes the percentage change in transport cost, $\alpha_{i,27}$ is input i's share of the cost, and $p_{i,27}$ is the price of input i for the transport industry. In the model, we assumed that only household consumption and exports are sensitive to price changes. If the transport price drops, export and household transport consumption would increase at different rates, corresponding to their elasticities. The first-round effect of a technical change in fuel efficiency would lead to a $1.55\% = \alpha_{i,27}a_{i,27}$ decrease in cost. This would have been the case if this were a partial equilibrium model. In actuality, the price of fuel and the output of transport would change, but we will leave this part of the discussion in section 4.

If the actual percentage change in transport output is y_{27}, input fuel for transport percentage change would be $y_{27} - 10$. We call this the "output demand effect". It is reasonable to think that other industries' outputs would also change. Therefore, if we sum over the industry output percentage changes, we will get the overall output demand effect. If fuel consumption in the economy changes by x_{14}%, while technical change is 10%, $x_{14} + \alpha_{i,27}10$ would be the percentage change induced by increased demand for overall outputs in the economy, or the so-called economy-wide rebound.

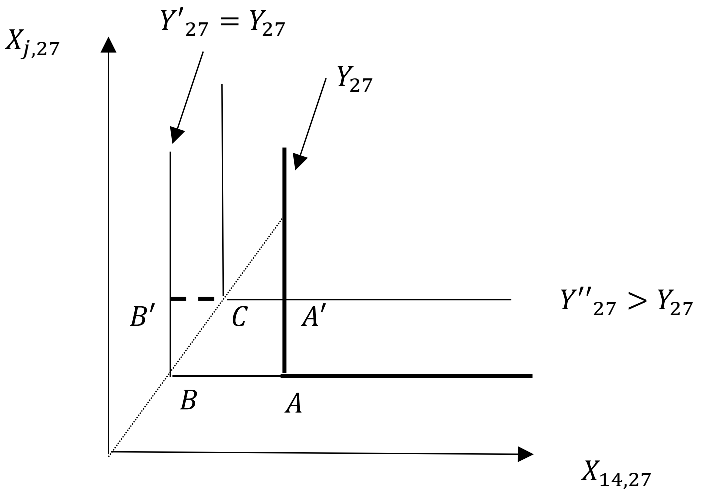

Figure 1 Mechanical effect and output demand effect for input fuel in transport production

As shown in Figure 1, a technological change in fuel use in the transport sector would first lead to a shift in the isoquant curve, from Y_{27} to Y'_{27}, holding the output constant. Therefore the direct mechanical effect results in fuel consumption savings by AB, without considering the actual changes in demand for transport services. Next comes the output demand effect. Since transport cost will drop due to the more efficient use of fuel, demand for transport service will increase, driving the supply curve up to Y''_{27}. $B'C$ is the increase, or rebound in fuel use in transport, an effect driven by an increase in output demand for transport. To see whether there is an overall saving or "backfire" in energy use in the transport sector, we have to compare the mechanical effect and output demand effect. For example, Figure 1 shows an energy saving case, where $B'C \leq AB$; in other words, the increase in energy consumption resulting from behavioural change is less than that saved by the mechanical change. Here we need to notice that the output demand effect is not the output increase in the transport service; rather, it is the increase in fuel use induced by larger demand for transport services.

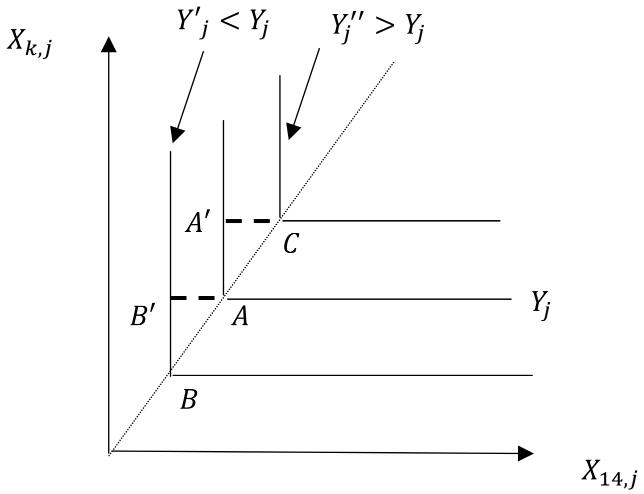

Figure 2 Possible output demand effect for input fuel in other industries' outputs. Here $j \neq 27$ *and* $k \neq 14$.

In a CGE framework, we have to consider the effect of the technological change in transport on other sectors. Obviously, for other industries, the mechanical effect would be zero if there is no technical change in the production process, other than transport. Therefore, demand for fuel in other industries adjusts only to output shrinkage and expansion. Figure 2 illustrates two possible consequences to the demand for the output of industries other than transport after a technological shock in transport fuel use in a general equilibrium framework. Y_j, Y'_j and Y''_j are isoquant production curves for the output produced by industry j, with input $X_{14,j}$ and $X_{k,j}$ under the same available technology, where $k \neq 14$. If the price of Y_j increases, the demand for it would decrease to Y'_j, and thus fuel consumption for this sector would decrease (shown as broken line AB'). If the price of Y_j otherwise decreases, demand for it would increase to Y''_j, and thus fuel consumption for this sector would increase (shown as broken line $A'C$).

2.2 Partial versus general equilibrium analysis of fuel-efficiency improvement in private road transport

The analytical results from partial equilibrium could be problematic regarding the magnitude of the rebound effect on energy consumption. Hence adopting a general equilibrium model is crucial for understanding the whole picture of a technological improvement in fuel efficiency. First consider the changes in output price (transport) following a mechanical shock to one of its inputs—petrol. From the previous partial equilibrium analysis, we have seen that when input petrol is more efficiently used, the price of transport will decrease, driving the supply curve S_1 downwards to S_2. As a result, the new equillibrum price (point B in Figure 3) will be lower, and demand for transport will be higher than that in the equilibrium without technological change (point A in Figure 3).

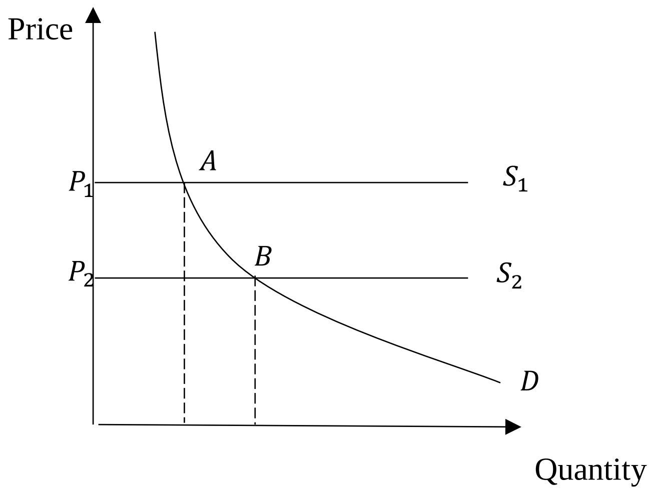

Figure 3 Effects of higher efficiency in petrol use in transport in the domestic transport industry.

Next, consider the general equilibrium analysis, or the interdependency between the transport sector and the rest of the economy. If transport workers ask for higher wages, the tyre equilibrium price will be higher than P_2, because the supply curve would be shifted upwards above S_2. If the transport equipment price increases due to an increase in demand from transport producers, similar effects on price to those of a wage increase would happen.

2.3 Evidence of the rebound effect

In the light of Sorrell's (2007) work on rebound typology, rebound effects have been categorised as direct, indirect and economy-wide. Direct rebound captures the immediate increase in demand for an energy-using activity once its average energy use has been reduced. For example, when an automobile becomes more fuel efficient, the higher demand for travelling by car is the direct rebound. Indirect rebounds involve an increase in the consumption of a number of energy goods or services indirectly related to the improvement in one energy efficiency improvement. For example, when people buy more efficient cars, they might travel farther, so that more tyres are required to meet the increase in driving distances. Producing tyres requires energy, and thus energy consumption may increase in the production of tyres. Similarly, if people not only increase their automobile travel, but also stay in motels or hotels when they are travelling, the demand for more hotel services would also grow. Consequently, energy consumption in hotels would soar (Michaels 2012). Another plausible case is that even if people do save money by adopting more efficient vehicles, they might spend the savings on other energy consuming activities, such as travelling by air or taking an overseas holiday. This behavioural change could be explained by the income effect—when the cost in driving private cars decreases, people's disposable income increases, so they are able to afford more goods and services. The summation of direct and indirect rebounds is the economy-wide rebound effect.

Generally, direct rebound is easier to measure empirically than indirect and economy-wide rebounds because the direct rebound only involves measuring the behavioural effect of one specific good or service, so a partial equilibrium model would do well in this circumstance. For instance, one of the widely adopted approaches in measuring the direct rebound of fuel efficiency improvement in automobiles is to estimate the price elasticity of the transport service demand, whereas measuring indirect or economy-wide rebound requires estimates for price elasticities and income elasticities for a wide range of goods and services. There are numerous empirical studies estimating the direct rebound in different sectors and different countries (Greening, Greene & Difiglio 2000; Small & Van Dender 2007). For rebounds in the private automotive transport sector, probably not surprisingly, nearly all studies are concentrated on estimating the direct rebound (Chitnis et al. 2013; Espey 1996; Johansson & Schipper 1997). A few more recent studies that have contributed to broader rebounds study have been conducted recently on indirect effects; for example, Murray (2013) and Chitnis et al. (2013).

Although results from partial equilibrium models are generally accepted as informative and accurate, they give little information on how the economy as a whole is affected by fuel efficiency improvements. Therefore, we believe a general equilibrium model is needed. As general equilibrium modelling requires a lot of data and complicated computational methods, very limited applied general equilibrium work has been done on the rebound effect so far. Still, there are a few important papers that have shed light on this topic Hanley et al. (2009) adopted a CGE model of the Scottish economy to measure the overall rebound effect of a 10% general energy efficiency improvement in all industries. Their results show a strikingly large economy-wide rebound that might lead to a "backfire" in the long run. Allan et al. (2006) developed an energy-economy-environment CGE model for the UK. In contrast to Scotland's economy, when efficiency improvements were found to be costless, these researchers found a 5% environmental improvement following an energy efficiency (measured by GDP/energy consumption) increase. Grepperud and Rasmussen (2004) applied a multi-sectoral growth model to the Norwegian economy. Rather than simulating a general energy use shock in all industries, they introduced separate exogenous technological shocks to six specific industry sectors which have been categorised as energy intensive, capital intensive, or resource intensive. Their results showed that some industries generated a large rebound while others generated a small one or even none at all. The variation on the magnitude could be explained by different policies in different sectors, which they illustrated in their paper. For example, catch quotas in the fisheries industry plays a role in undermining the rebound effect, for this sector, the market does not affect the demand and supply; instead, the annual quotas dominate the industry's outcome. Therefore they concluded that to reduce carbon dioxide, both technology and regulations on total output should be integrated.

3. ORANI-G: A generic multi-sectoral model of the Australian economy

Applied general equilibrium models have been regarded as a useful tool in economic policy formulation and implementation in many countries (Dervis & Robinson 1982). Especially in environmental economics, the computable general equilibrium (CGE) is widely accepted for analysing climate policy, having a number of advantages over conventional cost-benefit analysis (Hanley et al. 2009). The concerns over global climate change have given rise to a new growth in the use of CGE modelling. As pointed out by Hanley et al. (2009), CGE models might be the best option available to explicitly explore the rebound and backfire effects in the whole economy, because of their multi-sectoral capabilities and system-wide considerations.

Rebound effects, including direct, indirect and economy-wide impacts, in automotive road transport work through the following channels: (a) a mechanical effect—direct decrease in requirement in energy input to provide a given level of transport service, which would cause the cost of transport services to decrease; (b) a price effect, which may trigger a direct increase in demand for transport services, as its "implicit" price is now lower, although different users—households, producers, investors, etc.—may respond in different ways; (c) an input substitution effect—as firms are thought to minimise their costs, they may choose to substitute other inputs in favour of fuel (in the first round) and transport (in the second round), if inputs in the production process are substitutable (however, this effect was excluded from this model since we assumed a Leontief production function for every sector); (d) an indirect output demand substitution effect—consumers will react to all price changes according to price elasticities and relative price changes; e.g. more transport-oriented goods or services benefit more than other goods under the greater fuel efficiency; and (e) a rebound in overall demand, from the income effect attributable to a growth in real household income.

3.1 General structure

It will be instructive to present a brief outline of the ORANI-G model structure. The ORANI-G model, designed for comparative static analysis, is adopted in a wide range of areas in Australia as a tool for practical policy analysis by economists and researchers in both governmental departments and private sectors (Horridge 2000). ORANI-G has six demanders: domestic producers (divided into 35 industries), investors (35 industries), a representative single household, an aggregate foreign purchaser of exports, government demands, and changes in inventories. Additionally, four margin commodities are required to facilitate the flow of all 37 commodities (the agriculture industry produces three different commodities), from producers (or importers) to users including transport; retail and wholesale trade; hotel and café; and finance and insurance. Unlike some of the energy-environment-economics CGE models, ORANI-G does not treat the energy commodity as primary factor; instead, its primary factors are, capital, labour and land As in most GE models, we assumed that markets were competitive, that agents were price-takers, and that no pure profits were allowed.

Apart from its simplicity, the linearized approach allows free choice in which variables are to be exogenous or endogenous. Once again, the model requires cost minimisation in production with multi-level nested production functions, with CES, Leontief and CET as basic forms (see Figure 3).

3.1.1 Structure of production

ORANI-G allows each industry to produce at least one commodity, using both domestic and imported commodities, and a variety of categories of labour, capital and land as inputs, where labour, capital and land are categorised as primary factors in a CES production process. Export demand for commodities is differentiated from local demand; this distinction will turn out to be beneficial for understanding terms of trade. The special feature of multi-input and multi-output production is explicitly explained in Figure 3. When a firm decides on its activity level, it faces a Leontief production function of commodity composites, a primary-factor composite and other costs. After choosing how much of each commodity to use, the firm faces the second problem of choosing between domestic and imported goods, combined with a CES (constant elasticity of substitution) production function. Labour, capital and land aggregate a primary-factor composite using the CES function. The composite labour force is also a CES aggregation of occupational labour types. Since production processes vary across industries, the illustrated shared production structure for each industry may have unique input proportions and behavioural parameters.

3.1.2 From industry outputs to commodity outputs

It is worthwhile to reiterate the feature of ORANI-G that allows each industry to produce a wide variety of different goods. Variations in the mixture of commodities among different industries depend upon the relative prices of commodities. The final nest of Figure 3 depicts how industry outputs are determined by CET (constant elasticity of transformation) where revenue from all goods produced is maximised, subject to the production function.

CET is identical to CES, except for the sign of the parameters. For example, an increase in the relative price of a commodity leads to transformation in favour of that output. All industries that produce, say, transport, receive the same unit price. Transport provided by different industries is deemed to be a perfect substitute. But in most cases, there is a one-to-one correspondence between industries and commodities. Implied by the MAKE matrix in the database, transport as a commodity is produced by solely the transport industry.

3.2 Description of sectors, treatment of energy and transport in ORANI-G and the implementation of fuel efficiency improvements

In this section, we present a general picture of the major sectors that may be influenced by fuel efficiency improvements. A detailed mathematical description of how fuel efficiency improvements are translated in the CGE model is provided.

Transport activity accounts for approximately 25% of Australia's emissions attributable to fuel combustion activities (ABS 2001). More than 40% of total emissions by transport are attributable to household use of private motor vehicles. About 1.5% of the world's transport-oriented emissions are contributed by Australia. Total emissions from Australia's fleet have grown more than the world average; however, since 1990 (OECD/IEA 1999). Australia's proportion of total CO_2 emissions from fuel combustion (25.3%) are now higher than both the OECD Europe (24.6%) and the world average (22.7%). In general, Australia's transport-related carbon emissions are much higher than those of developing countries (ABS 2001).

On a per capita basis, Australia is exceedingly high in carbon emissions overall and in the transport sector in particular. In 1994, the per capita emissions by transport in OECD Europe was only 1936 kg CO_2, whereas Australia's was more than double that figure, amounting to 4183 kg CO_2 (ABS 2001).

Table 1 gives a brief description of energy use (petroleum, coal and electricity) in seven major sectors (agriculture; hunting and trapping; forestry and fishing, mining, manufacturing, electricity, construction, transport and other services). There are significant differences among the different sectors in terms of how much energy is consumed and what energy product is the main contributor. For example, the manufacturing sector consumes the most petroleum and electricity among all sectors in the economy, whereas the electricity-generation industry uses the most coal. The construction sector relies on petroleum entirely. However, other services sectors use an extremely large amount of electricity as an intermediate input. Transport relies heavily on petroleum goods, for that is the main fuel for road and air transport. The agriculture, hunting and trapping, forestry and fishing sector does not require coal in production, but does require petroleum and electricity. Mining uses all three energy products, but petroleum is its major input. We can see that manufacturing is the dominant energy-consuming sector, whereas petroleum, coal and electricity consumption, together, are just 3 PJ less than all of the consumption in the other industrial sectors. The figures in parenthesis in Table 1 are monetary values of the fuel consumption. Overall, petroleum accounts for about 77% of the petroleum and coal consumption measured in US dollars. In all of the sectors except electricity, petroleum consumption in monetary value exceeds 90% of the petroleum and coal consumption measured in US dollars.

Table 1 Energy use by industry, 1993, adjusted from ABS.

Product	Agriculture; hunting and trapping; forestry and fishing PJ (m$)	Mining PJ (m$)	Manufacturing PJ (m$)	Electricity Generation PJ (m$)	Construction PJ (m$)	Transport PJ (m$)	Other services (m$)
Petroleum	88 (2728)	176 (5456)	2003 (62093)	167 (5177)	62 (1922)	360 (11160)	143 (4433)
Coal	0	19	412	1363	0	4	4

	(0)	(285)	(6180)	(20445)	(0)	(60)	(60)
Electricity	9	38	206	76	0	7	108

Source: ABS, Energy and greenhouse gas emissions accounts, 4604.0, 1992-93 to 1997-98. P.32 The figures in parentheses are the monetary values of the energy consumed in each sector. The prices for fuel have been converted into USD/GJ. The prices for petroleum and coal are 31 USD/GJ and 15USD/GJ, respectively[2].

As shown in Table 2, although manufacturing consumes the largest amount of energy, its greenhouse gas emissions are lower than those of the largest emission industry – electricity generation, which accounts for nearly 50% of all industrial greenhouse gases emissions. Household emissions are significant, higher than emissions from each of the three sectors: agriculture, construction and other services. Interestingly, household methane and nitrous oxide emissions are the highest of all the industrial sectors individually. In addition, household methane and nitrous oxide emissions are even higher than the summation of all the industrial sectors.

Table 2 Australian contributions of greenhouse gas emissions, 1992-93

Industry	Carbon dioxide (CO_2) CO_2-e Gg (a)	Methane (CH_4) CO_2-e Gg (a)	Nitrous oxide (NO_2) CO_2-e Gg (a)	Total CO_2-e Gg (a)
Agriculture; hunting and trapping; forestry and fishing	5976	21	56	6053
Mining	10940	17	29	10986
Manufacturing	52122	40	274	52436
Electricity generation	134790	30	436	135256
Construction	4240	12	41	4293
Transport (b)	24882	178	382	25442
Other services (c)	8312	35	164	8511
Households	38175	2045	1974	42194
Total	**279437**	**2378**	**3356**	**285171**

Source: ABS, Energy and greenhouse gas emissions accounts, 4604.0, 1992-93 to 1997-98. P.46

(a) One billion grams. Equivalent to one thousand tonnes.
(b) Includes: road freight transport, bus transport, taxi transport, hire car service. Excludes industrial and household use of private motor vehicles.

[2] Prices were obtained from indexmundi.com. http://www.indexmundi.com/commodities/?commodity=crude-oil&months=300

(c) Other services include water and gas.

Transport production requires petrol, electricity and other goods. This allows separation of energy and non-energy inputs in the intermediate production process. Though in accordance with the “KLEM” (capital-labour-energy-materials) approach—a widely used method of energy and environmental CGE modelling—the appropriate approach to introducing energy as an input into the production function has been under investigation for at least a decade (Lecca, Swales & Turner 2011). Some suggest that energy should be treated as one of the primary input factors (Hertel & Mount 1985), while others treat energy as an intermediate input (Hanley et al. 2009). The latter approach was adopted in this study.

In the simulations presented in this research, the Leontief function in the transport sector is specified in the upper nest and a CES function of domestic and imported commodity composites in the lower nest. Both domestic and imported fuel were assumed to be shocked by efficiency technology.

3.3 Database

The 35-sector database used for ORANI-G was based on the ABS 1993-1994 Input-Output Tables. Using supplementary data from the ABS, the 108 sector tables were further disaggregated into a 119-industry, 122-commodity database. However, in this study, we used the aggregated 35-sector, 37-commodity database because it was the best data we could get access to. There are several limitations to the aggregated database, which could be overcome by using the disaggregated one. For example, petrol and coal are integrated into one commodity in the Australian input-output table (ABS 2015). Therefore, when petrol use is shocked, so is coal use. Since in the transport sector, input coal consumption is a small fraction of total fuel use (see Table 1), however, we concluded that this would not greatly affect the simulation results. Besides, commodity transport in the aggregated database included road transport, rail transport, water transport, air transport and transport services. The ideal shock would be imposed on the road sector only, but because of the database limitations, the best we could do was shock the entire transport sector.

3.4 Treatment of the standards in the model: A cooperative game between producers and consumers

The light vehicle efficiency standards can be viewed as a pre-play claim by an arbitrator in a cooperative game. If the claim is credible, players would switch to another equilibrium of the same game and achieve a more desirable outcome. Suppose there are two players, the producer and the consumer, in a game of selling and buying efficient vehicles. The producer can choose to produce fuel-efficient cars or not to produce. The consumer can choose to buy more efficient cars or. The payoff matrix of the game is shown in the table as follows. If the producer does not sell efficient cars, and the consumer does not want them, the utility for both is 10, for the consumer can realise her utility by buying a less efficient car while the producer still receives the profit from selling it. If the producer does not sell the efficient car which the consumer desires, both have zero payoffs, because no trade is made. This applies to the case where the producer produces efficient cars but the consumer has no inclination to buy. In the fourth case, when the seller produces efficient cars and the buyer purchases it, a win-win situation is achieved. In this game, the strategy profiles, $([x_1].[x_2])$ and $([y_1].[y_2])$ are pure Nash equilibria. There exists a mixed strategy Nash equilibrium, but we do not discuss it here. In both pure strategy Nash equilibria, the consumer could not achieve a higher pay-off by switching her strategy, taking into account what the other player chooses. Unfortunately, players may not choose to play the strategies that lead to a Pareto efficient equilibrium $([y_1].[y_2])$ due to their own beliefs. Thus, arbitration before playing the game has a role to play.

Table 3 The pay-off matrix of a game between a producer and a consumer.

		Consumer	
Producer		Do not buy efficient cars (x_2)	Buy efficient cars (y_2)
	Do not sell efficient cars (x_1)	10,10	0,0
	Sell efficient cars (y_1)	0,0	15,15

Since the consumer might be myopic about the benefit of purchasing an efficient car, the "perceived" payoff matrix might be distorted by a short-sight factor. The firm may also overestimate the cost of producing a fuel efficient car, thus a distorted payoff matrix is presented as shown in table 4. The focal equilibrium reached in the distorted game is to not purchase or sell efficient cars. This equilibrium, $([x_1].[x_2])$, in fact, is not truly welfare maximised for each player. Therefore, the policy maker can help the players to identify a more beneficial equilibrium than the equilibrium without an impartial arbitrator. Even if the arbitrator cannot correct the myopia of the firm and the consumer, it can perturb the game to an equilibrium which both players do not like by simply announcing publicly that all the players should implement this equilibrium, adopting a stringent vehicle efficiency standard. If each player believes that the other player will accept the arbitrator's suggestion, then each player will find it best to do as the arbitrator suggested, given the fact that the policy recommendation is an equilibrium.

Table 4 The distorted pay-off matrix of a game between a myopic producer and a myopic consumer.

		Consumer	
Producer		Do not buy efficient cars (x_2)	Buy efficient cars (y_2)
	Do not sell efficient cars (x_1)	10,10	0,0
	Sell efficient cars (y_1)	0,0	8,8

An obvious example of the higher fuel efficiency of new cars is shown in figure 1. The 2016 Toyota Corolla has 37 miles per gallon (MPG) compared to the 1994 Toyota Corolla, which has 27 MPG. The newer model emits 277g CO_2 per mile, much smaller than that of the older model, 370g CO_2 per mile. While new vehicles are considerably more fuel efficient than older vehicles, the average fuel consumption by passenger vehicles remained at around 11.5 litres per 100 kilometres between 1998 and 2007. This is in part due to the relatively slow drop in the average age of passenger vehicles which has inhibited efficiency gains. In 1999, the average age of passenger vehicles was 10.3 years, while in 2009 this figure was 9.7 years (shown as figure 2).

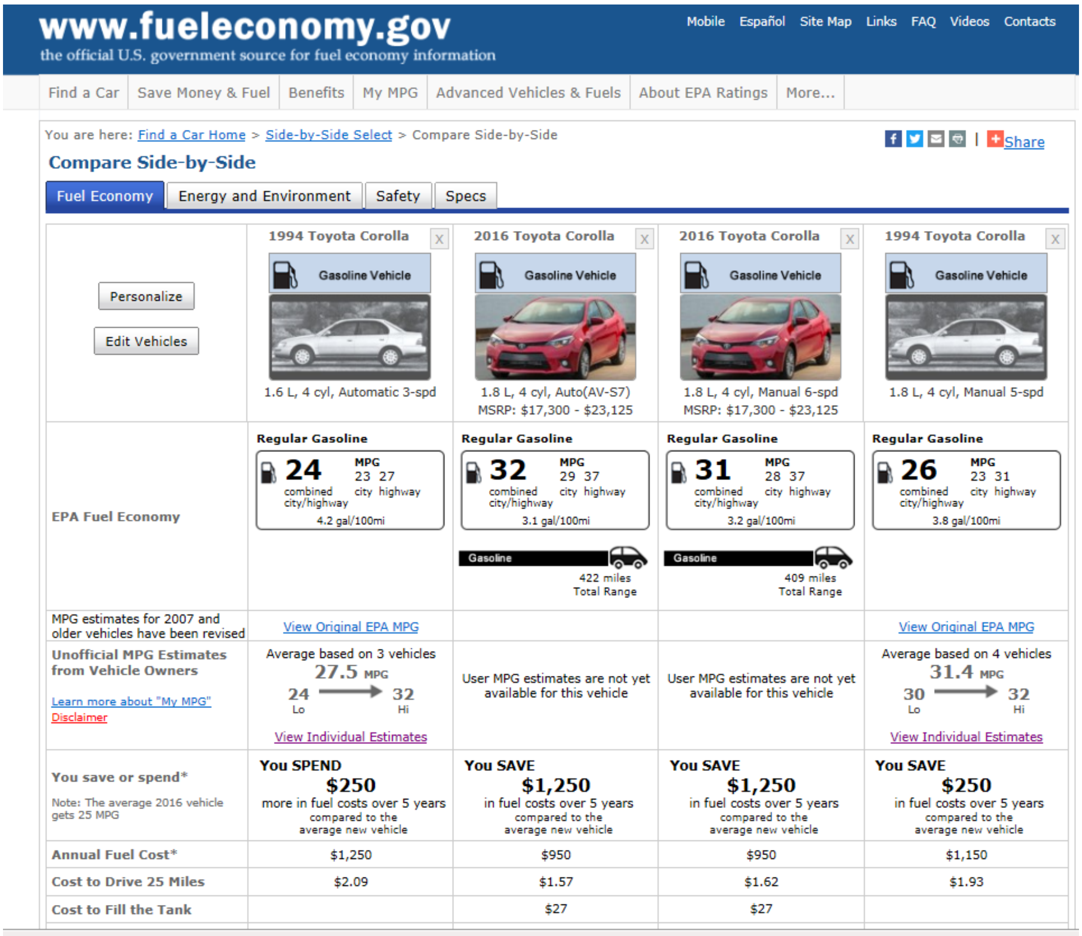

Figure 1 Comparison between 1994 and 2016 Corolla, Toyota, prices in USD.

Source: www.fueleconomy.gov

Therefore, for the policy scenario, we simply simulate a technological shock on the transport fuel use. No costs have been considered due to the above analysis from a game theoretic point of view.

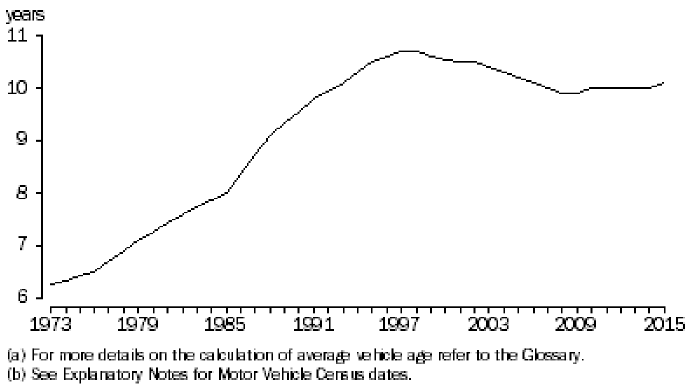

Figure 2 AVERAGE VEHICLE AGE(a) OF REGISTERED VEHICLES.[3]

4. Simulation results

4.1 Baseline Scenario

4.1.1 Forecast the technology improvement under the baseline scenario

Here we collect the time series data of the average rate of fuel consumption (L/100km) to forecast the fuel efficiency level in the predictive year 2025. The fuel efficiency, measured in km/L, is the inverse of the average rate of fuel consumption. Figure 3 illustrates the evolution of average fuel efficiency among Australian automobiles from the 1970s to the 2010s. There are many factors that may affect the rises and falls in fuel efficiency, but clearly a linear upward time trend is observable in this graph. Starting from 6.993 km in 1976, Australian vehicles first had a slight drop in fuel efficiency in 1979, before it increased to 7.1429 in 1985. It remained at the same level till 1988, then fell again in the following three years. Afterwards, cars became more efficient each year in the 1990s. The 2000s saw a fluctuation of fuel efficiency between 7.1409 and 7.3529. The fuel efficiency reached the highest level in 2014, which is the latest data available.

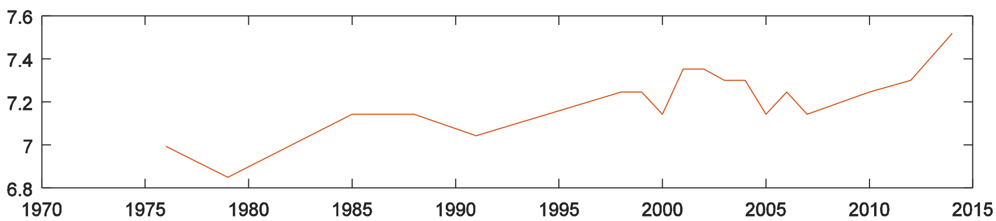

Figure 3. Average fuel efficiency of Australian fleet vehicles from the 1970s to the 2010s.

Here I use a simple regression model with a deterministic linear trend to predict the average fuel efficiency in model year 2025 without taking any mandatory policies.

The linear regression model is given by

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[3] Motor Vehicle Census, Australia, 31 Jan 2015 http://www.abs.gov.au/ausstats/abs@.nsf/mf/9309.0

$$y_t = \beta_1 + \beta_2 x_t + \epsilon_t \quad (6)$$

where y_t is the fuel efficiency of year t, x_t is the year t. Assume that ϵ_t is i.i.d. $N(0, \sigma^2)$.

I chose to use the Bayesian method for the regression because the Bayesian approach incorporates a prior belief of the coefficients that are of interest with the data. Next I specify how I chose the hyperparameters for the parameters. An independent Normal-Gamma prior is specified as follows. The assumption is no prior dependence between β and h, where $\beta = (\beta_1, \beta_2)'$ and $h = \frac{1}{\sigma^2}$ is the error precision. In particular, we assume $p(\beta, h) = p(\beta)p(h)$ with $p(\beta)$ being Normal and $p(h)$ being Gamma.

$$p(\beta) \sim N(\underline{\beta}, \underline{V}) \quad (7)$$

$$p(h) \sim G(\underline{s}^{-2}, \underline{\nu})) \quad (8)$$

Now we explain how to elicit an informative prior for the regression.

The fuel efficiency ranges from 6.993 to 7.5188 kilometres per litre. A regression model which fits well might have errors that typically are of the order of magnitude of 0.525 kilometres per litre at most. This suggests that σ might be roughly 0.25, that is, since the errors are Normally distributed with mean zero, if $\sigma = 0.25$ then 95% of the errors will be less than 1.96×0.25=0.49 kilometres per litre in absolute value. Since $h = \frac{1}{\sigma^2}$, this suggests that a reasonable prior guess for h would be $\frac{1}{0.25^2} = 16$. Thus, we set $\underline{s}^{-2} = 16$. Nevertheless, as this is a relatively crude guess, I would attach little weight to it by setting $\underline{\nu}$ to a value which is much smaller than T. Since $T = 18$, setting $\underline{\nu} = 5$ is relatively noninformative. Loosely speaking, we are saying our prior information about h should have approximately 28% of the weight as the data information (i.e. $\frac{\nu}{T} = 0.28$).

For the regression coefficients, we set:

$$\underline{\beta} = \begin{bmatrix} 0 \\ 0.2 \end{bmatrix} \quad (9)$$

$$var(\beta) = \begin{bmatrix} 0.2^2 & 0 \\ 0 & 0.1^2 \end{bmatrix} \quad (10)$$

$$\underline{s}^{-2} = 16 \quad (11)$$

$$\underline{\nu} = 5 \quad (12)$$

Our prior mean implies that if explanatory variable x_t is increased by one unit and all other explanatory variables are held constant, the fuel efficiency of the automobile tends to increase by 0.2 kilometres per litre.

All these guesses about the regression coefficients are rather rough, so it makes sense to attach a large prior variable to each of them. For example, suppose our prior information about the intercept is very uncertain. Therefore, we might want $var\left(\underline{\beta_1}\right) = 0.2^2$ (i.e. -the prior standard deviation is 0.2 and, hence, we are attaching approximately 95% prior probability to the region {-0.98, 0.98} which is a relatively wide interval. If we think it highly probable that the effect of time would be between 0 and 0.4, we would choose $var(\beta_2) = 0.01 = 0.1^2$ (choose a prior standard deviation for β_2 of 0.1).

Note that we have set all the prior covariances to zero. This is commonly done because it is often hard to make reasonable guesses about what they might be. In this case, the prior information implies that β_J might be uncorrelated with those for β_i when $i \neq j$. This completes our specification of an informative natural conjugate prior for the parameters of our model.

The posterior is proportional to the prior times the likelihood. However, the joint posterior density for β and h does not take the form of any conventional form, so the Gibbs Sampler is required to obtain the posterior simulation. Fortunately, the conditionals of the posteriors are simple; they has the convenient forms as follows,

$$p(\beta|y,h) \sim N\left(\bar{\beta},\bar{V}\right) \tag{13}$$

$$p(h|y,\beta) \sim G(\bar{s}^{-2},\bar{v}) \tag{14}$$

$$\bar{v} = \underline{v} + N \tag{15}$$

$$\bar{s}^{-2} = \frac{(y-X'\beta)\prime(y-X'\beta)+\underline{vs}^{-2}}{\bar{v}} \tag{16}$$

Implied by the Bayesian rule, if an initial draw is taken from $p(h|y,\beta)$, calling it $h^{(0)}$, then taking a random draw from $p\left(\beta|y,h^{(0)}\right)$ is a valid draw of $p(\beta,h|y)$ (Koop, 2003).Formally, the Gibbs sampler takes the following procedures:

Step 0: Choose a starting value, $h^{(0)}$.

For $s = 1,2,\ldots,S$.

Step 1: Take a random draw, $\beta^{(s)}$ from $p\left(\beta|y, h^{(s-1)}\right)$.

Step 2: Take a random draw, $h^{(s)}$ from $p\left(h|y, \beta^{(s)}\right)$.

Following these steps will yield a set of S draws, $\theta^{(s)}$ for $s = 1, \dots, S$, where $\theta^{(s)} = [\beta', h]'$. After dropping the first S_0 of these to eliminate the effect of $\theta^{(0)}$, the remaining S_1 draws can be averaged to create estimates of posterior features of interest. Under the weak law of larger numbers, the function $\hat{g}_{S_1} = \frac{1}{S_!}\sum_{s=S_0+1}^{S} g(\theta^{(s)})$.

Then $\hat{g}_{S_1}$ converges to $E[g(\theta)|y]$ as S_1 goes to infinity.

When $S_0 = 1000$, $S_1 = 10000$, the results are shown in Table 5. However, I will refrain the interpretations of the posterior because the interest is in the prediction of the fuel efficiency in 1994 and 2025. Geweke's convergence diagnostic CD and numerical standard error (NSE) are shown in Table 5. The Geweke's CD indicates that convergence of the MCMC has occurred (the absolute value of CD is smaller than 1.96). The NSE indicate that our estimates are quite accurate.

Table 5 Prior and Posterior Results for θ when $S = 11000$.

	Prior	Posterior	Standard error	Geweke's CD	NSE
β_1	0	-0.1114	0.633182	0.768284	0.006332
β_2	0.2	0.00366	0.000317	-0.7975	3.17E-06
h	16	38.52077	11.50689	-0.1396	0.115069

We want to carry out predictive inference on T unobserved values of the dependent variable, which we will denote by $y^* = (y_1^*, y_2^*, \dots, y_T^*)'$,

which are generated according to

$$y^* = X^*\beta + \epsilon^*, \tag{17}$$

where ϵ^* is independent of ϵ and is $N(0, h^{-1}I_T)$ and X^* is an $T \times k$ matrix analogous to X, containing the k explanatory variables for each of the T out-of-sample data points.

The predictive density is calculated as

$$p(y^*|y) = \iint p(y^*|\beta, h, y)p(\beta, h|y)d\beta dh \tag{18}$$

The fact that ϵ^* is independent of ϵ means that y^* is independent of y, and, hence, $p(y^*|\beta, h, y) = p(y^*|\beta, h)$, which can be written as

$$p(y^*|\beta, h) = \frac{h^{\frac{2}{T}}}{(2\pi)^{\frac{2}{T}}} \exp[-\frac{h}{2}(y^* - X^*\beta)'(y^* - X^*\beta)] \quad (19)$$

This can be done by Gibbs sampling again, since we know that anything the Bayesian rule may wish to calculate about the parameter vector θ will have the form

$$E[g(\theta)|y] = \int g(\theta)p(\theta|y)d\theta \quad (20)$$

for some $g(\theta)$.

If we set $g(y^*) = y^*$ and $g(y^*) = y^{*2}$, we will be able to calculate the predictive mean and variance. Furthermore, if $y^{*(s)}$for $s = 1, \dots, S$ are draws from $p(y^*|y)$, then

$$\widehat{g_y} = \frac{1}{S}\sum_{s=1}^{S} g\,(y^{*(s)}) \quad (21)$$

The Gibbs sampler for the required prediction involves the following steps:

For every $\beta^{(s)}$ and $h^{(s)}$, provided by the Gibbs sampler, take a draw, $y^{*(s)}$ from $p(y^*|\beta, h, y)$. Since the latter density is normal (Eq.(19)), such a strategy is rather simple. We now have $\beta^{(s)}, h^{(s)}$ and , $y^{*(s)}$ for $s = 1, \dots, S$. The rules of probability say that

$p(\beta, h, y^*|y) = p(y^*|\beta, h, y)p(\beta, h|y)$ and, hence, the strategy of first drawing from the posterior, then drawing from $p(y^*|\beta, h, y)$ will yield draws from $p(\beta, h, y^*|y)$. Therefore, our set of draws $\beta^{(s)}, h^{(s)}$ and, $y^{*(s)}$ thus created can be used to evaluate any predictive feature of interest using Eq. (21).

Using these methods, we find that the predictive mean of the fuel efficiency in 2025 is 7.3034 kilometres per litre and the predictive standard deviation is 0.1749. Figure 4 presents a plot of the predictive density. This figure is a histogram of all the draws, $y^{*(s)}$ for $s = S_0 + 1, \dots, S$. The graph shows that this dataset does not allow for very precise predictive inference. Although the best prediction of the fuel efficiency in the year 2025 is roughly 7.3 kilometres per litre, the prediction allocates non-negligible probability to the fuel efficiency being less than or more than 7.6 (see Figure 4).

For year 1994, the predictive mean and standard error is 7.1880 and 0.1739 respectively. Therefore, the percentage change of the fuel efficiency from year 1994 to 2025 is 1.61%, which is treated as the technology improvement in the baseline scenario.

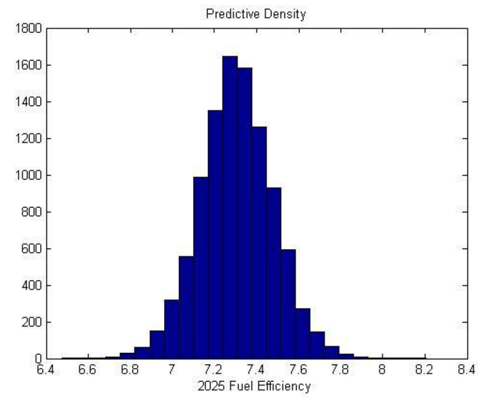

Figure 4 Predictive density of fuel efficiency in 2025.

4.2 Simulation results for baseline scenarios

Two simulations are run in baseline scenarios. The first simulation is a technological improvement in the transport production regarding the intermediate input of fuel. In this simulation, a technological shock was forced in the fuel efficiency of transport that translated into an increased fuel efficiency in the taxi service. The second simulation is a taste shift in the household fuel consumption. Households will be able to achieve the same utility of driving by using less petrol per kilometre. A special treatment is imposed on the second scenario where the household consumes less petrol per kilometre travelled. The utility function in the ORANI-G is the Stone-Geary/Linear Expenditure System (LES). The household is assumed to consume all 37 commodities, including petrol, produced by firms from local and overseas producers. If the quantity of the commodity consumed by the household drops, then this would have a negative effect on the overall household utility. This assumption, however, is problematic in the second policy scenario where the household maintains the same utility of driving by adopting more fuel-efficient cars, thus reducing the average fuel consumption per kilometre travelled. To alter this assumption of the utility function, we introduced another variable, 'the effective household consumption' for petrol, taking into account the technological change of fuel use. If we do not take this alternative calculation, the household welfare will decrease after a taste shift is implemented, leading to an unreasonable result. Another way to look at this alternative approach is that we added another nest in the consumer's utility function. We replaced the petrol commodity with the private transport service, and put the petrol down in a nest as an intermediate input to provide this commodity of private transport service. Historic figures show that fuel-efficient cars do not cost more than the inefficient ones (see figure 4), therefore we did not put the transport equipment down as an intermediate input. Both shocks of the industrial and final household demand scenarios have the same amount of technological shock, -1.6% on the shocked parameters, a1_s (industry) and a3_s (household). The simulations were carried out in long-run scenarios.

4.2.1 Baseline Scenario 1: An industry shock

First, I present the results of the baseline scenario 1 where no regulation is implemented. Table 5 shows the macro results for this simulation. For the simulation result of an industrial fuel efficiency improvement in the taxi service, we see an overall increase in GDP as expected. This technological shock is equivalent to a productivity shock, leading to positive outcomes for the economy. As shown in table 6, the real GDP from expenditure side increased by 0.02%. Consumption of final demanders household, government and export all increased by 0.01%, while real aggregate real investment expenditure increased by0.07%. This shock also expanded the volume of import by 0.02%. From the income side, technology contributed the most, 0.018% in the increase of GDP, followed by capital, 0.008%. Taxes from industry decreased by 0.004%, due to an overall decrease in intermediate input use.

Table 6 Simulation Results for Baseline 1 (1.6% industrial shock on transport fuel use) and Baseline 2 (1.6% household shock on petrol consumption). The number is the percentage change.

Description	Baseline1: Industry	Baseline 2: Household
Real GDP from expenditure side	0.02	-0.01
Real household consumption	0.01	-0.01
Quantity, collective export composite	-0.3	-0.01
Aggregate real government demands	0.01	-0.01
Import volume index, C.I.F. weights	0.02	-0.01
Aggregate real investment expenditure	0.07	-0.01

Figure 5 shows the selected industrial results of an exogenous fuel efficiency shock on the taxi service. Four industries, mining, petrol, electricity and transport are of interest because these are the major carbon emitters in the Australian economy. The blue bar in Figure 5 illustrates the overall output of each industry (the same as commodity). Petrol output of the local producers decreases the most, due to the mechanical change of 1.6% in transport fuel use. The orange bar represents the percentage change of intermediate demands for the transport sector since the transport output grew by 0.28%, all the intermediate input use increased by the same percentage as assumed in the Leontief production model, except for petrol, which has a slight 0.28% rebound (1.6%-1.32%). Mining, the major upstream industry of petrol, shrank by a third of the drop of the petrol industry. Electricity and gas were not affected.

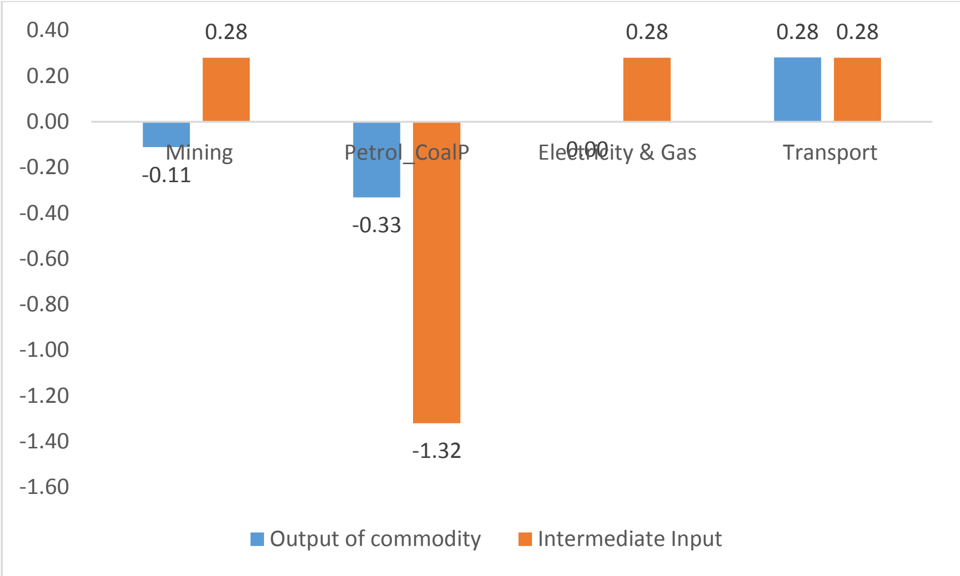

Figure 5 Output changes and intermediate input changes in transport sector of a baseline simulation.

This technological shock improved the transport productivity, and the household benefited from this change. The real income for households increased, leading to welfare improvement. However, the income percentage is small, so the growth of the commodity consumption is almost homothetic (with nearly constant budget share), around 0.02%. Taxi service increased most, by 0.13%, while the only commodity less demanded in is education, which dropped by 0.01%.

4.2.2 Baseline Scenario 1: A household fuel use technological shock

In the next baseline scenario, a simulation on household fuel use improvement has been designed. The household consumes petrol to produce the private road transport service. This technical change in the household means that the household will be able to use less petrol to achieve the same amount of private transport utility. We use an effective consumption variable including this technical change instead of the usual real consumption of the commodity.

As expected, household welfare improves. The household is able to spend the savings from the improved fuel efficiency on the consumption bundle that provides the highest utility for it. Household demand for all commodities increases by 0.3-0.5%, except for petrol, which decreases by 1.56%, meaning a 0.04% rebound (=1.6%-1.56%). The expected savings of fuel from mechanical change is 1.6%, but 25% of the savings are rebounded due to the real income change from higher efficiency. This level of rebound effect is approximately the same magnitude as the industrial rebound.

At the macro-level, the household fuel use improvement has a small but negative effect on GDP. Table 5 shows that real GDP, all the final demanders' consumption decreased by 0.01%. The overall household demand dropped, but the real household welfare improved by 0.03%. Since the long-run closure treated capital stocks as adjustable, the excess capital stocks flowed away from the Australian economy, especially significant in 'dirty industries', such as mining, which plunged by 0.05% in terms of capital use, following the output of petrol and coal, 0.39%. Outputs for these two sectors shrank by 0.06% and 0.39%, respectively. Though the electricity and gas output has grown by 0.01%, this is not large enough to offset the overall carbon emissions reduction.

In this simulation, the biggest winner, the household, could actually consume more with less “real income”, but the losers, mining and petrol producers, will feel pained to cut their production. Unfortunately, we do not observe any decoupling of economic growth and emissions reduction. The economic activity has to level off.

4.3 Policy scenario combined with industrial and household efficiency improvements

Based on the econometric forecast, the average fuel efficiency improvement in all Australian passenger vehicles under the mandatory standard would be 3% higher than that in 1994. Figure 6 shows the difference between the average fuel use (litres) per 100 kilometre under the baseline and the policy scenario from 1994 to 2025. The policy simulation combined the 3% efficiency shock in the supply side (transport service production) and the 3% taste shift in the demand side (household petrol consumption). Results are expected to be in the same direction of as summation of the two baseline scenarios, but with a larger magnitude in every variable. With regards to the shock on the taxi service, a positive effect on GDP and household consumption will be foreseen, which might be offset by the demand side shock on petrol consumption. The direct rebound effect comes from two sources; the first one is the increase in the industrial transport sector for the petrol use (corresponding to the baseline scenario 1), while the second is from the household consumption due to the relative real income increase use (corresponding to the baseline scenario 2). The indirect rebound effect derives from many possible, subtle roots. When the GDP increases, many of the industrial outputs increase, and the intermediate input petrol needs to rise in tandem, as assumed in the Leontief un-substitutable technology. Each of the “winning” industrials will contribute to the rebound effect of petrol in proportion to its output growth. In terms of final demanders, a reduction in transport price could induce more transport service export; the same applies to the household. If the emissions concern is only within Australia, we could neglect the export and only focus on the consumption by the household (and the government). However, as climate change is a global issue, it might be more responsible to look at the overall magnitude of the rebound effect, including export. The following context discusses both perspectives.

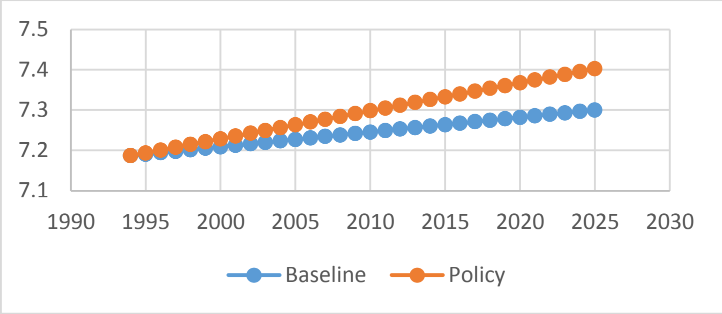

Figure 6 Projection of fuel efficiency in baseline scenarios and policy scenarios.

4.4 Simulation results for the combined policy scenario

First, the macro result shows a minor increase, 0.02%, in GDP. This growth is primarily contributed to by the expansion in investment. Private consumption, as well as government demand both fall by a small fraction. Nevertheless, with less consumption, the utility, as before, is enhanced, due to the fact that less petrol provided the same level of utility from the private transport service.

For most industries, this policy has a relatively insignificant effect on the production, except for petrol and transport production. The green line in Figure 7 represents the percentage change in the gross output of the 35 industries in the Australian economy. This green line is also the intermediate input percentage change for each sector, except for petrol. For example, the output of mining has declined by approximately 0.31%, meaning that all the intermediate input demands fell by the same percentage. The only exception is the transport sector, where an exogenous technological efficiency shock has been imposed upon fuel use.

Mining and petrol outputs shrank by 0.31% and 1.36%, respectively. What we expect, in the industrial sector, is the ideal 3% reduction in transport fuel use, or a reduction of 1% in overall petrol use, equivalent to 3%*2475/8329, where 2475/8329 is the cost share of petrol in the transport sector. The blue line in figure 7 shows that there is a 0.5% behavioural effect that has offset the mechanical effect to 2.5%. But fortunately, the overall production of petrol fell more than expected. Of course, we also have to take into account the household taste shift in petrol consumption. This taste shift is expected to have a 3% reduction in household fuel consumption, which accounts for one third of the petrol output demand. Therefore, another 1% decline in petrol production should be achieved. Therefore, we should see a 2% overall fall in the petrol production sector. The direct and indirect rebound effects, together, contribute to a 0.32% petrol production growth, which is nearly negligible compared to the overall savings.

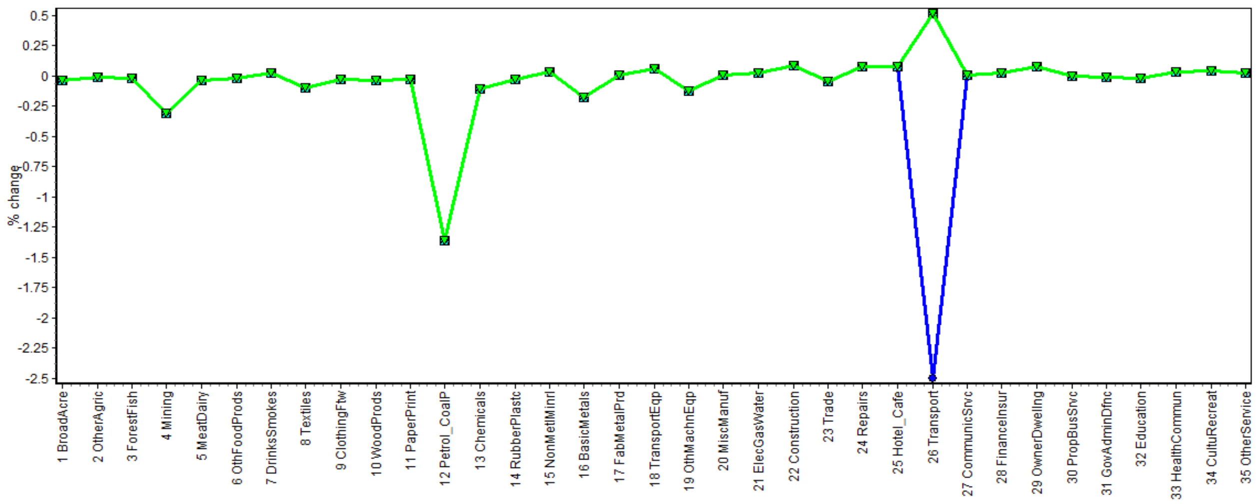

Figure 7 Results of the percentage change of outputs (the green line) and of the intermediate input use the blue line for petrol and green for others).

Similar results are found in the household consumption. The utility of the household has increased by 0.08%, though real income decreased. The consumption for every commodity has grown, except for petrol. However, in terms of effective consumption, petrol has increased by 0.10%. This is because the household purchases new fuel-efficient vehicles under the new policy arrangement, leading to a new equilibrium where less fuel provides the same utility. For example, the consumption change of petrol is -2.9% and the petrol efficiency improvement means that people can use more efficient cars to achieve the same utility provided by the private transport. The efficiency improvement is 3%, therefore, the effective consumption change is 0.10% (=-2.90%+3%). The initial cost of petrol in household consumption is 2715.26 million Australian dollars (see table 7). Following the shock, it would only cost the household $2636.59 m at the initial price to actually increase their effective consumption (utility) by 0.10%. Without the efficiency shock, to gain more utility means spending 0.1% more, $2.79 m on petrol consumption.

For other household consumptive commodities, the effective consumption change is the same as the final consumption change of this commodity in quantities. For example, the commercial transport service consumption increased most among all the commodities, by 0.31%, which is the same as the effective consumption change. The welfare gain from the shock in private transport consumption is the difference between column (5) and (1) in table . In the transport household consumption, the representative household is better off with $28.65 m equivalent value of transport consumption. If we sum up the welfare gain in each commodity, the overall welfare gain would be $18075.4 m.

Table 7 Calculating the effective real consumption measure of welfare.

	Consumption	Cost of	Cost of new	***Effective***	Cost of new

	change % (1)	initial quantity at initial prices (2)	quantity at initial prices (3)	consumption change % (4)	***effective*** consumption at initial prices (5)
Petrol	-2.90%	2715.26	2636.59	0.10%	2718.05
Transport	0.31%	9294.97	9353.62	0.31%	9323.62
Sum		12010.23	11960.21		12041.67

In ORANI-G, the measurement of utility is slightly different. This is done by measuring the change in the consumption of the luxury component of each commodity. If we do not apply the ***effective*** consumption approach, the welfare decreases by 0.01% following this policy scheme, only because of the reduction in petrol consumption.

Now I illustrate how I calculate the welfare change in ORANI-G's model with an altered effective consumption for the luxury component of petrol. To correctly calculate the welfare, I create an ***effective luxury component*** consumption variable, taking into account the technological change. In this case, petrol use shifts by 3% due to the fuel efficiency improvement, and then the effective luxury component consumption is the actual change plus 3%. For other goods, the change in effective consumption remains the same as the luxury consumption change. By this alternative welfare calculation, households are better off by 0.09%, which is slightly smaller than the method calculated by real consumption change in the third decimal, in accordance with the welfare theory that the equivalent variation is smaller than the real consumption measure of welfare.

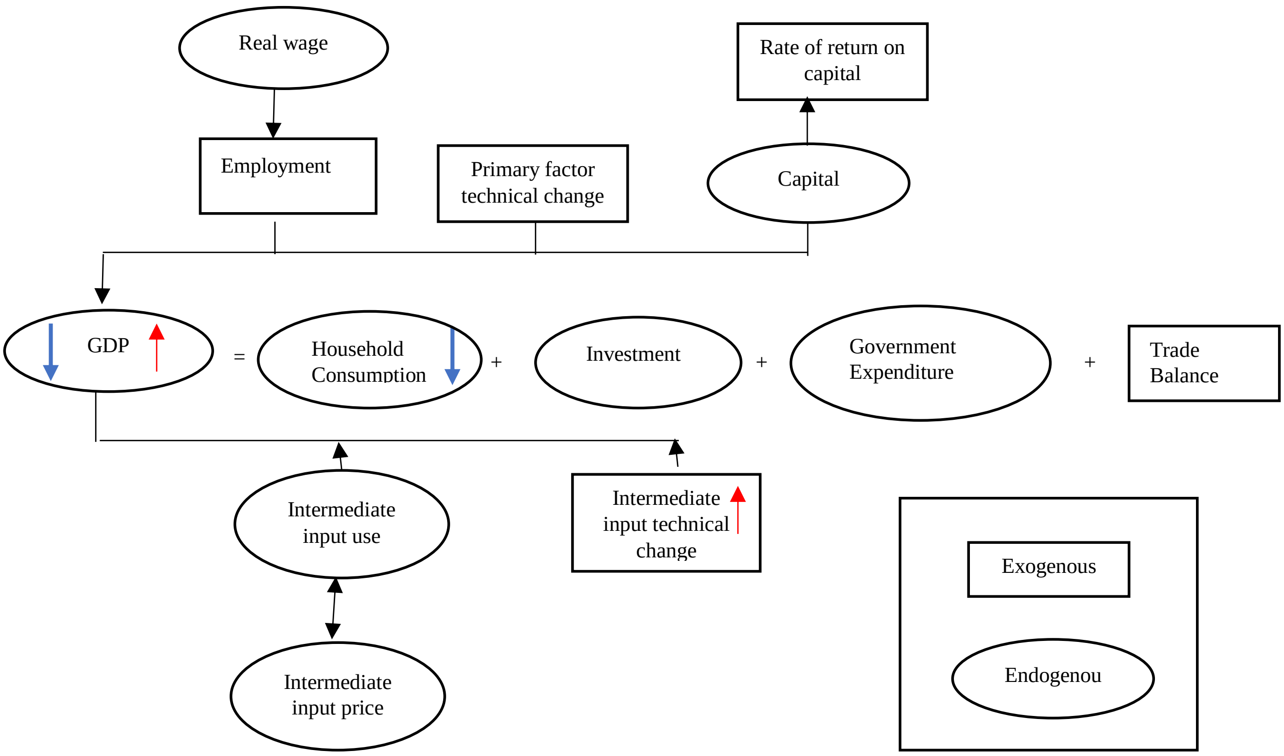

Figure 8 Schematic representation of the technical shock in long-run.closure of ORANI-G.

To summarise the result, I use a flow chart shown in Figure 8 depicting the policy shock in fuel efficiency in the long-run closure. In this typical long-run closure, instead of treating employment endogenously, we assume employment to be fixed while real wages are endogenously determined. Similarly, capital stocks are allowed to vary, relative to a given rate of return on capital, which is exogenously determined. As capital is allowed to flow, the sectoral investment is treated endogenously, following capital stocks adjustments. Household consumption and government expenditure can also change with GDP, but the balance of trade is exogenous. Under these conditions, when shocking the equilibrium with a 3% fuel efficiency improvement in the industrial transport sector and a 3% taste shift in household petrol consumption, GDP grows by 0.02%, with a welfare improvement of 0.09 %. As shown by the blue arrows in Figure 8, the reduction in household petrol use has a negative effect on real GDP growth, while the red arrows represent the positive effect of technology improvement in fuel use on GDP. The result shows that the supply-side shock dominates the demand-side shock, so the Australian economy benefits from this. This growth is decoupled by the fuel consumption. Both household fuel consumption and industrial petrol output decreases in this policy scenario. The rebound effect, to some extent, is negligible.

Table 8 compares the magnitude of rebounds and technical change. From the industrial sector, the rebound is relatively large, in terms of rebound/tech ratio, which is one sixth of the technical change. When aiming at a 3% energy efficiency use in the transport sector, the petrol use in transport only reduces by 2.5%. But in the household demand, rebound is comparatively small, around 3%. So the targeting efficiency level is almost achieved.

Table 8 Magnitude of rebounds in supply-side and demand-side

	Technical change (mechanical effect)	Rebound effects	Overall petrol quantity change	Rebounds/Tech ratio
Industry-Transport	-3%	0.5%	-2.5%	18.3%
Household	-3%	0.1%	-2.9%	3.3%

*-3% means that the petrol use is saved. The positive sign means that the energy is used more, as shown in the rebound effects column.

5. Conclusion

In this study, we explored the magnitude of rebound effects for the Australian economy. The approach was computable equilibrium modelling with a multi-sectoral model. A fuel-efficiency improvement in a specific sector, transport, together with a reduction in fuel use in the household due to adopting fuel efficient motor vehicles, was found to reduce the long-run energy consumption in the whole economy.

However, although household energy consumption may increase due to the technological advancement of the corresponding industrial sector, this increase is offset by the energy savings in its private fuel savings. Contrary to the findings of Hanley et al. (2009), where energy-efficiency improvements in production sectors of the economy induced rebound effects that eventually caused a backfire effect, we find that a single fuel-efficiency improvement scheme induces relatively small rebounds that do not threaten to backfire. In their study, Hanley et al. (2009) used a single-region CGE modelling framework parameterised on data from Scotland. Though Hanley's model and ours are similar, the long-run results are very different in that energy consumption decreases in the economy as a whole in our model. One may argue that the explanation for discrepancies in long-run results is rooted in the differences between the long-run closures in the two studies. The long-run closure in ORANI-G sets rates of capital return as exogenous, while endogenising the overall capital stocks. Therefore an open capital market is implicitly assumed, given that there is no link between capital accumulation and domestic savings. Another long-run closure feature is that real wages are free to adjust in such a way that aggregate employment remains fixed. This would be in line with the fact that the rate of unemployment is determined by mechanisms outside the model in the long run. Finally, government expenditures move together with household expenditures, to accommodate a balance-of-trade constraint. The idea is that, in the long run, the rest of the world may not be willing to fund a growing trade deficit. Aggregate investment follows the aggregate capital stock. However, Hanley et al. (2009) adopted a regional bargaining closure that allows for population growth. This may be the reason for the backfire in energy consumption in the long run.

Results in this study are in line with those of Grepperud and Rasmussen (2004), who examined the role of different types of energy-efficiency improvements in different industrial sectors for the Norwegian economy, using a CGE econometric approach. Although they found that there are substantial discrepancies across industrial sectors with respect to energy sources (electricity and oil), resulting in variations in the reactions to efficiency improvements, the rebound effect does not cause a backfire effect. In our model, we treat different composites (at the aggregate level) in the production process as non-substitutable, whereas Grepperud and Rasmussen (2004) allowed for limited substitution possibilities. It seems that the extent of substitutability among inputs plays a role in the final results arrived at, but the differences are not that significant.

The results show that the rebound effects induced by technological improvements in fuel use have limited negative impacts on energy consumption and carbon emissions. Although this research was tied to a particular light-vehicle emission-standards policy in Australia, which, compared to many other countries, including OECD and developing countries, has long lacked a mandatory standard on fuel efficiency for automobiles, it might have broader applications. Many economies aiming at reducing carbon emissions from stringent fuel-efficiency standards in the transport sector have not adjusted their policy targets in pace with autonomous technology advancement.

Interestingly, the finding that the long-run rebound effect was smaller than that of the short run is the same as confirmed in a study by Allan, Hanley, McGregor, Swales, and Turner (2007), who simulated a 5% energy-efficiency improvement in all industrial sectors in the UK economy. They argued that energy prices fall more in the short run than in the long run, and therefore, demand for energy increases more in the short run than in the long run. This result is counter-intuitive, and many researches have proven the opposite: that the long-run rebound is larger than the short-run one, at least in a partial equilibrium model, because the price elasticity of demand is expected to be greater in the long run (for example, Small & Van Dender, 2007). We attribute the magnitude of the difference between the long-run and short-run of the rebound, again, to the closure assumptions. In the short run, household consumption is fixed while exports can vary. Export elasticities are calibrated with large numbers, whereas a small open-economy theory would be appropriate for Australia. In such a scenario, in the long run, household consumption would be flexible whilst export and import would be fixed. The price elasticities of energy demand for a household are relatively smaller than those calibrated for export. That may explain why energy consumption in the long run does not exhibit high rebound or backfire effects.

6. Limitations

As with many of the economic analysis tools, CGE modelling has its disadvantages. First, CGE models rely heavily on conventional economic theory, which may not be sufficient to capture all the behaviours induced by energy-efficiency improvements; for example, imperfect markets and consumer myopia.

As mentioned before, the database used in this study was aggregated from ABS's 1993-1994 Input-Output table. For some variables, say, transport, the I-O table itself is aggregated. This situation required additional work to disaggregate the energy sector, by resorting to other data sources. In actuality, it is nearly impossible to find other data that would contain detailed energy use in each sector in the economy apart from ABS's IO table. The best we could do was to use the aggregated data, and we believe that in the future, ABS will publish more and more detailed databases for researchers and policy makers to carry out studies that can perform more accurate simulations.

Regarding the production behaviours in ORANI-G, firms are not allowed to substitute capital to energy, or substitute labour to energy. But in many cases, when the substitution happens in capital and labour use, for example, the firm chooses to use mechanised assembly equipment to save labour force, this more often than less, is accompanied by an energy input increase. If this is the case, the rebound effect should be larger than the simulation results reposted here, because the firm will be likely to substitute labour for energy when energy becomes cheaper.

Finally, in ORANI-G, household production is excluded. Therefore, household consumption for each commodity only responds to price, not to the household production process. For example, household private road sector transport is a production function of petrol, labour and private vehicles. If the representative household’s road transport demand increases, petrol use should increase proportionally, if other conditions remain the same. When fuel efficiency increases, more demand for transport would need less petrol than before the efficiency increase. However, in our model, the household is assumed to consume all commodities directly. How much it consumes of each commodity depends on the price elasticity, relative prices and budget constraints. It neglects the fact that the households also produce final goods by using intermediate commodities. This limitation might be overcome by developing a new household utility function, taking into account the possible household production structure. However, this design might be difficult, given that data for household production are unavailable.

References

2001, *Energy and greenhouse gas emissions accounts, Australia*, by ABS.

—— 2015, 'Australian National Accounts: Input-Output Tables, 2012-13 ', viewed 20/09/2015, <http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/5209.0.55.0012012-13?OpenDocument>.

Allan, G, Hanley, N, McGregor, PG, Swales, JK & Turner, K 2006, 'The macroeconomic rebound effect and the UK economy', *Final report to DEFRA*.

Brookes, L 1990, 'The greenhouse effect: the fallacies in the energy efficiency solution', *Energy Policy*, vol. 18, no. 2, pp. 199-201.

CCA 2014, *Light vehicle emissions standards for Australia reserch report*, Melbourne.

Chitnis, M, Sorrell, S, Druckman, A, Firth, SK & Jackson, T 2013, 'Turning lights into flights: Estimating direct and indirect rebound effects for UK households', *Energy Policy*, vol. 55, pp. 234-50.

Chu, S & Majumdar, A 2012, 'Opportunities and challenges for a sustainable energy future', *nature*, vol. 488, no. 7411, pp. 294-303.

Dervis, K & Robinson, S 1982, *General equilibrium models for development policy*, Cambridge university press.

Espey, M 1996, 'Watching the fuel gauge: an international model of automobile fuel economy', *Energy Economics*, vol. 18, no. 1, pp. 93-106.

Greening, LA, Greene, DL & Difiglio, C 2000, 'Energy efficiency and consumption—the rebound effect—a survey', *Energy Policy*, vol. 28, no. 6, pp. 389-401.

Grepperud, S & Rasmussen, I 2004, 'A general equilibrium assessment of rebound effects', *Energy Economics*, vol. 26, no. 2, pp. 261-82.

Hanley, N, McGregor, PG, Swales, JK & Turner, K 2009, 'Do increases in energy efficiency improve environmental quality and sustainability?', *Ecological Economics*, vol. 68, no. 3, pp. 692-709.

Hertel, TW & Mount, TD 1985, 'The pricing of natural resources in a regional economy (New York State)', *Land Economics*, vol. 61, no. 3, pp. 229-43.

Horridge, M 2000, 'ORANI-G: A General Equilibirum Model of the Australian Economy', *CoPS/IMPACT Working Paper Number OP-93*, <www.copsmodels.com/elecpapr/op-93.htm>.

Jevons, WS 1865, *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*, The Macmillan Company (republished in 1906).

Johansson, O & Schipper, L 1997, 'Measuring the long-run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance', *Journal of Transport Economics and policy*, pp. 277-92.

Khazzoom & Miller, S 1982, 'Economic implications of mandated efficiency standards for household appliances: response to Besen and Johnson's comment', *Energy J.;(United States)*, vol. 3, no. 1.

Lecca, P, Swales, K & Turner, K 2011, 'An investigation of issues relating to where energy should enter the production function', *Economic Modelling*, vol. 28, no. 6, pp. 2832-41.

Lovins, AB 1976, 'Energy strategy: the road not taken', *Foreign Aff.*, vol. 55, p. 65.

Michaels, RJ 2012, *Energy Efficiency and Climate Policy: The Rebound Dilemma*, viewed 17/07/2014, <www.instituteforenergyresearch.org/.../NJI_IER_MichaelsStudy_WEB_20120706_v5.pdf>.

Murray, CK 2013, 'What if consumers decided to all 'go green'? Environmental rebound effects from consumption decisions', *Energy Policy*, vol. 54, pp. 240-56.

OECD/IEA 1999, *CO2 emissions from fuel combustion, 1971-1997.*

Sinn, H-W 2012, *The green paradox: a supply-side approach to global warming*, MIT Press.

Small, KA & Van Dender, K 2007, 'Fuel efficiency and motor vehicle travel: the declining rebound effect', *The Energy Journal*, pp. 25-51.

Sorrell, S 2007, *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*, UK Energy Research Centre London.

Sorrell, S & Dimitropoulos, J 2007, 'UKERC review of evidence for the rebound effect: technical report 5—energy productivity and economic growth studies', *UK Energy Research Centre, London*.