

Policy resistance to fuel efficient cars and the adoption of next-generation technologies

Peter Stasinopoulos,* Paul Compston & Haley M Jones

Research School of Engineering, College of Engineering and Computer Science

The Australian National University, Canberra, ACT 0200, Australia

*Email: peter.stasinopoulos@anu.edu.au

Proceedings of the 30th International Conference of the System Dynamics Society

St. Gallen, Switzerland, July 22—July 26, 2012

Abstract

We present a stock-and-flow model that describes the growth in the fuel consumption of the Australian car fleet despite persistent policy intervention by government, compliance and technology innovation by automakers, and shifts in transportation preferences by travellers. To this model, we add processes that describe the adoption by automakers of aluminium bodies-in-white (BIWs) and battery-electric (BE) powertrains, and the competition between automakers of these next-generation technologies and conventional technologies.

The model shows that, in the future, growing congestion and declining oil security could cause the fuel consumption of the car fleet to decline, despite growth in the size of the car fleet. Under these conditions, the adoption of aluminium BIWs could cause fuel consumption to decline further. Also, the adoption of BE powertrains could cause energy (fuel and electricity) consumption to decline faster, down to a point, but then increase the long-term transportation energy consumption by encouraging travellers to continue to drive cars rather than shift to public transportation.

These results suggest that congestion, the price of fuel, and the security of fuel supply have high leverage for influencing car-fleet fuel consumption. Also, next-generation technologies have lower leverage, but this leverage could be enhanced by a competitive market environment.

Keywords

Car, fuel consumption, congestion, oil, steel, aluminium, body-in-white, battery-electric

1. Introduction

1.1. The problem

Car use is a major source of oil consumption and greenhouse gas (GHG) emissions in Australia. The earliest available data shows that the fuel consumption of the Australian car fleet, of which about 90% is petrol consumption, has been generally growing since at least 1998 (Australian Bureau of Statistics 1998-2007). Since fuel is a product of crude oil, a non-renewable resource, any rate of consumption is unsustainable. Recent rates of oil extraction are high, such that they have already peaked for many countries and, if sustained, are forecast to cause currently-known oil reserves to run out within a few decades (Schindler & Zittel 2008).

In response to growth in fuel consumption, GHG emissions, and the price of fuel, the Australian government has implemented policy interventions for new cars, many of which have been resisted in the wider system. Interventions include a series of gradually-declining, voluntary targets for the rated fuel consumption between 1978 and 2005, and for GHG emissions since 2005 (Clerides & Zachariadis 2008; Federal Chamber of Automotive Industries 2010); and the mandatory introduction of fuel consumption labels since 2001 and GHG emissions labels since 2003 (Office of Legislative Drafting and Publishing 2008). Despite compliance by automakers since the early 1980s and a rapid, market-driven decline in the sale of new large cars since 2000 (Australian Automotive Intelligence 2010, p. 28), the fuel consumption of the car fleet continued to grow until 2005. The latest available data shows that this fuel consumption remained stable until at least 2007.

1.2. Why does the problem need a system dynamics approach?

Car-fleet fuel consumption depends not only on the size of the car fleet, but also on the mass of cars, the energy conversion efficiency of powertrains, the driving intensity of cars, and the congestion on the road. These are all factors in accumulations and feedback mechanisms that may have caused the fuel consumption of the average car to remain stable despite the average rated fuel consumption of new cars declining (Australian Bureau of Statistics 1963-2011; Bureau of Infrastructure, Transport and Regional Economics 2009). The effects of accumulation and feedback may have gone unnoticed by policy makers, who seem to persist with similar policies despite limited results.

1.3. Our approach

In this paper, we aim to highlight the dynamical processes that are likely to resist the effects of fuel-efficient car innovations. We explain the growth in car-fleet fuel consumption using a system dynamics model, and investigate the potential effects of wide adoption of lightweight materials and electric powertrains in everyday cars¹. We focus on the Australian context, but, given the appropriate data, our model may be adapted to describe a similar problem in other car-dependent countries. Our review of literature did not uncover any investigations of similar problems that consider the Australian context or that consider future scenarios.

First, we present our dynamic hypothesis in the form of a simplified stock-and-flow model, highlighting our approach, main assumptions, and sources of data; and showing how our

¹ 'Everyday' cars, as opposed to exotic cars (some of which already comprise a relatively high proportion of lightweight materials) or specialised electric cars (which have driving ranges comparable to internal combustion engine cars), both of which are currently priced above the price range of everyday cars.

simulation model fits reference data. Next, we expand our dynamic hypothesis with emerging and potential future processes, and investigate various future scenarios of next-generation technology adoption. Finally, we discuss the implications of our results for policy, identifying high-leverage parameters.

2. Growth in the fuel consumption of the car fleet

2.1. Dynamic hypothesis

We propose a dynamic hypothesis that comprises three interrelated sub-models, described in the following subsections. Our dynamic hypothesis focuses on car transportation, but includes the exchange of travellers between car transportation and public transportation. We developed our dynamic hypothesis using documented relationships, probable values of variables, and reference data.

2.2. Demand sub-model

The ‘demand’ sub-model is shown in Figure 1. It allows cars with various rates of fuel consumption to accumulate into and drain out of the fleet. Since the rate of car production is greater than the rate of car retirement, the car fleet grows. The draining of cars out of the fleet is a source of a significant delay.

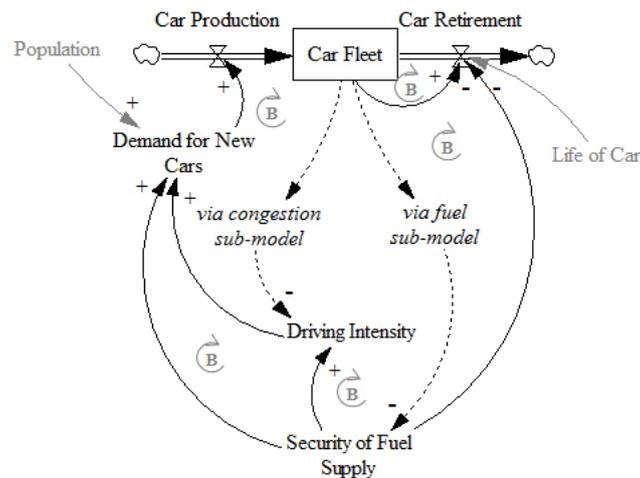


Figure 1. A simplified stock-and-flow diagram of the demand sub-model.

2.3. Fuel sub-model

The ‘fuel’ sub-model is shown in Figure 2. It assumes that (1) travellers will drive cars up to the maximum desired distance, until the travel budget is exhausted, or until a proportion of the saved travel costs is exhausted; (2) travellers all over the world have the same behaviour as Australian travellers such that the share of ‘Proven Oil Reserves’ for each region is constant; and (3) the proportion of all oil consumption by cars is constant.

We include this sub-model in our hypothesis because (1) some evidence is in support of the Jevons Paradox (rebound effect)—a decline in the rated fuel consumption of cars may increase driving in many countries (Hymel et al. 2010; Matiaske et al. 2012; Mizobuchi 2008; Nässén & Holmberg 2009; Small & Van Dender 2007; Su 2011; Wang et al. 2012a; Wang et al. 2012b); and (2) passenger vehicle use and public transportation use have changed inversely

to each other for 25 of the 30 years since 1971 (excluding the period between 1984 and 1991, when the price of oil rapidly declined and then rapidly grew) (Bureau of Infrastructure, Transport and Regional Economics 2011, p. 59).

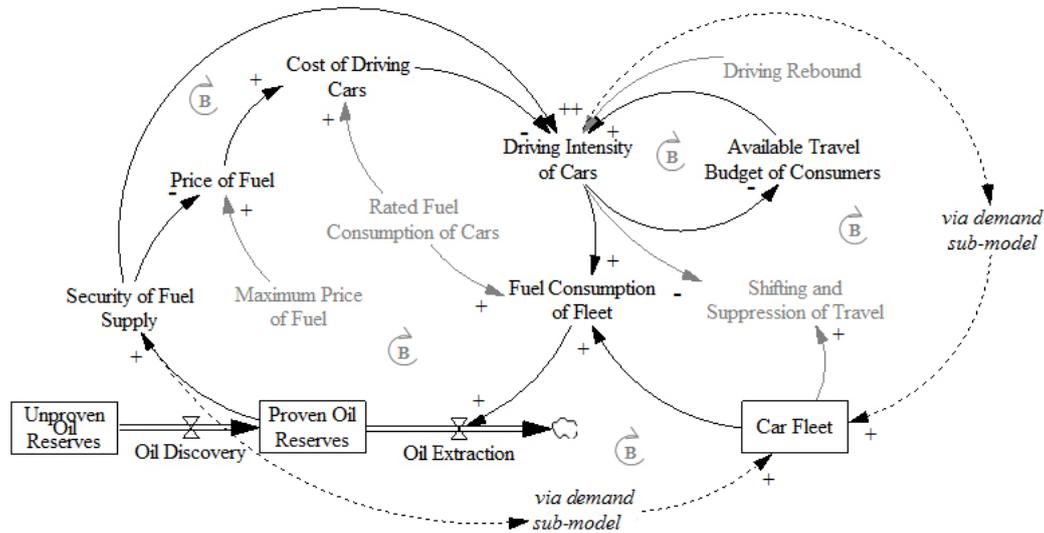


Figure 2. A simplified stock-and-flow diagram of the fuel sub-model.

2.4. Congestion sub-model

The ‘congestion’ sub-model is shown in Figure 3. It assumes that (1) roads are initially congested; (2) growth in population causes growth in the car fleet; (3) travellers respond to decongestion by increasing driving intensity; (4) some people prefer to live on the fringe of the region; (5) governments respond to congestion by building roads; and (6) ‘Road Capacity’ is equal to road length, a statistic for which we found data. The ‘Fractional Rate of Road Building’ is a source of a significant delay.

We include this sub-model in our hypothesis because (1) some evidence suggests that the construction of a few roads in Sydney (Mewton 2005; Zeibots 2003; Zeibots & Petocz 2005), and many roads in the UK and US (Cervero 2001; Goodwin 1996; Graham & Glaister 2002; Hymel et al. 2010; Litman 2003; Noland & Lem 2000; The Standing Advisory Committee on Trunk Road Assessment 1994), may have induced traffic by shifting people from public transportation and generating new car trips; (2) new high-speed roads are currently being constructed in most Australian capital cities, where 64% of the Australians live (Australian Bureau of Statistic 2011); (3) Australian cities, together with North American cities, have the world’s lowest urban densities and the world’s highest proportions of trips made by private motorised vehicles (Kenworthy & Laube 2001), two conditions that suggest that wide urban expansion has occurred; and (4) most Australian cities have reached a travel time budget limit of one hour (Newman & Kenworthy 2011). Similar models of urban expansion and induced traffic are centred on variables such as ‘travel time’ (Sterman 2000). Since Australian data for such variables are unavailable, we centre our sub-model on the variable ‘Congestion’.

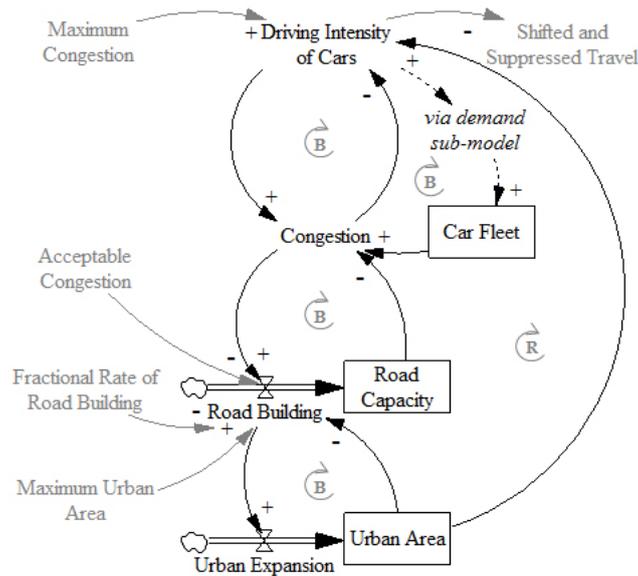


Figure 3. A simplified stock-and-flow diagram of the congestion sub-model.

2.5. Exogenous variables

The following variables are exogenous to our model:

- Demand for new cars, assumed to be such that the car fleet grows in proportion with the projected population growth (Australian Bureau of Statistics 2008)
- Life of car, assumed to be the average life of cars in Australian during the period 1998-2007 (Australian Automotive Intelligence 2010, pp. 28, 44) and independent of changes in driving intensity
- Maximum prices of fuel and electricity
- Initial volume of oil reserves, assumed to be share of the current estimated global volume of oil reserves, proportionally allocated to Australia by population, used by cars
- Available travel budget of travellers
- Maximum congestion (Bureau of Infrastructure, Transport and Regional Economics 2011, pp. 44, 76)
- Acceptable congestion, assumed to reflect the earliest available data (Bureau of Infrastructure, Transport and Regional Economics 2011, pp. 44, 76)
- Maximum Urban Area (estimated from Australian Bureau of Statistics)

2.6. Ignored processes

Our model ignores the following processes:

- Change in the demand for new cars due to a change in the strength of the economy
- Diversity and variation in the rated fuel consumption of cars
- Changes in spending of other goods and services to accommodate changes in spending on driving (Binswanger 2001; Finnveden et al. 2009; Greening et al. 2000; Mizobuchi 2008; Nässén & Holmberg 2009; Thiesen et al. 2008)
- Travellers acclimatising to high prices of energy sources, similar to a ‘drift to low performance’ or ‘eroding goals’ system archetype (Meadows 2009)
- Travel time budget (Ausubel et al., 1998; Marchetti, 1994)
- Changes in the preferences of public transportation mode
- Production and retirement of public transportation vehicles

- Introduction of fast transportation modes, such as high-speed trains, which could allow the urban area to expand (Ausubel et al., 1998; Marchetti, 1994)
- Change in the price of internal combustion engine (ICE) cars due to declining security of fuel supply

2.7. Reference data

The car fleet has operated under a relatively stable set of conditions for most of the last 30 years. Figure 4 compares the behaviour of our simulation model, constructed using the modelling software STELLA™ (version 9.1.2), to reference data sourced from Australian Government statistics. We consider the timeframe 1981-2010, during which we treat the size of the car fleet and the price of fuel as exogenous driving variables. We generate the value of the demand for new car production such that the car fleet grows as in Figure 4(b). We also use actual values of the price of fuel, which has varied considerably for political reasons exogenous to our model, enabling us to calibrate our model.

In 1981, driving intensity is slightly below the maximum level, fuel is plentiful, the fuel consumption rate of cars is high, roads are somewhat congested, and urban areas have room in which to grow. The combination of a growing car fleet and stable driving intensity cause fuel consumption to grow and congestion to grow faster than sufficient new road capacity can be built. From 2005, high fuel prices and maximal congestion encourage travellers to shift to public transportation, car pool, or forego some car trips. These behaviours cause public transportation intensity to grow, driving intensity to decline, and fuel consumption to stabilise.

The behaviours of our simulation model differ from the reference data in two ways. First, in Figure 4(c)-Figure 4(f), our model lags behind the reference data by one year due to our use of stocks to represent the mass of cars, the energy conversion efficiency of powertrains, and the driving intensity of cars, all of which vary in rough proportion with the price of fuel; the stock requires one year to take its intended value. Second, in Figure 4(f), our model does not reproduce the large trough and peak in the reference data (our dynamic hypothesis does not explain these features), but it does reproduce the small variations (which are opposite to the variations in driving intensity) as the price of fuel becomes high.

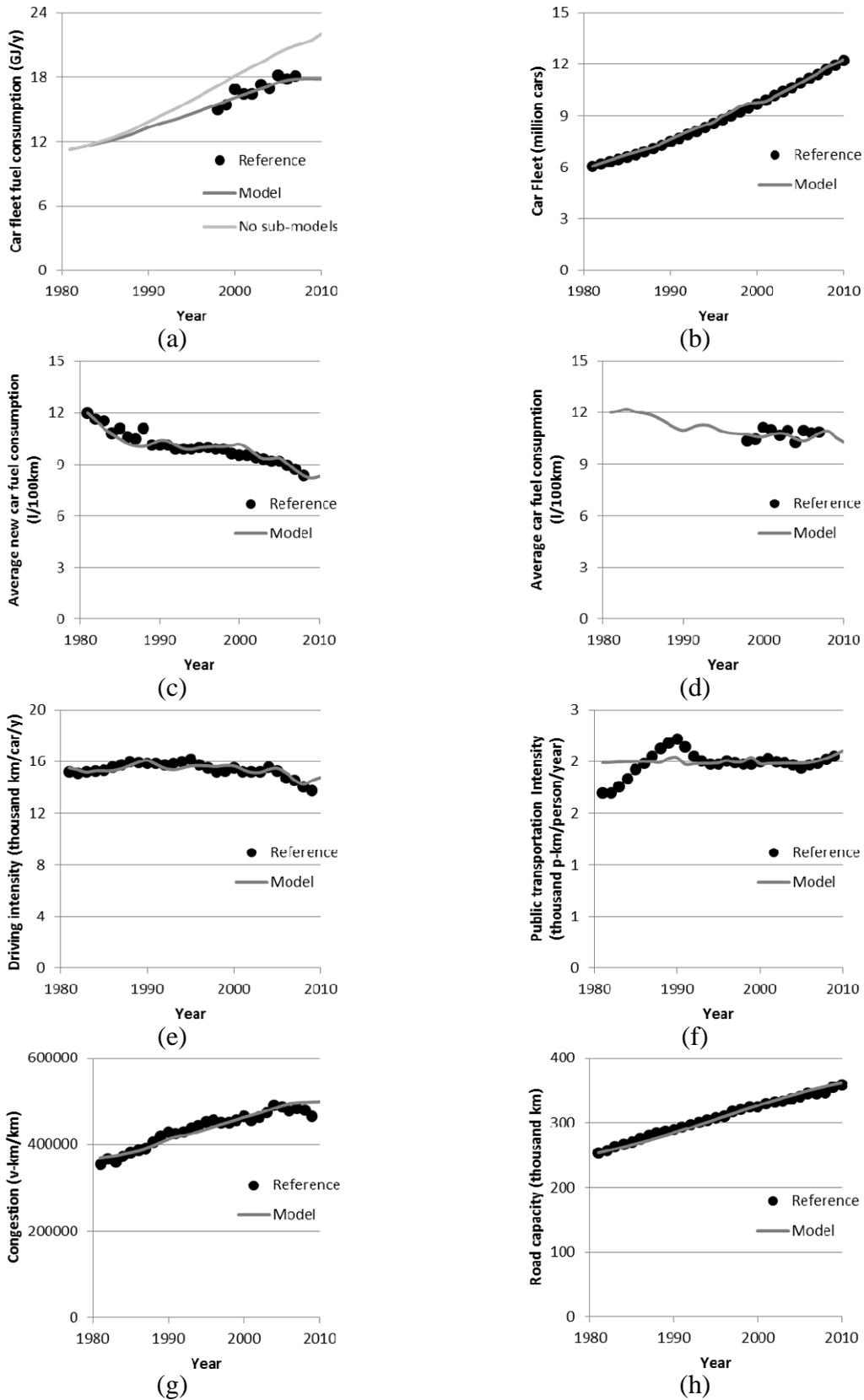


Figure 4. A comparison of the behaviours of the simulation model and the reference data, 1980-2010, for (a) car-fleet fuel consumption (Australian Bureau of Statistics 1998-2007), (b)

car fleet (Australian Bureau of Statistics 1995-2011; Bureau of Infrastructure, Transport and Regional Economics 2011, p. 81), (c) average new car fuel consumption (Bureau of Infrastructure, Transport and Regional Economics 2009), (d) average car fuel consumption (Australian Bureau of Statistics 1998-2007; Bureau of Infrastructure, Transport and Regional Economics 2011, p. 76), (e) driving intensity (Australian Bureau of Statistics 1995-2011; Bureau of Infrastructure, Transport and Regional Economics 2011, pp. 76, 81), (f) public transportation intensity (Bureau of Infrastructure, Transport and Regional Economics 2011, p. 59), (g) congestion (Bureau of Infrastructure, Transport and Regional Economics 2011, pp. 44, 76), and (h) road capacity (Bureau of Infrastructure, Transport and Regional Economics 2011, p. 44).

3. Intervention with lightweight materials and electric powertrains

3.1. The interventions

We investigate the potential effects of wide adoption of aluminium bodies-in-white (BIWs) and battery-electric (BE) powertrains in cars, and the influence of competition between manufacturers of current technologies and these new technologies. We consider the following scenarios:

1. No dynamical processes
2. Baseline: no intervention
3. Body-in-white: Aluminium BIW adoption with competition from steel BIWs
4. Powertrain: BE powertrain adoption with competition from internal combustion engine powertrains
5. Full intervention: scenarios 3 and 4, together

Steel has been the dominant material in car body-in-white (BIW) technology since the 1930s (Nieuwenhuis & Wells, 2007). We consider the aluminium BIW because aluminium has greater potential than steel to meet Australians' preferences of for large cars that are cheap to use. The decline in the average rated fuel consumption of new cars since 2005 is largely due to the decline in sales of large cars and the corresponding growth in the sales of small cars (Australian Automotive Intelligence, 2010, p. 28). This shift, however, is counter to the preference of many Australians for large cars. Australians compromised style and size for fuel economy. Aluminium, being less dense than steel, has greater potential for the production of a fuel-efficient, large car.

The internal combustion engine has been the dominant powertrain technology for cars since 1905 (Orsato & Wells, 2007). We consider the BE powertrain because the entry of BE cars into the Australian market is imminent, with automakers having already planned to release BE cars in the next few years and governments having deployed public car charging infrastructure.

3.2. Expanded dynamic hypothesis

In order to accommodate the interventions, we expand two sub-models and introduce a new sub-model, all described in the following subsections. Our expanded dynamic hypothesis is similar to a structural sensitivity analysis. Since reference data are unavailable, we expand our dynamic hypothesis using only documented relationships and probable values of variables.

3.3. Body-in-white sub-model

The ‘body-in-white’ (BIW) sub-model is shown in Figure 5. This sub-model, taken from Stasinopoulos et al. (2012b), expands the demand sub-model. It assumes that (1) all pre-existing BIWs are made from steel and that aluminium BIWs will phase into production over time; and (2) once the ‘Adoption Time of Aluminium BIWs’ has passed, the level of adoption of each material is proportional to the total cost of ownership of each type of car.

We include this sub-model in our hypothesis as a structure with which to investigate the proposed intervention of adopting of aluminium BIWs. We consider an aluminium BIW as the only alternative to a steel BIW because other commercialised alternatives, such as composite materials BIWs, are currently too costly for use in everyday cars.

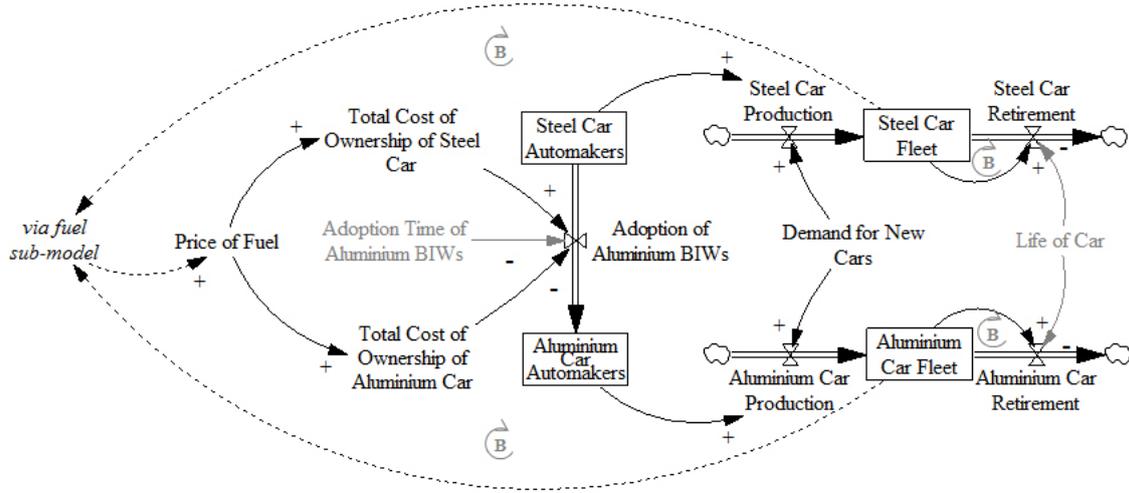


Figure 5. A simplified stock-and-flow diagram of the body-in-white sub-model. Interconnections with the fuel and congestion sub-models (shown in Figure 1) are not shown.

3.4. Powertrain sub-model

The ‘powertrain’ sub-model is shown in Figure 6. This sub-model, similar to the BIW sub-model, also expands the demand sub-model. It assumes that (1) all pre-existing powertrains are ICEs and that BE powertrains will phase into production over time; and (2) once the ‘Adoption Time of BE Powertrains’ has passed, the level of adoption of each powertrain is proportional to the total cost of ownership of each type of car. This sub-model differs from the BIW sub-model by allowing ICE cars to be retired early and replaced by BE cars.

We include this sub-model in our hypothesis as a structure with which to investigate the proposed intervention of adopting of BE powertrains. We consider a BE powertrain as the only alternative to an ICE powertrain because hybrid-electric technologies are a transition technology between ICE and BE technologies, and because we didn’t find any evidence of the Australian market pursuing hydrogen-powered technologies.

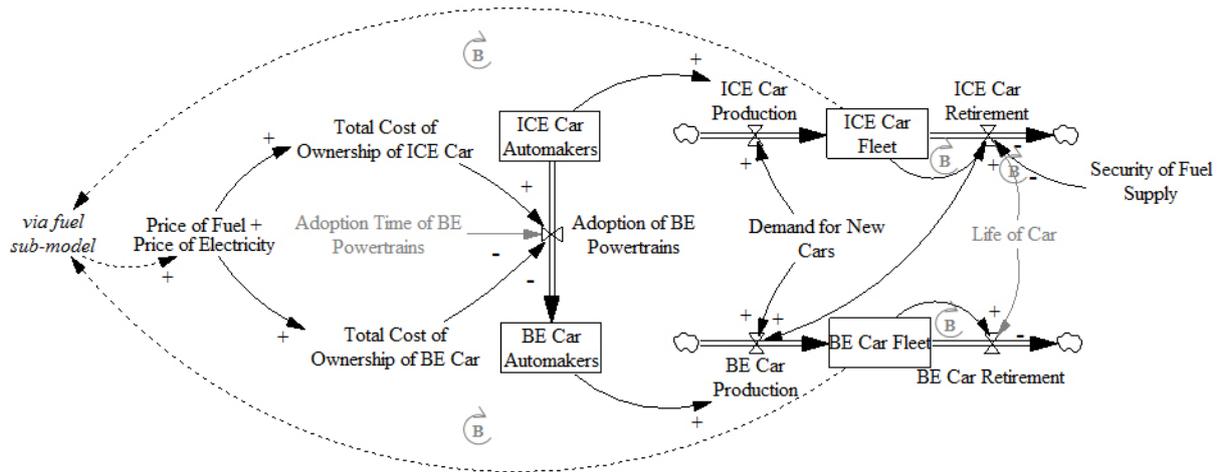


Figure 6. A simplified stock-and-flow diagram of the powertrain sub-model. Interconnections with the fuel and congestion sub-models (shown in Figure 1) are not shown.

3.5. Market competition sub-model

The ‘market competition’ sub-model, shown in Figure 7, is taken from Stasinopoulos et al. (2012a). It assumes that (1) manufacturers of steel BIWs and ICE powertrains will innovate to retain market share, and manufacturers of aluminium BIWs and BE powertrains will innovate to gain market share; and (2) manufacturers of BIWs maximise secondary lightweighting opportunities in other car components.

We include this sub-model in our hypothesis because (1) the steel industry has already initiated many projects to develop lightweight steel car components, including two projects on BIWs, in response to competition from aluminium car components (Carle & Blount 1999; FutureSteelVehicle 2011); and (2) with manufacturers having similarly large investments into ICE powertrain technology, we expect a similar response to competition from BE powertrain technology.

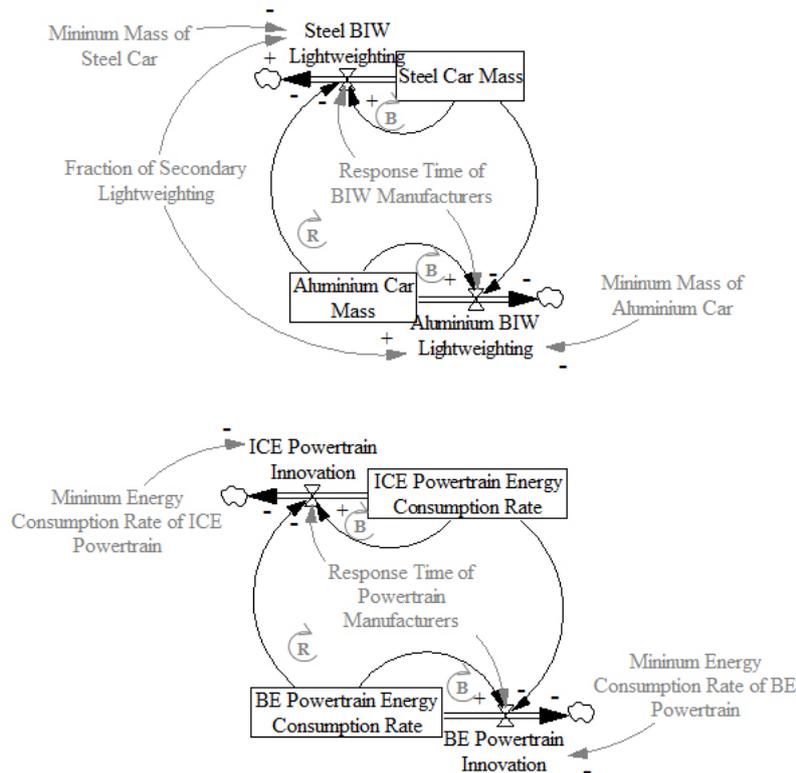


Figure 7. A simplified stock-and-flow diagram of the market competition sub-model.

3.6. Fuel sub-model

The expanded ‘fuel’ sub-model is shown in Figure 8. It assumes similar processes for ICE cars and BE cars, with the exception of the energy source and the security of fuel supply, which does not influence the driving intensity of BE cars.

We include this sub-model in our hypothesis because (1) in Australia, since 2005, the ‘Price of Fuel’ has rapidly grown (Bureau of Infrastructure, Transport and Regional Economics 2009), while, for first time since the data shows, the ‘Driving Intensity of ICE Cars’ declined (Australian Bureau of Statistics 1963-2011; Bureau of Infrastructure, Transport and Regional Economics 2011, p. 76, 81) and the sales of petrol declined (Bureau of Infrastructure, Transport and Regional Economics 2011, p. 135) despite growth in the ‘ICE Car Fleet’ (Australian Bureau of Statistics 1995-2011; Bureau of Infrastructure, Transport and Regional Economics 2011, p. 81); (2) passenger vehicle use and public transportation use have changed inversely to each other for 25 of the 30 years since 1971 (excluding the period between 1984 and 1991, when the price of oil rapidly declined and then rapidly grew) (Bureau of Infrastructure, Transport and Regional Economics 2011, p. 59); (3) the price of electricity in Australia is expected to grow, partly due to a price on carbon emissions; and (4) with the supply-and-demand market mechanism affecting many consumer goods, we expect the price of electricity to grow with the demand for electricity.

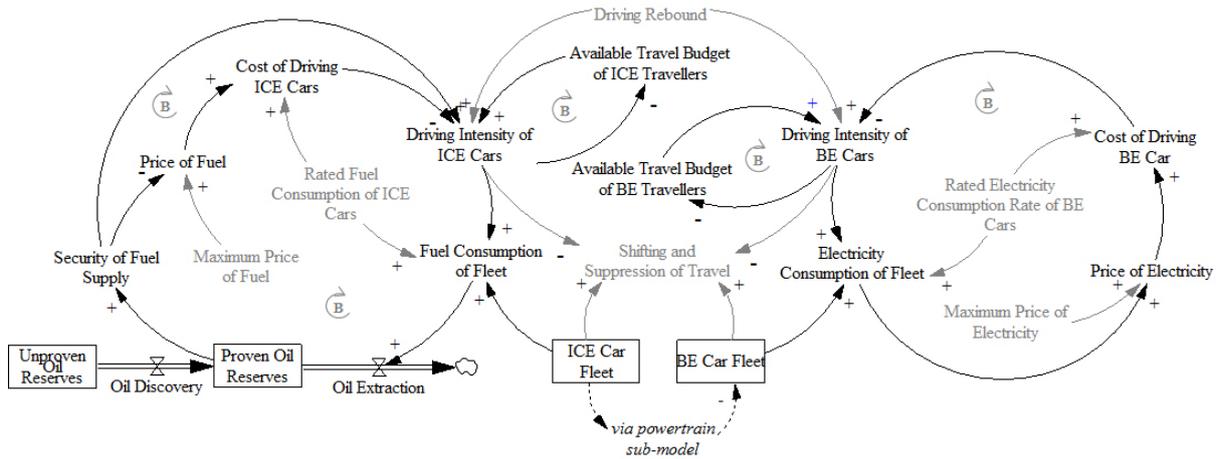


Figure 8. A simplified stock-and-flow diagram of the expanded fuel sub-model. Interconnections with the demand and congestion sub-models (shown in Figure 2) are not shown.

3.7. Exogenous variables

The following variables are exogenous to our model:

- Minimum masses of steel (FutureSteelVehicle 2011) and aluminium (Kelkar et al. 2001; Bertram et al. 2007, p. 29; Schäper 2006) BIWs
- Minimum energy consumption rates of ICE and BE powertrains, assumed to match the maximum practical energy conversion efficiency of the technologies
- Fraction of secondary lightweighting (Bjelkengren 2008)
- Minimum adoption time of aluminium BIWs and BE powertrains, assumed to be similar to the adoption time of other car technologies (Grübler 1991)
- Prices of steel and aluminium, variables not shown in the simplified stock and flow diagrams, vary with fuel price and are used to compute the variables “Total Cost of Ownership of...”
- Prices of BE and ICE powertrains (Mock et al. 2007)

3.8. Ignored processes

Our model ignores the following processes:

- Diversity and variation in the mass and rated fuel consumption of each type of car (Walther et al. 2010)
- Introduction of alternative lightweight materials, such as fibre-reinforced polymer composites
- The occurrence or introduction of alternative powertrains, such as hybrid-electric and any hydrogen-powered technology
- Travellers postponing retiring their cars until manufacturers have the capacity to manufacture the type of car they desire
- Differences in the masses of ICE and BE powertrains
- Changes in the mass of cars for reasons other than competition
- Changes in the energy consumption rate of powertrain technologies for reasons other than competition

3.9. The future of transportation energy consumption

The effects of accumulation and feedback cause many variables of our model to exhibit non-linear behaviour after 2010. Figure 9 compares the behaviour of our simulation model under the five scenarios, as well as a reference curve, which assumes that the sub-models do not operate. The distinct downturn in energy consumption makes all scenarios appear similar and makes the effects of the interventions appear relatively small. We consider the timeframe 2010-2081, during which we can observe the effects of the dynamical processes, and during which we continue to treat the size of the car fleet as an exogenous driving variable but now treat the price of fuel as an endogenous variable. We approximate the price of fuel as the long-term average value that varies inversely with the security of oil supply.

- **No sub-models:** This curve shows the projected transportation energy consumption with all of the sub-models ‘turned off’. It reflects a world view that lacks an appreciation of the potential influence of accumulation and feedback processes. Its numerical value is the product of the use-energy consumption of a current steel ICE car and the size of the car fleet, which grows over time. Use-energy consumption is always growing. Its growth rate slows slightly as population growth slows.
- **Baseline:** This curve shows the projected transportation energy consumption of our original dynamic hypothesis (§2). From 2010, the growth of the car fleet under persistent maximal congestion encourages travellers to shift away from driving, causing the transportation energy consumption to stabilise at a level that reflects the maximum passenger-kilometres that all travellers, collectively, can drive. From 2015, the decline in the security of fuel supply encourages more travellers to shift away from driving, causing the car-fleet energy consumption to decline faster than the public-transportation energy consumption grows. From 2060, the driving intensity approaches a level that enables oil extraction to match oil discovery, causing the security of fuel supply and the driving intensity to stabilise. A portion of the growth of the car fleet shifts to public transportation, causing the transportation energy consumption to grow slowly, as shown in Figure 10(a).
- **Body-in-white:** This curve shows the projected transportation energy consumption with the adoption of aluminium BIWs. The intervention causes car-fleet energy consumption to decline gradually over time, leading to lower transport energy consumption. The influence of the intervention is delayed by the adoption rate and, more significantly, steel cars draining out of the fleet.
- **Powertrain:** This curve shows the projected transportation energy consumption with the adoption of BE powertrains. Initially, the intervention causes car-fleet energy consumption to decline over time, leading to lower transport energy consumption. From 2040, the intervention causes car-fleet energy consumption to stabilise by providing travellers with an alternative to ICE cars, discouraging travellers from public transportation, as shown in Figure 10(b). The influence of the intervention is delayed by the adoption rate and, more significantly, ICE cars draining out of the fleet. The adoption rate of BE cars is faster than the adoption rate of aluminium cars because the low energy costs for BE powertrains are more effective at decreasing total cost of ownership. Market competition enhances the effect of the intervention.
- **Full intervention:** This curve shows the projected transportation energy consumption with both interventions implemented. It is similar to the mean of the BIW and powertrain

curves because the interconnection between the two interventions is small. Initially, the curve is similar to the powertrain curve. From 2040, the curve sits in between the BIW and powertrain curves, similar to the baseline curve. Even without the effects of our original dynamic hypothesis (§2), the adoption of both technologies in a competitive market could halt the growth of car-feet energy consumption for a few decades before the growth in cars regains dominance.

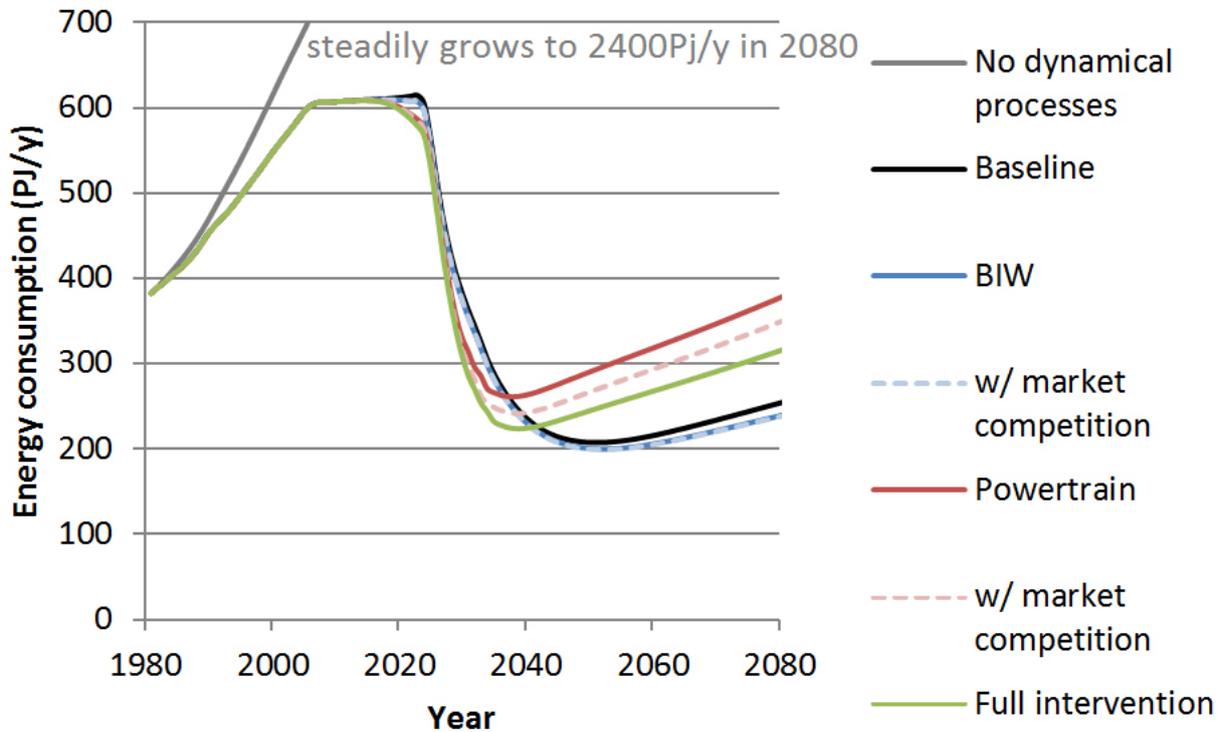


Figure 9. The transportation energy consumption, under a range of scenarios, computed by the simulation model.

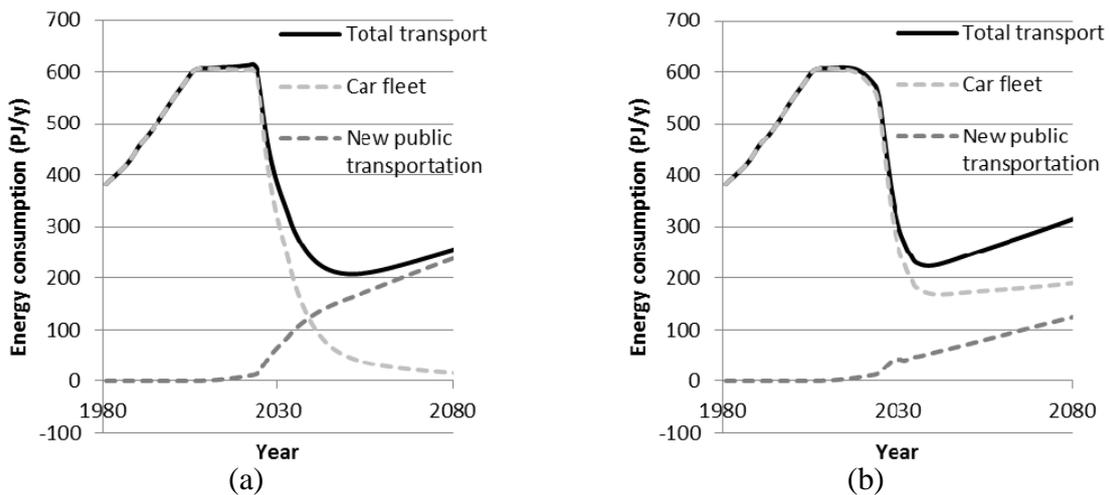


Figure 10. The transportation energy consumption, and its components, computed by the simulation model for (a) the baseline scenario, similar in shape to the body-in-white scenario, and (b) the full intervention scenario, similar in shape to the powertrain scenario.

3.10. Parametric sensitivity analysis

We explore the uncertainty in our model using a parametric sensitivity analysis. Specifically, we explore the best and worst case values of ‘Car fleet’ and ‘Driving intensity of cars’—the two parameters used to calculate the car-fleet energy—by adjusting all exogenous variables. We consider only the baseline scenario, the results of which suggest the range in which the results for the other scenarios lie.

Figure 11 shows the results of the parametric sensitivity analysis. ‘Car fleet’ and ‘Driving intensity of cars’ will always decline. The onset of the declines, however, may be advanced or delayed depending on the conditions—particularly the available oil volume (‘Proven oil reserves’, ‘Unproven oil reserves’) and the available driving space (‘Maximum congestion’, ‘Maximum urban area’).

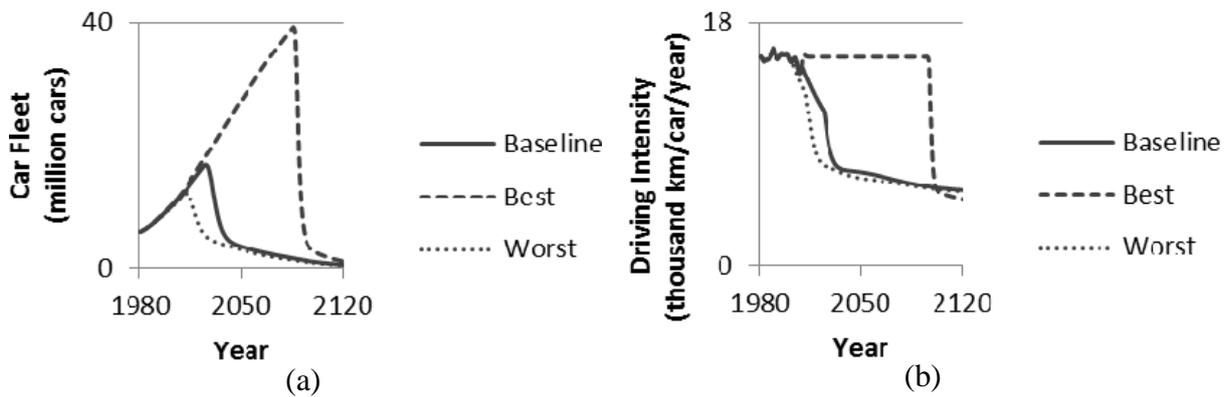


Figure 11. The best and worst case values of (a) ‘Car fleet’ and (b) ‘Driving intensity of cars’, computed by the simulation model.

4. Implications for policy

The simulation model of our original dynamic hypothesis (§2) indicates that, for transportation energy consumption, the price of fuel has been the most influential variable for the last 30 years; congestion and the price of fuel may be the most influential variables in the short-term future; and congestion and the security of fuel supply may be the most influential variable in the long-term future. The simulation model of our expanded dynamic hypothesis (§3) indicates that, compared to the adoption of aluminium BIWs, the adoption of BE powertrains (even in steel cars) is much more effective at decreasing car energy consumption but less effective at decreasing car-fleet energy consumption after 2040. It also indicates that market competition may at least double the direct effect of the technological interventions on car energy consumption.

The results suggest where high-leverage policies may lie. In the short-term, governments could implement a carbon price or similar policies that may shift some travellers away from cars, decreasing car-fleet energy consumption and delaying the conditions of maximum congestion. They could also shift their focus from the fuel consumption of new cars to the driving intensity of the car fleet, further delaying the conditions of maximum congestion and avoiding the delay of inefficient cars draining out of the fleet. Alternatively, governments could cease road building and implement policies that encourage higher urban densities, advancing conditions of maximum congestion and discouraging urban expansion. The money acquired or saved from these types of interventions could be used to support the growth in

public transportation use. Looking toward the long-term, in anticipation of fuel scarcity, governments could focus on policies that create a competitive market environment such that relatively small investments in energy efficient technologies could induce parallel investments by manufacturers of competing technologies. Manufacturers could intensify development of energy efficient technologies, with a focus on non-oil-dependent technologies, securing their ability to compete in an oil-constrained industry.

The results suggest that the conditions for urgent policy intervention could lapse. Current policies for decreasing the resource consumption of cars focus on fuel consumption because the use-energy consumption can comprise more than 90% of the life-cycle energy consumption (Puri et al. 2009). This focus may diminish as use-energy comes into the range of production-energy, leading to lenient requirements for the energy efficiency of next-generation technologies. Without persistent attention, there is a risk that next-generation technologies could not only discourage public transportation use, but could also allow for energy-intensive cars through a relaxed regulatory environment.

5. Summary

The recent strengthening of dynamical processes that involve congestion and oil production could resist the growth of the Australian car-fleet fuel consumption, despite the growth of the car fleet. Many urban areas are approaching conditions of maximum congestion, which imposes a limit on the maximum passenger-kilometres that all travellers, collectively, can drive. Oil production may be declining, increasing the price of fuel and discouraging travellers from driving. Car-fleet fuel consumption may decline under the influence of these two processes in the future. Under this scenario, the adoption of aluminium BIWs could cause car-fleet energy consumption to decline by slightly more, whereas the adoption of BE powertrains could cause car-fleet energy consumption to decline faster down to a point. The adoption of BE powertrains has the counterintuitive effect of increasing the long-term transportation energy consumption by encouraging travellers to continue to drive cars rather than shift to public transportation.

These results suggest that changes in congestion, the price of fuel, and the security of fuel supply have high leverage for influencing car-fleet fuel consumption. Technology substitutions have lower leverage, but this leverage might be enhanced by a competitive market environment.

Acknowledgements

This original research was proudly supported by Australian National University, and the Commonwealth of Australia, through the Cooperative Research Centre for Advanced Automotive Technology.

The authors thank Barry Newell for his assistance in the development of the SD model, and his useful comments and advice in the development of this paper.

References

- Ausubel, JH, Marchetti, C & Meyer, P 1998, 'Toward green mobility: the evolution of transport', *European Review*, vol. 6, no. 2, pp. 137-156.
- Australian Automotive Intelligence 2010, *Australian automotive intelligence yearbook 2010*, 9th edn, Australian Automotive Intelligence, Melbourne.
- Australian Bureau of Statistics 1963-2011, *9309.0: Motor vehicle census*, Commonwealth of Australia, Canberra.
- Australian Bureau of Statistics 1998-2007, *9208.0: Survey of motor vehicle use*, Commonwealth of Australia, Canberra.
- Australian Bureau of Statistics 2008, *3222.0: Population projections, Australia, 2006 to 2101*, Commonwealth of Australia, Canberra.
- Australian Bureau of Statistics 2010, *1310.0: Year book Australia 2009-2010*, Commonwealth of Australia, Canberra.
- Australian Bureau of Statistics 2011, *3218.0: Regional population growth, Australia, 2009-10*. Commonwealth of Australia, Canberra.
- Australian Bureau of Statistics, *Australian Standard Geographical Classification (ASGC)*, unpublished data.
- Bertram, M, Buxmann, K, Chase, R, Furrer, P, Gilmont, B, Hannagan, J, Martchek, K, Morton, P & Rebitzer, G 2007, *Improving sustainability in the transport sector through weight reduction and the application of aluminium*, Aluminum Association, European Aluminium Association and International Aluminium Institute.
- Binswanger, M 2001, 'Technological progress and sustainable development: what about the rebound effect?' *Ecological Economics*, vol. 36, no. 1, pp. 119-132.
- Bjelkengren, C 2008, 'The impact of mass decomposing on assessing the value of vehicle lightweighting', MSc. thesis, Massachusetts Institute of Technology, pp. 37, 38, 61, 66.
- Bureau of Infrastructure, Transport and Regional Economics 2009, *Information Sheet 30: Fuel consumption by new passenger vehicles in Australia 1979-2008*, Commonwealth of Australia, Canberra.
- Bureau of Infrastructure, Transport and Regional Economics 2011, *Australian infrastructure statistics yearbook 2011*, Commonwealth of Australia, Canberra.
- Carle, D. & Blount, G. 1999, 'The suitability of aluminium as an alternative material for car bodies', *Materials and Design*, vol. 20, no. 5, pp. 267-272.
- Cervero, R 2001, *Induced demand: an urban and metropolitan perspective*, 2nd revision, Policy forum: working together to address induced demand.
- Clerides, S. & Zachariadis, T. 2008, 'The effect of standards and fuel prices on automobile fuel economy: an international analysis', *Energy Economics*, vol. 30, no. 5, pp. 2657-2672.
- Federal Chamber of Automotive Industries 2010, *Response to the Public Discussion Paper on Vehicle Fuel Efficiency*, Federal Chamber of Automotive Industries, Canberra, p. 8.

Finnveden, G, Hauschild, MZ, Ekvall, T, Guinée, J, Heijungs, R, Hellweg, S, Koehler, A, Pennington, D & Suh, S 2009, 'Recent developments in Life Cycle Assessment', *Journal of Environmental Management*, vol. 91, no. 1, pp. 1-21.

FutureSteelVehicle 2011, *FutureSteelVehicle: overview report*, WorldAutoSteel, Middletown, OH, USA.

Goodwin, PB 1996, 'Empirical evidence on induced traffic: a review and synthesis', *Transportation*, vol. 23, no. 1, pp. 35-54.

Graham, D & Glaister, S 2002, *Review of income and price elasticities of demand for road traffic*, Centre for Transport Studies, Imperial College of Science, Technology and Medicine.

Greening, LA, Greene, DL & Difiglio, C 2000, 'Energy efficiency and consumption – the rebound effect – a survey', *Energy Policy*, vol. 28, no. 6-7, pp. 389-401.

Grübler, A 1991, 'Diffusion: long-term patterns and discontinuities', *Technological Forecasting and Social Change*, vol. 39, no. 1-2, pp. 159-180.

Hymel, KM, Small, KA & Van Dender, K 2010, 'Induced demand and rebound effects in road transport,' *Transportation Research Part B*, vol. 44, no. 10, pp. 1220-1241.

Kelkar, A, Roth, R & Clark, J 2001, 'Automobile bodies: Can aluminum be an economical alternative to steel?', *Journal of the Minerals, Metals and Materials Society*, vol. 53, no. 8, pp. 28-32.

Kenworthy, JR & Laube, FB 2001, *The millennium cities database for sustainable transport*, International Union of Public Transport (UITP), Brussels, and Institute for Sustainability and Technology Policy (ISTP).

Litman, T 2003, *Generated traffic and induced travel – implications for transport planning*, Victoria Transport Policy Institute, Victoria, BC, Canada.

Marchetti, C 1994, 'Anthropological invariants in travel behavior'. *Technological Forecasting and Social Change*, vol. 47, no. 1, pp. 75-88.

Matiasko, W, Menges, R & Spiess, M 2012, 'Modifying the rebound: It depends! Explaining mobility behavior on the basis of the German socio-economic panel', *Energy Policy*, vol. 41, pp. 29-35.

Meadows, DH 2009, *Thinking in systems: a primer*, Earthscan, London, pp. 145-165.

Mewton, R 2005, 'Induced traffic from the Sydney Harbour Tunnel and Gore Hill Freeway', *Road and Transport Research*, vol. 14, no. 3, pp. 24-33.

Mizobuchi, K 2008, 'An empirical study on the rebound effect considering capital costs', *Energy Economics*, vol. 30, no. 5, pp. 2486-2516.

Nässén, J & Holmberg, J 2009, 'Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden', *Energy Efficiency*, vol. 2, no. 3, pp. 221-231.

Newman, P & Kenworthy, J 2011, 'Peak car use: understanding the demise of automobile dependence', *World Transport, Policy and Practice*, vol. 17, no. 2.

Nieuwenhuis, P & Wells, P 2007, 'The all-steel body as a cornerstone to the foundations of the mass production car industry', *Industrial and Corporate Change*, vol. 16, no. 2, pp. 183-211.

Noland, RB & Lem, LL 2000, 'Induced travel: a review of recent literature and the implications for transportation and environmental policy', Presented at the *European Transport Conference 2000* and the *2000 Conference of the Association of Collegiate Schools of Planning*.

Office of Legislative Drafting and Publishing 2008, *Vehicle Standard (Australian Design Rule 81/01—Fuel Consumption Labelling for Light Vehicles) 2005 Amendment 1*, Commonwealth of Australia, Canberra.

Orsato, RJ & Wells, P 2007, 'U-turn: the rise and demise of the automobile industry', *Journal of Cleaner Production*, vol. 15, no. 11-12, pp. 994-1006.

Puri, P, Compston, P & Pantano, V 2009, 'Life cycle assessment of Australian automotive door skins', *International Journal of Life Cycle Assessment*, vol. 14, no. 5, pp. 420-428.

Schäper, S 2006, 'Sustainability-Optimised Material Selection and Product Design at Audi', in *Sustainable metals management: securing our future - steps towards a closed loop economy*, eds A Gleich, RU Ayres & S Gößling-Reisemann, Springer, Dordrecht, The Netherlands, pp. 535-562.

Schindler, J & Zittel, W 2008, *Crude oil: the supply outlook*, revised edition, Energy Watch Group/Ludwig-Boelkow-Foundation, Berlin, pp. 11, 70.

Sorrell, S, Dimitropoulos, J & Sommerville, M 2009, 'Empirical estimates of the direct rebound effect: a review', *Energy Policy*, vol. 37, no. 4, pp. 1356-1371.

Small, KA & Van Dender, K 2007, 'Fuel efficiency and motor vehicle travel: the declining rebound effect', *Energy Journal*, vol. 28, no. 1, pp. 25-51.

Stasinopoulos, P, Compston, P & Jones, HM 2012a, 'A System Dynamics approach to understanding the influence of lightweight materials on the development of fuel efficient cars', in *Sustainable automotive technologies: proceedings of the 4th international conference*, eds J Wellnitz, A Subic, M Leary & L Koopmans, Springer, pp. 33-38.

Stasinopoulos, P, Compston, P, Newell, B & Jones, HM 2012b, 'A System Dynamics approach in LCA to account for temporal effects—a consequential energy-LCI of car body-in-whites', *The International Journal of Life Cycle Assessment*, vol 17, no. 2, pp. 199-207.

Sterman, JD 2000, *Business dynamics: systems thinking and modeling for a complex world*, McGraw Hill, pp. 182-185.

Su, Q 2011, 'Induced motor vehicle travel from improved fuel efficiency and road expansion', *Energy Policy*, vol. 39, no. 11, pp. 7257-7264.

The Standing Advisory Committee on Trunk Road Assessment, 1994, *Trunk roads and the generation of traffic*, HMSO, London.

Thiesen, J, Christensen, TS, Kristensen, TG, Andersen, RD, Brunoe, B, Gregersen, TK, Thrane, M & Weidema, BP 2008, 'Rebound effects of price differences', *International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 104-114.

Walther, G, Wansart, J, Kieckhäfer, K, Schnieder, E & Spengler, TS 2010, 'Impact assessment in the automotive industry: mandatory market introduction of alternative powertrain technologies', *System Dynamics Review*, vol. 26, no. 3, pp. 239-261.

Wang, H, Zhou, DQ, Zhou, P & Zha, DL 2012a, 'Direct rebound effect for passenger transport: empirical evidence from Hong Kong', *Applied Energy*, vol. 92, pp. 162-167.

Wang, H, Zhou, P & Zhou, DQ 2012b, 'An empirical study of direct rebound effect for passenger transport in urban China', *Energy Economics*, vol. 34, no. 2, pp. 452-460.

Zeibots, ME 2003, 'Before and after Sydney's M4 Motorway: did it make the city more sustainable?', *State of Australian Cities National Conference*.

Zeibots, ME & Petocz, P 2005, 'The relationship between increases in motorway capacity and declines in urban rail passenger journeys: a case study of Sydney's M4 Motorway and Western Sydney Rail Lines', *28th Australasian Transport Research Forum*, Sydney, September 19.